Optimizing Bridge Decks Maintenance Strategies Based on Probabilistic Performance Prediction Using Genetic Algorithm

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A Thesis

in

The Department

of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Civil Engineering) at
Concordia University
Montreal, Quebec, Canada

September 2008

Your file Votre référence
ISBN: 978-0-494-45497-8
Our file Notre référence
ISBN: 978-0-494-45497-8

ABSTRACT

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Bridges are important structures in transportation networks, and their maintenance is essential to public safety. Therefore, there is a critical need for research about evaluating the condition of existing bridges, investigating rehabilitation methods and organizing a management model for these bridges. Bridge Management Systems offer an effective decision-making tool for prioritizing maintenance, repair and rehabilitation (MR&R) activities taking into consideration such factors as budget constraints, suitability of MR&R methods, type and severity of bridge damages, safety, and user cost.

In this research a multi-objective Genetic Algorithm is proposed to find the optimal long-term MR&R strategies for a set of reinforced concrete bridge decks based on the current status of the bridges, the applicability of several MR&R methods and their recovering effects, safety of the network, and the available budget. In this process, uncertainties associated with performance and safety have been modeled. The proposed methodology is demonstrated using a case study about bridges in Montreal partially based on real data obtained from the Ministry of Transportation of Quebec.

ACKNOWLEDGEMENTS

First, I would like to send my utmost gratitude to my advisor Dr. Amin Hammad for his abundant guidance and encouragement throughout this research. He gave me the opportunity to pursue my Master's degree and provided the initial concept for this research project.

I would also like to thank Mr. Adel R. Zaki, Vice President Engineering at SNC-Lavalin Inc., for his fruitful cooperation and invaluable feedback on the content. I am grateful to Mr. Guy Richard and Mr. René Gagnon in the structure department of the Ministry of Transportation of Quebec for providing the MTQ database.

Special thanks also to all my graduate friends, especially group members: Sepideh Zakikhani, Jianxia Yan and Behzad Mostofi for sharing the literature and valuable assistance. And not forgetting to my best friend, Arash Bastani, who has always been there.

My sincere thanks to my parents Mehrnoosh Maani and Mohammadhassan Pakniat, my sister, my brother, and my brother-in-low for their understanding and endless love. Without their support and contributions, it was impossible for me to succeed in this study. To my parents, I dedicated this thesis.

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LIST OF ABBREVIATIONS

Abbreviation	Description
ASCE	American Society of Civil Engineering
BMS	Bridge Management System
CSCE	Canadian Society of Civil Engineering
FHWA	Federal Highway Administration
GA	Genetic Algorithm
HMA	Hot Mix Asphalt
MR&R	Maintenance, Repair and Rehabilitation
MTQ	Ministry of Transportation of Quebec
NBIS	National Bridge Inspection Standard
NCHRP	National Cooperative Highway Research Program
OMT	Ontario Ministry of Transportation
PC	Pre-stress Concrete
RC	Reinforced Concrete

CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

Infrastructure underpins the well being of society by enabling activities that provide public benefit (Infrastructure Canada, 2006). Roads, railways, and bridges are samples of infrastructure components that are vital to facilitate the transportation of goods and people, and hence to the economic activity. Bridges represent 6.4% of all public infrastructure capital stock in Canada, which is almost equivalent to CAD$10 billion (Statistics Canada, 2003). Bridges are, furthermore, key elements in linking national roads and rail networks in the transportation system. The Canada transportation network, which includes more than 80,000 bridges, affects people's daily commute. The significant bridge stock of public capital and the important role that bridges have played in transportation compel bridges to be considered as particular structures.

Nevertheless, many of the bridges have aged and deteriorated from usage and aggressive environments. In Canada, the majority of the nation's bridges was constructed in the 1960's and 1970's and has not received adequate repair and rehabilitation, resulting in severe deterioration in many bridges (Hammad et al., 2007). According to FCM-McGill (1996), 83% of the nation bridges in Canada are not in an acceptable level and need some sort of repair. Many of these bridges are still in operation after being damaged because of deficit in financial resources. The rehabilitation needs for bridges in Canada are about CAD$ 0.7 billion annually (FCM-McGill, 1996).

The problem of these structures is the assessment of actual safety for modern traffic loads and remaining service life. Whatever the reasons are for the deterioration, traffic still passes over them. Failure to identify bridge deficiencies and to repair them can cause greater damages and even jeopardize lives as happened in the recent collapse of De La Concorde Overpass in Laval, Quebec (Johnson et al., 2007). Moreover, dramatic increase in both the weight and number of heavy commercial vehicles imposes exponential damages on the bridges and decreases the safety more rapidly.

Replacement of these bridges with new structures raises financial, technical and political problems. Thus, it has been deemed indispensable to do research about evaluating the condition of existing bridges, investigating maintenance, repair, and rehabilitation (MR&R) methods, and organizing a management model for bridges. Bridge management is important to coordinate and implement the key factors associated with the care of bridges. These factors include collection of inventory data, regular inspection, assessment of condition and strength, repair, rehabilitation, and replacement activities, prioritizing allocation of funds, and safety (Ryall, 2001). A Bridge Management System (BMS) is the mechanism that achieves the coordination and implementation and it aims at assisting bridge managers to: (1) have a clear picture of all bridges being managed, (2) prioritize the bridges in terms of importance relative to the overall road and rail traffic infrastructure, (3) understand the rehabilitation needs of the bridges and consider the MR&R strategies to optimize the cost-benefit ratio, (4) initiate and control the selected MR&R activity, and (5) assess the value of the bridges on a periodic bases by the inclusion of performance indicators (Ryall, 2001). This study is expected to aid bridge management decision making in selecting the optimal bridge MR&R strategies.

In preliminary BMSs, decisions were made only on the basis of lowest cost which yield unsatisfactory results (Patidar et al., 2007). Current BMSs are, however, enhanced to include other objectives, such as bridge condition, safety of the network, and traffic flow distribution. Therefore, by using these BMSs, more balanced, reasonable, and cost-effective decisions can be made (Patidar et al., 2007).

Nevertheless, there are still several limitations in current BMSs: (1) The MR&R activities are limited to three or four major categories: repair, maintenance, rehabilitation, and replacement; that is, an optimal MR&R category is selected instead of an optimal MR&R activity; (2) The objective functions in most of the cases are limited to two functions: cost and condition; and (3) The deterioration model is based on deterministic performance prediction, and thus the uncertainties are not considered.

1.2 RESEARCH OBJECTIVES AND CONTRIBUTION

In responding to the critical bridge management issues, this study aims at developing a methodology that: (1) considers several MR&R activities, (2) involves multiple objective functions, i.e., the applicability of the MR&R methods and their recovering effects, safety of the network, and the available budget, (3) considers uncertainties associated with performance and safety, and (4) comprises selection of MR&R choices based on a Genetic Algorithm (GA).

Inasmuch as bridges are managed at a network level rather than a project level, it is likely to select the optimal MR&R activities for a network of bridges as opposed to a single bridge. Therefore, in the present study, the MR&R strategies are optimized based on the network profits.

In order to effectively recognize the damages on a bridge, existing BMSs classify the bridge elements into simpler typologies, and hence define a group of MR&R activities for each category. Deck, super-structure, and sub-structure are three categories that are commonly used by BMSs. This study specifically focuses on bridge decks, yet the proposed methodology could be applied on other bridge elements. As the majority of bridge decks are made by reinforced concrete (RC), only bridges with RC decks are reflected in the present study.

1.3 THESIS ORGANIZATION

This study will be presented as follows:

Chapter 2 Literature Review: This chapter reviews the history of BMSs by classifying them into three generations. In addition, optimization techniques including classical and modern methods are covered and their applications in bridge MR&R are discussed. Furthermore, several approaches for creating bridge performance models are introduced. At the end, the more commonly used MR&R methods in repairing RC bridge decks and typical defects on RC bridge decks are presented.

Chapter 3 Methodology: In this chapter, multi-linear performance and safety models are introduced to predict the future condition of bridges. Moreover, the basic task is developed upon which the alternative bridge actions could be evaluated. This is done by establishing the following set of goals and criteria: (1) The total benefits of MR&R strategies should be maximized, i.e., recovering effect, applicability, and safety; (2) The MR&R activities should be chosen to give the best match possible to the types of damages and the deterioration level of each bridge; (3) The uncertainties associated with performance and safety should be modeled; (4) The MR&R activities should satisfy the performance and safety criteria; and (5) The total cost should be minimized and should not exceed the budget limitation. The methodology, at the end, results in the selection of optimal bridge MR&R activities.

Chapter 4 Problem Formulation: In this chapter, the selected objective functions, i.e., recovering effect, applicability, safety, and cost, are mathematically formulated. Constraint functions are also formulated to guarantee the bridge network safety and satisfy the budget limitation. The equations are later integrated to formulate the fitness function. At the end, the problem is coded in Matlab-R2007a to model the GA.

Chapter 5 Case Study: In this chapter, the proposed methodology is demonstrated using a case study of bridges in Montreal based on real data obtained from the Ministry of Transportation of Quebec (MTQ).

Chapter 6 Summary, Conclusions, and Future Work: This chapter summarizes the present research work, highlights its contributions, and suggests recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter starts by reviewing the history of Bridge Management Systems (BMSs) which are classified into three generations: first, second, and third generation. Thereafter, optimization techniques including classical optimization methods and modern optimization methods are covered. Optimization methods used in maintenance, repair, and rehabilitation (MR&R) of bridges are also illustrated. As a result, Genetic Algorithms (GAs) have been selected as an optimization tool in this study. This is forwarded by a section describing the working principals of GAs.

In order to have an appropriate bridge MR&R strategy, the existence of a suitable bridge performance model is essential. Thus, bridge performance models are explained in Section 2.5. These models rely on time-based, performance-based, or reliability-based interventions. In accordance with these interventions, a multi-linear model is proposed in the next chapter.

In Section 2.6, MR&R methods for reinforced concrete (RC) bridge decks are presented. The more commonly used MR&R methods in Quebec are also discussed. Section 2.7 reviews typical defects on RC bridge decks.

2.2 HISTORY OF BRIDGE MANAGEMENT SYSTEMS

The majority of the nation's 80,000 bridges in Canada were constructed in the 1960's and 1970's (Hammad et al., 2007) when transportation networks were expanding in an explosive rate after the second word war. Furthermore, harsh weather of Canada and lack of inspection made these bridges deteriorate more rapidly. Many concrete bridges designed to serve for more than 40 years are in critical demand for repair only after five to ten years and some of them may need to be replaced after 15 years (Yehia et al. 2008). Therefore, an appropriate bridge inspection guideline has been deemed indispensable.

In 1971, the Federal Highway Administration (FHWA) of the United States established the National Bridge Inspection Standard (NBIS) for the proper safety inspection and evaluation of highway bridges (FHWA website, 2008). Although the NBIS guided bridge engineers to assess the condition of bridges and to specify the deteriorated bridges, not all the bridges could be repaired or maintained on account of the fact that the budget was always limited. As a result, researches on BMSs have begun.

2.2.1 First Generation of BMSs

The first generation of BMSs provided a long term bridge MR&R strategy through the life cost analysis. They mostly considered bridges or bridge decks at the project level while condition and cost were optimized. In a study done by Manning and Ryell (1980), decision criteria that can be used to identify the most appropriate method of rehabilitation for concrete bridge decks have been introduced. Thenceforth, a mathematical model for evaluating alternative strategies for bridge deck protection, repair, rehabilitation, and replacement was developed by Cady (1985) with the goal of providing recommendations based on minimum costs.

In 1986, a demonstration project was initiated by FHWA to provide the foundation for the development of a generic bridge management system, later named Pontis. The first version of Pontis was completed and released as public domain software in January of 1992 (Thompson et al., 1999b).

Pontis is based on cost minimization and condition maximization of bridge elements; including super-structure, sub-structure, and deck (Cambridge Systematics, 2005). Pontis includes many features. The condition data included in the system are detailed. The bridge is divided into individual elements, or sections of the bridge which are comprised of the same material, and can be expected to deteriorate in the same manner (Czepiel, 1995). The condition of each element is reported according to a condition state, which is a quantitative measure of deterioration. Pontis has received further update considering probabilistic deterioration model and user cost; consequently, second generation of BMSs has been produced.

2.2.2 Second Generation of BMSs

There were several limitations in the first generation of BMSs: (1) Bridges were considered in the project level instead of the network level; (2) The bridge deterioration model was based on deterministic performance prediction; and (3) The optimization techniques could not search through the whole feasible solutions. These shortcomings caused researches on the second generation.

As it was mentioned above, revised versions of Pontis overcome some of the limitations. For instance, Pontis views bridge deterioration as probabilistic and recognizes the uncertainties associated with deterioration rates. It uses the Markovian chain to model deterioration of the bridge elements (Czepiel, 1995). Moreover, Pontis estimates accident costs, user costs resulting from detours, and travel time costs. This information is used in the optimization models to examine trade-offs between options. Pontis also applies a top-down analytical approach; thus, it optimizes the network before determining individual bridge projects (Czepiel, 1995). All these improvements make Pontis one of the today's primary tools used for bridge management.

In 1993, another BMSs came into existence called BRIDGIT. This project grew out of a National Cooperative Highway Research Program (NCHRP) project to develop a model of effective bridge management at the network level (Czepiel, 1995).

BRIDGIT is very similar to Pontis in terms of its modeling and capabilities. The system models the deterioration as a Markov process and cost models are determined in a similar way (Czepiel, 1995). Furthermore, BRIDGIT requires data at an element level and reports the condition of the elements in terms of condition states.

However, BRIDGIT and Pontis vary in some aspects. The primary difference between them lies in the optimization model. BRIDGIT adapted the bottom-up approach to optimization. The advantage is that BRIDGIT can perform multi-year analysis and consider delaying actions on a particular bridge to a later date. Pontis only has this capability at a network level. Bottom-up programming provides better results for smaller bridge populations than top-down programming. The disadvantage is that the system is slower than Pontis (Czepiel, 1995). Another difference between the two systems is the ability of BRIDGIT to define and distinguish between specific MR&R activities for elements when determining feasible solutions.

The Ontario Ministry of Transportation (OMT) has, likewise, provided a new BMSs in 1998, named OBMS (Thompson et al., 1999a). The use of object-oriented methods for design and development, the ability to incorporate third-party capabilities for mapping and document management, and the introduction of a potentially fast process for analyst-in-the-loop optimization at both the network and project levels made OBMS different from previous BMSs.

Parallel to initiation and improvement of such BMSs, some studies have been done to establish decision support models for the BMSs. For example, in a study done by Jacobs (1992), a mixed-integer mathematical model was presented to optimally schedule long-term bridge deck rehabilitation and replacement activities. This model was applicable to multiple bridge decks and was driven by overall cost considerations.

Liu et al. (1997), furthermore, used genetic algorithms (GAs) to implement the deck rehabilitation plan of a network of bridges aiming to minimize the total cost and deterioration. The main reason of using GAs was overcoming the complicated relationship between the rehabilitation cost and deterioration degree of bridges. Thereafter, GAs have been developed by other researchers for the same purpose (Liu and Frangopol, 2004; Miyamoto et al., 2000; Morcous and Lounis, 2005). It will be discussed later in Section 2.3.

2.2.3 Third Generation of BMSs

In spite of the fact that the selection of bridge MR&R activities where central to bridge experts' researches over the past three decades, there are still some vague parts: (1) The objective functions were limited to two functions: cost and condition; and (2) The MR&R methods were limited to three or four major categories: repair, maintenance, rehabilitation, and replacement.

Some studied have been aimed to involve more objective functions in the bridge MR&R strategies. Liu and Frangopol (2004) were among the first researchers who considered three objective functions: condition index, safety index, and cumulative MR&R cost. They proposed a multi-objective genetic algorithm to select the optimal MR&R strategy for a single bridge deck. Uncertainties associated with the deterioration process under no MR&R activities and under MR&R strategies were confined to the parameters that define the selected computational models and their effects were evaluated by means of Monte Carlo simulations.

In addition, Lounis (2005) presented an approach for network level bridge MR&R optimization that prioritized bridge MR&R activities by considering condition rating, traffic disruption, and MR&R costs. The Pareto optimality concept has been introduced as the solution. Markov chain was also used to model the condition rating of bridges.

In a study by NCHRP, furthermore, five objectives were defined to be optimized: preservation of bridge condition, traffic safety enhancement, protection from extreme event, agency cost, and user cost (Patidar et al., 2007). Lee and Kim (2007), similarly, considered recovering effect of MR&R methods, applicability indices, and cost to select the short term bridge decks MR&R strategy.

In the present study, four objective functions were investigated for the purpose of having an appropriate modeling in BMSs. These objective functions are: recovering effect of MR&R methods, applicability indices, safety of the network, and life cycle cost.

The second weakness of available BMSs is limitation in the definition of MR&R methods. This lack of knowledge will be discussed later in Section 2.6.

2.3 OPTIMIZATION TECHNIQUES

Optimization can be defined as finding the best solution of a specific problem under given conditions (Pun, 1969). Therefore, optimization problems could be known by three basic ingredients: (1) A set of objective functions which should be minimized or maximized; (2) A set of variables which affect the values of objective functions; and (3) A set of constraints that allow the variables to take on certain values but exclude others. In other words, the optimization is finding values of the variables that minimize or maximize the objective functions while satisfying the constraints (Optimization Technology Centre, 1996).

For twice-differentiable functions, unconstrained problems can be solved by finding the points where the gradient of the objective function is zero. However, existence of derivatives is not always guarantied. Many methods were devised for specific situations. In general, optimization methods are divided into two categorise: classical methods and modern methods.

2.3.1 Classical Optimization Methods

Classical optimization methods use an initial solution (central node) which has the entire responsibility or coordinating responsibility of deciding the optimal solution or near optimal solution to the problem (Davidsson et al., 2003). For example, the Simplex method and methods based on decomposition are classical methods. Also methods of solving integer and non-linear problems are included, e.g., Branch and Bound. The classical methods are presented in the third column of Table 2-1.

Table 2-1 Relationships between formulations and methods (modified from Pun, 1969)

Process	Problem Formulation	Method
Static	Unconstrained problems	Ordinary theory of maxima and minima
	Constrained problems	Lagrange-multipliers method
	Linear programs (programming)	Simplex method
	Nonlinear programs (programming)	Convex programming method
Dynamic	Linear problems	Variational methods
	Linear programs (programming)	Branch and bound algorithms
	Linear time-varying problems	Dynamic programming methods
	Nonlinear problems	Method of gradients

The first step in solving an optimization problem is formulating the problem and its constraints in a mathematical format. Thereafter, the method should be chosen based on whether (1) They are static or dynamic; (2) The problem function is constrained or not; (3) They are linear or non linear; and (4) They are one-dimensional or multi-dimensional (Pun, 1969). Table 2-1 shows the relationship between problem formulation and different classical methods.

Deb (1995) divided classical optimization methods into two distinct groups: direct methods and gradient-based methods. In direct search methods, only the objective function and the constraint values are used to guide the search strategy. Gradient-based methods, in contrast, use the first and/or second derivative of the objective function and/or constraints to guide the search process.

There are some limitations in classical optimization methods. The direct search methods are usually slow and require many function evaluations for convergence inasmuch as derivative information is not used (Deb, 2001). On the other hand, gradient-based methods quickly converge near optimal solution, yet are not efficient in non-differentiable or discontinuous problems which are very common in practice, e.g., in BMSs, MR&R activities are represented by discrete values.

Moreover, there are some common difficulties with most classical optimization methods, either direct or gradient-based techniques, such as: (1) The convergence to an optimal solution depends on the chosen initial solution; (2) Most algorithms tend to get stuck to a suboptimal solution; (3) Algorithms are not efficient in handling problems having a discrete search space; and (4) Algorithms cannot be efficiently used on a parallel computer (Deb, 2001).

The branch and bound algorithms, as an example, have one nice property: they guarantee that the optimum solution will be found if the problem can be formulated properly. However, they have one fatal flaw: they are combinatorial explosive, and hence will take excessive time and possibly computer memory for large scale problems (Chinneck, 2006). For instance, problem of finding optimal bridge MR&R strategy for a network of bridges is a large scale problem on the ground that the number of feasible solutions increases exponentially by the number of bridges in the network, the study period, and the number of MR&R activities.

2.3.2 Modern Optimization Methods

As a result of the classical methods' limitations, modern methods (heuristic methods) came into existence. A heuristic is a method that is not guaranteed to find the optimum, but usually gives a very good solution which is called near optimal solution (Chinneck, 2006). Heuristics are generally relatively fast and they do not have the limitations of classical methods. Table 2-2 shows some of modern methods (Chinneck, 2006; Dorigo and Stutzle, 2004).

Table 2-2 Modern optimization methods

Category	Method
Branch and bound variants	Beam search Stopping branch and bound with a guarantee of closeness to optimality
Problem-specific heuristics	Problem-specific heuristics
Controlled random search	Evolutionary algorithms (including GAs) Simulated annealing Tabu search
Pure random search	Pure random search
Swarm Intelligence	Ant colony optimization Bees algorithms

Modern optimization techniques are often simulated by interesting insights from other fields. Simulated annealing is, for instance, based on analogy to the heat-treatment of metals (known as annealing). When metals are carefully annealed certain very desirable properties such as hardness or flexibility can be obtained (Chinneck, 2006). In addition, GAs use an analogy to chromosome encoding and natural selection to evolve near optimizatal solutions. GAs will be reviewed latter in this chapter.

Likewise, ant colony optimization is inspired by the foraging behaviour of ant colonies and target discrete optimization problems (Dorigo and Stutzle, 2004). The main idea is that the self-organizing principles which allow the highly coordinated behaviour of real ants can be exploited to coordinate populations of artificial ants that collaborate to solve computational problems.

2.3.3 Optimization Methods in Bridge MR&R

The selection of appropriate MR&R methods for a network of bridges is a complex process. It is hard to decide which bridges need repair and what kind of activities should be used for the bridge to maximize defined benefits. The defined benefits are objectives, e.g., cost. These objectives, moreover, may conflict with each other and make the problem more complicated. To be noted, two objectives of an optimization problem are called "conflicting objectives" if their aims cannot be fully gained at the same time (Liu et al., 1997). For instance, minimization of cost and maximization of performance level are conflicting objectives because maximizing the performance level without considering the budget constraint does not result in minimized cost.

Therefore, selection of an optimal bridge MR&R strategy is a constrained nonlinear multi-dimensional problem that cannot easily be solved by simple optimization techniques. For example, ordinary theory of maxima and minima that calculate the optimal point by equating the first deviation of the main function to zero cannot solve such problem because: (1) There is not a continues function; and (2) There are some constraints that should be satisfied, e.g., budget and safety. Likewise, Lagrange-multipliers method cannot find the optimal solution on the ground that the objective functions and constraint functions are both nonlinear and multi-dimensional. This will be illustrated later in Chapter 4.

Since the early 1990's, several optimization techniques have been developed for selecting optimal bridge MR&R strategies. Pontis uses divide-and-conquer strategy to break a large optimization problem into smaller pieces (Cambridge Systematics, 2005). In other words, a network of bridges is considered not as a set of individual bridges, but as a combination of structural elements. This approach overcomes the multi-dimensionality of problem and results in optimal strategies for each element. Then, MR&R activities and costs can be combined for the element on each bridge. Finally, the problem of which bridge should be given priority for preservation activities can be addressed through a different model. Similar to Pontis, a research by NCHRP (Patidar et al., 2007) divided the problem into smaller parts and applied similar method to create a multi-objective optimization tool for BMSs.

BRIDGIT and OBMS, in contrast, adapted the bottom-up approach to optimization. The optimization model performs an analysis in two steps. In the first step, different life cycle MR&R strategies are developed for each bridge in the network. In the second step, an incremental benefit-cost analysis is performed to prioritize needs. This step ends in the selection of the most effective improvement strategies while the defined constrained or unconstrained budget are satisfied as well as the performance level of bridges (Hawk, 1999; Thompson et al., 1999a).

Cady (1985) was first to develop a simple mathematical model to evaluate the condition of bridge decks and then Jacobs (1992) proposed a mixed integer mathematical model to optimize a long-term bridge deck MR&R strategy.

Decision trees have been also built up for the same purpose (Thompson et al., 1999a; Yehia et al., 2008). These decision trees have been based on bridge expert opinions and assist in selecting proper MR&R activity for a deteriorated bridge.

However, the methods discussed above are not particularly robust in finding the near-optimal solution (Liu et al. 1997). The number of feasible solutions increases exponentially by the number of bridges in the network, the study period, and the number of MR&R activities. Therefore, it is almost impossible to compare all MR&R strategies and select the optimal one. Furthermore, the simple weighted method that has been commonly used (Thompson et al., 1999a) to integrate all objective functions into a single objective function can bias the results because the weights are subjective (Wu, 2008).

For the first time, Liu et al. (1997) introduced GAs to BMSs. They proposed a GA to implement the deck rehabilitation plan of a network of bridges aiming to minimize the total cost and deterioration. The ability to produce new MR&R strategies based on initial strategies let the GAs search through the whole feasible range and made them special tools as a search technique. Then, GAs have been developed by other researchers for the same purpose (Lee and Kim, 2007; Liu and Frangopol, 2004; Lounis, 2005; Miyamoto et al., 2000; Morcous and Lounis, 2005).

In recent years, GAs have been widely used in different areas, e.g., electrical, mechanical, and civil engineering, transportation networks, and medical research (Wu, 2008). This extensive use of GAs proves that these algorithms are useful tools in solving multi-objective optimization problems and therefore they have been exploited in the present study.

It should be mentioned that some other modern optimization methods such as simulated annealing, ant colony optimization, and bees algorithms could be applied in the selection of optimal bridge MR&R strategies. Nevertheless, GAs have been selected as an optimization tool in this study because they are simple to program (Chinneck, 2006). Moreover, extensive use of GAs in various domains forced researchers in computer science to provide user-friendly GA tools, which makes GAs' modeling straightforward. An important example is Matlab-R2007a software, which has a toolbox named "Genetic Algorithm and Direct Search Toolbox". The toolbox is specialized in solving optimization problems via GAs. It will be explained later in Chapter 4.

2.4 GENETIC ALGORITHMS

GAs are part of evolutionary computing, which was invented by Rechenberg in 1960s (Obitko, 1998). The concept was further developed by Holland (1975), who introduced GAs to combine problem solving algorithms.

GAs are search and optimization techniques, which are established on the principals of natural genetics and natural selection (Deb, 2001). Figure 2-1 presents a schematic diagram of a simple GA. The GA working principles can be summarized in the following steps:

Step 1

A GA begins with a random set of solutions called an initial population. Each solution is represented by chromosomes. Once the initial population is created, each is evaluated and a fitness value is assigned to each solution. The evaluation of a solution means calculating the objective function value and constraint violations (Deb, 2001).

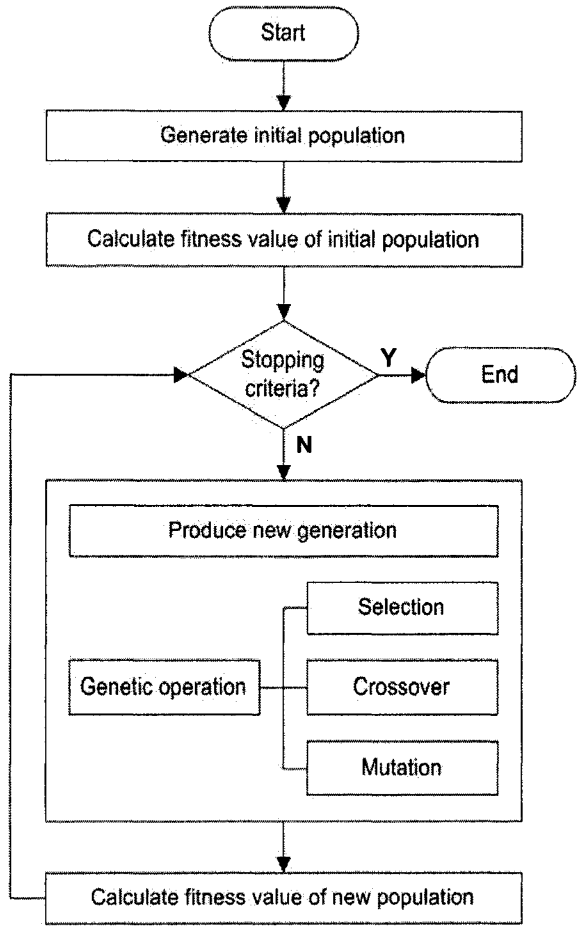


Figure 2-1 Sample genetic algorithm (modified from Turban, 1995)

Step 2

Then, stopping criteria (termination conditions) is checked. If stopping criterion is not satisfied, the population of the solutions is modified by three main operators (selection, crossover, and mutation) and a new population is produced aiming to reach a better population. The more suitable any solution is, the more chances it has to reproduce (Deb, 2001; Obitko, 1998).

Step 3

This process, production of a new generation and calculation of the new solutions' fitness values, is repeated until any stopping criterion is satisfied; for example, number of populations exceeds a certain amount or improvement of the best solution be less than a defined value (Deb, 2001; Obitko, 1998).

2.5 BRIDGE PERFORMANCE MODEL

Current BMSs, including Pontis, BRIDGIT, and OBMS, rely on the following assumptions to model deterioration of bridges: (1) A Markovian deterioration model has been defined to predict the probability of transition among condition states; (2) Deterioration is assumed to be a single step function, that is quantities may not transit more than one condition state; and (3) Transition probabilities are not time variant (Frangopol et al., 2001).

The limitations of the above assumptions have been revealed by Frangopol and Das (1999). The main limitations could be summarized as: (1) The Markovian model is not able to consider the entire history of the bridge deterioration process; and (2) Bridge system performance is not addressed; for instance, only element failures are considered instead of the whole bridge failure.

It is essential to develop an appropriate bridge performance model in order to predict the performance of bridges in their life cycle. In this study, a multi-linear model proposed by Frangopol et al. (2001) has been adapted to predict the performance of bridges under no MR&R activities and MR&R strategies. It will be illustrated later in Chapter 3.

While there is no MR&R activity applied to a bridge, the performance level of the bridge stays the same for a certain period of time, which is named time to damage initiation T_0. Then, the bridge will be deteriorating by a constant deterioration rate α, until it passes a target performance value P_{target}, and fails. Figure 2-2 shows the performance model of a bridge under no MR&R activities.

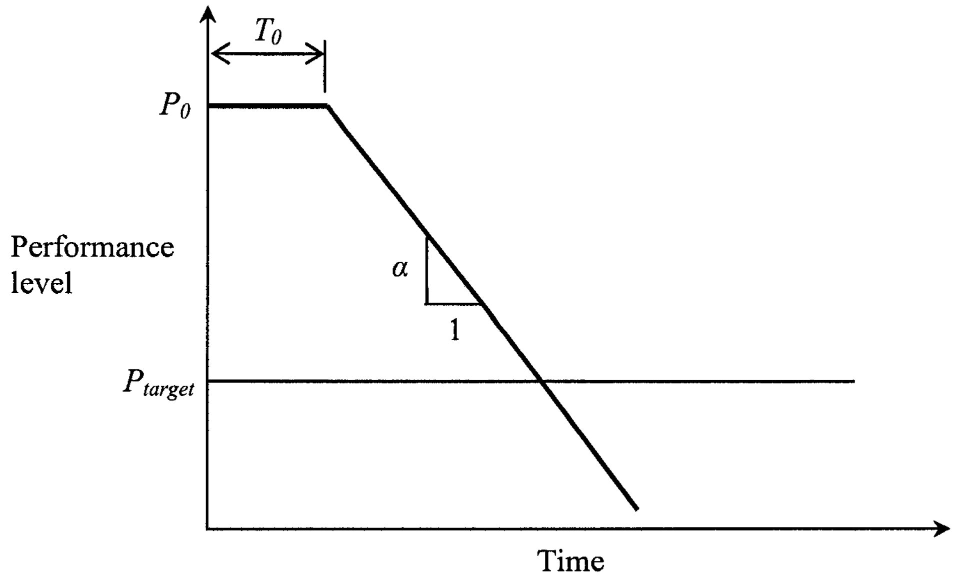


Figure 2-2 Performance model of a bridge under no MR&R activities

The selection of MR&R strategies relies on three types of interventions: time-based, performance-based, and reliability based. The difference between these interventions results in dissimilar bridge performance models.

2.5.1 Time-Based Intervention

The time-based intervention triggers MR&R actions at predefined time intervals, e.g., annual bridge cleaning and snow removals (Liu and Frangopol, 2004). These actions provide preventive improvement to assure minimum bridge performance. Figure 2-3 depicts the performance model of a bridge under time-based MR&R strategy. The first MR&R activity is applied when the time of first application T_{p0}, is reached. Then, it impacts on the bridge performance upon certain time T_{pd}. The second MR&R activity is applied once the time interval of subsequent application T_p, passed. This process is repeated continuously.

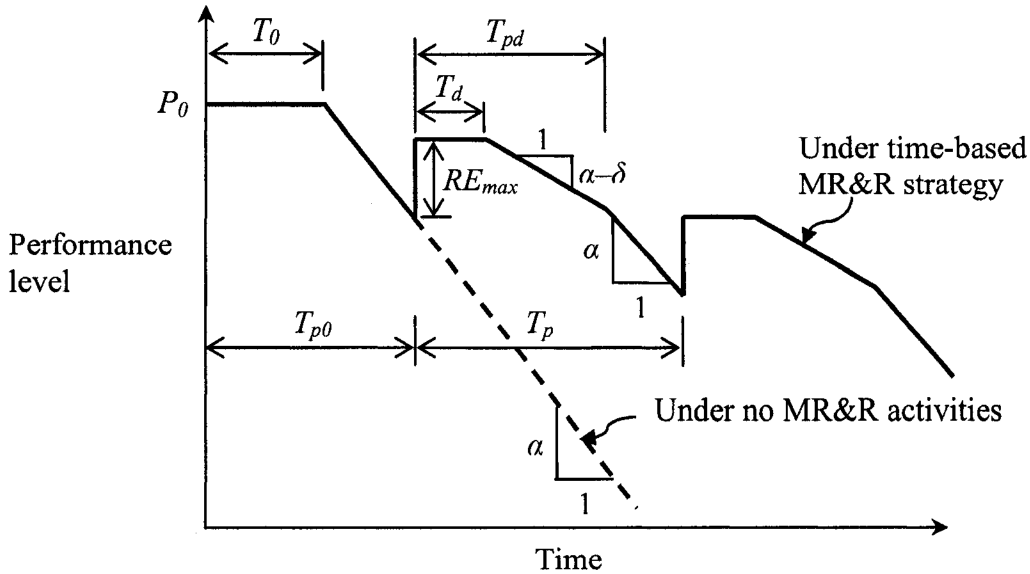


Figure 2-3 Performance model of a bridge under time-based MR&R strategy (modified from Liu and Frangopol, 2004)

It should be mentioned that an MR&R activity affects the performance level of the bridge by the following aspects regardless of the selected intervention: (1) instant improvement of performance index upon application, (2) delay of performance deterioration upon application, and (3) subsequent alleviation of performance deterioration, followed by complete loss of MR&R functionality after a period of effective time (Frangopol et al., 2001; Liu and Frangopol, 2004; Noortwijk and Frangopol, 2004). These effects can be characterized by a set of parameters including maximum recovering effect RE_{max}, time delay in deterioration T_d, reduction in deterioration rate α-δ, and duration of MR&R effect T_{pd}.

2.5.2 Performance-Based Intervention

The performance-based intervention suggests applying an MR&R action as a target performance value is reached, and thereby results in essential improvements (Liu and Frangopol, 2004; Noortwijk and Frangopol, 2004). Increasing slab thickness and attaching steel plate could be examples of essential improvements. The performance model of a bridge under performance-based MR&R strategy is presented in Figure 2-4.

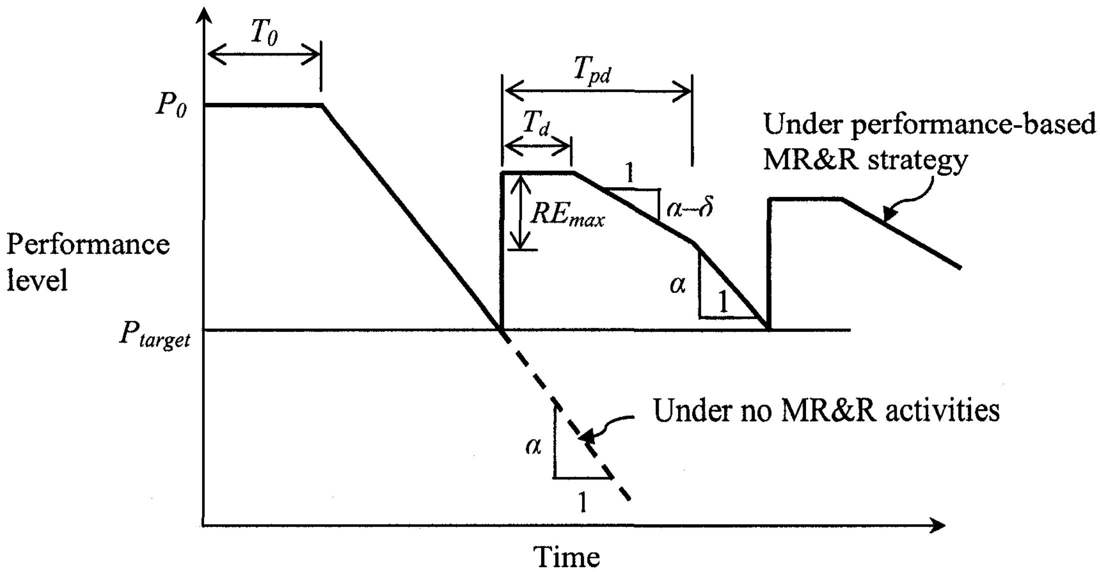


Figure 2-4 Performance model of a bridge under performance-based MR&R strategy (modified from Liu and Frangopol, 2004)

2.5.3 Reliability-Based Intervention

Reliability-based intervention, likewise, proposes to utilize an action once a target value is reached, but the target is a threshold for reliability (Frangopol et al., 2001; Noortwijk and Frangopol, 2004). In fact, there are fundamental differences between performance-based and reliability-based interventions: (1) The performance model refers to deterioration mostly based on visual inspection, whereas the reliability model refers to the deterioration as a measure of structural performance defined by the reliability index; (2) The performance-based and reliability-based strategies may have little or no correlations; and (3) An MR&R activity due to performance-based intervention may have no effect on reliability level (Noortwijk and Frangopol, 2004).

The main unsatisfactory aspect of the reliability-based model is lack of real data in defining reliability of bridge elements. Therefore, in the present study, this model has not been employed.

2.6 MAINTENANCE, REPAIR, AND REHABILITATION METHODS

Currently, many repair methods are used to maintain bridges. The selection of repair methods is made based on materials, construction techniques, types of damages and available budget. However, researchers have attempted to simplify the process of selecting methods by suggesting different classifications of MR&R needs. It should be mentioned that the terms maintenance, repair, and rehabilitation do not have a universal, agreed-upon definition, and are used interchangeably in different research papers are reports as can been seen in the references (Brinckerhoff, 1993; Cady, 1985; Frangopol and Das, 1999; Frangopol et al., 2001; Jacob, 1992; Lee and Kim, 2007; Liu et al., 1997; Liu and Frangopol, 2004; Manning and Ryell, 1980; Miyamoto et al., 2000; Morcous and Lounis, 2005; Noortwijk and Frangopol, 2004; Thomas and Deen, 1993; Wu, 2008; Yehia et al., 2008). The following paragraphs introduce the main MR&R categories.

Shallow repair, deep repair, and deck replacement are three levels commonly used by many researchers (Yehia et al., 2008). American Concrete Institute (2003, 2004) defines these methods as follows. Shallow repair is low budgeted repair, which is recommended when the rebars are exposed. In this method, the deteriorated concrete is saw-cut and removed. Then, the surface is cleaned and the repair material is applied and cured. Deep repair, as the secondary level, is required when the deterioration has gone deeper than the top mat of the steel reinforcement. The deteriorated material is chipped off at least 1 in. of the concrete under the reinforcing steel and the repair material is poured once the bars are cleaned. Deck replacement is the last level recognized in this classification. It is a treatment option with highest initial cost and it should always be treated as the last alternative.

In another way of categorization, routine maintenance, repair, rehabilitation, and replacement are delineated by Harper et al. (1990) and Liu et al. (1997). Routine maintenance activities do not affect bridge structure and its function, e.g., timely cleaning and removing snow. Repair activities, however, restore a good surface condition of bridge decks and prolong their life of them, e.g., patching and sealing. Rehabilitation activities restore damaged structures and rehabilitate them to as-new condition, e.g., attaching additional girder or plates. Replacement activities, finally, replace components of the bridge decks with new ones when it is impossible to restore the function of the structure by using repair and rehabilitation activities.

Moreover, Brinckerhoff (1993) suggested dividing MR&R methods into two main levels: non-protective repairs and protective repairs. Non-protective repairs are those which do not provide any water proofing mechanism while protective repairs provide a water proofing mechanism that delays the bridge deck replacement.

While such categorization schemes aim to simplify the selection process, they only offer a means of choosing optimal categories, not optimal methods. Because of the fact that it is important to select a proper MR&R method corresponding to type and severity of damages, this study seeks to overcome this emphasis on categories by presenting MR&R methods for RC bridge decks.

Ministry of Transportation of Quebec (MTQ) in its guideline for rigid pavement maintenance and rehabilitation (Thébeau et al., 2003) recognized 25 MR&R methods. These methods are selected based on weather conditions and availability of materials in Quebec. Table 2-3 summarizes the methods and their unit costs. Most of these methods may apply to repair RC bridge decks, e.g., bonded concrete overly and slab stabilization.

MTQ has, furthermore, determined eleven MR&R methods for RC bridge decks in its database (MTQ database) and has applied them to repair the deteriorated bridges in Quebec. Table 2-4 displays the methods. Some of these methods are too general; for instance, "grouting binder in cracks" does not specify whether "mortar filling" or "polymer injection" or "epoxy injection" should be done. Nevertheless, it is a sagacious choice to define "injection" and let the experts to choose the proper material for the injection based on the bridge specifications, its location, and availability of the material.

This table, in addition, includes the unit costs of different MR&R methods. The unit cost of a method varies very much because of the following reasons: (1) Market factors vary based on the scope of the project or the scale of economy; (2) The urgency of the execution is different; and (3) In some cases, a certain method includes more activities

Table 2-3 Rigid pavement MR&R Methods (Thébeau et al., 2003)

Method	Cost	Unit
Joint resealing	5 to 10	CAD$ / m
Partial-depth concrete repair	250 to 400	CAD$ / m^2
Slab fracturing	1 to 3	CAD$ / m^2
Bonded concrete overlay	25 to 35	CAD$ / m^2
Partial-depth removal	1.5 to 3.5	CAD$ / m^2
HMA recycling techniques	6 to 10	CAD$ / m^2
Fine aggregate spreading	300 to 500	CAD$ / hour
Full-depth concrete repair	250 to 400	CAD$ / m^2
Pressure relief joint		
With dowel bar retrofit relief joint	150 to 200	CAD$ / m
Without load transfer relief joint	30 to 40	CAD$ / m
Slab stabilization	15 to 20	CAD$ / m
Load transfer restoration	40 to 70	CAD$ / dowel
Cross-stitching	15 to 25	CAD$ / m
Slab jacking	Varies from case to case	
Crack sealing	2 to 5	CAD$ / m
Manual cold-mix repair	250 to 500	CAD$ / tonne
Manual hot-mix repair	200 to 350	CAD$ / tonne
Machine patching with HMA	60 to 95	CAD$ / tonne
Drainage improvement or restoration	10 to 35	CAD$ / m
Diamond Grinding	5 to 7	CAD$ / m^2
HMA overlay	1.5 to 2.25	CAD$ / m^2
Unbounded concrete overlay	130 to 170	CAD$ / m^3
Transition treatment	20,000 to 30,000	CAD$ / 40 m transition for two lanes
Reconstruction	700,000 to 1,000,000	CAD$ / km for two lanes
Pavement insulation	5 to 9	CAD$ / m^2
Mechanical sweeping	1,000	CAD$ / km

Table 2-4 RC bridge deck MR&R methods (MTQ database)

Method	Cost range	Cost average	Unit
Cleaning bridge	1 to 50	11	CAD$ / m^2
Resurface of coating layer	15 to 250	32	CAD$ / m^2
Removal of concrete fragments	100 to 3,000	255	CAD$ / hr
Temporary repair of slab	50 to 500	264	CAD$ / hr
Modification of drainage	25 to 10,000	895	CAD$ / unit
Repair of system of drainage	20 to 70,000	2,964	(not available)
Repair of coating layer	20 to 1,000	62	CAD$ / m^2
Repair of concrete paving slab	5 to 1,250	344	CAD$ / m^2
Repair / replacement of grating	125 to 600	363	CAD$ / m^2
Sealing cracks of coating layer	3 to 2,000	40	(not available)
Patching of coating layer	5 to 3,000	83	(not available)

(Belanger and Gagnon, 2008). Some values in this table have no units because, depending on the nature of the MR&R activity, it is sometimes very difficult to suggest a unit cost. It is more complicated to define a unit for a specialized method or a method that is applied very rarely (Belanger and Gagnon, 2008).

Other researchers have also distinguished MR&R methods for RC bridge decks. Yehia et al. (2008) characterized thirteen methods in two categories: non-protective and protective repairs (Table 2-5).

Moreover, Lee and Kim (2007) recognized eight activities as alternative MR&R methods for RC bridge decks (Table 2-6). These methods include a wide range of activities that could fix typical damages, e.g., cracks, scaling, delamination, rebar exposure and corrosion, spalling, leakage, and efflorescence.

Table 2-5 RC bridge deck MR&R methods (Yehia et al., 2008)

Category	Method
Non-protective repair	Non-protective patching (bitumen, cement based mortar, concrete)
	Non-protective overlay
	Non-protective sealing (bitumen, cement based mortar, concrete)
Protective repair	Protective low-slump dense concrete overlay
	Protective steel fiber reinforced concrete overlay
	Protective latex modified concrete overlay
	Hydraulic cement grouting (portland cement plus slag or pozzolanas)
	Epoxy grouting (epoxy resins, polyester resins)
	Polymer injection
	Low pressure polymer spraying
	Penetrating and coating sealers
	Gravity feed resin (epoxy or polymer resin)
	Replacement

Table 2-6 RC bridge deck MR&R methods (modified from Lee and Kim, 2007)

Method	Cost*	Unit
Surface repair	120	CAD$ / m^2
Mortar filling	160	CAD$ / m^2
Epoxy injection	280	CAD$ / m^2
Corrosion inhibiting	420	CAD$ / m^2
Increasing slab thickness	620	CAD$ / m^2
Attaching steel plate	560	CAD$ / m^2
Attaching carbon fiber sheets	520	CAD$ / m^2
Replacement	1420	CAD$ / m^2

* Costs are converted from Korean won (KRW) to Canadian dollar (CAD $).

It is assumed that 1 KRW = 1.15×10^{-3} CAD $

In this study, ten types of MR&R methods are chosen to be considered in RC bridge deck MR&R optimization. Table 2-7 indicates the methods with their specifications (Brinckerhoff, 1993; Karbhari, 1998; Montani, 2006; Thomas and Deen, 1993; US Army Corps of Engineers, 1995; Watson, 2003). These methods include new repair methods, e.g., attaching carbon fiber sheets, as well as typical deck repair methods, e.g., surface repair and latex modified concrete overlay. Some of them are commonly used in Quebec such as mortar filling, polymer injection, and epoxy injection while some others are applied less often, e.g., attaching carbon fiber sheets. A deck is replaced when only any MR&R cost is beyond the replacement cost. Increasing slab thickness is the only MR&R method that affects the performance of bridge sub-structure and super-structure because the dead load of the bridge deck is increased. Therefore, in the studies that consider all bridge elements, the effects of this particular method on all bridge components should be taken into account. The present study does not consider such affects as it focuses on the bridge decks only.

Table 2-7 Selected RC deck MR&R methods

Method (l)	Description	Application
Surface repair (l_1)	This method involves removing deteriorated concrete either by pneumatic hammer or by hydrodemolition, cleaning it to ensure proper adhesion, and applying repair material.	When deterioration depth < ¾ in. (19 mm) When crack width < 0.25 in. (6 mm)
Mortar filling (l_2)	This method is similar to surface repair but the repair material is mortar.	When crack width > 0.25 in. (6 mm)
Polymer injection (l_3)	This method is similar to surface repair but the repair material is polymer.	When crack width < 0.05 in. (1.27 mm)
Epoxy injection (l_4)	This method is similar to surface repair but the repair material is epoxy.	When crack ranges from 0.003 to 0.25 in. (0.076 to 6 mm)
Corrosion inhibiting (l_5)	This method involves removing deteriorated concrete up to 1 in. under the reinforcement steel, cleaning bars, adding bars if there is section loss, and applying repair material.	When the concrete deterioration extends to the top mat of steel reinforcement.
Latex modified concrete overlay (l_6)	This method involves sacrifying a thickness of o.25 in. (6 mm) to remove all oil, grease, and solvents, cleaning the surface by air or water jets, mixing the latex modified concrete at the site, placing and distributing the latex modified concrete.	When crack width > 0.25 in. (6 mm) When preventive overlay is required to protect against salt, temperature extremes, and moisture.
Increasing slab thickness (l_7)	This method is similar to latex modified concrete overlay but the main filling material is silica fume concrete which produces a very dense concrete.	When crack width > 0.25 in. (6 mm) When preventive overlay is required to protect against salt, temperature extremes, and moisture.
Attaching steel plate (l_8)	This method involves attaching steel plates to plane concrete surfaces using epoxy resin adhesive and bolted fixings.	When additional resistance to bending, additional load capacity, or less deflections is required.
Attaching carbon fiber sheets (l_9)	This method involves bonding layers of carbon fiber sheets to form a lattice pattern. In another method the material is laid up in continuous fashion with overlaps between adjacent sheets, and with no gaps or areas where concrete is left uncovered.	When protective repair is required. When high early strength is required. When high fatigue resistance is required.
Replacement (l_{10})	This method involves removing the concrete, installing forms for the bottom surface of the deck slab, and placing and distributing the new concrete.	When the concrete deterioration extends below the top half of the deck slab.

2.7 COMMON DAMAGES IN REINFORCED CONCRETE BRIDGE DECKS

There are various causes and numerous types of damages of RC bridge decks. The top surface of exposed decks is directly subjected to the adverse effects of weather, traffic, and the use of de-icing salts and chemicals which result in rapid deterioration. Even protected decks with wearing surfaces are prone to similar deteriorations as exposed decks (OMT, 2000). The wearing surface is the portion of the deck cross section which resists traffic wear and in most cases it is made by bituminous materials (Tonias, 1995). The difference between unprotected and protected decks is that the wearing surfaces in the protected decks may hide the defects on the deck surface until they are well advanced (OMT, 2000; Tonias, 1995).

Typical types of RC bridge deck damages are cracks, spalling, cavitation, rebar corrosion, leakage, scaling, efflorescence, and delaminations (Brinckerhoff, 1993; Lee and Lim, 2007; OMT, 2000; Thomas and Deen, 1993; Yehia et al., 2008).

According to the MTQ database, common RC bridge deck problems in Quebec are cracks, rebar corrosion, delaminations or debonding, spalling or cavitation, leakage or efflorescence, and scaling. Table 2-8 provides descriptions and causes of these common problems (Brinckerhoff, 1993; OMT, 2000; Yehia et al., 2008).

Table 2-8 Common RC bridge deck damages in Quebec

Damage type	Definition	Cause
Cracks	A breakage in concrete causing a discontinuity without causing a complete separation of the structure.	Cracks form due to tensile forces caused by shrinkage, temperature changes, bending, loading, corrosion of reinforcement, sulphate, and chemical attacks.
Micro-crack	Crack width < 0.05 in. (1 mm)	
Moderate crack	Crack width between 0.05 in. (1 mm) and 0.25 in. (6 mm)	
Macro-crack	Crack width > 0.25 in. (6 mm)	
Rebar corrosion	The weakness of rebar steel due to exposure to a corrosive environment where it becomes brittle and goes back to its ore state.	Presence of a conductive solution, corrosion agent, and a corrosion cell.
Delamination/debonding	Cracks or fractures planes at or just above the level of reinforcement that grow big and can affect the integrity of the structure.	Corrosion of steel reinforcement, high amount of moisture and chloride content, and the presence of cracks in concrete surface.
Spalling/cavitation	Concrete falls away leaving a little hole that defines the fracture surface. Spalling is a continuation of the delamination process.	Internal pressure due to freezing and thawing, insufficient consolidation during construction, and formation of inner cracks that transforms into spalls.
Leakage/efflorescence	The existence of a white substance, known as efflorescence, which is a result of water seeping through concrete and reacting with the cement in the concrete.	Occurs due to dissolving water constitutes like calcium hydroxide at crack locations.
Scaling	Deterioration of concrete into smaller parts and individual aggregates.	Scaling may be a result of freezing and thawing as well as chemical attacks. It is common in non air-entrained concrete.

2.8 SUMMARY AND CONCLUSIONS

In this chapter the working principals and optimization techniques of existing BMSs are explained. Furthermore, bridge performance models, MR&R methods, and RC bridge damages are reviewed. Meanwhile, the deficiencies in the existing BMSs and current researches are discussed to illustrate the objectives of the current study and its contributions to the literature.

As the results: (1) Recovering effect, applicability, safety, and cost are selected as the set of goals which the alternative bridge actions could be evaluated; (2) A group of MR&R methods are selected in repairing bridges; (3) Common RC bridge deck defects are characterized; and (4) GA is selected as an optimization tool.

CHAPTER 3 METHODOLOGY

3.1 INTRODUCTION

In this research, the proposed methodology considers the current status (performance level) of deteriorated bridges in a network. The methodology, at the end, results in the selection of optimal bridge MR&R activities by investigating recovering effects of MR&R methods and their applicability indices, safety of the network, and cost.

In this chapter, a multi-linear performance model is introduced to predict the future condition of bridges. Performance parameters under MR&R methods are also defined. Thenceforward, the selected objective functions (recovering effect, applicability, safety, and cost) are determined. Meanwhile, the uncertainties associated with deterioration process of performance and safety are modeled.

3.2 MULTI-LINEAR PERFORMANCE MODEL

Based on the discussion in Section 2.5, a new performance model is proposed to predict the future conditions of bridges. Since it is desirable to define both preventive and essential MR&R activities for a BMS, the proposed multi-linear performance model is relied on the time-based and performance-based interventions.

Figure 3-1 shows the multi-linear performance model. The model is defined by some parameters. While no MR&R activity is applied, the model is recognized by three parameters: initial performance index P_0, time to damage initiation T_0, and constant deterioration rate α. However, when an MR&R method is applied, the performance index will be improved by maximum recovering effect RE_{max}, the performance deterioration will be delayed upon application by T_d, and deterioration rate will be decreased to α-δ. Each method impacts the performance level for a period of time named duration of MR&R effect, T_{pd}. The selection of an MR&R action for any time within the study period is an optimization problem while the performance level is not allowed to go bellow the target level, P_{taregt}.

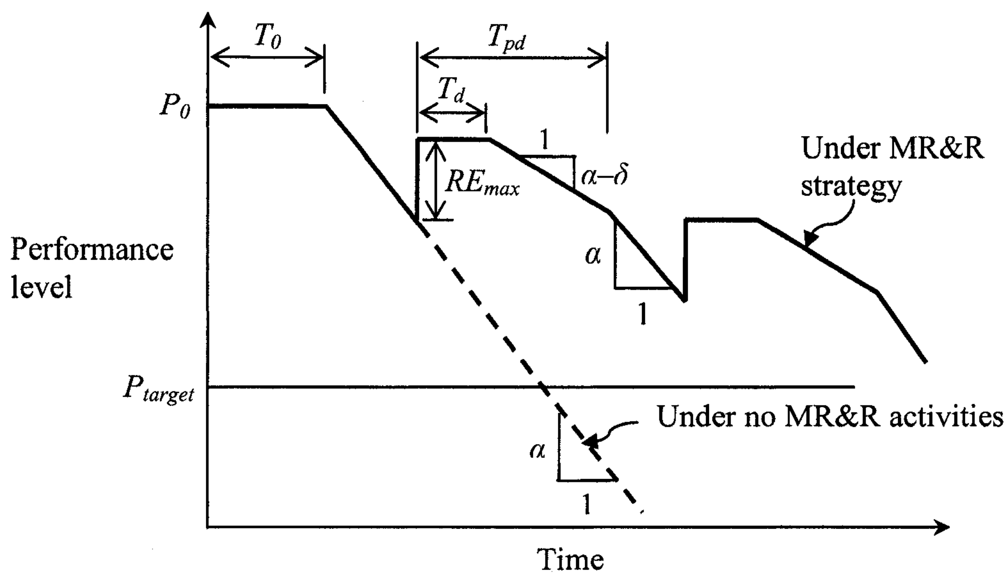
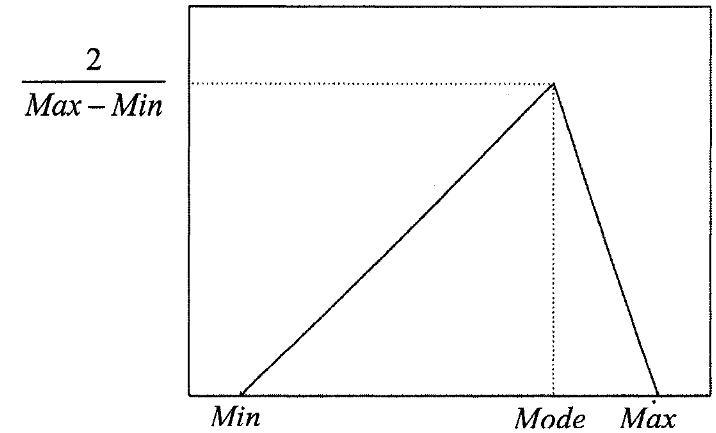
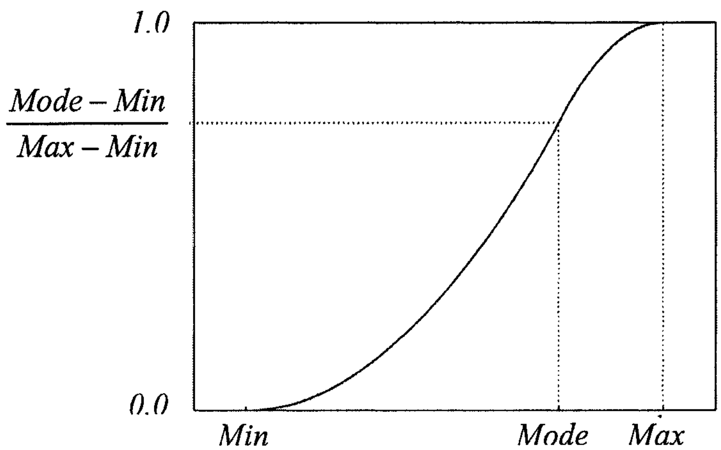


Figure 3-1 Multi-linear performance model of a bridge

Characteristic parameters of the performance profile under MR&R methods are assumed to be triangularly distributed (Liu and Frangopol, 2004). The triangular distribution is typically used as a subjective description of a phenomenon for which there is only limited sample data (Rothschild and Logothetis, 1985). Since real data on performance parameters under selected MR&R methods does not exist, it is presumed that these parameters have triangular distribution. The triangular distribution is based on the knowledge of the minimum and maximum and an inspired guess as to what the modal value might be. Figure 3-2 depicts triangular probability density function and its cumulative distribution function.



(a) Probability density function



(b) Cumulative distribution function

Figure 3-2 Triangular Distribution (Rothschild and Logothetis, 1985)

The distribution of delay in deterioration T_d, deterioration rate during effect α-δ, and duration of MR&R effect T_{pd} are presented in Table 3-1, Table 3-2, and Table 3-3, respectively. The deterioration rate for performance under no MR&R activities, α, is

Table 3-1 Distribution of delay in deterioration

Method (l)	Delay in deterioration (years), T_d		
	Minimum	Mode	Maximum
Surface repair (l_1)	1.0	1.2	2.0
Mortar filling (l_2)	1.0	1.4	2.0
Polymer injection (l_3)	1.0	1.6	2.0
Epoxy injection (l_4)	1.0	2.0	3.0
Corrosion inhibiting (l_5)	1.0	2.5	3.0
Latex modified concrete overlay (l_6)	1.5	2.5	3.5
Increasing slab thickness (l_7)	2.0	4.0	5.0
Attaching steel plate (l_8)	2.0	3.5	5.0
Attaching carbon fiber sheets (l_9)	2.0	3.0	5.0
Replacement (l_{10})	4.0	6.0	12.0

Table 3-2 Distribution of deterioration rate during effect

Method (l)	Deterioration rate during effect (% per year), α-δ		
	Minimum	Mode	Maximum
Surface repair (l_1)	0.00	1.71	3.43
Mortar filling (l_2)	0.00	1.71	3.43
Polymer injection (l_3)	0.00	2.00	2.86
Epoxy injection (l_4)	0.00	1.43	2.86
Corrosion inhibiting (l_5)	0.00	1.43	2.86
Latex modified concrete overlay (l_6)	0.00	1.14	2.28
Increasing slab thickness (l_7)	0.00	0.57	1.43
Attaching steel plate (l_8)	0.00	0.86	1.43
Attaching carbon fiber sheets (l_9)	0.00	0.86	1.43
Replacement (l_{10})	0.00	2.28	4.57

Table 3-3 Distribution of duration of MR&R effect

Method (l)	Duration of MR&R effect (years), T_{pd}		
	Minimum	Mode	Maximum
Surface repair (l_1)	2.0	3.0	4.0
Mortar filling (l_2)	2.0	3.0	4.0
Polymer injection (l_3)	2.0	3.5	4.0
Epoxy injection (l_4)	3.0	4.0	5.0
Corrosion inhibiting (l_5)	3.0	4.0	5.0
Latex modified concrete overlay (l_6)	4.0	6.0	7.0
Increasing slab thickness (l_7)	5.0	8.0	13.0
Attaching steel plate (l_8)	5.0	7.0	12.0
Attaching carbon fiber sheets (l_9)	5.0	6.0	12.0
Replacement (l_{10})	12.0	13.0	15.0

assumed to be triangularly distributed with minimum, mode, and maximum values of 0%, 2.28%, and 4.57% per year, respectively.

To be noted, these values are hypothetical numbers based on the literature (Liu and Frangopol, 2004), but they should be collected from real data in future studies. To get more realistic prediction of bridge performance, mechanistic models can be developed. In mechanistic modelling, fundamental knowledge of interaction between different variables are used to define the performance model as discussed in this section. Then, experiments are performed to determine the parameters of the model. At the end, the data is collected to validate the model. If the model is not satisfactory, the procedure should be repeated and re-examined (Tham, 2000).

3.3 RECOVERING EFFECT OF MR&R METHODS

MR&R methods improve the condition of damaged areas on bridges, and hence increase performance level of bridges. The recovering effects are impact values of methods on damaged areas and performance levels of bridges and they vary between 0% and 90%. If an activity does not improve the condition of a damaged area on a bridge, its recovering effect for that damage is 0%. In contrast, if it restores the damaged area to the initial construction performance, its recovering effect is 90%. That is, the performance of a bridge section can only be restored to 90% of the initial performance even if the replacement method is applied (Lee and Kim, 2007). Table 3-4 shows the recovering effects of selected MR&R methods. Columns two to seven give the recovering effects of the methods on a variety of damages. In addition, the last column shows the maximum recovering effect to which the performance of a bridge can be increased.

Most of the recovering effect values that are shown in Table 3-4 have been determined based on bridge experts' opinions in a study done by Lee and Kim (2007). The rest of the numbers in this table are assumed based on the available recovering effect values. However, all the recovering effect values should be collected from real data in future studies.

In assigning recovering effect values, RE, three cases might occur (Figure 3-3):

(1) The initial performance level of the bridge, P0, is greater than 90%. In this case, the effective recovering effect value, REe, is 0% even though the replacement method is applied. Thus, the secondary bridge performance level stays the same as the initial performance level (Equation 3-1).

Table 3-4 Recovering effects of MR&R methods (modified from Lee and Kim, 2007)

Method (l)	Damage types (k)								Maximum recovering effect (RE_{max})
	Micro-crack (k_1)	Moderate crack (k_2)	Macro-crack (k_3)	Rebar corrosion (k_4)	Delamination (k_5)	Spalling (k_6)	Leakage (k_7)	Scaling (k_8)	
Surface repair (l_1)	5	3	0	1	1	0	3	1	14
Mortar filling (l_2)	3	4	5	2	2	1	4	1	22
Polymer injection (l_3)	7	4	0	1	2	0	2	2	18
Epoxy injection (l_4)	3	4	2	1	2	2	0	2	16
Corrosion inhibiting (l_5)	3	3	4	4	4	4	5	4	31
Latex modified concrete overlay (l6)	35	35	35	35	35	35	35	35	35
Increasing slab thickness (l_7)	40	40	40	40	40	40	40	40	40
Attaching steel plate (l_8)	40	40	40	40	40	40	40	40	40
Attaching carbon fiber sheets (l_9)	40	40	40	40	40	40	40	40	40
Replacement (l_{10})	90	90	90	90	90	90	90	90	90

$$\begin{cases} if & P_0 \geq 90\% \\ then & RE_e = 0\%,\ and \\ & Secondary\ Performance = P_0 \end{cases} \tag{3-1}$$

(2) The initial performance level of the bridge, P_0, is less than 90% but after applying a chosen method the performance is supposed to raise to a value greater that 90%. In this case, the effective recovering effect value, RE_e, is equal to the deference between 90% and the initial bridge performance. Thereby, the secondary bridge performance level is 90% (Equation 3-2).

$$\begin{cases} if & P_0 \leq 90\% \\ & if \quad P_0 + RE \geq 90\% \\ & then \quad RE_e = 90\% - P_0,\ and \\ & Secondary\ Performance = 90\% \end{cases} \tag{3-2}$$

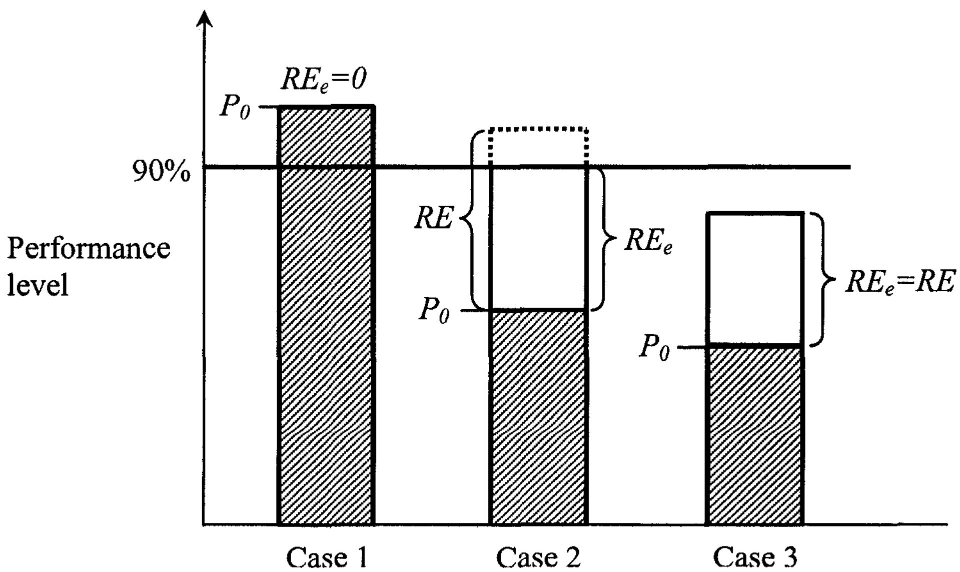


Figure 3-3 Effective recovering effect, RE_e (modified from Lee and Kim, 2007)

(3) The initial performance level of the bridge, P_0, is less than 90% before applying a chosen MR&R method and it does not reach 90% even after getting impacts of the chosen method. In this case, the effective recovering effect value, RE_e, is equal to the recovering effect value, RE, presented in Table 3-4. The secondary bridge performance is summation of the initial performance level and effective recovering effect value (Equation 3-3).

$$\begin{cases} if \quad P_0 \leq 90\% \\ \quad if \quad P_0 + RE \leq 90\% \\ \quad then \quad RE_e = RE, \; and \\ \quad Secondary\ Performance = P_0 + RE \end{cases} \tag{3-3}$$

3.4 APPLICABILITY OF MR&R METHODS

Applying a replacement method that needs enormous effort and cost to repair a slight damage such as micro-cracking is not a sensible solution although the recovering effect is enough to restore the deck to as-new condition (Lee and Kim, 2007). Therefore, applicability indexes are used to overcome such difficulties in selecting a suitable MR&R method.

Applicability indices represent the fitness of an MR&R method for each damage type and they may range from 10% to 100%. The more applicable a method is, the bigger the index is. For example, "replacement" is not an applicable method for micro cracks; thus, its applicability index is small (20%). However, "surface repair" is a well suited method for maintaining micro cracks, so its applicability index is 100%. Table 3-5 presents the applicability indices of the MR&R methods.

Table 3-5 Applicability indices of MR&R methods (modified from Lee and Kim, 2007)

Method (l)	Damage types (k)							
	Micro-crack (k_1)	Moderate crack (k_2)	Macro-crack (k_3)	Rebar corrosion (k_4)	Delamination (k_5)	Spalling (k_6)	Leakage (k_7)	Scaling (k_8)
Surface repair (l_1)	100	90	10	20	70	50	80	10
Mortar filling (l_2)	50	70	100	50	50	50	50	20
Polymer injection (l_3)	100	80	10	30	20	10	50	20
Epoxy injection (l_4)	70	100	60	20	50	70	50	20
Corrosion inhibiting (l_5)	40	50	70	100	60	50	50	30
Latex modified concrete overlay (l_6)	20	50	100	70	60	60	70	80
Increasing slab thickness (l_7)	30	40	100	80	60	70	40	90
Attaching steel plate (l_8)	50	50	100	70	50	80	20	30
Attaching carbon fiber sheets (l_9)	60	60	100	50	50	50	50	50
Replacement (l_{10})	20	40	100	80	50	80	50	60

Most of the applicability indices that are shown in Table 3-5 have been determined based on bridge experts' opinions in the study done by Lee and Kim (2007). The rest of the numbers in this table are defined based on the applications of the MR&R methods that have been presented in Table 2-7.

3.5 SAFETY PARAMETERS UNDER MR&R METHODS

The safety factor is the ratio of available to required live load capacity, which defines the approximate reliability level of a bridge (DB12/01, 2001). In order to consider the effects of MR&R methods on the safety of a bridge, there is a need to define a safety model. Similar to the performance-based intervention, safety-based intervention could be defined and merged with the time-based intervention to introduce the safety model. Indeed, the safety-based intervention recommends applying an MR&R action when a target safety value is reached, and hence results in essential repair. On the other hand, the time-based intervention suggests applying MR&R actions at predefined time intervals; thus, it results in preventive repair.

In this study, a multi-linear safety model is introduced (Figure 3-4). The model relies on both time-based and safety-based interventions and it is defined by some parameters. Figure 3-4 shows the safety level of a bridge versus time. The initial safety level S_0, stays constant for a period of time called time to damage initiation T_0. After that, the safety decreases by a constant deterioration rate, β. During which no MR&R activity applies, the safety decreases until the bridge fails. However, as an MR&R activity is applied, the safety will be improved by immediate safety improvement, γ. The applied

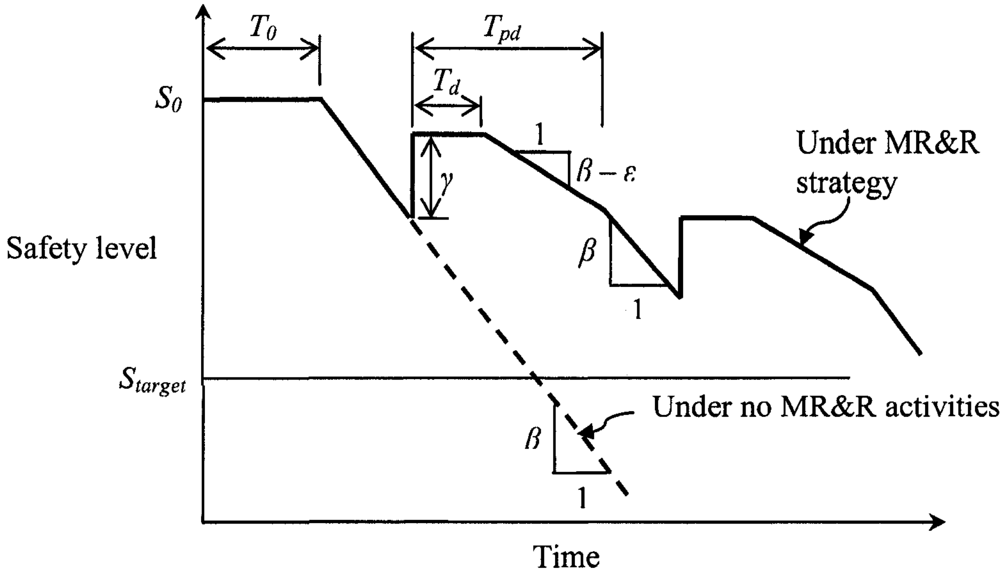


Figure 3-4 Multi-linear safety model of a bridge

MR&R activity delays the deterioration in safety for a period of time named delay in deterioration, T_d. Thenceforth, safety will be declined slowly by safety deterioration rate during effect, $\beta - \varepsilon$. In fact, the MR&R activity reduces the safety deterioration rate, β, by reduction in safety deterioration value, ε, for the duration of MR&R effect, T_{pd}. Then, the safety will be decreased constantly by the deterioration rate, β, till the next MR&R activity is applied.

This process continues for the whole study period. Meanwhile, the safety level of the bridge is not allowed to go below the safety target value, S_{target}, to keep the network safe enough.

In most studies, safety is defined as a value that varies between 0 and 2.5. The safety target value was assumed to be 0.95 in a study by Liu and Frangopol (2004). To be on the safe side, the target value is set to 1.10 in the present study. Moreover, the safety range is scaled to 100 to make safety values more homogeneous with recovering and applicability values. Thus, the safety target value is 44%, i.e., the ratio of 1.1 to 2.5.

As with performance parameters, safety parameters are assumed to be triangularly distributed (Liu and Frangopol, 2004). Table 3-6 gives the improvement values, γ, and the distribution of safety deterioration rate during effect, $\beta - \varepsilon$. The deterioration rate for safety under no MR&R activities, β, is also assumed to be triangularly distributed with minimum, mode, and maximum values are 0%, 0.6%, and 1.4% per year, respectively. It is noted that delay in deterioration, T_d, and duration of MR&R effect, T_{pd}, under different methods for the safety function have the same distribution values as those of the performance function (Table 3-1 and Table 3-3). To be mentioned, these values are hypothetical numbers based on the literature (Liu and Frangopol, 2004), but they should

Table 3-6 Distribution of safety parameters

Method (l)	Safety Improvement (%), γ	Safety deterioration rate during effect (% per year), $\beta - \varepsilon$		
		Minimum	Mode	Maximum
Surface repair (l_1)	10	0.00	0.60	1.20
Mortar filling (l_2)	10	0.00	0.60	1.20
Polymer injection (l_3)	20	0.00	0.40	1.00
Epoxy injection (l_4)	20	0.00	0.40	0.80
Corrosion inhibiting (l_5)	40	0.00	0.40	0.80
Latex modified concrete overlay (l_6)	46	0.00	0.28	0.60
Increasing slab thickness (l_7)	60	0.00	0.16	0.48
Attaching steel plate (l_8)	60	0.00	0.24	0.48
Attaching carbon fiber sheets (l_9)	60	0.00	0.24	0.48
Replacement (l_{10})	90	0.00	0.60	1.40

be collected from real data in future studies.

The following assumptions are used for determining safety parameters: (1) The maximum safety improvement is 90% even if the replacement method is used; and (2) Effective improvement, γ_e, must be defined to valid improvement and it can be calculated as following:

$$\begin{cases} if \quad S_0 \geq 90, \\ \quad \gamma_e = 0; \\ otherwise \quad if \quad S_0 + \gamma \geq 90, \\ \qquad\qquad \gamma_e = 90 - S_0; \\ \qquad otherwise \quad \gamma_e = \gamma. \end{cases} \tag{3-4}$$

3.6 COST OF MR&R METHODS

In most optimization problems, cost is an inseparable factor and maybe the most important one. This study is not an exception. The cost of long-term bridge MR&R strategies should be minimized.

In order to calculate the cost of an MR&R strategy, the unit cost of the MR&R methods should be defined in advance. It is hard to determine deterministic values as the unit costs of the methods. The cost of an MR&R activity varies based on the thickness of bridge decks, the available equipments, and the location of bridges (Table 2-4). For instance, it might be less expensive if a bridge in a city is repaired in comparison with a bridge in a mountain area.

In this study, for simplicity, the MR&R unit costs are fixed for all bridge decks. Table 3-7 presents the assumed unit cost of the MR&R methods. These values are hypothetical numbers based on the literature (Lee and Kim, 2007).

It should be mentioned that only the cost of MR&R strategies are calculated in this study and others, e.g., user costs, are excluded.

Table 3-7 Cost of MR&R methods

Method (l)	Unit cost (CAD$ / m^2)
Surface repair (l_1)	120
Mortar filling (l_2)	160
Polymer injection (l_3)	180
Epoxy injection (l_4)	280
Corrosion inhibiting (l_5)	420
Latex modified concrete overlay (l_6)	500
Increasing slab thickness (l_7)	620
Attaching steel plate (l_8)	560
Attaching carbon fiber sheets (l_9)	520
Replacement (l_{10})	1420

3.7 MODELING UNCERTAINTIES

Once probability distributions are assigned to the uncertain parameters (performance and safety), the next step is to perform a sampling operation from the multi-variable uncertain parameter domain (Diwekar, 2003).

Therefore, random variables for performance and safety parameters are generated several times for any MR&R strategy (a series of MR&R activities) based on the variables in

Tables 3-1, 3-2, 3-3, and 3-6. In each try, each objective function is calculated based on the selected parameters and formulation shown in Chapter 4. The final value of each objective function is calculated by averaging the corresponding values in all the tries. In this study five tries are performed for any solution.

3.8 SUMMARY AND CONCLUSIONS

In this chapter, multi-linear performance and safety models are introduced to predict the future conditions of bridges and consider uncertainties associated with deterioration. Moreover, the selected objective functions, i.e., recovering effect, applicability, safety, and cost, and constraint functions, i.e., performance, safety, and cost, are defined.

In conclusion, the basic concepts are developed upon which the alternative bridge actions could be evaluated. This is done by establishing a set of goals and criteria: (1) The total benefits of MR&R strategies should be maximized, i.e., recovering effect, applicability, and safety; (2) The MR&R activities should be chosen to give the best match possible to the types of damages and the deterioration level of each bridge; (3) The uncertainties associated with deterioration of performance and safety should be modeled; (4) The MR&R activities should satisfy the performance and safety criteria; and (5) The total cost should be minimized and should not exceed the budget limitation. The methodology, at the end, results in the selection of optimal bridge MR&R activities.

CHAPTER 4 PROBLEM FORMULATION

4.1 INTRODUCTION

Central to this study is selecting the optimal bridge MR&R strategies for a network of bridges. Bridge managers have a variety of objectives that should be considered to insure the bridges' current safety for modern traffic loads and remaining service life. In this chapter, the selected objective functions (recovering effect, applicability, safety, and cost) are mathematically formulated. Constraint functions are also formulated to guarantee the bridge network safety and satisfy the budget limitation. The equations are later integrated to make the fitness function. At the end, the problem is coded in Matlab-R2007a to model the GA.

4.2 OBJECTIVE FUNCTIONS

Selection of optimal MR&R strategies deals with maximization of recovering effect, applicability, and safety, and minimization of total cost while certain criteria are satisfied: (1) The performance level of any bridge at the end of each MR&R cycle has to be equal to or larger than a target value, assumed to be 55%; (2) The safety index has to be equal to or larger than a target value, assumed to 44%; and (3) The cost of MR&R strategy for the whole cycles should not exceed the available budget. Table 4-1 presents the definition of variables used in Equation 4-1 to Equation 4-19.

4.2.1 Recovering Effect

As it was mentioned in Chapter 3, the recovering effects are impact values of a method on a bridge and they vary between 0 and 90%. To calculate the recovering effect value of an MR&R strategy (a series of MR&R activities), first the related effective recovering effect of the selected MR&R method l for damage type k at cycle j for bridge i, R_{ijkl}, should be calculated based on the values shown in Table 3-4 and the defined cases in Section 3.3.. Then, all the effective recovering effects of all MR&R activities at all cycles for all bridges should be added up as described in Equation 4-1. For simplicity, RE_e is renamed as R.

$$\begin{cases} F(Recovering\ effect) = \max f_1 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}\sum_{l=0}^{q} R_{ijkl} \cdot X_{ijl} \\ Subject\ to \quad 0 \le R_{ijkl} \le MaxRec \\ \qquad for \quad i = 1, 2, 3, ..., m \\ \qquad\quad for \quad j = 1, 2, 3, ..., n \\ \qquad\qquad \sum_{k=1}^{p}\sum_{l=0}^{q} R_{ijkl} \cdot X_{ijl} \le \sum_{l=0}^{q} (RE_{\max})_l \cdot X_{ijl} \\ \qquad X_{ijl} = 0\ or\ 1 \end{cases} \tag{4-1}$$

In this equation, i, j, k, and l are bridge deck, cycle, damage type, and MR&R indices, respectively. m, n, p, and q are total number of bridge decks, cycles, damage types, and MR&R methods, respectively. R_{ijkl} is the recovering effect of MR&R method l on damage type k at cycle j on bridge deck i. X_{ijl} is a binary variable of MR&R method l at cycle j on bridge deck i; if method l is selected $X_{ijl}=1$, otherwise $X_{ijl}=0$. *MaxRec* is the maximum allowable recovering effect which is assumed to be 90%. $(RE_{max})_l$ is the maximum recovering effect of MR&R method l.

Some constraints have been essentially observed when applying the recovering effect function: (1) The effective recovering effect of MR&R method l on damage type k at cycle j on bridge deck i, R_{ijkl}, must be limited to the maximum allowable recovering effect, *MaxRec*, assumed to be 90%; (2) The summation of recovering effects of MR&R method l on all damages of a bridge at each cycle must be less than the corresponding MR&R method's maximum recovering effect, $(RE_{max})_l$, this constraint is satisfied by selecting suitable values of R and RE_{max} as shown in Table 3-4; and (3) Binary variable of MR&R method l at cycle j on bridge deck i, X_{ijl}, should be one if method l is selected, otherwise it should be zero.

4.2.2 Applicability

Applicability indices represent the fitness of an MR&R method for each damage type and they may range from 0 and 100%. To calculate the applicability value of an MR&R strategy, the applicability index of MR&R method l for damaged type k at cycle j on bridge deck i, A_{ijkl}, should be multiplied by related area of damage type k at cycle j on bridge deck i, D_{ijk}; and then all the applicability indices of all MR&R activities at all cycles for all bridges should be summed up as indicated in Equation 4-2.

Similar to recovering effect function, applicability function has to follow some constraints: (1) The applicability of MR&R method l on damage type k at cycle j on bridge deck i, A_{ijkl}, must be limited to the maximum allowable applicability index, *MaxApp*, assumed to be 100%; and (2) Binary variable of MR&R method l at cycle j on bridge deck i, X_{ijl}, should be one if method l is selected, otherwise it should be zero.

$$
\begin{cases}
F(Applicability) = \max f_2 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}\sum_{l=0}^{q} A_{ijkl} \cdot D_{ijk} \cdot X_{ijl} \\
Subject\ to \quad 0 \le A_{ijkl} \le MaxApp \\
\qquad\qquad X_{ijl} = 0\ or\ 1
\end{cases}
\tag{4-2}
$$

In this equation, A_{ijkl} is the applicability index of MR&R method l on damage type k at cycle j on bridge deck i, D_{ijk} is the area of damage type k at cycle j on bridge deck i, and *MaxApp* is the maximum allowable applicability index which is assumed to be 100%.

4.2.3 Safety

The safety index is the ratio of available to required live load capacity, which defines the approximate reliability level of a bridge (DB12/01, 2001). In this study, safety level is defined as a value that varies between 0 and 100%, where larger values represent higher reliability. To calculate the safety value of an MR&R strategy, the related safety index of the selected MR&R method l at cycle j for bridge i, S_{ijl}, should be calculated based on the initial safety values, safety probabilistic distribution of the MR&R method as presented in Tables 3-1, 3-3, and 3-6, and assumptions discussed in Section 3-5. Thereafter, all the safety indices of all MR&R activities at all cycles for all bridges should be added up as shown in Equation 4-3. As the result, improvement in the safety of the network is calculated.

Safety function must follow a couple of constraints: (1) The safety of MR&R method l at cycle j on bridge deck i, S_{ijl}, must be limited to the maximum allowable safety index, *MaxSft*, assumed to be 90%; and (2) Binary variable of MR&R method l at cycle j on bridge deck i, X_{ijl}, should be one if method l is selected, otherwise it should be zero.

$$\begin{cases} F(Safety) = \max f_3 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{l=0}^{q} S_{ijl} \cdot X_{ijl} \\ Subject\ to \quad 0 \le S_{ijl} \le MaxSft \\ \qquad\qquad\quad X_{ijl} = 0\ or\ 1 \end{cases} \tag{4-3}$$

In this equation, S_{ijl} is the safety index of MR&R method l at cycle j on bridge deck i, and *MaxSft* is the maximum allowable improvement in safety which is assumed to be 90%.

4.2.4 Cost

In view of the fact that the costs occur at various times, they should be processed using their present values. Therefore, each cost item is reduced by discount factor based on the time that the method is applied. Indeed, cash flows that occur in future are discounted to lower value when compared with cash value that occur today to reflect the fact that the cash received today is more valuable than cash receive in the future (Patidar et al., 2007).

The discount factor, *DisFac*, is based on the forecast real discount rate, *dis*. In this study, the discount rate, *dis*, is assumed to be 5% per year according to the NCHRP report 590 (Patidar et al., 2007). Equation 4-4 indicates the relation between discount factor and discount rate.

$$DisFac = \frac{1}{1 + dis} \tag{4-4}$$

Certain assumptions in the cost analysis govern the length of discount: (1) MR&R implementation costs occur at the beginning of corresponding cycle; and (2) All costs are discounted to the beginning of the first cycle. Therefore, the discount factor of an MR&R

implementation cost done in cycle j, $DisFac_j$, should be calculated as show in Equation 4-5 while L_C represents length of each cycle in years.

$$DisFac_j = \frac{1}{(1+dis)^{(j-1)\times L_C}} \tag{4-5}$$

Inflation, furthermore, may affect the cost analysis but it does not have a major effect on the results unless different cost factors are modeled to inflate at different rates (Patidar et al., 2007). Because only the MR&R implementation costs are used in this study, inflation has been removed from the cost calculation.

Consequently, the cost function can be formulated as shown in Equation 4-6. In order to calculate the total cost of an MR&R strategy, first the unit cost of selected MR&R method, C_l, should be discounted by the related discount rate, $DisFac_j$. Second, the discounted unit cost should be multiplied by the area of damage type k at cycle j on bridge deck i; and at the end, the costs should be added up to make the total cost value.

$$\begin{cases} F(Cost) = \min f_4 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p}\sum_{l=0}^{q} \cdot \frac{1}{(1+dis)^{(j-1)\times L_C}} \cdot C_l \cdot D_{ijk} \cdot X_{ijl} \\ Subject\ to \quad X_{ijl} = 0\ or\ 1 \end{cases} \tag{4-6}$$

In this equation, dis is the annual discount rate which is assumed to be 5%, L_C is the length of each cycle, and C_l is the unit cost of MR&R method l.

4.3 CONSTRAINT FUNCTIONS

As declared in the previous section, multiple criteria are included in the selection of the optimal MR&R strategies. These are denoted as constraints to be met. Any MR&R

strategy attempts to make the objective functions as large (or small) as possible, but it is not guaranteed to reach a feasible solution if it violates a constraint. Therefore, the constraint functions have been defined to cover the network's basic needs.

From a decision making point of view, the constraints could be (1) a bridge performance limitation, (2) a minimum threshold for the bridge safety, and (3) a budgetary limitation. Any MR&R strategy that does not satisfy any of the constraints should not be considered as an optimum solution.

4.3.1 Performance Constraint

In order to assure quality of the network, the performance level of any bridge at the end of each MR&R cycle, P_{ijl}, has to be equal to or greater than a target performance value, P_{target}, as shown in Equation 4-7. In this study the target performance value is assumed to be 55%.

$$P_{target} \leq P_{ijl} \tag{4-7}$$

4.3.2 Safety Constraint

To assure the safety of the network, the safety level of any bridge at the end of each MR&R cycle, S_{ijl}, has to be equal to or greater than a target safety value, S_{target}, as shown in Equation 4-8. In this study the target safety value is assumed to be 44%.

$$S_{target} \leq S_{ijl} \tag{4-8}$$

4.3.3 Budget Constraint

Because of the fact that the available budgets in municipalities are limited, it is always suggested to have a budget constraint to limit the cost of MR&R strategies to the existing budget.

$$f_4 \leq Budget \tag{4-9}$$

4.4 NORMALIZING FACTORS

For the purpose of this study, all objective functions are gathered into a single function. It is likely that different objectives take different orders of magnitude (Deb, 2001). For example, recovering effect of an MR&R activity varies between zero and 90 while cost of an MR&R activity may vary between zero and 900 dollars. When such objectives are weighted to form a single objective function, it is suggested to scale them so that each has almost the same order of magnitude (Deb, 2001). In the above example, the MR&R recovering effect could be multiplied by ten or the MR&R cost could be divided by ten in order to be equally important. One of the simplest methods to normalize the objective functions is to calculate them out of one. In this study, normalizing factors are defined in a way to limit the range of objective function values into the range of zero to one.

4.4.1 Recovering Effect Normalizing Factor

The recovering effect of the ideal MR&R activity for a specific damage type is equal to the maximum allowable recovering effect, *MaxRec*, which is assumed to be 90%. Thus, the recovering effect of the ideal MR&R strategy (a series of MR&R activities) is equal to the maximum allowable recovering effect, *MaxRec*, multiplied by the number of bridges, *m*, multiplied by the number of cycles, *n*. In other words, the recovering effect of any MR&R strategy ranges between zero and $MaxRec \times m \times n$. Consequently, recovering effect normalizing factor can be defined as shown in Equation 4-10.

$$h_1 = \frac{1}{MaxRec \times m \times n} \tag{4-10}$$

4.4.2 Applicability Normalizing Factor

The applicability of the ideal MR&R activity for a specific damaged area is equal to the maximum allowable applicability, *MaxApp*, which is assumed to be 100%. Therefore, the applicability of the ideal MR&R strategy (a series of MR&R activities) is equal to the maximum allowable applicability, *MaxApp*, multiplied by the summation of damaged areas at all cycles on all bridges. That is, the applicability of any MR&R strategy varies from zero to $MaxApp \times \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} D_{ijk}$. Hence, applicability normalizing factor can be defined as explained in Equation 4-11.

$$h_2 = \frac{1}{MaxApp \times \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} D_{ijk}} \tag{4-11}$$

4.4.3 Safety Normalizing Factor

The safety of the ideal MR&R activity for a specific damage type is equal to the maximum allowable safety index, *MaxSft*, which is assumed to be 90%. Therefore, the safety of the ideal MR&R strategy (a series of MR&R activities) is equal to the maximum allowable safety index, *MaxSft*, multiplied by the number of bridges, *m*, multiplied by the number of cycles, *n*. In other words, the safety of any MR&R strategy ranges between zero and $MaxSft \times m \times n$. As the result, safety normalizing factor can be defined as shown in Equation 4-12.

$$h_3 = \frac{1}{MaxSft \times m \times n} \tag{4-12}$$

4.4.4 Cost Normalizing Factor

Owning to the fact that the budget constraint function has been defined, the cost of any MR&R strategy is limited to the available budget. Consequently, the cost normalizing factor can be formulated as Equation 4-13.

$$h_4 = \frac{1}{Budget} \tag{4-13}$$

4.5 FITNESS FUNCTION

Several methods are used to alter multi-objective optimization problems into single composite objective functions such as weighted sum method, e-constraint method, weighted metric methods, Benson's method, and goal programming methods (Deb, 2001). Each of these methods has some advantages depending on the nature of problem although they may have some drawbacks. For instance, the weighted sum method is easy to use to solve a multi-objective optimization problem but it needs all objective functions to be converted into one type which is a big challenge in mixed optimization problems, those who have different objectives by different dimensions.

In the present study, weighted Euclidean metric method, which is the second type of weighted metric methods, is used. This method can handle multi-objective optimization problems like bridge MR&R optimization. By using different combinations of weight factors, this method can also find almost all non-dominated solutions called Pareto optimal set (Miettinen, 1999; Deb, 2001).

In this method, the weighted distance measure of any solution from the ideal solution z* is minimized. Therefore, it is essential to have a good knowledge of the upper/lower limit of objective functions. On the ground that the objective functions of the present study are normalized and calculated out of 1, it is straightforward to predict their upper/lower limits which lead to define z*. Equation 4-14, as the result, shows the fitness function.

$$\begin{cases} F = \left(\sum_{u=1}^{U} w_u \left| h_u \times f_u - z_u^* \right|^2 \right)^{1/2} \\ \textit{Subject to} \quad P_{target} \leq P_{ijl}, \quad S_{target} \leq S_{ijl}, \quad \textit{and} \quad f_4 \leq \textit{Budget}. \\ \textit{Where} \quad z_1^* = 1, \quad z_2^* = 1, \quad z_3^* = 1, \quad \textit{and} \quad z_4^* = 0.5 \end{cases} \tag{4-14}$$

In this equation, u is the objective function index and U is the total number of objective functions. w_u and h_u are the weight factor and normalizing factor of objective u, respectively. f_u is the objective function u, and z_u^* is the ideal solution of objective u. P_{target} and S_{target} are the performance and safety target values, respectively. P_{ijl} is the performance of bridge i at cycle j by solution l and S_{ijl} is the safety index of MR&R method l at cycle j on bridge deck i.

The ideal solution, z^*, can be defined as follows:

(1) It is desirable to maximize the recovering effects of all MR&R activities at all cycles for all bridges; that is, to improve the condition of all bridges at all cycles by maximum allowable recovering effect, which is assumed to be 90%. By setting the normalizing factor to $\frac{1}{MaxRec \times m \times n}$, the recovering effect objective function is normalized and calculated out of one. Thus, the first dimension of the ideal solution, z_1^*, should be one.

(2) Similar to the recovering effect, applicability and safety objective functions are normalized and calculated out of one. Consequently, the second and the third dimensions of the ideal solution, z_2^* and z_3^*, should be one.

(3) It is desirable to minimize the total cost of MR&R strategies. So, the ideal strategy from cost point of view is to spend nothing on MR&R activities. However, in reality, the bridges should be repaired and maintained. Taking into account that the cost objective function is also normalized and calculated out of one, the fourth dimension of the ideal solution, z_4^*, is assumed to be 0.5 to let the MR&R strategies spend at least half of the available budget.

4.6 PENALTY TERM

In order to handle present constraints in the objective functions or the fitness function, there are several methods that exist in the literature. These methods can be classified into five categories: (1) methods based on preserving feasibility of solutions, (2) methods based on penalty functions, (3) methods biasing feasible over infeasible solutions, (4) methods based on decoders, and (5) hybrid methods (Michalewicz et al., 1996; Deb, 2001).

In the present study, static penalty method, a constraint handling method based on penalty functions, is used. This method penalizes infeasible solutions and suits both equality and non-equality constraints. To be noted, it is not a good idea to enforce the constraints on the problem to simply eliminate solutions that do not satisfy the constraints because many good solutions will be lost (Deb, 2001).

Based on each constraint violation (performance, safety or budget violation) a penalty term is added to the fitness function. Equation 4-15 shows the penalize fitness function while v, V, and g_v represent constraint index, total number of constraints, and penalty function of constraint v, respectively. In addition, Y is a user defined penalty parameter which is assumed to be five in this study.

$$Penalized\ fitness\ \ function = F + Y \times \sum_{v=1}^{V} \left(violation\ of\ g_v \right) \tag{4-15}$$

According to the definition of constraint functions in Section 4.3, the penalty functions could be defined as follows: (1) Performance penalty function is the summation of the performance level of all infeasible solutions which do not fit within the performance boundary; (2) Safety penalty function is the summation of the safety level of all infeasible solutions which do not fit within the safety boundary; and (3) Budget penalty function is one over the total calculated cost, f_4, of an infeasible MR&R strategy which costs more than the available budget. Equation 4-16 represents the penalty functions.

$$
\begin{cases}
g_1 = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{b=0}^{B} P_{ijb} \\
g_2 = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{e=0}^{E} S_{ije} \\
g_3 = \dfrac{1}{f_4}
\end{cases}
\tag{4-16}
$$

In this equation, b and e are infeasible solution out of first constraint (performance) and second constraint (safety) indices, respectively. B and E are the total number of infeasible solutions out of first constraint (performance) and second constraint (safety), respectively. P_{ijb} is the performance of bridge i at cycle j by solution b, and S_{ije} is the safety of bridge i at cycle j by solution e.

As in the case of objective functions, penalty functions should be normalized and calculated out of one so that all constraint violations take the same order of magnitude. Penalty function normalizing factors can be defined as follows:

(1) Performance penalty function is limited to $P_{target} \times B$ because any infeasible MR&R strategy might have B number of MR&R activities which results in non acceptable performance level. Therefore, the performance normalizing factor is equal to $\frac{1}{P_{target} \times B}$.

(2) Similarly, safety penalty function is limited to $S_{target} \times E$ since any infeasible MR&R strategy might have E number of MR&R activities which results in non acceptable safety level. Thus, the safety normalizing factor could be equal to $\frac{1}{S_{target} \times E}$.

(3) The downstream threshold of an infeasible solution from cost point of view is the available budget. Consequently, the budget normalizing factor is equal to $Budget$.

Equation 4-17 represents the penalty functions normalizing factors.

$$\begin{cases} a_1 = \dfrac{1}{P_{target} \times B} \\ a_2 = \dfrac{1}{S_{target} \times E} \\ a_3 = Budget \end{cases} \tag{4-17}$$

Therefore, penalty term can be summarized as shown in Equation 4-18.

$$\begin{cases} Penalty\ \ term = Y \times \sum_{v=1}^{V} (1 - a_v \times g_v) \\ Where\ \ g_1 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{b=0}^{B} P_{ijb},\ \ g_2 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{e=0}^{E} S_{ije},\ \ and\ \ g_3 = \dfrac{1}{f_4}, \\ \qquad a_1 = \dfrac{1}{P_{target} \times B},\ \ a_2 = \dfrac{1}{S_{target} \times E},\ \ and\ \ a_3 = Budget \end{cases} \tag{4-18}$$

Consequently, the following fitness function is determined to formulate the problem for both feasible and infeasible solutions (Equation 4-19).

$$\begin{cases} if\ \ P_{target} \le P_{ijkl}, S_{target} \le S_{ijl},\ and\ f_4 \le Budget \\ \qquad F = \left(\sum_{u=1}^{U} w_u \left| h_u \times f_u - z_u^* \right|^2 \right)^{1/2} \\ otherwise, \quad F = \left(\sum_{u=1}^{U} w_u \left| h_u \times f_u - z_u^* \right|^2 \right)^{1/2} + Penalty\ \ term \end{cases} \tag{4-19}$$

Table 4-1 Definitions of the variables in Equations 4-1 to 4-19

i, j, k, l	Bridge deck, cycle, damage type, and MR&R indices
m, n, p, q	Total number of bridge decks, cycles, damage types, and MR&R methods
a_v	Normalizing factor of constraint v
A_{ijkl}	Applicability index of MR&R method l on damage type k at cycle j on bridge deck i
b	Infeasible solution out of first constraint (performance)
B	Total number of infeasible solutions out of first constraint (performance)
C_l	Unit cost of MR&R method l
D_{ijk}	Area of damage type k at cycle j on bridge deck i
dis	Annual discount rate; assumed to be 5%
$DisFac$	Annual discount factor
$DisFac_j$	Discount factor of an activity done in cycle j
e	Infeasible solution out of second constraint (safety)
E	Total number of infeasible solutions out of second constraint (safety)
f_1	Function of recovering effect
f_2	Function of applicability
f_3	Function of safety
f_4	Function of cost
F	Fitness function
g_v	Penalty function of constraint v
h_u	Normalizing factor of objective u
L_C	Length of each cycle (year)
$MaxApp$	Maximum allowable applicability index; assumed to be 100%
$MaxRec$	Maximum allowable recovering effect; assumed to be 90%
$MaxSft$	Maximum allowable improvement in safety; assumed to be 90%
P_{ijb}	Performance of bridge i at cycle j by solution b
P_{ijl}	Performance of bridge i at cycle j by solution l
P_{target}	Target performance value/limit; assumed to be 55%
R_{ijkl}	Recovering effect of MR&R method l on damage type k at cycle j on bridge deck i
$(RE_{max})_l$	Maximum recovering effect of MR&R method l; varies from 13% to 90%
S_{ije}	Safety of bridge i at cycle j by solution e
S_{ijl}	Safety index of MR&R method l at cycle j on bridge deck i
S_{target}	Target safety value; assumed to be 44%
u	Objective function index
U	Total number of objective functions; assumed to be 4
v	Constraint index
V	Total number of constraints; assumed to be 3
w_u	Weight factor of objective u
X_{ijl}	Binary variable of MR&R method l at cycle j on bridge deck i; if method l is selected $X_{ijl}=1$, otherwise $X_{ijl}=0$.
Y	User defined penalty parameter; assumed to be 5
z_u^*	Ideal solution of objective u

4.7 SOFTWARE IMPLEMENTATION

The problem of selecting an optimal long-term bridge MR&R strategy was coded in Matlab-R2007a based on the formulation discussed in this chapter and the flowchart shown in Figure 4-1. The software has a toolbox called "Genetic Algorithm and Direct Search Toolbox" which is specialized in solving optimization problems via a genetic algorithm. The coded fitness function is presented in Appendix A. Two functions are also developed to produce initial generation and mutation solutions according to digits that represent MR&R methods (Appendix B and Appendix C). Furthermore, in order to get optimal results for different combinations of weight factors, i.e., Pareto optimal set, the last function is coded to put the fitness function into a loop and force it to run several times (Appendix D).

The program stars by getting network data, the available budget, analysis period, and number of MR&R cycles. Thereafter, for the first combination of weight factors, the GA runs to get the first optimal MR&R strategy and then it runs again for the subsequent combinations of weight factors to find the rest of optimal MR&R strategies and to identify Pareto optimal set.

Now the question is how the GA finds the optimal MR&R strategy for each combination of weight factors. At the beginning, the GA generates the initial population which includes number of solutions (MR&R strategies). Then, for the first solution, the first try, the first bridge, and the first cycle, the GA generates random variables for performance safety parameters based on respective distributions. After that, the GA

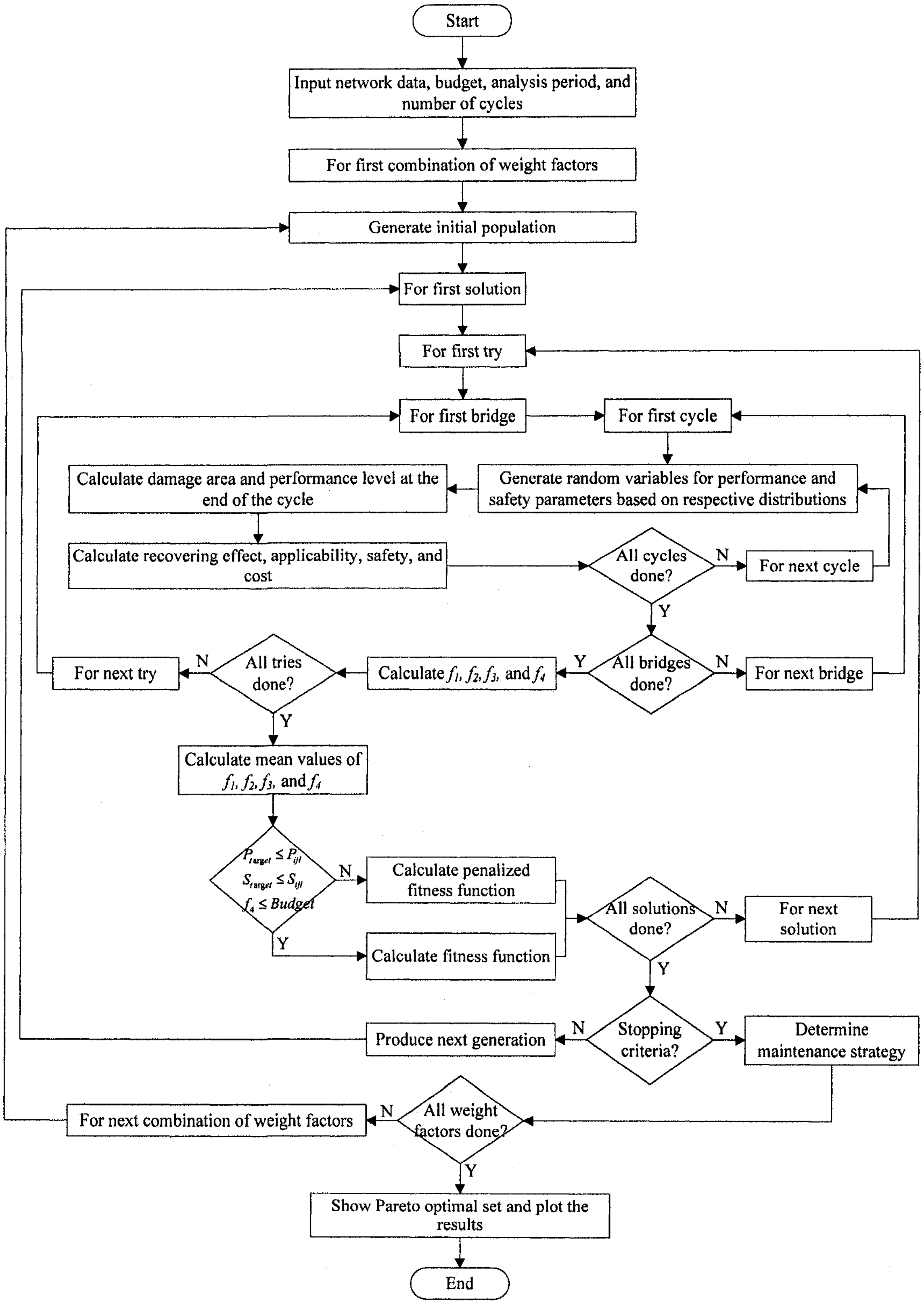


Figure 4-1 Flowchart for coding the bridge MR&R optimization problem

calculates damage area and performance level at the end of the cycle and then calculates the recovering effect, applicability, safety, and cost values.

The GA repeats the process for all cycles and then for all bridges. When all cycles for all bridges have been considered, the GA calculates the objective functions values (f_1, f_2, f_3, and f_4) for the first try. Likewise, the GA calculates the objective functions values for the rest of tries. Then, it calculates the mean values of the objective functions values.

Afterwards, the GA checks the constraints. If all constraints are satisfied the fitness function should be computed; otherwise, the penalized fitness function should be computed.

In the next step, the whole process should be repeated for the rest of solutions in the first population. After that, the next generation should be produced based on the fitness values of the previous generation and selection, crossover, and mutation regulations that have been defined in advance. This process continues till any stopping criteria satisfy. The stopping criteria could be number of generations, weighted average change in fitness values of consecutive generations, or even time. The assumptions used in the GA calculations are given in Section 5.4.

4.8 SUMMARY AND CONCLUSIONS

In this chapter, the objective functions and constraint functions are formulated. Furthermore, weighted Euclidean metric method is used to integrate the objective functions and to create the fitness function. In order to unify the objective functions, normalizing factors are defined and formulated. Moreover, to handle constraint functions, a penalty term is determined to penalize infeasible solutions. A flowchart is, in addition, created to illustrate the computational procedure. At the end, the GA is coded based on the equations introduced in this chapter and the flowchart.

The proposed equations are able to represent the objective functions according to their specifications. These equations are also able to model a multi-objective GA which finds the optimal bridge MR&R strategies.

CHAPTER 5 CASE STUDY

5.1 INTRODUCTION

The objective of describing an example application here is not so much to show the accuracy of the GA. The reason this cannot be accomplished has been discussed in Chapter 2: the problem is considerably large to be solved by any classical non-heuristic techniques. The number of feasible solutions increases exponentially with the number of bridges, m, the number of MR&R cycles, n, and the number of MR&R activities, q. The number of all MR&R strategies is $q^{m \times n}$. For instance, in case of having ten bridges in a network and defining 11 MR&R activities that can be applied at four cycles, the total number of MR&R strategies is $11^{10 \times 4}$. That is, the problem is significantly larger than anything that can be solved by any classical non-heuristic techniques within a reasonable period of time.

To check the accuracy, the GA runs for several times to select the optimal MR&R strategy for a sample bridge network and then the results of different runs are compared with each other. As the convergence criterion is always satisfied and the results of the GA are almost the same, the GA performance is acceptable. To be added, the proposed GA cannot result in exactly the same MR&R strategies because the fitness function is not a deterministic function and it varies from time to time.

The main objective is, therefore, to demonstrate the feasibility and usefulness of the proposed methodology and formulation. This chapter includes the sample network data, which is collected from the MTQ database, and the GA optimization results. The results are analyzed in the network level as well as the project level.

5.2 MTQ DATABASE

The data used in developing the case study are obtained from the MTQ during one inspection period (2000-2004). The database consists of 10,335 structures that are classified into eight categories of structures: culverts, slab bridges, beam bridges, box-girder bridges, truss bridges, arch bridges, cable bridges, and other structures (MTQ, 2004a). The main material of the structures are, furthermore, divided into six categories: RC, steel, thermoplastic, pre-stress concrete (PC), wood, and others. The number of structures in each category and their materials are presented in Appendix E.

The province of Quebec is divided to seventeen regions. Montreal Island is considered as a regional area that has 366 bridges. Table 5-1 includes the bridge types in Montreal and their materials.

Table 5-1 Montreal bridge types and materials (MTQ database)

Bridge type			Material		
Category	Number	Percentage	Category	Number	Percentage
Slab Bridge	215	58.7%	RC	253	69.1%
Beam Bridge	104	28.4%	Steel	43	11.7%
Box-Girder Bridge	46	12.6%	PC	69	18.9%
Cable Bridge	1	0.3%	Others	1	0.3%
Total	366	100.0%	Total	366	100.0%

The database recognises eight types of bridge decks: concrete deck, asphalt surfacing, RC deck, deck with corrugated metal sheet covered with concrete, wooden deck, rubbery bitumen, grating, and granular material (MTQ, 2004b).

The database, moreover, includes three types of data for each bridge: (1) inventory data, (2) inspection data, and (3) maintenance data. The data are summarized in eleven tables as presented in Table 5-2 (MTQ, 2004a).

Table 5-2 Inspection tables used by MTQ (Hu, 2006)

Type	Table name	Description
Inventory	SGSD010P	General information about structure
Inspection	SGSD400P	Obstacles in the section inventory
	SGSD410P	The elements of foundation in the inventory
	SGSD420P	The structural systems of the inventory
	SGSD700P	Inspection form (type A - V)
	SGSD710P	Details about inspection form
	SGSD720P	The inspection evaluation
	SGSD730P	The inspection comment
	SGSD740P	The inspection summary
Maintenance	SGSD750P	Maintenance activities
	SGSD770P	Maintenance cost

5.3 SAMPLE NETWORK BRIDGE DATA

According to the information provided in the previous section, ten RC bridge decks are selected. The selection of sample bridges is based on the following terms: (1) In order to minimize the uncertainties associated with cost function, the bridges are chosen from one

Table 5-3 Sample network bridge data selected from MTQ database

Bridge	Construction time (year)	Length of deck (m)	Damage area (m^2)								Initial performance (%), P_0	Initial safety* (%), S_0	Time to damage initiation* (years), T_0
			Micro-crack (k_1)	Moderate crack (k_2)	Macro-crack (k_3)	Rebar corrosion (k_4)	Delamination (k_5)	Spalling (k_6)	Leakage (k_7)	Scaling (k_8)			
1	1966	116	2	1	7	226	10	0	0	0	86	47	0
2	1966	692	0	20	8	544	0	50	0	32	96	50	0
3	1966	39	0	2	0	0	13	0	0	0	89	60	2
4	1965	130	0	0	0	49	6	82	14	11	79	39	0
5	1963	11	0	0	0	0	63	12	0	0	21	44	0
6	1965	130	2	12	0	78	13	5	21	0	71	45	0
7	1965	100	0	0	0	46	21	0	0	17	71	50	0
8	1966	42	670	0	6	0	2	0	0	84	34	23	0
9	1966	32	0	0	0	0	13	0	0	0	89	65	2
10	1966	32	400	300	4	0	0	0	4	0	25	52	0
Average		132	-	-	-	-	-	-	-	-	66	47	-

* Assumptions based on the initial performance values, evaluation material codes, and deteriorated areas.

region, i.e., Montreal Island; (2) Although the database includes all the Montreal bridges built between 1953 and 2003, bridges built in the 1960's are considered, which mostly have severe deterioration; and (3) The selected decks should vary in length to represent a wide variety of bridges.

Table 5-3 shows the sample network bridge data by summarizing the construction year, length of deck, and damaged areas on the bridges. Initial performance, P_0, is calculated based on the evaluation performance codes. Initial safety, S_0, and time to damage initiation, T_0, values are assumed based on the initial performance values, evaluation material codes, and deteriorated areas (Appendix F).

Figure 5-1 depicts the percentages of the damaged areas on the sample bridge decks. Micro-crack and rebar corrosion are more common damages in the network being 37.7% and 31.1% of the damaged areas, respectively. In contrast, macro-crack and leakage are less frequent. They cause 2.3% of the deteriorated areas in the network. Moreover,

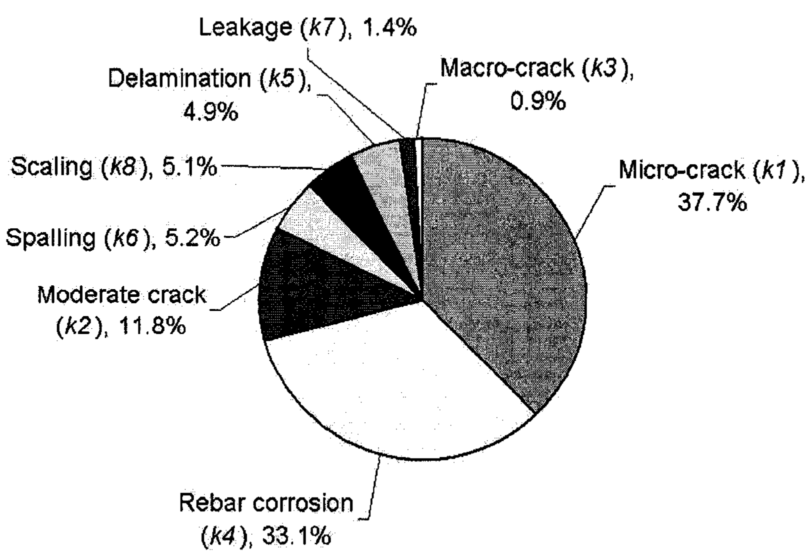


Figure 5-1 Damaged areas on the sample bridges

delamination, scaling, and spalling are equally important in the network deterioration. They result in 15.2% of the damaged areas. Likewise, moderate crack composes 11.8% of damaged area which is almost one third of micro-crack or rebar corrosion damages. The moderate crack damages are as twice as delamination, scaling, or spalling damages.

5.4 ASSUMPTIONS

In defining the cost function, it is assumed that the thickness of bridge decks are equal and the bridges are located in the same region; and therefore the unit cost of an MR&R method is a constant value for all the bridges. The discount rate that is used in cost calculation is assumed as 5% per year.

Furthermore, the criteria that should be satisfied are presumed as following: (1) The performance target value is 55%; (2) The safety target value is 44%; and (3) The total available budget is CAD$2,000,000.

In the present case study it is assumed that: (1) The bridges are subjected to a long-term MR&R strategy for 20 years; (2) An MR&R activity can be applied once in five years on each bridge; that is, there are four MR&R cycles available; and (3) MR&R activities are applied at the first year of each MR&R cycle.

Finally, in defining the GA, the options are set as following: (1) GA population size is 150; (2) The selection, crossover, and mutation probabilities are 5%, 90%, and 5%, respectively; (3) The initial population is generated based on the defined initial population function (Appendix B); (4) The crossover children are generated based on the scattered function[1]; (5) The mutation children are generated based on the defined mutation generation function (Appendix C); (6) The range of values of a gene is zero to ten where zero refers to "no action" and the rest of the numbers refer to the MR&R methods (Table 2-7); and (7) The algorithm stops when the number of generations exceeds 100 or when the weighted average change in fitness function value is less than 10^{-6}.

5.5 RESULTS AND DISCUSSION

The GA-based procedure is used for optimal MR&R planning of the deteriorated bridges. The relative weight factors of the objective functions could be defined in advance by two alternative approaches: direct questionnaire survey or analytic hierarchy process approach (Patidar et al., 2007). In this case, the GA should run one time for the specific combination of weight factors, and hence results in one optimal MR&R strategy. However, in the present study, to give bridge managers more options, 20 combinations of weight factors are defined in the Pareto producer function (Appendix D); and therefore, the GA results in 20 Pareto optimal solutions. Bridge managers can, from the Pareto optimal solutions, select the final MR&R strategy that compromises recovering effect, applicability, safety, and cost in the most desirable manner.

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[1] The scattered function creates a random binary vector and selects the genes where the corresponding vector values are ones from the first parent, and the genes where the corresponding vector values are zeros from the second parent, and combines the genes to form the child (MathWorks, 2007). For instance, if p1=[a b c d e f g h] and p2=[1 2 3 4 5 6 7 8] are parents and the binary vector is [1 0 0 0 1 1 0 0], then the scattered function returns to child1=[a 2 3 4 e f 7 8].

Table 5-4 demonstrates the outcomes. Each Pareto optimal solution has 40 chromosomes that include four MR&R activities for each bridge. From performance point of view, bridge 5, bridge 8, and bridge 10 are in essential need of repair as their initial performance is lower than 55% (Table 5-3). Therefore, all the Pareto optimal solutions suggest to apply either the 8th (attaching steel plate) or the 9th (attaching carbon fiber sheets) MR&R activities on bridge 5 at the first cycle which improves the performance to 61%. Similarly, for bridge 8 with P_0=34%, it is recommended to do the 5th (corrosion inhibiting), the 6th (latex modified concrete overlay), or the 9th (attaching carbon fiber sheets) method at the first cycle. The initial performance of Bridge 10 is, also, low which can be increased by the 6th or 9th MR&R activities. Obviously, replacement (10th method) can raise the performance of these three bridges to 90% but it was not suggested by any Pareto solution because its unit cost is high and the damaged areas are large.

Furthermore, there is an acute need for an MR&R activity on bridge 4 and bridge 8 on the ground that there initial safety is lower than the safety target value (44%). As bridge 4 initial safety is 39%, any MR&R method that applies at the first cycle could make the bridge safe. This logic is represented by the Pareto optimal solutions. However, only methods with high safety improvement values could satisfy the bridge 8 safety conditions. As it was mentioned before, the Pareto optimal solutions suggest applying any of the 5th, 6th, or 9th activities as the initial MR&R activity for bridge 8.

The rest of bridges are indeed in appropriate conditions from both performance and safety points of view. These bridges could be categorized into two groups to simplify the analysis process. The first group contains bridge 1, bridge 2, bridge 6, and bridge 7.

Table 5-4 Pareto optimal solutions' MR&R strategies

Number	Bridge 1				Bridge 2				Bridge 3				Bridge 4				Bridge 5				Bridge 6				Bridge 7				Bridge 8				Bridge 9				Bridge 10			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	0	0	0	1	0	0	3	1	9	0	1	3	3	1	0	1	9	3	0	3	1	0	1	0	2	1	0	2	5	1	0	1	10	6	2	5	9	0	0	1
2	0	1	0	0	1	0	0	0	10	0	7	2	3	1	0	0	9	6	2	0	1	1	0	0	4	2	2	3	5	1	1	0	8	1	2	4	6	3	0	0
3	0	2	0	0	0	0	1	0	7	0	1	3	1	1	2	1	9	2	0	0	1	0	0	3	1	0	1	1	5	1	3	0	10	2	9	7	9	0	0	1
4	0	0	1	3	0	0	0	0	6	4	2	0	1	0	0	0	9	2	1	3	0	1	0	0	2	0	2	1	5	1	1	0	10	0	8	6	9	0	0	1
5	0	0	1	0	0	0	1	0	7	2	0	0	2	1	0	0	9	0	1	0	3	0	1	2	1	1	1	0	9	1	0	0	9	0	3	2	6	0	1	0
6	0	0	3	1	0	0	1	1	10	0	6	6	1	0	0	1	9	1	1	2	3	1	0	1	3	1	0	1	5	1	0	0	7	9	8	1	6	0	1	1
7	1	0	0	1	0	0	0	1	10	0	6	8	3	0	0	2	9	3	0	0	3	0	0	0	1	0	1	0	6	1	0	1	8	2	9	2	6	1	0	1
8	0	0	3	3	0	0	1	0	8	0	3	1	2	0	1	0	9	0	1	0	2	3	1	0	1	2	0	0	9	1	0	1	2	1	2	0	9	1	0	0
9	0	0	4	1	0	0	3	1	0	0	3	3	2	1	0	0	9	1	2	0	1	1	1	1	2	0	0	1	5	1	0	0	9	1	0	1	9	1	0	0
10	0	0	3	0	0	0	0	4	10	0	8	5	1	0	1	0	8	9	4	3	2	0	0	0	1	1	2	1	5	1	1	0	7	6	7	5	9	0	1	0
11	0	0	1	0	0	0	1	0	8	0	3	1	1	0	1	0	8	1	0	1	1	0	1	2	3	0	2	3	5	1	1	0	7	0	0	0	9	1	0	0
12	0	1	0	0	0	0	2	1	7	4	2	0	2	0	0	0	9	2	1	2	1	1	0	0	1	1	0	0	5	1	1	1	9	8	9	0	6	1	1	0
13	1	0	0	1	0	0	1	2	10	0	8	3	2	2	0	1	8	1	1	0	3	0	1	1	1	0	1	2	6	1	0	1	6	3	1	1	6	0	1	1
14	0	0	5	0	0	0	2	1	7	0	1	0	1	0	1	0	9	0	1	0	2	1	1	1	1	0	2	0	5	1	1	0	8	0	0	1	9	0	0	1
15	0	0	2	1	0	0	1	0	9	4	0	3	1	3	0	0	8	4	0	1	2	0	0	1	1	1	0	0	5	1	1	0	9	0	1	2	6	1	0	0
16	0	1	0	0	0	0	1	2	9	0	4	2	1	1	0	2	9	0	4	1	3	0	1	1	0	2	0	0	6	0	1	0	9	6	3	3	9	3	1	1
17	1	1	1	0	0	0	1	1	7	2	6	0	1	1	0	0	8	0	2	1	3	0	1	0	1	0	1	0	5	1	2	0	8	6	1	1	9	1	0	0
18	0	0	2	1	0	0	1	1	9	9	3	0	1	0	0	1	9	2	1	1	2	1	2	1	0	2	1	0	9	0	0	1	1	1	0	0	9	0	1	1
19	0	0	2	1	0	0	1	3	9	7	1	3	2	2	0	2	9	0	2	0	2	1	1	0	0	0	2	0	6	0	2	0	8	7	0	3	9	3	1	0
20	1	0	0	0	0	1	0	0	8	7	1	1	2	0	0	2	9	0	3	1	1	0	1	3	3	2	0	2	5	1	0	1	9	0	2	1	6	1	0	1
Min	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	1	0	0	0	6	0	0	0
Max	1	2	5	3	1	1	3	4	10	9	8	8	3	3	2	2	9	9	4	3	3	3	2	3	4	2	2	3	9	1	3	1	10	9	9	7	9	3	1	1

These bridges have relatively high initial performance (71% to 96%) and moderate initial safety (45% to 50%) values. The deterioration covers large areas on these bridges. Thus, the results suggest applying a mild MR&R activity (1^{st} to 4^{th} methods) or do not take any activity at the first cycle to minimize the expenses of the MR&R strategies. To be noted, the MR&R costs of these bridges highly affect the MR&R cost of the network inasmuch as the damaged areas are wide.

On the other hand, the second group includes bridges with high initial performance, high initial safety, and low amount of damages (bridge 3 and bridge 9). The MR&R cost of these bridges does not have a major influence on the network MR&R cost even though "replacement" is applied. Therefore, the results contain all kind of MR&R methods (0^{th} to 10^{th} activity).

In this section, only the first cycle of MR&R activities of Pareto optimal solutions are discussed. It is recommended that the readers scrutinize the data provided in Table 5-4 to discover more about the Pareto optimal solutions. In the following sub-section (network level), objective function values for the Pareto optimal solutions are deliberated and compared with each other. Thereafter, in project level sub-section, the long-term effects of a Pareto optimal solution on one of the bridges in the network are illustrated.

5.5.1 Network Level

As was explained in Section 3.7, random variables for performance and safety parameters are generated five times in order to consider uncertainties. Table 5-5 comprises the mean value (μ) of the objective functions for the Pareto optimal solutions. These solutions exhibit a distribution of the objective functions. Specifically, recovering effect varies between 6.9% and 9.7%, applicability ranges from 17.1% to 32.0%, safety stays in the range of 7.0% and 8.7%, and MR&R cost lies between CAD$1,032,000 and CAD$1,391,000.

Bridge managers can, from the Pareto optimal solutions, select the final MR&R plan that compromises recovering effect, applicability, safety, and cost in the most desirable manner. However, if a bridge manager needs more confidence in evaluation of objective functions, mean plus/minus standard deviation ($\mu \pm \sigma$) may be used instead of mean value (μ). As an illustration, for the objective functions that are aimed to be maximized, i.e., recovering effect, applicability, and safety, mean minus standard deviation ($\mu - \sigma$) should be considered. In contrast, mean plus standard deviation ($\mu + \sigma$) is used for the objective function that are aimed to be minimized, i.e., cost.

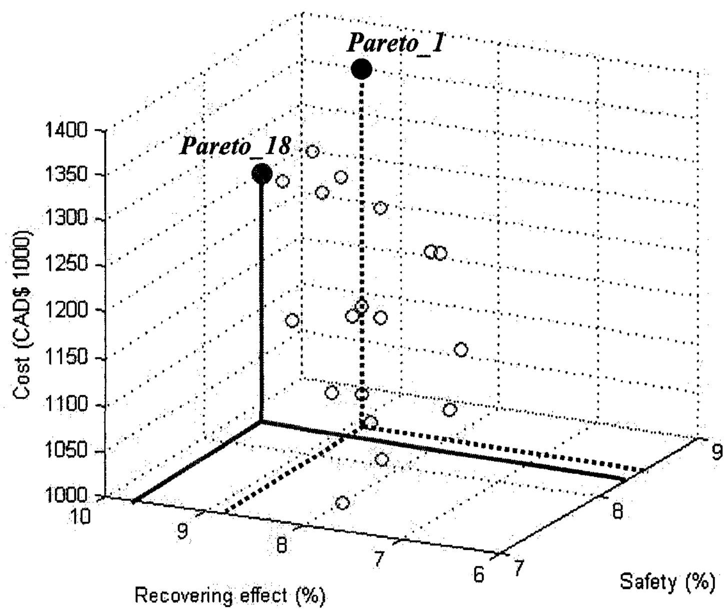
Table 5-5, in addition, gives the standard deviation (σ) of the objective functions. The standard deviations of the objective functions include narrow distributions. Standard deviation of recovering effect, applicability, safety, and cost is limited to 0.3%, 0.7%, 0.2%, and CAD$26,000, respectively.

As an example, suppose the optimal MR&R strategy is selected based on mean plus/minus standard deviation ($\mu \pm \sigma$) values and suppose the total budget is CAD$1,400,000, the 1st optimal solution (μ=CAD$1,391,000 and σ=CAD$26,000) should not be selected as the final MR&R strategy since the budget constraint is not satisfied ($\mu + \sigma$=CAD$1,417,000$\geq$ *budget*).

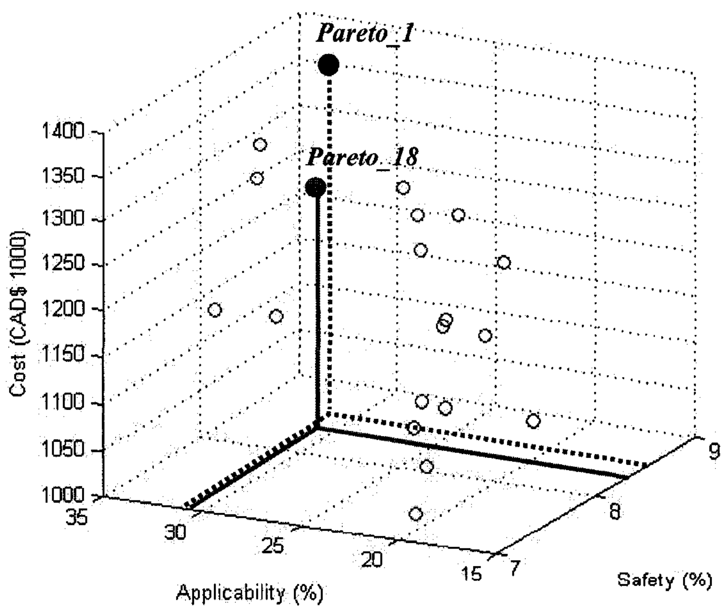
Table 5-5 Mean value (μ) and standard deviation (σ) of Pareto optimal solutions

Number	Weight factors of objective functions				Mean value of objective functions				Standard deviation of objective functions			
	Recovering effect	Applicability	Safety	Cost	Recovering effect (%)	Applicability (%)	Safety (%)	Cost (CAD$ 1000)	Recovering effect (%)	Applicability (%)	Safety (%)	Cost (CAD$ 1000)
1	0.7	0.1	0.1	0.1	8.9	30.9	8.5	1,391	0.2	0.7	0.1	26
2	0.1	0.7	0.1	0.1	6.9	31.8	7.5	1,178	0.1	0.2	0.1	8
3	0.1	0.1	0.7	0.1	8.3	23.2	8.1	1,150	0.1	0.4	0.2	10
4	0.1	0.1	0.1	0.7	7.6	19.1	7.0	1,032	0.2	0.3	0.1	14
5	0.4	0.2	0.2	0.2	7.3	17.1	7.8	1,088	0.2	0.4	0.1	8
6	0.2	0.4	0.2	0.2	8.9	27.5	8.7	1,220	0.3	0.4	0.1	10
7	0.2	0.2	0.4	0.2	7.7	21.0	7.5	1,047	0.2	0.5	0.2	11
8	0.2	0.2	0.2	0.4	8.2	22.6	8.6	1,188	0.2	0.4	0.1	8
9	0.1	0.3	0.3	0.3	9.3	24.4	8.5	1,244	0.3	0.3	0.2	7
10	0.3	0.1	0.3	0.3	7.8	21.7	7.5	1,086	0.2	0.4	0.1	10
11	0.3	0.3	0.1	0.3	8.1	22.3	7.7	1,099	0.3	0.4	0.1	10
12	0.3	0.3	0.3	0.1	8.3	27.2	7.2	1,205	0.2	0.4	0.1	9
13	0.4	0.3	0.2	0.1	9.2	27.7	8.6	1,258	0.3	0.7	0.1	18
14	0.1	0.4	0.3	0.2	8.1	25.8	8.4	1,205	0.3	0.4	0.1	8
15	0.2	0.1	0.4	0.3	8.2	20.1	7.5	1,111	0.2	0.3	0.2	6
16	0.3	0.2	0.1	0.4	9.1	31.6	7.9	1,300	0.3	0.6	0.1	10
17	0.4	0.2	0.3	0.1	8.4	20.1	7.9	1,163	0.3	0.4	0.1	10
18	0.6	0.2	0.1	0.1	9.7	30.8	8.3	1,267	0.2	0.4	0.2	9
19	0.2	0.6	0.1	0.1	8.9	32.0	8.0	1,331	0.2	0.3	0.1	7
20	0.25	0.25	0.25	0.25	8.4	22.6	8.0	1,166	0.2	0.2	0.2	6
Min	-	-	-	-	6.9	17.1	7.0	1,032	0.1	0.2	0.1	6
Max	-	-	-	-	9.7	32.0	8.7	1,391	0.3	0.7	0.2	26

Figure 5-2 shows the Pareto optimal solutions based on the mean objective values. These solutions are also presented in two dimensional plots (Figure 5-3) to provide clearer



(a)



(b)

Figure 5-2 Trade-off among different objective functions for Pareto optimal solutions (3D plots)

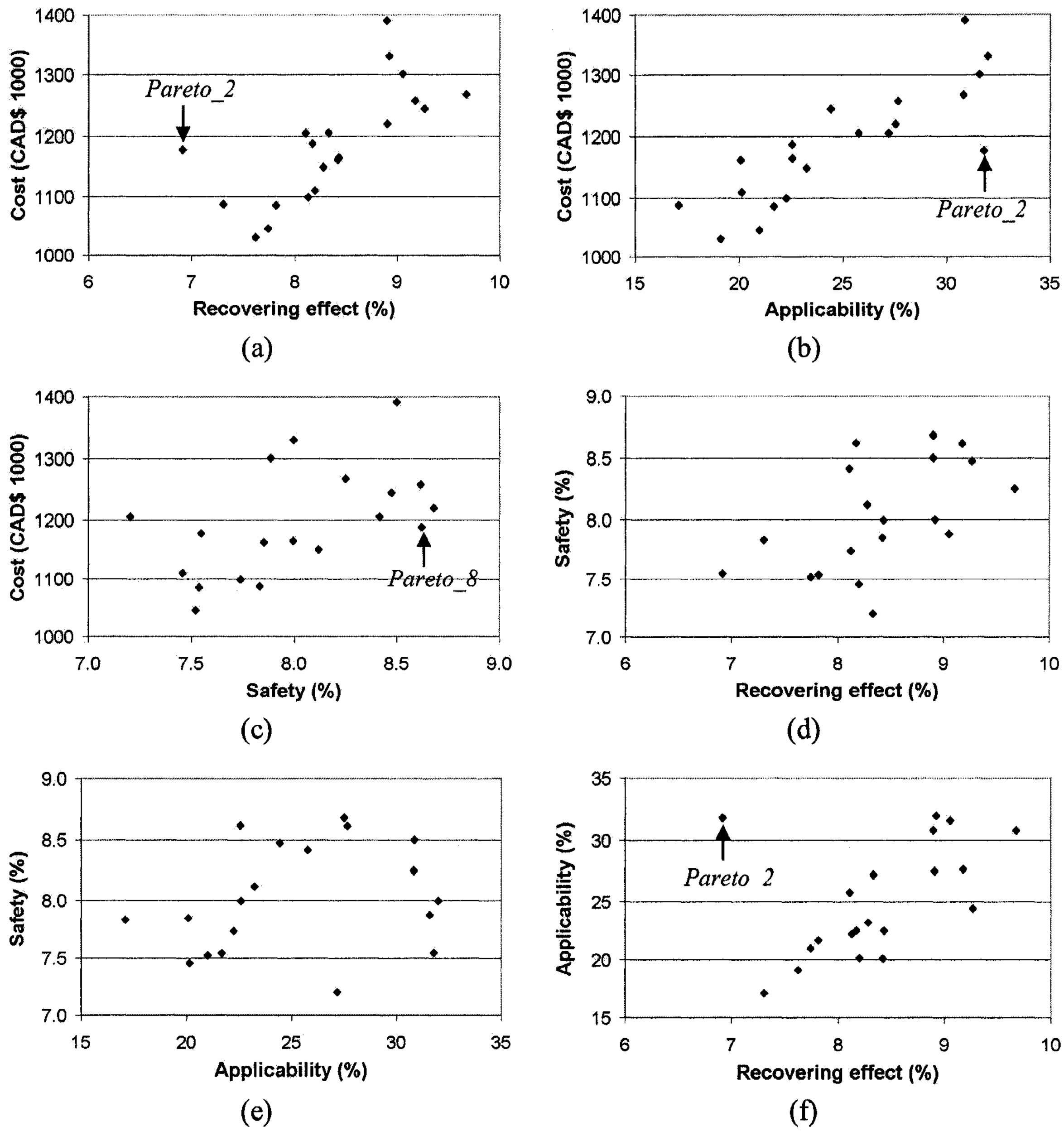


Figure 5-3 Trade-off among different objective functions for Pareto optimal solutions (2D plots)

images. Solutions with high recovering effect cost relatively more (Figure 5-3(a)). Likewise, solutions that are highly applicable are more expensive (Figure 5-3(b)). *Pareto_2* is an exception that has low recovering effect, high applicability, and moderate cost. In contrast with recovering effect and applicability, high costs do not guarantee solutions that cause higher safety for the network (*Pareto_8* in Figure 5-3(c)). Safety, in addition, does not have direct correlation with recovering effect and applicability. In fact, no proportional relationship can be made from safety versus either recovering effect or applicability plots (Figure 5-3(d) and Figure 5-3(e)) while applicability and recovering effect are in direct relation (Figure 5-3(f)).

As examples of the solutions, two Pareto optimal solutions are compared with each other (Figure 5-2 and Table 5-6). Solution *Pareto_18* recovers the performance of the network by 9.5% while *Pareto_1* recovers by 8.9%. Moreover, *Pareto_18* is less expensive than *Pareto_1*. In contrast, *Pareto_1* is more applicable and makes the network safer. In overall, *Pareto_1* is favourable in terms of applicability and safety while *Pareto_18* is preferable in terms of recovering effect and cost. Bridge engineers can select any of these solutions that compromises recovering effect, applicability, safety, and cost in the most desirable manner.

Table 5-6 Two Pareto optimal solutions

Solution	Recovering effect (%)	Applicability (%)	Safety (%)	Cost (CAD$ 1000)
Pareto_1	$\mu = 8.9$ $\mu - \sigma = 8.7$	$\mu = 30.9$ $\mu - \sigma = 30.2$	$\mu = 8.5$ $\mu - \sigma = 8.4$	$\mu = 1{,}391$ $\mu + \sigma = 1{,}417$
Pareto_18	$\mu = 9.7$ $\mu - \sigma = 9.5$	$\mu = 30.8$ $\mu - \sigma = 30.4$	$\mu = 8.3$ $\mu - \sigma = 8.1$	$\mu = 1{,}267$ $\mu + \sigma = 1{,}277$

5.5.2 Project Level

In order to study the long term effects of the Pareto optimal solutions on the bridges at the project level, one bridge is selected as an example and the influences of one Pareto solution on the bridge are considered. Among all the bridges in the network, bridge 8, which is initially in poor condition ($P_0 = 34\% \leq 55\%$, $S_0 = 23\% \leq 44\%$), is chosen. In parallel, *Pareto_1* is picked up form the Pareto optimal solutions.

Table 5-7 indicates bridge 8 MR&R strategy which is suggested by *Pareto_30.* This solution recommends applying "corrosion inhibiting" at the first cycle, doing "surface repair" at the second and fourth cycles, and doing nothing at the third cycle. The maximum recovering effect and the improvement in safety of these MR&R methods are extracted from Table 3-4 and Table 3-6, respectively. Furthermore, assuming that the performance and safety parameters are equal to their mode values, the mode values of the characteristic parameters are collected from Tables 3-1, 3-2, 3-3, and 3-6.

Table 5-7 Bridge 8 MR&R strategy suggested by solution *Pareto_1*

Variables		Cycle 1	Cycle 2	Cycle 3	Cycle 4
MR&R Method		5	1	0	1
Maximum recovering effect (%), RE_{max}		31	14	0	14
Mode values of performance parameters	T_d (years)	2.50	1.20	0.00	1.20
	α-δ (year^{-1})	1.43	1.71	2.28	1.71
	T_{pd} (years)	4.00	3.00	0.00	3.00
	α (year^{-1})	2.28	2.28	2.28	2.28
Improvement in safety (%), γ		40	10	0	10
Mode values of safety parameters	T_d (years)	2.50	1.20	0.00	1.20
	$\beta-\varepsilon$ (year^{-1})	0.40	0.60	0.60	0.60
	T_{pd} (years)	4.00	3.00	0.00	3.00
	β (year^{-1})	0.60	0.60	0.60	0.60

Figure 5-4 (a) depicts bridge 8 performance profile based on the data provided in Table 5-7. The initial performance level improves by 31% as "corrosion inhibiting" is applied.

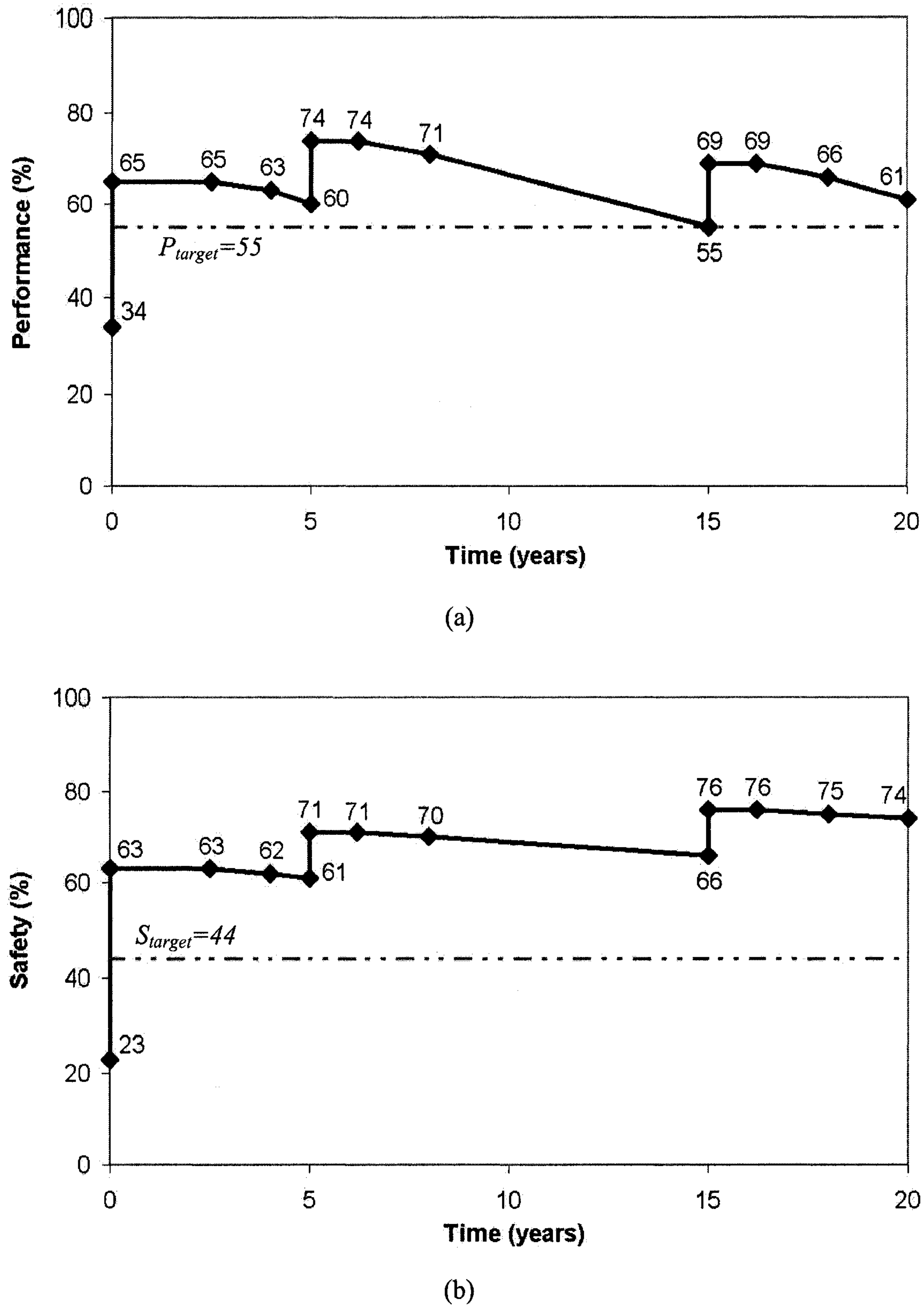


Figure 5-4 Bridge 8 under solution *Pareto_1*: (a) performance profile; (b) safety profile

During the first cycle, the performance decreases to 60% and then it is rises to 74% as "surface repair" is applied. After 1.2 year, the performance declines continuously and it reaches 55% at the beginning of the fourth cycle. Finally, it is increased to 69% as the last MR&R activity is applied. To be mentioned, the performance of the bridge has been above the target value (55%) for the study period.

Similarly, Figure 5-4 (b) shows bridge 8 safety profile. The initial safety is drastically improved by the first MR&R method. Thereafter, it is increased by two minor growths at the 5^{th} and the 15^{th} year. Meanwhile, it is deteriorating slowly. At the end, the safety reaches 74% which is well above the safety target value.

5.6 SUMMARY AND CONCLUSIONS

In this chapter, a case study on ten bridges in Montreal has been done to demonstrate the feasibility and usefulness of the proposed methodology and formulation. The data is obtained from the MTQ database and are aimed to represent the entire network. The assumptions that are taken in the methodology, formulation, and case study are summarized and the GA optimization results are presented. The validity of the results is also discussed in this chapter.

The following conclusions can be drawn from the present study:

(1) The GA results in 20 Pareto optimal solutions. All of these solutions are optimal MR&R strategies and none of them can dominate any others. Bridge managers can, from the Pareto optimal solutions, select the final MR&R solution that compromises recovering effect, applicability, safety, and cost in the most desirable manner.

(2) The Pareto optimal solutions satisfy the constraints. For instance, the performance and safety level of the bridges with low initial values are increased to be greater than the target values. The costs of these solutions are, furthermore, within the budget limitation.

(3) Using mean plus/minus standard deviation values of the objective functions, omits some of the Pareto optimal solution. This decreases the risk of unsatisfactory events in probabilistic prediction.

CHAPTER 6 SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 SUMMARY

The present work has built on multi-linear performance and safety models which predict future condition of bridges and consider uncertainties associated with deterioration. A set of goals and criteria were defined upon which the alternative MR&R strategies could be evaluated: (1) The total long-term benefits of MR&R strategies should be maximized, i.e., recovering effect, applicability, and safety; (2) The MR&R activities should be chosen to give the best match possible to the types of damages and the deterioration level of each bridge; (3) The uncertainties associated with deterioration of performance and safety should be modeled; (4) The MR&R activities should satisfy the performance and safety criteria; and (5) The total cost should be minimized and should not exceed the budget limitation.

To achieve these goals, ten types of MR&R activities were selected in repairing RC bridge decks, eight kinds of damages were characterized as common RC bridge deck defects, and GA was selected as an optimization tool. In accordance with the objective functions and constraint functions, a multi-objective GA was formulated to find the optimal long-term network-level bridge MR&R strategies.

A case study on ten bridges in Montreal was done to demonstrate the feasibility and usefulness of the proposed methodology and formulation. The data were obtained from the MTQ database and were aimed to represent the entire network.

6.2 CONCLUSIONS AND CONTRIBUTIONS

The contributions of this thesis are grouped into the following areas:

(1) Multi-linear performance and safety models have been proposed. The models are characterized by several parameters which have triangular distributions. These models represent uncertainties associated with deterioration of performance and safety and results in the selection of both preventive and essential MR&R activities.

(2) The objective functions, i.e., recovering effect, applicability, safety, and cost, and constraint functions, i.e., performance target value, safety target value, and budget, have been formulated to evaluate the alternative MR&R strategies.

(3) A multi-objective GA-based model has been developed to select Pareto optimal solutions. The model is based on the specific types of MR&R activities and a variety of damage types for RC bridge decks.

(4) The Pareto optimal solutions include a group of optimal long-term bridge MR&R strategies at the network-level. Bridge managers can, from the Pareto optimal solutions, select the final MR&R solution that compromises recovering effect, applicability, safety, and cost in the most desirable manner.

6.3 FUTURE WORK

While pursuing this research, several limitations have been identified related to the requirements and the performance of the proposed method. In order to enhance the bridge MR&R model and to improve the accuracy of the GA results, the following points should be explored in the future research.

(1) Performance parameters, recovering effect values, applicability indices, safety parameters, and unit costs could be defined based on read data collected from bridge MR&R projects.

(2) Probabilistic cost model could be delineated. The cost model comprises uncertainties associated with cost, and hence decreases the risk of unsatisfactory events.

(3) User cost or user travel time delay could be defined as a new objective function.

(4) To do life-cycle cost analysis, bridge constructional costs could be added to the MR&R and user costs.

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APPENDIX A: FITNESS FUNCTION

```
function [x fval] = Wei_Sin_Obj(a,b,c,d,p,NVARS)

options =
gaoptimset('PopulationSize',150,'EliteCount',7,'CrossoverFraction',0.95
,'PopInitRange',[1;11],'Generations',100,...
    'TimeLimit',Inf,'StallTimeLimit',Inf,'TolFun',1.0000e-
006,'TolCon',1.0000e-
006,'CreationFcn',@int_pop,'MutationFcn',@int_mutation);

[x fval] = ga(@Single_Objective,NVARS,[],[],[],[],[],[],[],options);

% Single_Objective is the nested function that computes the fitness
function

function F = Single_Objective(x)

% Bgt = Total budget (1000 CAD$)
Bgt = 2000;

% T = Study period (year)
T = 15;

% L = Length of each cycle
L = 5;

% int_rate = annual interest rate
int_rate = 0.05;

% NVAR = Number of variables = (1 + floor(T/L))*size(D0,1);

% Num_Try = Number of trys should be done to calculate fitness function
based on ...
            % sample mean values or sample mean values plus/minus
sample standard deviation values
Num_Try = 5;

% D0 = Damages type of each bridge in the network at t=0
D0=[2   1   7   226 10  0   0   0;
    0   20  8   544 0   50  0   32;
    0   2   0   0   13  0   0   0;
    0   0   0   49  6   82  14  11;
    0   0   0   0   63  12  0   0;
    2   12  0   78  13  5   21  0;
    0   0   0   46  21  0   0   17;
    670 0   6   0   2   0   0   84;
    0   0   0   0   13  0   0   0;
    400 300 4   0   0   0   4   0];

% P0 = Performance level of each bridge in the network at t=0 (the
higher the better) (%)
```

```
P0=[86;
    96;
    89;
    79;
    21;
    71;
    71;
    34;
    89;
    25];

% Td0 = Time to damage initiation for each bridge (year)
Td0=[0;
     0;
     2;
     0;
     0;
     0;
     0;
     0;
     2;
     0];


% S0 = Safety index of bridges in the network at t=0
S0 =[47;
     50;
     60;
     39;
     44;
     45;
     50;
     23;
     65;
     52];

% R = Recovering effect value of MR&R methods
R =[ 0      0      0      0      0      0      0      0;
     5      3      0      1      1      0      3      1;
     3      4      5      2      2      1      4      1;
     7      4      0      1      2      0      2      2;
     3      4      2      1      2      2      0      2;
     3      3      4      4      4      4      5      4;
    35     35     35     35     35     35     35     35;
    40     40     40     40     40     40     40     40;
    40     40     40     40     40     40     40     40;
    40     40     40     40     40     40     40     40;
    90     90     90     90     90     90     90     90];

% MaxR = Maximum recovering effect value of MR&R methods
MaxR =[  0;
        14;
        22;
        18;
        16;
        31;
```

```
         35;
         40;
         40;
         40;
         90];

% A = Applicability index of MR&R methods
A =[  0       0       0       0       0       0       0       0;
    100      90      10      20      70      50      80      10;
     50      70     100      50      50      50      50      20;
    100      80      10      30      20      10      50      20;
     70     100      60      20      50      70      50      20;
     40      50      70     100      60      50      50      30;
     20      50     100      70      60      60      70      80;
     30      40     100      80      60      70      40      90;
     50      50     100      70      50      80      20      30;
     60      60     100      50      50      50      50      50;
     20      40     100      80      50      80      50      60];

% MaxS = Maximum safety index of MR&R methods
MaxS =[  0;
         10;
         10;
         20;
         20;
         40;
         46;
         60;
         60;
         60;
         90];

% C = Unit cost of MR&R methods (1000 CAD$)
C =[ 0.000;
     0.120;
     0.160;
     0.180;
     0.280;
     0.420;
     0.500;
     0.620;
     0.560;
     0.520;
     1.420];

% Num_Cyc = Number of cycles in study period
Num_Cyc = 1 + floor(T/L);

% Prob_det = Probabilistic deterioration <11x4x3 double>
% First dimention represents MR&R methods varys from 1 to 11
% Second dimention represents deterioration indeces varys from 1 to 4
as following:
                  %alpha = deterioration rate with no MR&R (1/year);
                  %Td = Delay in deterioration (years);
                  %alpha-delta = deterioration rate during effect
(1/year);
```

```
            %Tpd = duration of MR&R effect (years);
% Third dimention represents parameters of triangular distribution
Prob_det(1,1,:)=[0.00  2.28  4.57];
Prob_det(1,2,:)=[0.00  0.00  0.00];
Prob_det(1,3,:)=[0.00  2.28  4.57];
Prob_det(1,4,:)=[0.00  0.00  0.00];

Prob_det(2,1,:)=[0.00  2.28  4.57];
Prob_det(2,2,:)=[1.00  1.20  2.00];
Prob_det(2,3,:)=[0.00  1.71  3.43];
Prob_det(2,4,:)=[2.00  3.00  4.00];

Prob_det(3,1,:)=[0.00  2.28  4.57];
Prob_det(3,2,:)=[1.00  1.40  2.00];
Prob_det(3,3,:)=[0.00  1.71  3.43];
Prob_det(3,4,:)=[2.00  3.00  4.00];

Prob_det(4,1,:)=[0.00  2.28  4.57];
Prob_det(4,2,:)=[1.00  1.60  2.00];
Prob_det(4,3,:)=[0.00  2.00  2.86];
Prob_det(4,4,:)=[2.00  3.50  4.00];

Prob_det(5,1,:)=[0.00  2.28  4.57];
Prob_det(5,2,:)=[1.00  2.00  3.00];
Prob_det(5,3,:)=[0.00  1.43  2.86];
Prob_det(5,4,:)=[3.00  4.00  5.00];

Prob_det(6,1,:)=[0.00  2.28  4.57];
Prob_det(6,2,:)=[1.00  2.50  3.00];
Prob_det(6,3,:)=[0.00  1.43  2.86];
Prob_det(6,4,:)=[3.00  4.00  5.00];

Prob_det(7,1,:)=[0.00  2.28  4.57];
Prob_det(7,2,:)=[1.50  2.50  3.50];
Prob_det(7,3,:)=[0.00  1.14  2.28];
Prob_det(7,4,:)=[4.00  6.00  7.00];

Prob_det(8,1,:)=[0.00  2.28  4.57];
Prob_det(8,2,:)=[2.00  4.00  5.00];
Prob_det(8,3,:)=[0.00  0.57  1.43];
Prob_det(8,4,:)=[5.00  8.00  13.0];

Prob_det(9,1,:)=[0.00  2.28  4.57];
Prob_det(9,2,:)=[2.00  3.50  5.00];
Prob_det(9,3,:)=[0.00  0.86  1.43];
Prob_det(9,4,:)=[5.00  7.00  12.0];

Prob_det(10,1,:)=[0.00  2.28  4.57];
Prob_det(10,2,:)=[2.00  3.00  5.00];
Prob_det(10,3,:)=[0.00  0.86  1.43];
Prob_det(10,4,:)=[5.00  6.00  12.0];

Prob_det(11,1,:)=[0.00  2.28  4.57];
Prob_det(11,2,:)=[4.00  6.00  12.0];
Prob_det(11,3,:)=[0.00  2.28  4.57];
```

```
Prob_det(11,4,:)=[12.0  13.0  15.0];

% Prob_sft = Probabilistic safety <11x4x3 double>
% First dimention represents MR&R methods varys from 1 to 11
% Second dimention represents deterioration indeces varys from 1 to 4
as following:
                    %alpha = deterioration rate with no MR&R (1/year);
                    %Td = Delay in deterioration (years);
                    %alpha-delta = deterioration rate during effect
(1/year);
                    %Tpd = duration of MR&R effect (years);
% Third dimention represents parameters of triangular distribution

Prob_sft(1,1,:)=[0.00  0.60  1.40];
Prob_sft(1,2,:)=[0.00  0.00  0.00];
Prob_sft(1,3,:)=[0.00  0.60  1.40];
Prob_sft(1,4,:)=[0.00  0.00  0.00];

Prob_sft(2,1,:)=[0.00  0.60  1.40];
Prob_sft(2,2,:)=[1.00  1.20  2.00];
Prob_sft(2,3,:)=[0.00  0.60  1.20];
Prob_sft(2,4,:)=[2.00  3.00  4.00];

Prob_sft(3,1,:)=[0.00  0.60  1.40];
Prob_sft(3,2,:)=[1.00  1.40  2.00];
Prob_sft(3,3,:)=[0.00  0.60  1.20];
Prob_sft(3,4,:)=[2.00  3.00  4.00];

Prob_sft(4,1,:)=[0.00  0.60  1.40];
Prob_sft(4,2,:)=[1.00  1.60  2.00];
Prob_sft(4,3,:)=[0.00  0.40  1.00];
Prob_sft(4,4,:)=[2.00  3.50  4.00];

Prob_sft(5,1,:)=[0.00  0.60  1.40];
Prob_sft(5,2,:)=[1.00  2.00  3.00];
Prob_sft(5,3,:)=[0.00  0.40  0.80];
Prob_sft(5,4,:)=[3.00  4.00  5.00];

Prob_sft(6,1,:)=[0.00  0.60  1.40];
Prob_sft(6,2,:)=[1.00  2.50  3.00];
Prob_sft(6,3,:)=[0.00  0.40  0.80];
Prob_sft(6,4,:)=[3.00  4.00  5.00];

Prob_sft(7,1,:)=[0.00  0.60  1.40];
Prob_sft(7,2,:)=[1.50  2.50  3.50];
Prob_sft(7,3,:)=[0.00  0.28  0.60];
Prob_sft(7,4,:)=[4.00  6.00  7.00];

Prob_sft(8,1,:)=[0.00  0.60  1.40];
Prob_sft(8,2,:)=[2.00  4.00  5.00];
Prob_sft(8,3,:)=[0.00  0.16  0.48];
Prob_sft(8,4,:)=[5.00  8.00  13.0];

Prob_sft(9,1,:)=[0.00  0.60  1.40];
Prob_sft(9,2,:)=[2.00  3.50  5.00];
```

```
Prob_sft(9,3,:)=[0.00  0.24  0.48];
Prob_sft(9,4,:)=[5.00  7.00  12.0];

Prob_sft(10,1,:)=[0.00  0.60  1.40];
Prob_sft(10,2,:)=[2.00  3.00  5.00];
Prob_sft(10,3,:)=[0.00  0.24  0.48];
Prob_sft(10,4,:)=[5.00  6.00  12.0];

Prob_sft(11,1,:)=[0.00  0.60  1.40];
Prob_sft(11,2,:)=[4.00  6.00  12.0];
Prob_sft(11,3,:)=[0.00  0.60  1.40];
Prob_sft(11,4,:)=[12.0  13.0  15.0];

% To simulate the triangular distribution
function FunTri=trirnd(min,mode,max)
FunTri=zeros(1,1,1);
z=rand;
if sqrt(z*(max-min)*(mode-min))+min < mode
    FunTri(1)=sqrt(z*(max-min)*(mode-min))+ min;
else
    FunTri(1)=max-sqrt((1-z)*(max-min)*(max-mode));
end
end

% To organize single-row children into matrix children
for bridge=1:size(D0,1)
    for cycle=1:Num_Cyc
        X(bridge,cycle)=x((bridge-1)*Num_Cyc+cycle);
    end
end

% Fitness function
SumD0=sum(D0,2);
for Try=1:Num_Try %to calculate fitness function based on sample mean
values or sample mean values plus/minus sample standard deviation
values
for bridge=1:size(D0,1)
    % Generate realization of random variables based on respective
distribution of deterioration factors
    for cycle=1:Num_Cyc
        for det_index=1:4

FunTri(bridge,cycle,det_index)=trirnd(Prob_det(X(bridge,cycle),det_inde
x,1),Prob_det(X(bridge,cycle),det_index,2),...
            Prob_det(X(bridge,cycle),det_index,3));
        end
    end
    alpha0=trirnd(0.00,  2.28,  4.57);
    % Generate realization of random variables based on respective
distribution of safety factors
    for cycle=1:Num_Cyc
        for det_index=1:4

FunTri_sft(bridge,cycle,det_index)=trirnd(Prob_sft(X(bridge,cycle),det_
index,1),Prob_sft(X(bridge,cycle),det_index,2),...
            Prob_sft(X(bridge,cycle),det_index,3));
```

```
        end
    end
    alpha0_sft=trirnd(0.00,  0.60,  1.40);
    % Damaged areas of each bridge at the end of cycle=1
    if X(bridge,1)>=2;
        for damage=1:size(D0,2)
            if FunTri(bridge,1,2)>=L
                D(bridge,1,damage)=D0(bridge,damage)*(1-
R(X(bridge,1),damage)/100);
            else
                if FunTri(bridge,1,4)>=L
                    if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                        D(bridge,1,damage)=D0(bridge,damage)*(1-
R(X(bridge,1),damage)/100)+(FunTri(bridge,1,3))*(L-FunTri(bridge,1,2));
                    else
                        D(bridge,1,damage)=D0(bridge,damage)*(1-
R(X(bridge,1),damage)/100)+(FunTri(bridge,1,1))*(L-FunTri(bridge,1,2));
                    end
                else
                    if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                        D(bridge,1,damage)=D0(bridge,damage)*(1-
R(X(bridge,1),damage)/100)+(FunTri(bridge,1,3))*...
                            (FunTri(bridge,1,4)-
FunTri(bridge,1,2))+(FunTri(bridge,1,1))*(L-FunTri(bridge,1,4));
                    else
                        D(bridge,1,damage)=D0(bridge,damage)*(1-
R(X(bridge,1),damage)/100)+(FunTri(bridge,1,1))*...
                            (L-FunTri(bridge,1,2));
                    end
                end
            end
        end
    else
        for damage =1:size(D0,2)
            if Td0(bridge,1)>=L
                D(bridge,1,damage)=D0(bridge,damage);
            else
                D(bridge,1,damage)=D0(bridge,damage)+alpha0*L;
            end
        end
    end
    % Damages type of each bridge at the end of each cycle
    for cycle=2:Num_Cyc
        if X(bridge,cycle)>=2
            for damage=1:1:size(D0,2)
                if FunTri(bridge,cycle,2)>=L
                    D(bridge,cycle,damage)=D(bridge,(cycle-
1),damage)*(1-R(X(bridge,cycle),damage)/100);
                else
                    if FunTri(bridge,cycle,4)>=L
                        if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                            D(bridge,cycle,damage)=D(bridge,(cycle-
1),damage)*(1-R(X(bridge,cycle),damage)/100)+FunTri(bridge,cycle,3)*...
                                (L-FunTri(bridge,1,2));
                        else
```

```
                              D(bridge,cycle,damage)=D(bridge,(cycle-
1),damage)*(1-R(X(bridge,cycle),damage)/100)+FunTri(bridge,cycle,1)*...
                                   (L-FunTri(bridge,1,2));
                         end
                    else
                         if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                              D(bridge,cycle,damage)=D(bridge,(cycle-
1),damage)*(1-
R(X(bridge,cycle),damage)/100)+(FunTri(bridge,cycle,3))*...
                                   (FunTri(bridge,cycle,4)-
FunTri(bridge,cycle,2))+(FunTri(bridge,cycle,1))*(L-
FunTri(bridge,cycle,4));
                         else
                              D(bridge,cycle,damage)=D(bridge,(cycle-
1),damage)*(1-
R(X(bridge,cycle),damage)/100)+(FunTri(bridge,cycle,1))*...
                                   (L-FunTri(bridge,cycle,2));
                         end
                    end
               end
          end
     else
          cycle_last_MRR=0;
          for i=cycle:-1:1
               if X(bridge,i)>=2
                    cycle_last_MRR=i;
                    break
               end
          end
          if cycle_last_MRR>=1
               if FunTri(bridge,cycle_last_MRR,2)>=((cycle-
cycle_last_MRR)*L)
                    for damage=1:1:size(D0,2)

D(bridge,cycle,damage)=D(bridge,cycle_last_MRR,damage);
                    end
               else
                    if FunTri(bridge,cycle_last_MRR,4)>=((cycle-
cycle_last_MRR)*L)
                         if
FunTri(bridge,cycle_last_MRR,3)<=FunTri(bridge,cycle_last_MRR,1)
                              for damage=1:1:size(D0,2)

D(bridge,cycle,damage)=D(bridge,cycle_last_MRR,damage)+FunTri(bridge,cy
cle_last_MRR,3)*...
                                        ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2));
                              end
                         else
                              for damage=1:1:size(D0,2)

D(bridge,cycle,damage)=D(bridge,cycle_last_MRR,damage)+FunTri(bridge,cy
cle_last_MRR,1)*...
                                        ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2));
                              end
```

```
                        end
                    else
                        if
FunTri(bridge,cycle_last_MRR,3)<=FunTri(bridge,cycle_last_MRR,1)
                            for damage=1:1:size(D0,2)

D(bridge,cycle,damage)=D(bridge,cycle_last_MRR,damage)+FunTri(bridge,cy
cle_last_MRR,3)*...
                                    (FunTri(bridge,cycle_last_MRR,4)-
FunTri(bridge,cycle_last_MRR,2))+...

FunTri(bridge,cycle_last_MRR,1)*((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,4));
                            end
                        else
                            for damage=1:1:size(D0,2)

D(bridge,cycle,damage)=D(bridge,cycle_last_MRR,damage)+...

FunTri(bridge,cycle_last_MRR,1)*((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2));
                            end
                        end
                    end
                end
            else
                if Td0>=cycle*L
                    for damage=1:1:size(D0,2)
                        D(bridge,cycle,damage)=D0(bridge,damage);
                    end
                else

D(bridge,cycle,damage)=D0(bridge,damage)+alpha0*(cycle*L-Td0(bridge,1));
                end
            end
        end
    end
    % Performance level of each bridge in the network at the end of
cycle=1
    if X(bridge,1)>=2
        if P0(bridge,1)>=90
            if FunTri(bridge,1,2)>=L
                P(bridge,1)=P0(bridge,1);
            else
                if FunTri(bridge,1,4)>=L
                    if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                        P(bridge,1)=P0(bridge,1)*(1-
FunTri(bridge,1,3)/100)^(L-FunTri(bridge,1,2));
                    else
                        P(bridge,1)=P0(bridge,1)*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                    end
                else
                    if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                        P(bridge,1)=(P0(bridge,1)*(1-
FunTri(bridge,1,3)/100)^(FunTri(bridge,1,4)-FunTri(bridge,1,2)))*...
```

```
                              (1-FunTri(bridge,1,1)/100)^(L-
FunTri(bridge,1,4));
                    else
                        P(bridge,1)=P0(bridge,1)*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                    end
                end
            end
        else
            if P0(bridge,1)+MaxR(X(bridge,1),1)>=90
                if FunTri(bridge,1,2)>=L
                    P(bridge,1)=90;
                else
                    if FunTri(bridge,1,4)>=L
                        if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                            P(bridge,1)=90*(1-
FunTri(bridge,1,3)/100)^(L-FunTri(bridge,1,2));
                        else
                            P(bridge,1)=90*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                        end
                    else
                        if FunTri(bridge,1,3)<=FunTri(bridge,1,1)
                            P(bridge,1)=(90*(1-
FunTri(bridge,1,3)/100)^(FunTri(bridge,1,4)-FunTri(bridge,1,2)))*...
                                (1-FunTri(bridge,1,1)/100)^(L-
FunTri(bridge,1,4));
                        else
                            P(bridge,1)=90*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                        end
                    end
                end
            else
                if FunTri(bridge,1,2)>=L
                    P(bridge,1)=P0(bridge,1)+MaxR(X(bridge,1),1);
                else
                    if FunTri(bridge,1,4)>=L
                        if FunTri(bridge,1,3)<=FunTri(bridge,1,1)

P(bridge,1)=(P0(bridge,1)+MaxR(X(bridge,1),1))*(1-
FunTri(bridge,1,3)/100)^(L-FunTri(bridge,1,2));
                        else

P(bridge,1)=(P0(bridge,1)+MaxR(X(bridge,1),1))*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                        end
                    else
                        if FunTri(bridge,1,3)<=FunTri(bridge,1,1)

P(bridge,1)=((P0(bridge,1)+MaxR(X(bridge,1),1))*(1-
FunTri(bridge,1,3)/100)^(FunTri(bridge,1,4)-FunTri(bridge,1,2)))*...
                                (1-FunTri(bridge,1,1)/100)^(L-
FunTri(bridge,1,4));
                        else
```

```
P(bridge,1)=(P0(bridge,1)+MaxR(X(bridge,1),1))*(1-
FunTri(bridge,1,1)/100)^(L-FunTri(bridge,1,2));
                            end
                        end
                    end
                end
            end
        else
            if Td0(bridge,1)>=L
                P(bridge,1)=P0(bridge,1);
            else
                P(bridge,1)=P0(bridge,1)*(1-alpha0/100)^(L-Td0(bridge,1));
            end
        end
        % Performance level of each bridge in the network at the end of
each cycle
        for cycle=2:Num_Cyc
            if X(bridge,cycle)>=2
                if P(bridge,(cycle-1))>=90
                    if FunTri(bridge,cycle,2)>=L
                        P(bridge,cycle)=P(bridge,(cycle-1));
                    else
                        if FunTri(bridge,cycle,4)>=L
                            if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                P(bridge,cycle)=P(bridge,(cycle-1))*(1-
FunTri(bridge,cycle,3)/100)^(L-FunTri(bridge,cycle,2));
                            else
                                P(bridge,cycle)=P(bridge,(cycle-1))*(1-
FunTri(bridge,cycle,1)/100)^(L-FunTri(bridge,cycle,2));
                            end
                        else
                            if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                P(bridge,cycle)=(P(bridge,(cycle-1))*(1-
FunTri(bridge,cycle,3)/100)^(FunTri(bridge,cycle,4)-
FunTri(bridge,cycle,2)))*...
                                    (1-FunTri(bridge,cycle,1)/100)^(L-
FunTri(bridge,cycle,4));
                            else
                                P(bridge,cycle)=P(bridge,(cycle-1))*(1-
FunTri(bridge,cycle,1)/100)^(L-FunTri(bridge,cycle,2));
                            end
                        end
                    end
                else
                    if P(bridge,(cycle-1))+MaxR(X(bridge,cycle),1)>=90
                        if FunTri(bridge,cycle,2)>=L
                            P(bridge,cycle)=90;
                        else
                            if FunTri(bridge,cycle,4)>=L
                                if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                    P(bridge,cycle)=90*(1-
FunTri(bridge,cycle,3)/100)^(L-FunTri(bridge,cycle,4));
                                else
```

```
                                        P(bridge,cycle)=90*(1-
FunTri(bridge,cycle,1)/100)^(L-FunTri(bridge,cycle,4));
                                    end
                                else
                                    if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                        P(bridge,cycle)=(90*(1-
FunTri(bridge,cycle,3)/100)^(FunTri(bridge,cycle,4)-
FunTri(bridge,cycle,2)))*...
                                            (1-FunTri(bridge,cycle,1)/100)^(L-
FunTri(bridge,cycle,4));
                                    else
                                        P(bridge,cycle)=90*(1-
FunTri(bridge,cycle,1)/100)^(L-FunTri(bridge,cycle,2));
                                    end
                                end
                            end
                        else
                            if FunTri(bridge,cycle,2)>=L
                                P(bridge,cycle)=P(bridge,(cycle-
1))+MaxR(X(bridge,cycle),1);
                            else
                                if FunTri(bridge,cycle,4)>=L
                                    if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                        P(bridge,cycle)=(P(bridge,(cycle-
1))+MaxR(X(bridge,cycle),1))*(1-FunTri(bridge,cycle,3)/100)^(L-
FunTri(bridge,cycle,2));
                                    else
                                        P(bridge,cycle)=(P(bridge,(cycle-
1))+MaxR(X(bridge,cycle),1))*(1-FunTri(bridge,cycle,1)/100)^(L-
FunTri(bridge,cycle,2));
                                    end
                                else
                                    if
FunTri(bridge,cycle,3)<=FunTri(bridge,cycle,1)
                                        P(bridge,cycle)=((P(bridge,(cycle-
1))+MaxR(X(bridge,cycle),1))*(1-FunTri(bridge,cycle,3)/100)^...
                                            (FunTri(bridge,cycle,4)-
FunTri(bridge,cycle,2)))*(1-FunTri(bridge,cycle,1)/100)^(L-1-
FunTri(bridge,cycle,4));
                                    else
                                        P(bridge,cycle)=(P(bridge,(cycle-
1))+MaxR(X(bridge,cycle),1))*(1-FunTri(bridge,cycle,1)/100)^(L-
FunTri(bridge,cycle,2));
                                    end
                                end
                            end
                        end
                    end
                else
                    cycle_last_MRR=0;
                    for i=cycle:-1:1
                        if X(bridge,i)>=2
                            cycle_last_MRR=i;
                            break
                        end
```

```
            end
            if cycle_last_MRR>=1
                if FunTri(bridge,cycle_last_MRR,2)>=(cycle-
cycle_last_MRR)*L
                    P(bridge,cycle)=P(bridge,cycle_last_MRR);
                else
                    if FunTri(bridge,cycle_last_MRR,4)>=(cycle-
cycle_last_MRR)*L
                        if
FunTri(bridge,cycle_last_MRR,3)<=FunTri(bridge,cycle_last_MRR,1)

P(bridge,cycle)=P(bridge,cycle_last_MRR)*((1-
FunTri(bridge,cycle_last_MRR,3)/100)^...
                            ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2)));
                        else

P(bridge,cycle)=P(bridge,cycle_last_MRR)*((1-
FunTri(bridge,cycle_last_MRR,1)/100)^...
                            ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2)));
                        end
                    else
                        if
FunTri(bridge,cycle_last_MRR,3)<=FunTri(bridge,cycle_last_MRR,1)

P(bridge,cycle)=(P(bridge,cycle_last_MRR)*((1-
FunTri(bridge,cycle_last_MRR,3)/100)^...
                            (FunTri(bridge,cycle_last_MRR,4)-
FunTri(bridge,cycle_last_MRR,2))))*((1-
FunTri(bridge,cycle_last_MRR,1)/100)^...
                            ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,4)));
                        else

P(bridge,cycle)=P(bridge,cycle_last_MRR)*((1-
FunTri(bridge,cycle_last_MRR,1)/100)^...
                                ((cycle-cycle_last_MRR)*L-
FunTri(bridge,cycle_last_MRR,2)));
                        end
                    end
                end
            else
                P(bridge,cycle)=P0(bridge,1)*((1-alpha0/100)^(cycle*L-
Td0(bridge,1)));
            end
        end
    end
    % Safety level of each bridge in the network at the end of cycle=1
    if X(bridge,1)>=2
        if S0(bridge,1)>=90
            if FunTri_sft(bridge,1,2)>=L
                S(bridge,1)=S0(bridge,1);
            else
                if FunTri_sft(bridge,1,4)>=L
                    if FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)
```

```
                        S(bridge,1)=S0(bridge,1)*(1-
FunTri_sft(bridge,1,3)/100)^(L-FunTri_sft(bridge,1,2));
                    else
                        S(bridge,1)=S0(bridge,1)*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                    end
                else
                    if FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)
                        S(bridge,1)=(S0(bridge,1)*(1-
FunTri_sft(bridge,1,3)/100)^(FunTri_sft(bridge,1,4)-
FunTri_sft(bridge,1,2)))*...
                            (1-FunTri_sft(bridge,1,1)/100)^(L-
FunTri_sft(bridge,1,4));
                    else
                        S(bridge,1)=S0(bridge,1)*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                    end
                end
            end
        else
            if S0(bridge,1)+MaxS(X(bridge,1),1)>=90
                if FunTri_sft(bridge,1,2)>=L
                    S(bridge,1)=90;
                else
                    if FunTri_sft(bridge,1,4)>=L
                        if
FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)
                            S(bridge,1)=90*(1-
FunTri_sft(bridge,1,3)/100)^(L-FunTri_sft(bridge,1,2));
                        else
                            S(bridge,1)=90*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                        end
                    else
                        if
FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)
                            S(bridge,1)=(90*(1-
FunTri_sft(bridge,1,3)/100)^(FunTri_sft(bridge,1,4)-
FunTri_sft(bridge,1,2)))*...
                                (1-FunTri_sft(bridge,1,1)/100)^(L-
FunTri_sft(bridge,1,4));
                        else
                            S(bridge,1)=90*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                        end
                    end
                end
            else
                if FunTri_sft(bridge,1,2)>=L
                    S(bridge,1)=S0(bridge,1)+MaxS(X(bridge,1),1);
                else
                    if FunTri_sft(bridge,1,4)>=L
                        if
FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)

S(bridge,1)=(S0(bridge,1)+MaxS(X(bridge,1),1))*(1-
FunTri_sft(bridge,1,3)/100)^(L-FunTri_sft(bridge,1,2));
```

```
                        else
S(bridge,1)=(S0(bridge,1)+MaxS(X(bridge,1),1))*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                        end
                    else
                        if
FunTri_sft(bridge,1,3)<=FunTri_sft(bridge,1,1)
S(bridge,1)=((S0(bridge,1)+MaxS(X(bridge,1),1))*(1-
FunTri_sft(bridge,1,3)/100)^(FunTri_sft(bridge,1,4)-
FunTri_sft(bridge,1,2)))*...
                                (1-FunTri_sft(bridge,1,1)/100)^(L-
FunTri_sft(bridge,1,4));
                        else
S(bridge,1)=(S0(bridge,1)+MaxS(X(bridge,1),1))*(1-
FunTri_sft(bridge,1,1)/100)^(L-FunTri_sft(bridge,1,2));
                        end
                    end
                end
            end
        end
    else
        if Td0(bridge,1)>=L
            S(bridge,1)=S0(bridge,1);
        else
            S(bridge,1)=S0(bridge,1)*(1-alpha0_sft/100)^(L-
Td0(bridge,1));
        end
    end
    % Safety level of each bridge in the network at the end of each
cycle
    for cycle=2:Num_Cyc
        if X(bridge,cycle)>=2
            if S(bridge,(cycle-1))>=90
                if FunTri_sft(bridge,cycle,2)>=L
                    S(bridge,cycle)=S(bridge,(cycle-1));
                else
                    if FunTri_sft(bridge,cycle,4)>=L
                        if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                            S(bridge,cycle)=S(bridge,(cycle-1))*(1-
FunTri_sft(bridge,cycle,3)/100)^(L-FunTri_sft(bridge,cycle,2));
                        else
                            S(bridge,cycle)=S(bridge,(cycle-1))*(1-
FunTri_sft(bridge,cycle,1)/100)^(L-FunTri_sft(bridge,cycle,2));
                        end
                    else
                        if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                            S(bridge,cycle)=(S(bridge,(cycle-1))*(1-
FunTri_sft(bridge,cycle,3)/100)^(FunTri_sft(bridge,cycle,4)-
FunTri_sft(bridge,cycle,2)))*...
                                (1-FunTri_sft(bridge,cycle,1)/100)^(L-
FunTri_sft(bridge,cycle,4));
                        else
```

```
                              S(bridge,cycle)=S(bridge,(cycle-1))*(1-
FunTri_sft(bridge,cycle,1)/100)^(L-FunTri_sft(bridge,cycle,2));
                          end
                      end
                  end
              else
                  if S(bridge,(cycle-1))+MaxS(X(bridge,cycle),1)>=90
                      if FunTri_sft(bridge,cycle,2)>=L
                          S(bridge,cycle)=90;
                      else
                          if FunTri_sft(bridge,cycle,4)>=L
                              if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                                  S(bridge,cycle)=90*(1-
FunTri_sft(bridge,cycle,3)/100)^(L-FunTri_sft(bridge,cycle,4));
                              else
                                  S(bridge,cycle)=90*(1-
FunTri_sft(bridge,cycle,1)/100)^(L-FunTri_sft(bridge,cycle,4));
                              end
                          else
                              if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                                  S(bridge,cycle)=(90*(1-
FunTri_sft(bridge,cycle,3)/100)^(FunTri_sft(bridge,cycle,4)-
FunTri_sft(bridge,cycle,2)))*...
                                      (1-
FunTri_sft(bridge,cycle,1)/100)^(L-FunTri_sft(bridge,cycle,4));
                              else
                                  S(bridge,cycle)=90*(1-
FunTri_sft(bridge,cycle,1)/100)^(L-FunTri_sft(bridge,cycle,2));
                              end
                          end
                      end
                  else
                      if FunTri_sft(bridge,cycle,2)>=L
                          S(bridge,cycle)=S(bridge,(cycle-
1))+MaxS(X(bridge,cycle),1);
                      else
                          if FunTri_sft(bridge,cycle,4)>=L
                              if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                                  S(bridge,cycle)=(S(bridge,(cycle-
1))+MaxS(X(bridge,cycle),1))*(1-FunTri_sft(bridge,cycle,3)/100)^(L-
FunTri_sft(bridge,cycle,2));
                              else
                                  S(bridge,cycle)=(S(bridge,(cycle-
1))+MaxS(X(bridge,cycle),1))*(1-FunTri_sft(bridge,cycle,1)/100)^(L-
FunTri_sft(bridge,cycle,2));
                              end
                          else
                              if
FunTri_sft(bridge,cycle,3)<=FunTri_sft(bridge,cycle,1)
                                  S(bridge,cycle)=((S(bridge,(cycle-
1))+MaxS(X(bridge,cycle),1))*(1-FunTri_sft(bridge,cycle,3)/100)^...
                                      (FunTri_sft(bridge,cycle,4)-
FunTri_sft(bridge,cycle,2)))*(1-FunTri_sft(bridge,cycle,1)/100)^(L-1-
FunTri_sft(bridge,cycle,4));
```

```
                                        else
                                            S(bridge,cycle)=(S(bridge,(cycle-
1))+MaxS(X(bridge,cycle),1))*(1-FunTri_sft(bridge,cycle,1)/100)^(L-
FunTri_sft(bridge,cycle,2));
                                        end
                                    end
                                end
                            end
                        end
                    else
                        cycle_last_MRR=0;
                        for i=cycle:-1:1
                            if X(bridge,i)>=2
                                cycle_last_MRR=i;
                                break
                            end
                        end
                        if cycle_last_MRR>=1
                            if FunTri_sft(bridge,cycle_last_MRR,2)>=(cycle-
cycle_last_MRR)*L
                                S(bridge,cycle)=S(bridge,cycle_last_MRR);
                            else
                                if FunTri_sft(bridge,cycle_last_MRR,4)>=(cycle-
cycle_last_MRR)*L
                                    if
FunTri_sft(bridge,cycle_last_MRR,3)<=FunTri_sft(bridge,cycle_last_MRR,1)

S(bridge,cycle)=S(bridge,cycle_last_MRR)*((1-
FunTri_sft(bridge,cycle_last_MRR,3)/100)^...
                                        ((cycle-cycle_last_MRR)*L-
FunTri_sft(bridge,cycle_last_MRR,2)));
                                    else

S(bridge,cycle)=S(bridge,cycle_last_MRR)*((1-
FunTri_sft(bridge,cycle_last_MRR,1)/100)^...
                                        ((cycle-cycle_last_MRR)*L-
FunTri_sft(bridge,cycle_last_MRR,2)));
                                    end
                                else
                                    if
FunTri_sft(bridge,cycle_last_MRR,3)<=FunTri_sft(bridge,cycle_last_MRR,1)

S(bridge,cycle)=(S(bridge,cycle_last_MRR)*((1-
FunTri_sft(bridge,cycle_last_MRR,3)/100)^...
                                        (FunTri_sft(bridge,cycle_last_MRR,4)-
FunTri_sft(bridge,cycle_last_MRR,2))))*((1-
FunTri_sft(bridge,cycle_last_MRR,1)/100)^...
                                        ((cycle-cycle_last_MRR)*L-
FunTri_sft(bridge,cycle_last_MRR,4)));
                                    else

S(bridge,cycle)=S(bridge,cycle_last_MRR)*((1-
FunTri_sft(bridge,cycle_last_MRR,1)/100)^...
                                            ((cycle-cycle_last_MRR)*L-
FunTri_sft(bridge,cycle_last_MRR,2)));
                                    end
                                end
```

```
                end
            else
                S(bridge,cycle)=S0(bridge,1)*((1-
alpha0_sft/100)^(cycle*L-Td0(bridge,1)));
            end
        end
    end
    % Condition: if performance level of each bridge at the end of each
cycle is smaller than 55...
        % penaltize fitness function
    Per_Con(bridge,1)=0;
    Num_Per_Con(bridge,1)=0;
    for cycle=1:(Num_Cyc)
        if P(bridge,cycle)<55
            Per_Con(bridge,1)=Per_Con(bridge,1)+P(bridge,cycle);
            Num_Per_Con(bridge,1)=Num_Per_Con(bridge,1)+1;
        end
    end
    % Condition: if safety of each bridge at the end of each cycle is
smaller than 44...
        % penaltize fitness function
    Sft_Con(bridge,1)=0;
    Num_Sft_Con(bridge,1)=0;
    for cycle=1:(Num_Cyc)
        if S(bridge,cycle)<44
            Sft_Con(bridge,1)=Sft_Con(bridge,1)+S(bridge,cycle);
            Num_Sft_Con(bridge,1)=Num_Sft_Con(bridge,1)+1;
        end
    end
    % Total damaged area on each bridge at the end of each cycle
    for cycle=1:Num_Cyc
        SumD(bridge,cycle)=0;
        for damage=1:1:size(D0,2)

SumD(bridge,cycle)=D(bridge,cycle,damage)+SumD(bridge,cycle);
        end
    end
    % Rec_Eff = Recovering effect(f1) of the first MR&R
    if P0(bridge,1)>=90
        Rec_Eff(bridge,1)=0;
    else
        if (P0(bridge,1)+MaxR(X(bridge,1)))>=90
            Rec_Eff(bridge,1)=90-P0(bridge,1);
        else
            Rec_Eff(bridge,1)=MaxR(X(bridge,1));
        end
    end
    % Rec_Eff = Recovering effect(f1) of each MR&R
    for cycle=2:Num_Cyc
        if P(bridge,(cycle-1))>=90
            Rec_Eff(bridge,cycle)=0;
        else
            if (P(bridge,(cycle-1))+MaxR(X(bridge,cycle)))>=90
                Rec_Eff(bridge,cycle)=90-P(bridge,(cycle-1));
            else
                Rec_Eff(bridge,cycle)=MaxR(X(bridge,cycle));
            end
```

```
        end
    end
    % App = Applicability of the first MR&R
    for damage=1:size(D0,2)
        App(bridge,1,damage)=A(X(bridge,1),damage)*D0(bridge,damage);
    end
    % App = Applicability of each MR&R
    for cycle=2:Num_Cyc
        for damage=1:size(D0,2)

App(bridge,cycle,damage)=A(X(bridge,cycle),damage)*D(bridge,(cycle-
1),damage);
        end
    end
    % App_Sum = Applicability(f2)
    for cycle=1:Num_Cyc
        App_Sum(bridge,cycle)=0;
        for damage=1:1:size(D0,2)

App_Sum(bridge,cycle)=App(bridge,cycle,damage)+App_Sum(bridge,cycle);
        end
    end
    % Sft_Imp = Improvment in Safety (f3)of the first MR&R
    if S0(bridge,1)>=90
        Sft_Imp(bridge,1)=0;
    else
        if (S0(bridge,1)+MaxS(X(bridge,1)))>=90
            Sft_Imp(bridge,1)=90-S0(bridge,1);
        else
            Sft_Imp(bridge,1)=MaxS(X(bridge,1));
        end
    end
     % Sft_Imp = Improvment in Safety (f3)of each MR&R
    for cycle=2:Num_Cyc
        if S(bridge,(cycle-1))>=90
            Sft_Imp(bridge,cycle)=0;
        else
            if (S(bridge,(cycle-1))+MaxS(X(bridge,cycle)))>=90;
                Sft_Imp(bridge,cycle)=90-S(bridge,(cycle-1));
            else
                Sft_Imp(bridge,cycle)=MaxS(X(bridge,cycle));
            end
        end
    end
    % Cost_Sum = Cost(f4)
    Cost_Sum(bridge,1)=SumD0(bridge,1)*C(X(bridge,1),1);
    for cycle=2:Num_Cyc
        Cost_Sum(bridge,cycle)=SumD(bridge,(cycle-
1))*C(X(bridge,cycle),1)/((1+int_rate)^((cycle-1)*L));
    end
end
f1(Try,1)=sum(sum(Rec_Eff,1),2);
f2(Try,1)=sum(sum(App_Sum,1),2);
f3(Try,1)=sum(sum(Sft_Imp,1),2);
f4(Try,1)=sum(sum(Cost_Sum,1),2);
if sum(Num_Per_Con,1)<=0;
    g1(Try,1)=0;
```

```
else
    g1(Try,1)=abs(sum(Per_Con,1)/(55*sum(Num_Per_Con,1))-1);
end
if sum(Num_Sft_Con,1)<=0;
    g2(Try,1)=0;
else
    g2(Try,1)=abs(sum(Sft_Con,1)/(44*sum(Num_Sft_Con,1))-1);
end
end
% mean value of each function
mean_f1=sum(f1,1)/(Num_Try);
mean_f2=sum(f2,1)/(Num_Try);
mean_f3=sum(f3,1)/(Num_Try);
mean_f4=sum(f4,1)/(Num_Try);
mean_g1=sum(g1,1)/(Num_Try);
mean_g2=sum(g2,1)/(Num_Try);
if mean_f4<=Bgt
    mean_g3=0;
else
    mean_g3=abs((Bgt/mean_f4)-1);
end
% final multi objective formulation
if mean_g1<=(Num_Try*0.01)
    if mean_g2<=(Num_Try*0.01)
        if mean_f4<=Bgt
            F = (a*(abs((mean_f1/(90*size(D0,1)*Num_Cyc))-
1)^p)+b*(abs((mean_f2/(100*sum(sum(SumD,1),2)))-1)^p)+...
                 c*(abs((mean_f3/(90*size(D0,1)*Num_Cyc))-
1)^p)+d*(abs(mean_f4/Bgt-0.5)^p))^(1/p);
        else
            F = (a*(abs((mean_f1/(90*size(D0,1)*Num_Cyc))-
1)^p)+b*(abs((mean_f2/(100*sum(sum(SumD,1),2)))-1)^p)+...
                 c*(abs((mean_f3/(90*size(D0,1)*Num_Cyc))-
1)^p)+d*(abs(mean_f4/Bgt-0.5)^p))^(1/p)+...
                 5*(mean_g1+mean_g2+mean_g3);
        end
    else
        F = (a*(abs((mean_f1/(90*size(D0,1)*Num_Cyc))-
1)^p)+b*(abs((mean_f2/(100*sum(sum(SumD,1),2)))-1)^p)+...
                 c*(abs((mean_f3/(90*size(D0,1)*Num_Cyc))-
1)^p)+d*(abs(mean_f4/Bgt-0.5)^p))^(1/p)+...
                 5*(mean_g1+mean_g2+mean_g3);
    end
else
    F = (a*(abs((mean_f1/(90*size(D0,1)*Num_Cyc))-
1)^p)+b*(abs((mean_f2/(100*sum(sum(SumD,1),2)))-1)^p)+...
                 c*(abs((mean_f3/(90*size(D0,1)*Num_Cyc))-
1)^p)+d*(abs(mean_f4/Bgt-0.5)^p))^(1/p)+...
                 5*(mean_g1+mean_g2+mean_g3);
end
end
end
```

APPENDIX B: INITIAL POPULATION FUNCTION

```
function Population = int_pop(GenomeLength,FitnessFcn,options)

totalpopulation = sum(options.PopulationSize);
range = options.PopInitRange;
lower= range(1,:);
span = range(2,:) - lower;
% The use of ROUND function will make sure that individuals are
integers.
Population = repmat(lower,totalpopulation,1) +  ...
    round(repmat(span,totalpopulation,1) .*
rand(totalpopulation,GenomeLength));
% End of creation function
```

APPENDIX C: MUTATION GENERATOR FUNCTION

```
function mutationChildren =
int_mutation(parents,options,GenomeLength, ...
    FitnessFcn,state,thisScore,thisPopulation)

shrink = .01;
scale = 1;
scale = scale - shrink * scale * state.Generation/options.Generations;
range = options.PopInitRange;
lower= range(1,:);
upper= range(2,:);
scale = scale * (upper - lower);
mutationPop =  length(parents);
% The use of ROUND function will make sure that childrens are integers.
mutationChildren =  repmat(lower,mutationPop,1) +  ...
    round(repmat(scale,mutationPop,1) .*
rand(mutationPop,GenomeLength));
% End of mutation function
```

APPENDIX D: PARETO PRODUCER FUNCTION

```
function Y = Multi_Objective (a,b,c,d,p)

% Bgt = Total budget (CAD$ 1000)
% Bgt = 2000;
% T = Study period (year)
% T = 15;
% L = Length of each cycle
% L = 5;
% number of chromosomes in each child = 8x4=40

% p = power in the weighted metrics. When p=2 is used, a weighted
      % Euclidean distance of any point in the objective space from the
      % ideal point is used
p = 2;

% Wfs = different combination of weight factors
WFs=[0.7000    0.1000    0.1000    0.1000;
     0.1000    0.7000    0.1000    0.1000;
     0.1000    0.1000    0.7000    0.1000;
     0.1000    0.1000    0.1000    0.7000;
     0.4000    0.2000    0.2000    0.2000;
     0.2000    0.4000    0.2000    0.2000;
     0.2000    0.2000    0.4000    0.2000;
     0.2000    0.2000    0.2000    0.4000;
     0.1000    0.3000    0.3000    0.3000;
     0.3000    0.1000    0.3000    0.3000;
     0.3000    0.3000    0.1000    0.3000;
     0.3000    0.3000    0.3000    0.1000;
     0.4000    0.3000    0.2000    0.1000;
     0.1000    0.4000    0.3000    0.2000;
     0.2000    0.1000    0.4000    0.3000;
     0.3000    0.2000    0.1000    0.4000;
     0.4000    0.2000    0.3000    0.1000;
     0.6000    0.2000    0.1000    0.1000;
     0.2000    0.6000    0.1000    0.1000;
     0.2500    0.2500    0.2500    0.2500];

for k = 1:size(WFs,1)
    a(k)=WFs(k,1);
    b(k)=WFs(k,2);
    c(k)=WFs(k,3);
    d(k)=WFs(k,4);
end

% Run the GA for each combination of weight factors
for k = 1:size(WFs,1)
        [x fval] = Wei_Sin_Obj(a(k),b(k),c(k),d(k),p,40);
        Y(k,:)= x;
end
```

APPENDIX E: STRUCTURE TYPES AND NUMBERS IN QUEBEC

Category	Structure type	Material	System	Frequency	Total	Percentage(%)
Culvert	11	R.C.	Solid slab	16	1141	11.1
	12	R.C.	Rigid frame	0		
	13	R.C.	Box section	499		
	14	R.C.	Circular section	2		
	15	Steel	Circular section	141		
	16	Thermoplastic	Circular section	1		
	17	Steel	Elliptic section	25		
	18	Steel	Curved closed section	285		
	19	R.C.	Arc	106		
	20	Steel	Arc	66		
Slab Bridge	31	R.C.	Solid slab	615	1883	18.2
	32	P.C.	Solid slab	39		
	33	R.C.	Hollow slab	153		
	34	P.C.	Hollow thick slab	22		
	35	R.C.	Portal frame	496		
	36	R.C.	Portal frame below ground	394		
	37	P.C.	Portal frame	1		
	38	R.C.	Rigid frame	154		
	39	P.C.	Rigid frame	9		
Beam Bridge	41	R.C.	Rectangular beams	1430	5984	57.9
	42	P.C.	Precast beams	849		
	43	P.C.	Rectangular beams	210		
	44	Steel	I-beams under R.C. slab	782		
	45	R.C.	I-beams under wood slab	2420		
	46	Wood	Rectangular beams	30		
	47	R.C.	Portal frame	27		
	48	R.C.	Portal frame below ground	1		
	49	Steel	Portal frame	0		
	50	R.C.	Rigid frame	50		
	51	Steel	Rigid frame	8		
	52	Steel	Covered with concrete	177		
Box-Girder Bridge	56	R.C.	Two boxes	57	146	1.4
	57	P.C.	One box	52		
	58	Steel	Two boxes	37		
Truss Bridge	61	Steel	Through N truss	104	313	3.0
	62	Steel	Intermediate N truss	3		
	63	Steel	Through W truss	73		
	64	Steel	Through Bailey truss	12		
	65	Steel	Deck N truss	35		
	66	Wood	Triangular truss	3		
	67	Steel	Covered truss	83		
Arch Bridge	71	R.C.	Through arch	1	74	0.7
	72	Steel	Through arch	15		
	73	R.C.	Intermediate arch	1		
	74	Steel	Intermediate arch	0		
	75	R.C.	Deck arch	52		
	76	Steel	Deck arch	5		
Cable Bridge	81	Any	Suspension bridge	5	11	0.1
	82	Any	Cable-stayed bridge	6		
Other Structures	91	Any	Movable bridge	2	783	7.6
	92	Any	Foot bridge	0		
	94	Any	Tunnel	12		
	95	Any	Signals support	0		
	96	Any	Platform	0		
	97	Any	Retaining wall	726		
	98	Any	Pumping station	30		
	99	Any	Others	13		

Total Number of Structures: 10335 100.0

APPENDIX F: RAW DATA USED IN CASE STUDY

Table F-1 Inspection notes on the sample bridges in the network (MTQ database)

Bridge	Inspection note
1	1) pelade 2m2. 2) Flaque d'eau importante au point bas du devers et drain obstrué. 3-4) Éclats légers et trace de rouille. 5-6-7) Fissures longitudinales étroites. 10,25m2 à réparer. 8) Potentiel de corrosion entre -200 et -350mV est de 64% et inférieur à 350mV est de 17%.Total: 196m2. 2) Flaque d'eau importante au point bas du devers.1 drain obstrué.3-4) Fissures longitudinales,trace de rouille et 0,75m2 à réparer 5-6-7) Fissures longitudinales étroites et 7m2 à réparer.8) Potentiel de corrosion entre -200 et 350mV est de 59% et inférieur à -350mV est de 1%.Total: 226m2
2	4) 3m2 à réparer. 3@7) fiss.longitudinales filiformes à étroites. 5) 1,5m2 à réparer.5-6-7) fiss.transversales filiformes à certain. 6) 27m2 à réparer.endroit. 7) 3m2 à réparer. 3) 5,5m2 à réparer. 8) Potentiel de corrosion en 2002: moins de 5% est inférieur à -350mV et 20 à 40% est entre -200 et -350mV.Les surfaces à réparer totalisent 544m2. **Travées 13,15,16,17: détérioration importante car réparations récentes sur 21m2 visibles sur le dessus de la dalle. 3) 4m2 à réparer.(14%) 4) 1m2 à réparer. 5) 1m2 à réparer. 6) Fissures transversales filiformes à étroites. 7) 4m2 à réparer.(21%). 8) Potentiel de corrosion en 2002: 1% est inférieur à -350mV et 24% entre -200et -350mV.Total à réparer: 26m2.
3	Travée 1: 3-4) fissures verticales étroites aux 1m. 6) 13m2 délaminé et/ou éclaté (photo 3) Travée 2: 3) éclat (accrochage camion) 1m2 (photo 4). 3-4) fissures verticals.
4	1) Trous de carottes à boucher. 3) 1m2 délaminé et fissures filiformes à étroites. 4) Fissures filiformes à étroites. 5) Trace de rouille 6) 1.5m2 délaminé. 7) 1m2 délaminé et trace de rouille. 8) Relevé de potentiel 1999: potentiel inférieur à -350mV est de 13,4% et entre -200 et -350mV est de 34,1%.Donc 49m2 à réparer. 2) Trous carottes à boucher. 3-4) Fissures filiformes. 5) Trace de rouille. 6) Fissures transversales étroites sur 50% de la surface et 4m2 délaminé avec éclats importants. 8) Voir note sur fiche E1.Donc 82m2 à réparer.
5	3) Fissures en réseau, délamination 6,5 m2. 4) Délamination 0,5 m2 + éclatement 1 m2. 5) Délamination 2 m2. 6) Fissures en réseau étroites à moyennes, délamination 46,5 m2 + éclatement 11 m2 (Photos). 7) Délamination 6 m2
6	1) Début fissuration. 3) Fissures filiformes,trace de rouille et 1,5m2 délaminé. 4-6) Fissures filiformes à étroites. 5) Écaillement léger,efflorescence sur 20% et une fissure verticale au dessus de l'assise. 7) Éclats légers,trace de rouille et 3,25m2 délaminé. 8) Expertise de la dalle en 1999: potentiel de corrosion entre -200 et -350mV est de 49.2% et inférieur à -350mV est de 23,9%.Total à réparer: 78m2. 1) Fissures lézardées et affaissement sur 2m2. 3-4) Fissures filiformes à étroites,trace de ouille. élamination et armaturesapparentes sur 1m2 côté est et 3,5m2 côté ouest. 5) Trace de rouille et 0,5m2 délaminé. 6) Fissures transversales filiformes et éclats légers localisés. 8) Voir note fiche E-1.Total à réparer: 131m2.
7	1) Quelques fissures 30 ml et inégalités. 3,4) 17 m2 de délamination et d'éclatements. 5-6-7) Fissures longitudinales étroites. 21m2 à réparer. 8) 46 m2 à réparer,potentiel de corrosion inférieur à -350mV affectant de 10 à 15 % de la surface de la dalle. ** Dalle neuve à prévoir suite à expertise de dalle et potentiel de corrosion en 1999.
8	1) Dommage moyen sur 25 %. Asphalte sera refaite au complet en tenant compte des réparations apportées à la dalle. 670 m2. 3-4) Béton éclaté sur 50 % avec danger de chute de béton, 84 m2 à réparer. Act.3134 ne s'applique pas. Act 3130 pour côté extérieur. 5-6-7) Délamination 1.5 m2 + éclatement 6 m2.
9	3,4) 9 m2 de béton délaminé (act.3130 face vert.) ** A sécuriser le côté Sud. 5,6,7) 4 m2 de béton délaminé. ** A sécuriser proche du joint long. dir.Sud
10	1) Fissuration de la chaussée sur les voies rapides.700m2 à refaire. 3) Éclats importants avec armatures corrodées sous le trottoir. 4m2 à réparer. 5-6-7) Fissures longitudinales filiformes à étroites et début de fissures en réseau.Efflorescence,rouille et 4m2 à réparer et localisé près du joint longitudinal.

Table F-2 Performance and material codes of the sample bridges in the network (MTQ database)

Element		Bridge 1		Bridge 2		Bridge 3		Bridge 4		Bridge 5		Bridge 6		Bridge 7		Bridge 8		Bridge 9		Bridge 10	
		Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code	Performance code	Material code
1	Surface de roulement	5	5	5	5	6	6	5	5	5	5	5	5	5	4	3	3	4	4	3	3
2	Drainage et systeme de drainage	2	5	5	5	6	0	5	0	5	0	5	0	5	0	5	0	4	0	5	0
3	Cote exterieur en beton	5	5	5	6	5	5	5	4	5	1	5	5	4	4	1	1	2	3	3	1
4	Cote exterieur en beton	5	5	5	5	5	5	4	2	5	2	4	4	4	4	1	1	4	4	3	5
5	Dessous a l'extremite	5	5	5	6	5	5	5	5	5	5	5	4	5	5	5	5	5	5	3	5
6	Dessous au centre	5	5	5	4	5	5	5	5	5	3	4	4	5	5	5	5	5	5	4	2
7	Dessous a l'extremite	5	5	5	5	5	5	5	4	5	3	5	5	5	5	5	5	5	5	2	3
8	Dessus de la dalle en beton	5	4	5	4	6	6	4	3	5	6	4	1	5	3	4	2	5	6	4	5

APPENDIX G: BRIDGE ENGINEER INTERVIEW

The author met Mr. Adel R. Zaki, Vice President, Engineering at SNC-Lavalin Inc., on June 23, 2008. He reviewed the content and confirmed that the numbers used in defining objective functions are logical and can meet the real problems. According to Mr. Adel Zaki's information, a bridge deck replacement, for instance, costs 600 to 1,000 CAD\$/m^2 in Quebec. In this study, the replacement unit cost is assumed CAD\$1,420 which is greater than the actual cost. In overall, the assumed numbers are on the safe side.

Furthermore, he suggested that the author explain the MR&R activities and damage types. Thus, two sections were added to the literature review explaining MR&R categories and methods, and damage types.

He also provided new ideas on diving replacement into two activities, i.e., composite and non-composite replacement, which could be done in continuation of this study.

The author gratefully appreciate the invaluable feedback of Mr. Adel R. Zaki.

APPENDIX H: LIST OF PUBLICATIONS

Pakniat, P. and Hammad, A. (2008). Optimizing Bridge Decks Maintenance Strategy Based on Probabilistic Performance Prediction Using Genetic Algorithm. Canadian Society of Civil Engineering (CSCE) Annual Conference, Quebec, QC, Canada.

Pakniat, P. and Hammad, A. (to be submited). Selecting Optimal Long-Term Bridge Decks Maintenance and Rehabilitation Strategies, Journal of Performance of Constructed Facilities, ASCE.