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Decision support system for remediation of concrete bridges

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Department of Civil, Mining and Environmental (CME) Engineering

&

Department of Mechanical, Materials and Mechatronics (MMM) Engineering

Decision Support System for Remediation of Concrete Bridges

Maria Rashidi

This thesis is presented as part of the requirement for the

Award of the Degree of PhD

of the

University of Wollongong

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ABSTRACT

The management of bridges as a key element in transportation infrastructure has become a major concern due to increasing traffic volumes, deterioration of bridges and well-publicised bridge failures. Identification of the nature of deterioration and appropriate remediation treatments remains a complex task. A critical responsibility for asset managers in charge of bridge remediation is to identify risks and assess the conditions to ensure that remediation decisions are transparent and lead to the lowest predicted loss in pre-determined constraint areas. Bridge management agencies have traditionally made decisions based on a subjective judgment using organisational rules of thumb. Lack of a generic method for quantifying the overall condition of bridges (following inspection) is one of the major issues. Moreover most existing models deal separately with network level and project level problems. This thesis demonstrates that the subjective nature of decision making in bridge remediation could be replaced by the application of Decision Support System (DSS) as a tool for assisting decision makers to deal with an extensive spectrum of problems. The main goal of this research is to develop a requirements-driven decision support methodology for remediation of concrete bridges with the aim of maintaining bridge assets within acceptable limits of safety, serviceability and sustainability. In this study a quantitative methodology has been developed and illustrated to give insights for decision makers to select the best bridge management strategy. The methodology includes two phases with different steps in each phase:

Phase one is focused on condition assessment and priority ranking of bridge projects which makes use of an integrated priority index addressing the structural and functional efficiency of bridge, taking into account the clients' preferences. Phase two includes a multi criteria decision

making technique which is able to select the best remediation strategy at both project and network level. The modified Simple Multi Attribute Rating Technique (SMART) is used as a decision analysis tool that employs the eigenvector approach of the Analytical Hierarchy Process (AHP) for criteria weighting. A method for selection of the best remediation plan in terms of fund allocation for top ranked bridges of the network is also proposed using the outputs of the previous procedures considering the budget as the main constraint.

The model proposed in this thesis introduced as CBR-DSS has significant benefits over the currently used methods. The thesis clearly shows that the developed model is able to add more objectivity and holism to the current approaches through considering the main aspects of the problem and attempting to quantify the major parameters. CBR-DSS is also flexible enough to allow decision makers to engage their judgments in the decision making process. It can handle multi layer of data and multi criteria decision problems and is able to combine the project and network levels of the bridge management process.

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I wish to express my sincere thanks to my parents Farangis and Parviz, my husband Shahrokh and my little daughter Aveesa for their love, care and sacrifice.

Last but not least I dedicate my thesis to all victims of human rights abuses all over the world wishing them freedom, peace and security.

LIST OF PUBLICATIONS

The following papers were published or submitted to disseminate the concept and results of the work undertaken during the course of this PhD research study.

Journal Publication

Rashidi, M. and Lemass B. (2011b). "A Decision Support Methodology for Remediation Planning of Concrete Bridges." Journal of Construction Engineering and Project Management (JCEPM) **1**(2): 1-10.

Rashidi, M. and Gibson P. (2012). "A Methodology for Bridge Condition Evaluation." Journal of Civil Engineering and Architecture **6**(9): 1149–1157.

Conference Publication

Rashidi, M., Lemass B. and Gibson P. (2010). A Decision Support System for Concrete Bridge Maintenance 2nd International Symposium on Computational Mechanics and the 12th International Conference on the Enhancement and Promotion of Computational Methods in Engineering and Science, Hong Kong- Macau (China) American Institute of Physics (AIP)

Rashidi, M. and Hadi M. N. (2010). Modelling of high strength concrete reinforced columns wrapped with FRP. The 5th Civil Engineering Conference in the Asian Region & Australasian Structural Engineering Conference, Barton, A.C.T., Aust.

Rashidi, M. and Lemass B. (2011a). Holistic Decision Support for Bridge Remediation. The 4th International Conference on Construction Engineering and Project Managment (ICCEPM), Sydney, Australia.

Rashidi, M. and Gibson P. (2011). Proposal of a Methodology for Bridge Condition Assessment. Australasian Transport Research Forum (ATRF), Adelaide, Australia.

Submitted

Buckley, P. S. and M. Rashidi (2013). "Concrete Remediation Techniques with Recent Applications and Future Needs." Australian Journal of Civil Enginering.

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1 INTRODUCTION

1.1 Research Significance

The deterioration of structural assets is a common problem throughout the world. More specifically, deficiencies related to ageing bridges have become a major concern for engineers, asset managers and society globally. The collapse of the bridge carrying Highway 35W over the Mississippi River in Minneapolis, USA, is an event that sparked world interest in infrastructure. The bridge had been known to be structurally deficient since the 1990s, when corrosion in a number of beam members and connection plates was identified. Although known, these faults had not been prioritised to allow sufficient remediation to take place, and so the bridge was left to deteriorate. A debate on how safe the country's ageing infrastructure is, and what funding is required to fix the infrastructure, has been occurring in the USA (Rashidi and Lemass, 2011b).

This debate is not confined to the United States, the operation, maintenance, repair and eventual renewal of the "built environment" represents a major, rapidly growing cost (Vanier, 2001,). In 2003 the structural condition of the Menangle rail bridge, the oldest iron bridge in New South Wales (NSW) Australia, was cause for concern with the bridge being closed for a month while it was assessed. The concern, along with the lack of importance given to its condition, later led to an investigation by the NSW Independent Commission Against Corruption (ICAC). Major public infrastructure also attracts widespread media attention due to the potential risk to the public if there is a breakdown in that infrastructure. While government and media attention is focused on large public infrastructure issues, seemingly innocuous local bridges also need to be effectively maintained (Rashidi and Lemass, 2011a).

Bridges are often subjected to high loads, harsh environments, and accidental damage. Determining what level of repair is required to achieve the most economical lifespan from a bridge structure has been a source of dilemma for asset managers and owners for many years. It is possible to determine what constraints are relevant in ageing bridge structures, how to use these constraints to appropriately rate the condition of structures, and to determine an economical but timely plan of remediation to extend their working life.

The U.S Department of Transportation has recently rated about 200,000 bridges. One in every three was reported to be structurally deficient or functionally obsolete. In addition, more than one quarter were over 50 years old, the average design-life of a bridge. The U.S. National Research Council stated that the cost of damage to America's bridges is about $20 billion per year and is increasing at the rate of $500 million per year (Faiz and Edirisinghe, 2009).

A recent study on bridge inventory estimated that there are approximately 50,000 bridges in Australia and only approximately 18% were constructed after 1976. Due to changes and increases in traffic load, structural degradation, and design code, many of these bridges do not meet the current Australian standards (Sumitomo, 2009).

Due to the substantial role of bridges in road networks, any failure or deficiency of a bridge may have severe consequences for the safety of individuals and properties. It may also restrict or interrupt the traffic flow over a large part of the network.

In accordance with the limited funding for bridge management, maintenance, rehabilitation and replacement (MR&R) strategies have to be prioritised. A conservative bridge assessment will result in unnecessary actions, such as costly bridge strengthening or repairs (Stewart, 2001). But on the other hand, any bridge maintenance negligence and delayed actions (or ignoring the cause of defects) may lead to heavy future costs or degraded assets (Rashidi and Lemass, 2011a).

The service life of a bridge can be subdivided into four different phases (ARRB, 2000):

Phase A-Design and construction

Phase B-Propagation of deterioration has not yet begun but initiation processes are underway

Phase C-Damage propagation has just started

Phase D- Extensive deterioration is occurring

In line with the Law of Fives, one dollar spent in Phase A equals five dollars spent in Phase B; twenty-five dollars in Phase C and hundred and twenty five dollars in Phase D. Implying this law is the basis for any asset management decision making.

Therefore bridge design codes and specifications should provide assurance to good engineering quality in Phase A and bridge monitoring and maintenance should be accomplished during Phase B to prevent the structure from progressing into Phase C and D.

As a result a key responsibility for asset managers in charge of bridge remediation is to make transparent decisions with the lowest predicted losses in recognised constraint areas (Rashidi et al., 2010). Each organisation needs to establish an appropriate level of funding for its assets based on various parameters such as bridge type, age, environmental condition and traffic load (ARRB, 2000). For example, Organisation for Economic Co-operation and Development (OECD), recommends that the annual maintenance costs on bridge structures should be at least 3% of their value."

1.2 Decision Support for Bridge Management

Decision support processes have been widely used to assist managers to determine the most appropriate paths to take (McCowan and Mohamed, 2007). Whether remediation constraints are technical, economic, environmental or social, applying decision support principles will assist asset owners and managers to clarify in a transparent manner what may be the best course of remediation for a given bridge.

Decision-making in this field is more complicated than it has been in the past for two reasons. Firstly, expanding technology and communication systems have spawned a greater number of feasible solution alternatives from which a decision-maker must choose. Secondly, the increased level of structural complexity and design complication typical of today's problems can result in a chain reaction magnification of costs if an error should occur.

The increasing level of the decision support system (DSS) implementation in organisations over the past two decades is strong proof that they are feasible and well accepted managerial tools (Lemass, 2004). These developed systems are now providing enormous benefits, both in time and cost savings.

A conventional decision support system (DSS) is broadly defined as an interactive computer-based system that uses a model to identify relevant data in order to make decisions. The word system implies that a DSS is a set of interrelated components. By partially cloning human expert knowledge and supporting it with deep algorithmic knowledge, it seems likely that successful intelligent decision support systems (IDSS) could improve user understanding and work productivity, reduce uncertainty and anxiety, and preserve the valuable knowledge of experts in short supply. They could also effectively save time and investment capital by making domain knowledge readily available throughout the decision process (Faiz and Edirisinghe, 2009).

Ideally a DSS must be planned to assist in identifying and evaluating alternative options in response to various scenarios. It will include three elements: 1) the decision variables that describe the problem; 2) the constraints which limit the outcomes; and 3) the objectives, which in turn favour some alternatives over other (Rardin, 1998; Khare and Chougule, 2012).

The research project presented in this thesis deals with the development of a knowledge-based decision support model which includes a procedure for condition assessment and remediation strategy selection of concrete bridges.

1.3 Research Objectives

Practically, asset managers and bridge owners manage a set of bridges rather than a single bridge. Therefore when it comes to the decision making for remediation planning, the network level strategies should be considered as well as the project level.

The main goal of this research is to develop a decision support methodology for selecting and prioritising the actions necessary to maintain a bridge network within acceptable limits of safety, functionality and sustainability. The system will assist decision makers and bridge authorities in priority ranking of bridges in terms of budget allocation and the selection of the best remediation plans within the related agency constraints so that feasible and practical solutions can be determined.

The following objectives have been defined to achieve this goal:

-Develop an appropriate methodology for bridge condition evaluation addressing structural and functional efficiency of the asset.

–Propose a structured inspection form that can address all the condition factors.

-Develop a quantitative methodology for priority ranking of bridges at the network level considering structural efficiency, functional efficiency and client preferences.

-Identify all the possible course of actions and major client constraints through a risk assessment process.

-Propose an appropriate decision analysis method that can assist the decision maker in choosing the best remediation strategy.

-Provide a methodology for budget allocation based on the target level of improvement for top ranked bridge projects.

-Develop a holistic prototype system that integrates all previous developments in a user-friendly automated environment which can be further refined using industry case studies.

1.4 Research Outline

Along with the objectives defined above, the thesis structure is organised as follows:

Chapter 2 presents a literature review on Bridge Management Systems (BMS) and their basic components such as inventory, cost and condition information. The advantages and limitations of the existing models and a review of BMS elements is presented along with a description of recent developments in the relevant areas. The project level and network level decisions are reviewed. The most common concrete repair techniques are also listed and discussed at the end.

Chapter 3 introduces a detailed review of decision support systems and their background. The DSS capabilities for bridge management and the most commonly used decision analysis tools are also introduced and compared.

Chapter 4 discusses the proposed methodology and describes the conceptual framework developed for remediation of concrete bridges that is known as CBR-DSS (which stands for Concrete Bridge Remediation-Decision Support System). A detailed description of CBR-DSS components is presented.

Chapter 5 describes a procedure for condition evaluation (addressing structural, functional and social/political factors) and priority ranking of bridges in the network. An inspection form addressing all the involved parameters has been developed. Following a multi-criteria type of analysis, a methodology for developing an integrated index introduced as Priority Index (PI) which indicates the maintenance priority is presented. The proposed system provides flexibility for the decision makers in stating their degree of satisfaction with each criterion and captures the decision makers' outlook toward risk.

Chapter 6 introduces a multi objective method for bridge remediation strategy selection. Identifying the possible course of actions, major criteria and the best decision analysis tool (addressing the tools and techniques that have been introduced in chapter 3) with the aim of proposing a rational remediation plan at both project and network level, is discussed in this chapter.

Chapter 7 is focused on the last stage of the project which is implementation and verification. It presents the methodology for development of a prototype system as a decision support tool for remediation of concrete bridges employing the different techniques presented in the previous chapters. Different case studies are also provided to validate the developed model.

Chapter 8 includes the summary of research work, conclusions accompanied with the recommendations and suggestions for future study.

1.5 Terminology

The most frequent terms throughout the thesis have been defined as follows:

-Risk is generally defined as probability of attaining an unwanted state and has different meanings in different contexts.

-Structural failure refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself.

-Objectives are the mission, goals, standard or purpose that is being achieved by the criteria.

-Criteria are the measurable elements: Statement of minimum requirements that must be met to form accurate judgement regarding the objective.

-Constraint is a subsystem or the element factor that works as a filter and limits the outcomes.

-Attribute is the characteristic of an alternative.

2 LITERATURE REVIEW (PART I): BRIDGE MANAGEMENT

2.1 Introduction

A country's road and bridge network is a substantial national asset. Monitoring and maintenance of the system is a highly sensitive and complex task due to increasing traffic volumes, deterioration of existing bridges and well-publicised bridge failures. Bridge management is entrusted to the road organisations and shaped by technical, environmental, political, managerial and historical constraints. It deals with all activities during the bridge life from construction to replacement, aiming to ensure bridge safety and functionality. It also addresses prioritisation of protection needs, planning the maintenance systems, and the minimisation of the bridge life-cycle cost. The most effective way to select an effective maintenance strategy among all the possible solutions, including replacement, repair, rehabilitation, strengthening and preventive maintenance is to employ a mathematical modeling in computerised systems (Chassiakos et al., 2005).

With advances in technology, bridge inspection and repair methods are combined with bridge monitoring systems and are often managed and operated by a computerised Bridge Management System (BMS) where is used worldwide by various government authorities to improve their bridge management processes, and to resolve the complexity of decision making in a large network. However, every BMS will vary slightly as different inspection and repair methods are adopted (Branco and de Brito, 2004).

A rationale BMS can determine the complexity of decision-making for bridge maintenance, repair and rehabilitation (MR&R) strategies within the allocated budgets. The first commercial BMS software was developed in the early 1990s and has become a reliable tool for effective bridge management. However with or without BMS software, bridge MR&R must be carried out by the bridge authority at the appropriate time, since most infrastructure facilities were designed, constructed, and modified or rehabilitated under uncertain circumstances (Frangopol et al., 2000). Most bridge authorities have begun the transition to BMS-based judgment through performance-based management and strategic arrangement for their local and state bridge management. The inconsistencies between bridge agencies, accessible datasets and BMS inputs are usually an obstacle to implementing BMS software. A large number of bridge information for a BMS database is an essential requirement to evaluate a bridge network (Lee, 2007). The following definitions for a bridge management system are quoted from leading authors in this area of research to highlight the importance of BMS (ibid):

> "*A bridge management system can be defined as a comprehensive method for making decisions about bridge management activities in a systematic manner*."
>
> (James et al., 1991)

> "*The bridge management system assists in determining the optimal time for an agency to execute improvement actions on a bridge, given the funds available.*"
>
> (Czepiel, 1995)

> "*The goal of bridge management is to determine and implement the best possible strategy that ensures an adequate level of safety at the lowest possible life-cycle cost. Bridge*

Management Systems (BMSs) represent a unique convergence of the disciplines of structural engineering, operation research, economics, planning, and information technology.”

(Frangopol et al., 2000)

2.2 Existing BMSs

Bridge management systems have been developed and used worldwide. For example, in the USA POINTS has been developed, in Denmark DANBRO, in Japan MICHI, in Finland FinnRABMS and most European countries use BRIME (Ryall, 2001). Lee et al. (2010) compare a few BMSs adopted by different bridge agencies such as:

POINTS - a widespread bridge management tool licensed by AASHTO and developed by Federal Highway Administration (FHWA).

BRIDGIT – developed under the National Cooperative Highway Research Program (NCHRP).

OBMS- a tool developed by the Ontario Ministry of Transportation and was implemented in 2002.

DANBRO- the Danish computer-based BMS, developed to manage Denmark’s bridges based on estimations of the best return on investment of bridge funding.

J-BMS- a Japanese BMS implementing Genetic Algorithm (GA) method to find out an optimal maintenance option that directs the cost minimisation in the optimisation module.

In Australia, bridge authorities such as the Roads and Maritime Services (RMS, New South Wales), Main Roads (Queensland) and VicRoads (Victoria) have also developed similar BMS. They mostly adopted POINTS software packages, which are based on inspection and condition rating records. Condition information on bridge structural elements is obtained through so-called "level-two" inspection, in accordance with current inspection systems (Wang and Foliente, 2008).

However all these systems are based on the inspection plan and yet the condition ratings of these programs could not reflect the actual structural health status of a structure appropriately. The collapse of I-35W over the Mississippi River in Minneapolis is a big lesson to learn from. This is due to the following drawbacks related to their application in most bridge agencies:

-lack of structured inspection methods by professional inspectors and insufficient inspection records;

-ineffective bridge condition evaluation (ratings do not change significantly in short term periods);

-lack of an objective condition assessment methodology which can quantify all the parameters involved in serviceability and reliability of bridges;

-some human factors (political/ social constraints) are ignored through the risk identification process to define the decision criteria.

2.3 General Structure of a Standard BMS

As discussed earlier, bridge management systems include technical documentation and software designed to facilitate a systematic and rational approach to organising the activities of bridge management. Godart and Vassie (1999) argue that a more sophisticated system demands greater needs in terms of the experience of the personnel, the software and hardware available, running costs, and particularly the amount and complexity of input data. This means that more time and resources are spent in data collection and that very often the bridge manager/decision maker is faced with incomplete data. A remarkable characteristic of the BMS evolution is that much of the required information is achieved through the operation of simpler management systems. Therefore, it is usually better to start with a simple bridge management system and progressively increase its complexity as required than to start with a complicated system (Rashidi et al., 2010).

Generally, bridge management covers both levels of decision making: the project level and the network-level. Project-level bridge management is related to individual bridges and is mostly concerned with alternative options for each bridge on an individual basis for inspection, routine maintenance, repair, and rehabilitation. Network-level bridge management is related to the entire bridge stock. It deals with bridge inventory and performs multiannual network assessment. The aim of network-level management is to keep the functionality of all the bridges in a network at a pre-determined level. This ability allows a BMS to perform analyses of all of the bridges in an agency's inventory and to investigate the impacts of implementing, changing or deferring action plans (Dabous et al., 2008).

According to Yanev (2007), a typical BMS consists of three main parts: 1) Database module; 2) Inspection system; and 3) Decision system. The database module consists of both the bridge dossier and computer database. The inspection system controls the whole process of life cycle from the reception tests until the end of its service life and provides part of the information required for the decision system. The decision system is responsible for all choices made during bridge's life, its routine maintenance and repair, as well as capacity upgrading and replacement.

Figure 2.1 shows the constituents and main relations required to form a system to provide effective bridge management practices. According to Austroads (2004), a typical bridge management system would have all or some of the constituents presented in Figure 2.1.

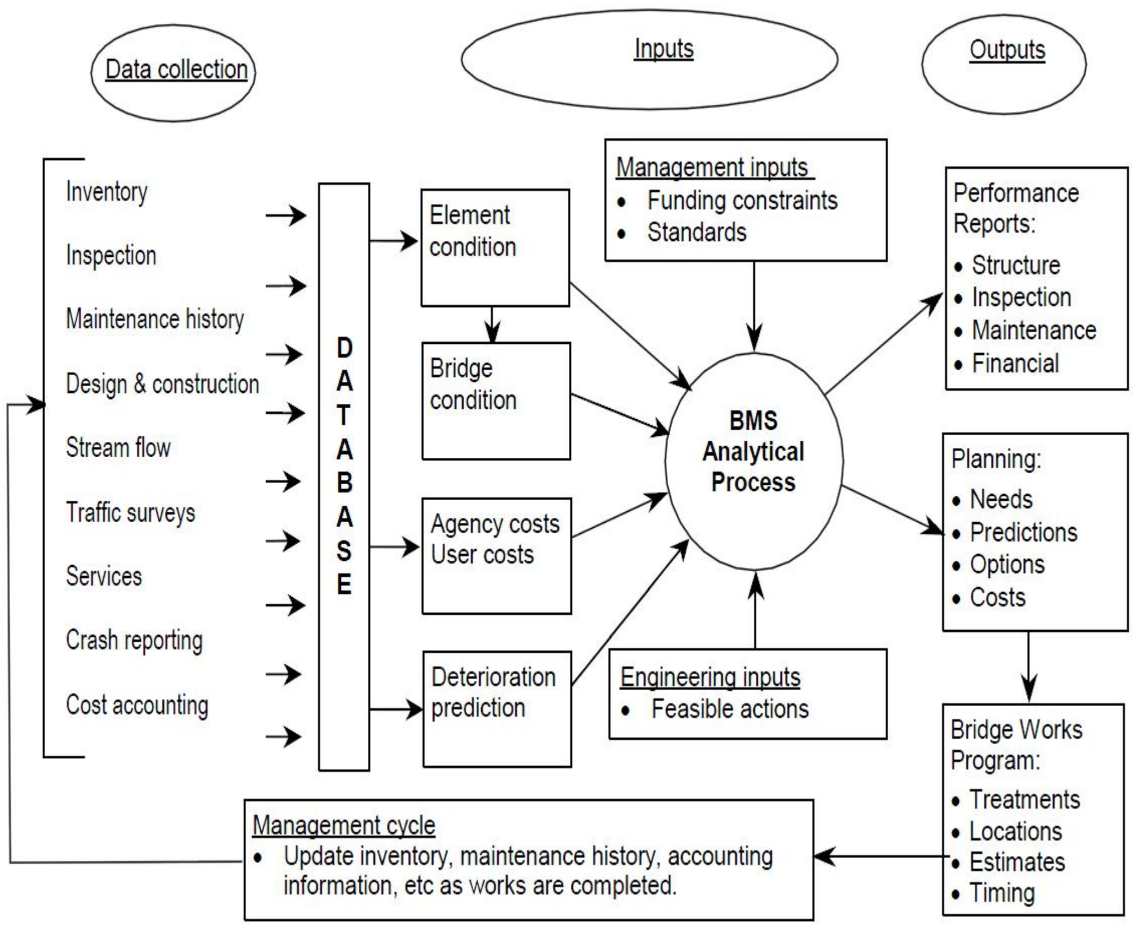


Figure 2.1 Conceptual Framework of a BMS (Austroads, 2004)

As shown in the diagram the bridge management, like all other management areas, is a cyclic process so that as works are finalised, the effects are recorded, and the relevant database modules such as inventory, inspection and maintenance history are consequently updated.

2.3.1 Data Collection

The quality and reliability of system outputs is extremely sensitive to the quality of input data. Software and hardware change over time, and data can be transported from one platform to another.

The main focus of BMS is at the network level, relying on statistical factors such as element based structural condition and bridge width rather than physical factors like crack width in the concrete. However, all the statistical parameters are the result of observations or detailed technical information. Some of the most relevant categories of data collection are as follows:

2.3.1.1 Bridge Inventory

One of the essential requirements of a BMS is comprehensive stored and accessible data inventory for the bridge stock. The inventory should be retrievable and should also include maintenance information, a set of descriptive data employed for a variety of purposes such as administering a structure or a collection of structures, supporting the management of a large network of bridges, evaluating overall condition states, etc. A more detailed inventory of component details is also required for condition history management, and performance reporting. The management level determines the expectations and dictates the degree of details. Bridge location, type, material of construction, cost and maintenance history are some of the basic information included in the inventories (ARRB, 2000).

2.3.1.2 Bridge Inspection

A disciplined approach to bridge inspection is a basic and essential pre-requisite for sustainable bridge management. The frequency of inspection is usually determined either on a time basis, or by the bridge condition and the liability associated with the deterioration rate.

Watson and Everett (2011) state that a common bridge inspection regime includes four levels:

Level 1 – Routine inspections to confirm the general safety and serviceability of the structure for road users.

Level 2 – Comprehensive visual inspections undertaken by a skilled inspector for condition rating of each bridge.

Level 3 – Detailed structural inspections performed when concerns requiring further examination are identified throughout the Level 2 inspection process, and are carried out by qualified engineers.

Level 4 – Load assessment due to applied changes in legal loading, new vehicle types or the need to confirm the bridge structural capacity.

2.3.1.3 Bridge Maintenance History

Records of any deficiencies, structural changes to the original bridge design and maintenance actions should be accurately retained for future knowledge and reference. The maintenance history not only provides some information for an individual bridge but also when collectively analysed can lead to the understanding of common problems requiring more than a solution at the project or network level (Moore et al., 2011).

Generally, historical bridge condition rating can be used both directly and indirectly as an input data for many important tasks in BMS software. Figure 2.2 is a graphical re-presentation of Table A1 and Table A.2 from Godart and Vassie (1999), provided by Lee (2007) which shows bridge condition assessments and their correlations with the relevant BMS modules in project and network level analyses. As shown in Figure 2.2, more than half of the BMS outputs are influenced by bridge inspections and condition ratings, i.e. 6 out of 12 in the project level and 12 out of 18 in the network level outputs. Therefore it is clear that without a sufficient record of inspections the functions of various BMS modules are complicated.

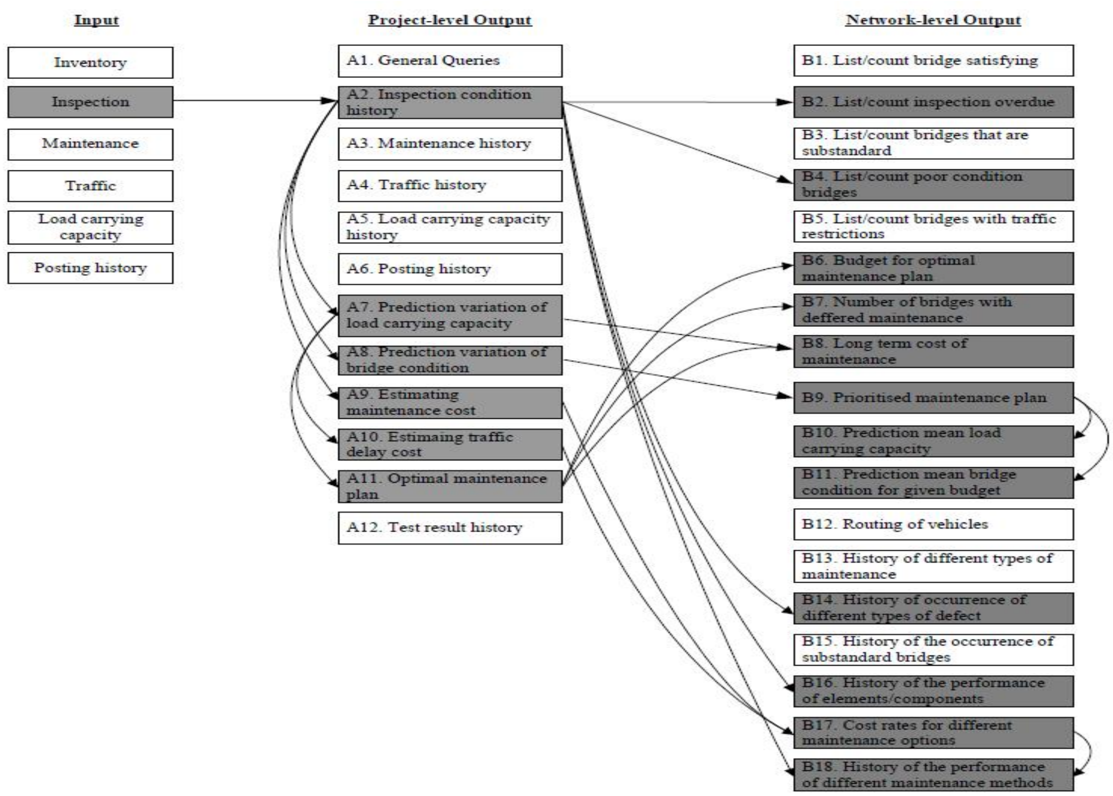


Figure 2.2 Relationships Between Historical Bridge Inspection Datasets and BMS Outputs

2.3.2 Bridge Condition Information

Bridge agencies manage massive amounts of bridge related information. Even with access to the best computer programmes the outcomes must be clearly communicated to the top level decision makers and funding agencies in an uncomplicated manner. A professional condition assessment will enable the managers to comprehend and compare the condition of various bridges in the network. Bridge condition is also an input to the analytical procedure, and has a major impact on determining bridge repair proposals. In fact, it is a summary indicator from element condition, which in turn is drawn from bridge inspections.

Expressions of bridge condition are just indications of the relative state of each bridge obtained from the element condition ratings, to provide an overall comparative feeling for the relative requirements of bridges. Road agencies use various methods to evaluate bridge conditions from the element condition. The outputs, whether numeric or descriptive, have no physical meaning, and are used only as management tools (Austroads, 2004; Rashidi and Lemass, 2011a). An applicable pattern of the condition states for the concrete elements is given in Table 2.1 below.

According to Abu Dabous et al. (2008) three quantities are indicators of the concrete element condition of the bridges. These quantities are:

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

Table 2.1 Summary of Condition States for Concrete Bridge Elements (RTA, 2007)

Condition State	Condition State Description
1	No deterioration
2	Minor cracks and spalls No evidence of corrosion
3	Some delamination &/or spalls No evidence of deterioration of the prestress system Some corrosion of other reinforcement may be present, minor section loss
4	Delamination, spalls and corrosion of reinforcement is prevalent Prestress system may also be exposed & deteriorated

In terms of assessing treatment options at a given time, spalling is the most important factor, delamination is the second, and chloride contamination at the level of the reinforcing steel is the third most important. The following weights have been allocated for these factors:

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

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

$$S = CL + 2.5(DELAM) + 7.5(SPALL)/8.5 \qquad \text{(Equation 2.1)}$$

2.3.3 Costs

The cost of various repair/rehabilitation options are compared through the analytical process. Cost estimates are based upon historical cost information and include road user costs and agency costs in order to indicate the most reasonable treatments from a community perspective. It is essential to make specific allowances in case of changed circumstances such as new regulations. Austroads has put significant effort into supporting consistency in evaluation of road user costs for the major Australian road authorities (Austroads, 2004).

2.3.4 Deterioration Prediction

Generally, bridge management involves defining both the current and future facility conditions. Current conditions are determined by using a condition assessment methodology and future conditions are forecasted using a deterioration model. Deterioration can be defined as the gradual decrease in performance of an element or a structure under normal operating conditions (Ariyaratne et al., 2009). The reliability of the process and the predictability of the outcomes depend on the amount and quality of data available for analysis. Visual inspection alone is not usually sufficient. There is a need to develop adequate sampling and testing methods to investigate material properties and bridge condition deterioration details (Morcous et al., 2002).

In a study conducted by Frangopol at al. (2001), the factors affecting the deterioration of a bridge condition were examined. It has been concluded that the top ranking factors involved in deterioration are age, road type, the environment, design parameters, and the quality of the construction and materials used.

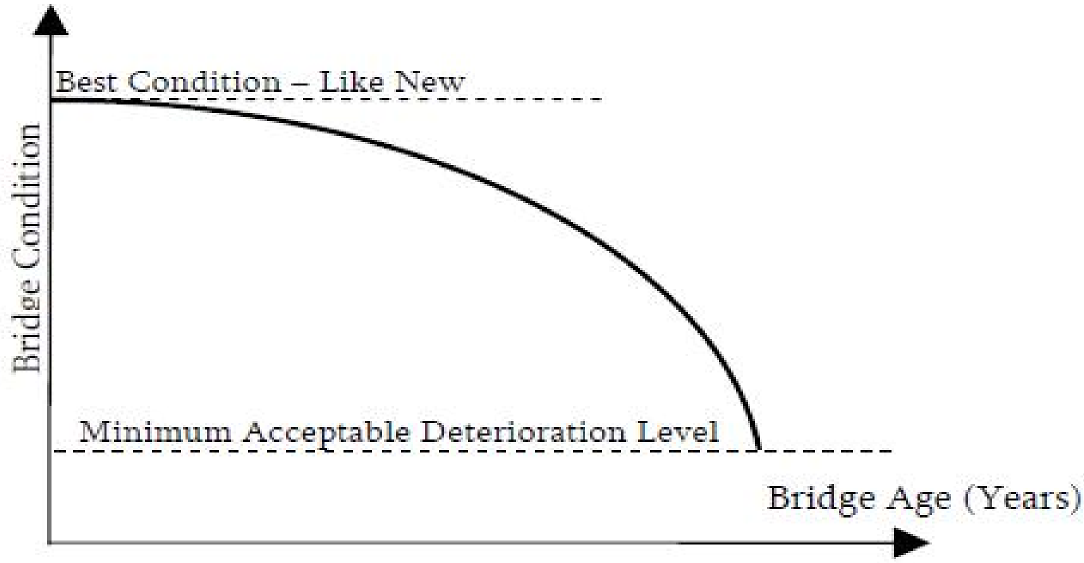


Figure 2.3 Bridge Deterioration (Elbehairy and Hegazy, 2004)

According to Elbehairy and Hegazy (2004), most studies of deterioration rates predict slower declines in condition ratings after 15 years. The report included outcomes from a regression analysis for the deterioration of structural conditions. For instance, the average deck condition rating declines at the rate of 0.104 points per year for approximately the first 10 years and 0.025 points per year for the remaining years. In addition, the overall structural condition declines at a value of 0.094 per year for 10 years and 0.025 per year thereafter. It has also been found that the condition will not fall below 6 until after 60 years. In another study, the estimated average deterioration of bridge decks was 1 point in 8 years and 1 point in 10 years for the superstructure and substructure, respectively. A simple deterioration process over time is illustrated in Figure 2.3.

2.3.5 Performance Report

Performance reporting includes some information related to the inspection, maintenance, financial and management and facilitates justifying/verifying management actions. Reports may address the performance of the whole bridge stock, for sub-sets of bridges or even for individual structures, and are usually tailored to satisfy the expected level of management. Reports may be either systemic to the particular BMS or may be created based on user-defined factors.

At a more strategic stage, reports on topics such as changes in functionality and serviceability indicators (eg., flood immunity, and suitability for specific loadings such as large freight vehicles, etc), are also required (Austroads, 2004; Watson and Everett, 2011).

2.3.6 Planning

In bridge management plan performance targets and intervention levels for all the structures should be defined. According to Austroads (2004), the main outputs of a BMS analytical process are as follows:

-**Needs:** identifies assets and elements not meeting required standards, and estimates costs to restore structural and functional efficiency to at least the minimum standards;

-**Prediction:** the effect on future serviceability and sufficiency of assets if repairs are not undertaken or delayed;

-**Costs:** the estimated cost for prioritised actions to manage the remaining life of the structure; and

-**Strategies**: the full spectrum of available options for projects ranging from “do nothing” to “replacement”.

According to Yehia et al. (2007) several important factors influence the decision in any repair and rehabilitation project. Some of these factors are:

-the nature, extent and severity of the defect;

-the effect of the proposed repair method on the service life of the bridge;

-the extent to which the repair process will disrupt traffic flow and

-the availability of funds.

2.4 Strategic Decision Making for Bridge Remediation

Decision making for carrying out the activities for bridge maintenance, rehabilitation and replacement (MR&R) has become a major concern for transportation authorities, since many bridges are old and older bridge design characteristics do not accommodate the current traffic features. Limited budget is another major consideration. The majority of the existing decision making techniques attempt to optimise the long term actions in order to minimise the total cost and to maintain bridges at an adequate level of safety and serviceability. Therefore, the budget for MR&R activities should be carefully allocated, particularly when the life cycle cost is taken to account (Rashidi and Lemass, 2011a).

Priority setting for MR&R activities is a multi-attribute decision-making problem which requires simultaneous assessment at both the network level and the project level. The prioritisation of bridges for remediation is considered a network-level decision, while the selection of repair methods for an individual bridge is a project-level decision. At the project level, the focus is mostly on repair alternatives, the cost of the repair, and the improvement expected from the selected solution. Both the network and project levels are complementary and dealing with these two levels separately will lead to a non-optimal decision. Therefore, they should be used simultaneously in BMS (Thompson et al., 2003).

2.4.1 Network Level Decisions

The rule of "Selecting projects with the worst conditions" is a common way of bridge prioritisation for repair actions. However, this rule does not necessarily maximise the benefits or reduce the life cycle cost. Prioritisation techniques for choosing bridges for remediation range from subjective decisions based on engineering judgement to complex optimisation techniques. Ranking on the subjective basis of engineering judgement is only acceptable for small and young networks of bridges (Jiang, 1990; Elbehairy et al., 2006b). The main types of existing prioritisation methods are: sufficiency rating (SR), level-of-service (LOS) deficiency rating, mathematical optimisation, and risk based priority ranking. A short summary of each technique is presented below.

2.4.1.1 Condition and Sufficiency-Rating System

Condition and sufficiency rating models are used to classify the bridges according to their relative importance in the network. The term "important" indicates the type, position, and condition of each bridge. Maintenance actions are chosen to the bridges based on a few criteria including the available budget. This method still does not provide an optimal allocation of the budget.

The sufficiency-rating (SR) approach is widely used by agencies to determine the eligibility of bridges for rehabilitation or replacement. Through this methodology a numerical value is calculated as an indicator of whether the bridge can remain in service or not. The results can be expressed as a percentage on a scale from 0 to 100, with 100 representing a completely sufficient bridge and 0 representing an insufficient bridge. Deficiencies are expressed as one of two categories: structurally deficient or functionally obsolete. The disadvantage of the SR method is that it is based on standards for load capacity and bridge width. Based on this model, narrow bridges that have a low capacity are subjected to low sufficiency ratings, although these bridges may be in adequate level of service. The SR method also ignores the Average Daily Traffic (ADT) and user cost in the decision making (Xanthakos, 1996; Elbehairy et al., 2006a).

2.4.1.2 Level-of-Service-Deficiency Rating

The level-of-service deficiency rating (LOS) is another type of priority ranking, proposed by Johnston and Zia (1984) as a way of overcoming the disadvantages of the SR system. According to this approach, priorities should be set based on the degree in which a bridge is deficient in meeting the public's requirements. To assess if bridge is meeting its planned function, three characteristics are used: load capacity, vertical roadway clearance, and clear deck width. Although, the LOS rating has been proved to be more efficient than a condition and sufficiency rating, it still has some drawbacks. The LOS rating does not have the ability to determine the best remedial action (i.e., ignoring the project level). Secondly, it is unable to predict the optimal timing for any repair alternative (Elbehairy et al., 2006b).

2.4.1.3 Mathematical Optimisation Techniques

In an attempt by AL-Subhi et al. (1989) to extend mathematical optimisation techniques from project-level decisions to include network-level decisions, an optimisation model called OPBRIDGE was established for the North Carolina Department of Transportation where was able to optimise the budget allocation by minimising the overall reductions in the annual costs for all bridges in the network. The prioritisation was set for each individual year using an integer-linear programming formulation. The criteria used were the budget, the level of service, and the minimum allowable condition rating. The weak point of this method is the limited number of bridges that can be handled at the same time (Elbehairy et al., 2005).

To balance between keeping the deteriorated bridges connected in the network and minimising maintenance cost, Liu and Frangopol (2005) presented a probabilistic based approach in order to keep the highway network connected.

Liu and Frangopol (2006) and Lee and Sanmugarasa (2011) also presented a novel approach to consider conflicting criteria such as life-cycle failure and socio-economic significance in a multi-objective optimisation; however, the proposed methods are not able to handle large-scale networks.

2.4.1.4 Risk Based Priority Ranking

Through the risk assessment process, a schedule of high risk items is used to identify the highest priority maintenance issues. Risk is defined as the product of the probability of failure and the consequence of failure, ie:

Risk Score = Probability (of failure) x Consequence (of failure)

According to Prasad and Coe (2007) the analysis of both probability and consequence of failure can be simplified in order to make the overall procedure easier to interpret. It can be performed via a computer program which automatically calculates risk scores. Finally bridges will be prioritised based on their risk scores in a descending order.

The probability of failure is expressed as a function of the structural capacity of the bridge. Condition, load bearing capacity, material and criticality factors are also included in the evaluation of probability (of failure).

The consequence of failure is an analysis of the failure impact to the community and to the bridge structure itself. For each bridge the consequence of failure is assessed under the factors including structural damage, potential for damage, loss of service and loss of life. Assigning quantities for the subjective factors is not an easy task and this can be considered as a major drawback of this methodology.

2.4.2 Project-Level Decisions

A Project-level decision generally includes the determination of the MR&R strategy associated with repair cost and required time for performing the repairs. In the literature, a few approaches for project-level decisions have been presented. Project-level decisions can be categorised based on the following techniques: Benefit/Cost ratio (B/C), LCC mathematical optimisation, and Decision Support Systems.

2.4.2.1 Benefit/Cost ratio (B/C)

The B/C ratio technique can be employed at the project level to compare different remediation strategies. This parameter is introduced as the benefit gained by moving from one repair solution to another more expensive option divided by the related extra costs. The benefits include those for both the user and the agency. User benefits are measured in terms of cost reductions or savings to the user as a result of an improvement. Agency benefits are defined based on "the present value of future cost savings because of the expenditures" (Elbehairy et al., 2005). Over exaggeration of cost as a constraint and subjectivity of benefit evaluation are the negative aspects of this technique.

2.4.2.2 Mathematical Optimisation Techniques

In mathematical optimisation models, an optimal solution can be reached through the manipulation of the trade-off between the objectives and the constraints.

Jiang (1990) constructed an optimisation model using integer-linear programming for the Indiana Department of Transportation (INDOT). Three key solutions were considered: bridge replacement, deck replacement and deck rehabilitation. Each option is represented a zero-one variable: "0" if the activity is not selected and "1" if it is selected. The model subdivides the decision problem into stages; each year is defined as a stage. The Markov chain technique is used to predict the future bridge condition at each stage, and integer-linear programming is employed to maximise the effectiveness of the network. The only criterion considered in this model was the budget and the fact that only one strategy can be undertaken. As the age of bridge increases, the condition rating gradually decreases (Elbehairy et al., 2005). As shown in Figure 2.4, the area between the performance curves representing the old condition and the new one, shows the condition improvement that is expected if the activity is carried out. To consider user costs, the expected area of improvement (A_i) is multiplied by the average daily traffic (ADT). This value represents a measure of improvement and effectiveness which can be experienced by users. Traffic safety conditions and the community impact are two other aspects affecting the decisions. The effectiveness of the bridge is obtained by the following equation

$$E_i = ADT_i * \Delta A_i(\alpha) * \left(1 + X_{impc_i}\right) * (1 + C_{safe_i}) \qquad \text{(Equation 2.2)}$$

Where E = the effectiveness gained by bridge i if activity a is selected (a = 1 deck rehabilitation; a = 2 deck replacement; a = 3 - bridge replacement).

α = the improvement activity;

ADT = the average daily traffic;

A_i the expected area of improvement;

$Ximpc_i$ = the community impact of bridge expressed in terms of detour length and

$Csafe_i$ = the traffic safety index for bridge i.

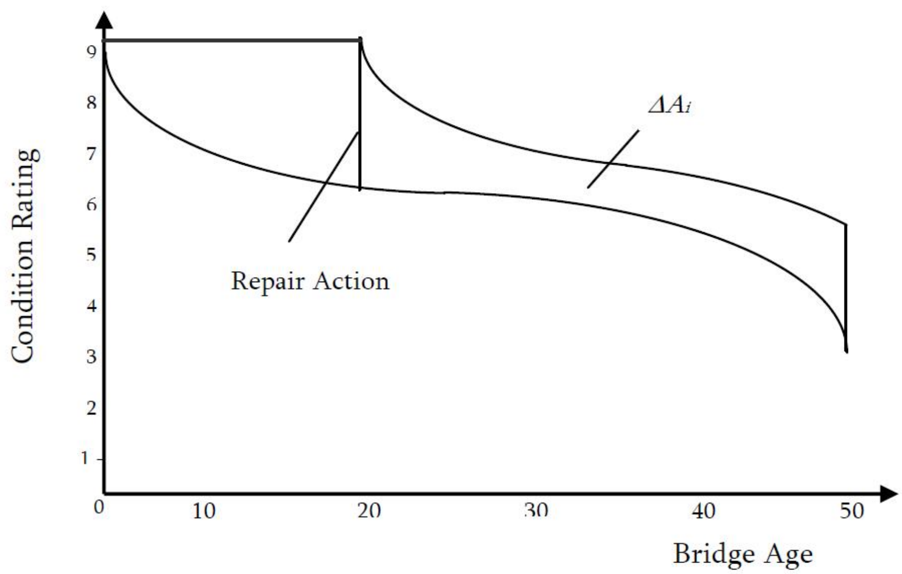


Figure 2.4 Area of a Performance Curve Gained by Rehabilitation (Jiang, 1990; Elbehairy et al., 2005)

However, the shortcoming of such a model is that one alternative can not be undertaken more than once on one bridge in (T) years, that is no multiple visits are considered; if the bridge is not taken into account in a specified year, the remediation cost will increase in the coming years; the application of this technique at each level does not provide an optimal result for a large number of decision variables for too many years and the agency cost is ignored in evaluating the system's effectiveness (Elbehairy et al., 2005).

2.4.2.3 Decision Support Systems

Decision support techniques were developed as a response to the perceived inadequacy of optimisation models (Lemass, 2004). They make it easier to define more than one constraint for improvement of bridges on the planning horizon.

Yehia et al. (2008), developed a decision support system using a rule based shell software which has the ability to suggest repair and rehabilitation strategies for just a few common problems in concrete bridge decks including corrosion, delamination, and cracking.

2.5 Review of the Most Common Concrete Repair Techniques

It is essential for an asset manager or remedial engineer to understand the various causes and mechanisms of concrete deterioration. Once the contributing aspects are understood, it is possible to diagnose and assess the current condition of elements, estimate their remaining service-life and if necessary intelligently design and implement appropriate remedial options.

Concrete structures deteriorate gradually, over a long period of time. It is a medium to long-term process as the rate of deterioration is a function of various factors. The main factors are the environment in which the structure is required to perform, the actions that are conducted within or upon the structure, and the physical features of the concrete used to construct the structure (Rashidi et al., 2010).

Branco and de Brito (2004) have provided a comprehensive categorisation of defects, defect causes and treatment alternatives. They have also attempted to present the correlation between the defects and cause of defects through a correlation matrix (See Appendix A).

However, it is not as simple to find proposals of classification systems for repairs. When available, they do not apply specifically to bridges and do not consider the multitude of works that needs be undertaken to keep the bridges functionally and structurally safe. Besides taking these facts into account, the classification should also consider maintenance work, in addition to repair techniques (Branco and de Brito, 2004; Raina, 2005).

Table 2.2 illustrates the common treatment options for concrete elements in bridges including ingress protection, restoring passivity, increasing resistivity/moisture control, cathodic control/protection, control of anodic areas, strengthening and replacement.

Table 2.2 Treatment Options for Concrete Components (Buckley and Rashidi, 2013)

Principle	Technique	Principle	Technique
Ingress Protection	Protective coating	Control of Anodic Areas	Apply Barrier to reinforcement
	Crack sealing & repair		Apply Chemical to reinforcement
			Apply Sacrificial coating to reinforcement
Restoring Passivity	Chloride extraction		
	Replacement of contaminated concrete	Strengthening	Add external reinforcement
			Post- tension
Moisture Control/ Increase Resistivity	Surface coating		Plate bond
	Over cladding		Enlarge component
			Span shortening techniques
			Resin or grout injection of voids or cracks
Cathodic Control	Saturation (saline treatment)		
	Surface coating		
	Cathodic inhibitors	Concrete restoration by replacement	Hand applied mortar
			Recasting with concrete
Replacement	Replace the element		Sprayed concrete (shot-crete)

The review of the fore mentioned remediation techniques will be presented in the next sections.

2.5.1 Ingress Protection

Ingress protection controls the deterioration rate of concrete by preventing the introduction of undesirable causes that promote chemical attack or steel reinforcement corrosion. The main adverse agents include water, water-borne chlorides and sulphates, carbon dioxide, acidic gases and aggressive liquids. The main effective ingress protection methods are protective coating and crack sealing (Raina, 2005; Buckley and Rashidi, 2013).

2.5.1.1 Protective Coatings

One of the most efficient techniques to prevent or reduce the concrete deterioration is known as protective coating. Surface coatings are used to protect concrete include anti-carbonation coatings, sulphate resistant coatings, chloride barriers, acid/chemical barriers, and vapour barriers.

According to Yehia et al. (2008) the most common protective repair methods are: low-slump dense concrete (LSDC) overlay, protective steel fiber reinforce concrete (FRC) overlay, protective latex modified concrete (LMC) overlay, hydraulic cement grouting, epoxy grouting, polymer injection, low pressure polymer spraying, penetrating and coating sealers and gravity feed resin.

2.5.1.2 Crack Sealing and Repair

Crack sealing is a method in which concrete deterioration can be reduced or prevented. Cracks in concrete usually pose a big threat to the durability of the structure. Successful long-term repair procedures target the causes of the cracks as well as the cracks themselves (Issa and Debs, 2007). Cracking of the concrete surface allows a direct pathway of contaminates such as chloride ions, oxygen, water, carbon dioxide and sulphur dioxide to penetrate directly to the steel reinforcement. It is generally accepted that crack widths greater than 0.5mm can initiate crack-induced corrosion.

Before selecting a crack sealing technique a careful evaluation of the progression and cause of cracking must be undertaken. Gravity filling, epoxy injection (with positive or negative pressure), chemical grouting, dry packing and autogenous healing are the most common techniques of crack sealing.

2.5.2 Restoring Passivity

The embedded reinforcement in fresh concrete is protected from corrosion by an adherent passive film of iron oxide which forms on the surface of the reinforcement. Under this circumstance, the reinforcing is in a passive state and protected from corrosion. The passive film is maintained by the highly alkaline environment of fresh concrete. Disruption in the passive film may happen by a loss in alkalinity of the host concrete-most often caused in the process of carbonation, or through the electrochemical action of chloride ions at the surface of the reinforcement, or a combination of both mechanisms. The loss of passivity (breakdown in the passive film) will result in the activation of corrosion (Yanev, 2007; Rashidi et al., 2010).

The most effective method to restore passivity will depend on the cause of depassivation and hence, activation of corrosion (carbonation or chlorides). The most popular passivity restoring techniques are realkalisation of concrete, chloride extraction, replacement of contaminated concrete with fresh concrete, and realkalisation of carbonated concrete by application of external cementations renders.

2.5.2.1 Electrochemical Realkalisation of Carbonated Concrete

The process of electrochemical realkalisation restores the alkalinity to carbonated, but otherwise sound concrete. This method consists of a temporary application of voltage between an internal cathode-the reinforcing bars and an anode, external to the concrete. The external anode is submerged in an alkaline solution containing sodium carbonate as an electrolyte. Under the passage of electrical current the electrolyte is moved into the concrete towards the steel reinforcement, a process which is known as electro-osmosis. At the reinforcement a process of electrolysis produces hydroxyl ions. Consequently, the alkalinity of surrounding concrete increases and repassivation of the steel reinforcement begins. The realkalisation process takes three to five days. The pH of the concrete is expected to be in excess of 10.5, high enough to support the passivity of the steel reinforcement (Buckley and Rashidi, 2013).

2.5.2.2 Realkalisation by Application of External Cementations Renders

This technique is performed through the application of a cementitious render to the surface of concrete suffering from carbonation. Hydroxyl ions (OH^-) migrate by ionic diffusion into the carbonated concrete under the influence of a concentration gradient between the alkaline render and the carbonated concrete (Daly, 2010).

2.5.2.3 Electrochemical Chloride Extraction

Electrochemical chloride extraction is a permanent solution for extracting chlorides from concrete. Like realkalisation, chloride extraction is achieved by putting a voltage between an external anode and the steel reinforcement, which performs as a cathode. The anode is submerged in an electrolyte such as saturated calcium hydroxide or water. The positive anode attracts the chloride ions and the cathode repels them. Chloride ions will either be repositioned away from the reinforcement or removed from the concrete into the electrolyte. In addition, a process of electrolysis produces hydroxyl ions, repassivating the steel reinforcement. The electrochemical chloride extraction takes three to five weeks to complete (Raina, 2005)

2.5.2.4 Replacement of Contaminated Concrete

Repairs to the carbonated and chloride contaminated concrete is usually focused on the effects and not the cause of corrosion. Most of the patch repairs to carbonated or chloride contaminated concrete are not effective because of the phenomenon known as incipient anode effect. It will initiate corrosion in concrete adjacent to the patch, thereby escalating the problem. Replacement of concrete can be more effective in circumstances where chloride concentrations are low or carbonation has not exceeded the depth of the reinforcement (Daly, 2010).

2.5.3 Cathodic Control

Electrochemical corrosion consists of two half-cell reactions, one occurring at the anode and the other at the cathode. These two reactions are highly dependent on each other. That is, the rate of electron consumption at the cathode must be equal to the rate of electron production at the anode.

Therefore if any of these half-cell reactions is disrupted, it will affect the overall corrosion rate (Buckley and Rashidi, 2013).

Cathodic control involves changing the potentially cathodic regions on the steel reinforcement. This reaction is dependent on the availability of oxygen. As a result, if oxygen can be restricted from diffusing to the level of steel reinforcement to take part in the cathode reaction, the rate of corrosion can be stopped or reduced dramatically. Some examples of cathodic control techniques include:

-Limiting oxygen content by encapsulation i.e. grouted sleeves, resins, etc,

-Limiting oxygen content by saturation i.e. submergence,

-Cathodic control with the use of cathodic or multi-function inhibitors that are applied externally and permeate to the reinforcement, forming a film on the surface of the reinforcement restricting the access of oxygen (Branco and de Brito, 2004).

2.5.4 Control of Anodic Areas

The control of anodic areas uses the same principal as previously discussed for cathodic control of areas of the steel reinforcement. If the anode reaction can be controlled then the overall rate of steel reinforcement corrosion is controlled. The anode reaction may be controlled by the application of chemical, or sacrificial coatings to the reinforcement. The application of these systems however, is restricted, since direct access to the reinforcement is required. There is also the risk of corrosion in locations adjacent to the repair caused by the incipient anode effect.

Alternative anodic control treatments are anodic and multi-functional inhibitors. These treatments are applied to the surface of concrete by brush or spray and are absorbed through the cover of the concrete to the reinforcement. The length of application is dependent on the permeability of the concrete. It is also recommended that inhibitors be used in conjunction with other repair treatments for an effective remedial strategy (Daly, 2010; Buckley and Rashidi, 2013).

2.5.5 Cathodic Protection

Cathodic protection (CP) systems are suited to large structures requiring massive patch repair caused by chloride-induced corrosion. In such situations the only other options are to demolish and rebuild, completely encase or structurally strengthen the concrete structure from ingress of deleterious substances.

CP systems will immediately stop or reduce corrosion but can not rehabilitate the steel nor return it to its original condition. They require a supplemental anode to be bonded to the concrete surface. These anode materials should be capable of sustaining oxidation reactions without suffering physical damage. A direct potential is then applied, by connecting the positive terminal of the power supply to the supplemental anode and the negative terminal to the steel reinforcement. Electrons are forced into the steel reinforcement at a higher voltage than the corrosion potential, forcing the reinforcement to become more electro-negative.

Produced electrons by the supplemental anode consumed at the steel reinforcement, which is cathodically protected. At the steel surface, reduction occurs, producing hydroxyl ions. The production of hydroxyl ions reverts the pore water back to an alkaline substance, which regenerates the passivating of the steel reinforcement. Another benefit of this method is that the negatively charged chloride ions are forced away from the more electro-negative steel reinforcement towards the supplemental anode, which further assists in the establishment of the passivating layer on the steel reinforcement ((Branco and de Brito, 2004).

2.5.6 Concrete Restoration –by Replacement

Concrete restoration is a very common repair principle used to repair spalled, laminated and badly cracked concrete related to steel reinforcement corrosion. For patch repairs or other concrete restoration techniques to be efficient, all contaminated concrete beyond the depth of the reinforcement and adjacent to the damaged area must be removed. When chloride infested or carbonated concrete remains adjacent to repairs, incipient anode corrosion occurs. This causes reinforcement corrosion and concrete spalling in areas adjacent to the repair (Raina, 2005; Buckley and Rashidi, 2013).

2.5.6.1 Hand –Applied Mortar

Patch repairs are discrete repairs carried out in small areas on a structure. They are usually less than half a square metre in area and are implemented using mortar applied by hand.

It is a common practice to carry out patch repairs with proprietary cementitious repair packages. These 'repair packages' include a sophisticated repair mortar and bond coat (bonding bridge). Together these materials promote good adhesion between the repair mortar and the concrete. These packages also include an anti-corrosion primer for the steel reinforcement and anti-carbonation coating as a protection. Often, a leveling mortar is required to fill blow-holes and irregularities in the areas of concrete not requiring repair, in order to create a uniform and tightly closed surface upon which to apply the anti-carbonation coating (ibid).

2.5.6.2 Replacement- by Recasting with Concrete

In large volume repairs it may not be suitable or economical to use hand –applied mortars or sprayed concrete. In this situation, concrete poured behind shutters is often used. In many cases there are limited openings in the shutters and access for vibration may be highly restricted or non-existent. To overcome this problem, flowing concrete, which requires little compaction, has been developed. These are known as *super-fluid microcret* (Branco and de Brito, 2004).

2.5.6.3 Replacement of the Concrete by Spraying Concrete or Mortar

The main advantages of spraying concrete (shotcrete) are that it can be applied quickly and economically to large areas and new reinforcement can be incorporated easily. The sprayed concrete process, projects a high velocity stream of material into the position. The process produces dense concrete and no additional compaction is needed (Buckley and Rashidi, 2013).

2.5.7 Increasing Resistivity/Moisture Control

Another alternative to combat steel reinforcement corrosion is to increase the electrical resistivity of the concrete. By reducing the moisture content of the concrete, the concrete resistivity will increase. This causes an increase in the electrical potential needed to activate and sustain steel reinforcement corrosion.

The moisture content of concrete can be reduced by covering concrete with protective coatings, overcladding to shelter the concrete, electro-osmosis treatments or heating.

A good way to control the moisture content of concrete is to ensure that the drainage systems are working properly. The drainage systems of concrete structures should be routinely maintained to dissipate water runoff. This will prevent water from pooling on concrete surfaces and raising the moisture content of the concrete. If water continues to pool on the concrete surface, the existing drainage system should be redesigned or a new system installed to dissipate the water (Buckley and Rashidi, 2013).

2.5.8 Additional Strengthening

Structural strengthening techniques may be used to restore or increase the structural or functional performance of concrete structures. The design of strengthening systems is subject to design and construction constraints which are unique to each structure. Remedial designers must develop innovative strengthening solutions, which may deviate from the more common techniques presented in this review.

Corrosion of reinforcement causes reduction in strength, which may also influence structural behaviour and stability. Advanced corrosion causes a reduction reinforcement section, reduction in concrete section due to spalling, and a reduction or loss of composite behaviour. Consequently the member undergoes a reduction in structural capacity, resulting in a change in structural behaviour with possible stability problems (Daly, 2010).

2.5.8.1 Adding Embedded or External Reinforcement

Adding extra reinforcement to strengthen reinforcement concrete has been well proven in the application to bridge girders. Inserting reinforcing bars and bonding them in place with epoxy provides additional strength. This method consists of sealing major cracks, drilling holes that intersect the crack plane at approximately 90 degrees, filling the hole and crack with injected epoxy and placing a reinforcing bar into the drilled hole (Raina, 2005; Buckley and Rashidi, 2013).

One example of external reinforcement for strengthening is the technique of stitching. Stitching is used when tensile strength must be reestablished across major cracks. It should be noted that stitching a crack tends to stiffen the structure, and this stiffening may increase the overall structural restraint, causing the concrete to crack elsewhere.

The stitching procedure consists of drilling holes on both sides of the crack, cleaning the holes, and anchoring the legs of the staples in the holes, with either a non-shrink grout or an epoxy resin-based bonding system. The staples should vary in length, orientation, or both. They should be located so that the tension transmitted across the crack is not applied to a single plane within the section but is spread over an area (Raina, 2005).

2.5.8.2 Post-Tensioning

Post- tensioning is a good solution for the following situations: when a major portion of a member must be strengthened, when cracks have formed that must be closed, or when excessive deflections have to be counteracted. In this method prestressing tendons, bars or straps are used to apply a compressive force to the concrete. Post-tensioning can be effective in providing additional shear strength, flexural strength and tensile strength in concrete members. Adequate anchorage must be provided for the prestressing steel, and care is required so that the problem will not merely migrate to another part of the structure (Rashidi et al., 2010).

2.5.8.3 Plate Bonding

Steel plates bonded to the tensile face of concrete beams increase flexural strength, stiffness, and can reduce cracking and deflections. Bonded steel plates can also be applied to vertical faces of concrete beams to increase shear capacity. The technique of plate bonding involves, steel plates which are glued to the concrete surface by an epoxy adhesive creating a three phase concrete-glue-steel composite system. Anchors are used to position the steel plates while the epoxy cures and gives an additional shear capacity between the concrete and plate (Riana, 2005).

2.5.8.4 Fibre Reinforced Polymers (FRP)

Fibre reinforced polymer (FRP) has an outstanding effect on improving the ductility and strength of reinforced concrete. FRPs are being used extensively all over the world for bridge strengthening, because of their advantages over other traditional methods such as plate bonding (Rashidi and Hadi, 2010). This includes its ability to be used in a wider range of situations. It can be formed into complicated shapes, lighter with the same strength, easily cut on site. However the main disadvantages of FRP being applied externally is the risk of fire, vandalism or accidental damage unless protected (Raina, 2005).

West Gate bridge is now the leading bridge strengthening project in the world, in terms of the volume of FRP used for upgrading the whole structure. The significant outcomes were major cost and time saving for the project, whilst being able to maintain the tight construction schedule, in extremes of weather (Sarkady, 2011).

2.5.8.5 Enlargement

Enlargement is the addition of concrete and reinforcement to increase the dimensions of a structural member. This technique can be used successfully on beams, slabs, columns, and walls, to add stiffness and load carrying capacity. The enlargement is bonded to the existing member to create a monolithic member (Raina, 2005).

2.5.8.6 Span Shortening Techniques

Span shortening is usually used to increase flexural capacity or stiffness of a slab or beam. This technique is simple and cost effective. Methods of span shortening include enlarging the column capitals, adding steel or concrete braces, shifting the bearing point, adding intermediate piers between the existing piers and abutments, etc (Daly, 2010; Buckley and Rashidi, 2013).

2.6 Summary

The importance of bridges as key elements in transportation networks and the enormous number of the current bridge infrastructures has made maintaining the existing bridge infrastructure (rather than building new bridges) a major issue for transportation authorities.

In this chapter, a review of the previous work on bridge management systems and their limitations and the current status of research in the area of bridge management have been presented. The main components of a bridge management system have also been introduced and discussed.

The strategic decision making at both project level and network level has been investigated and finally the most common concrete repair techniques were introduced.

The literature survey revealed the most suitable elements for integration into the present study. The present research is focused on the development of a framework to assist bridge engineers and asset managers to arrive at an optimal decision for managing their bridge networks, taking into consideration both network-level and project-level constraints.

3 LITERATURE REVIEW (PART II): DECISION SUPPORT SYSTEM

3.1 Introduction

Extensive studies have been carried out to improve the reliability and reduce the uncertainty of BMS outputs. Bridge decision support systems have developed mainly to support bridge experts in order to provide a more realistic future status of the bridge networks.

In this chapter, decision characteristics are identified and the need for decision-making support in bridge remediation is discussed. Decision support systems are defined, and their history is explained. Decision analysis concepts and tools are introduced, and their advantages and disadvantages are compared.

3.2 Decision Making in Bridge Management

Bridge remediation has become a major issue for asset managers and society due to increasing traffic volumes, deterioration of existing bridges and well-publicised bridge failures. A key responsibility for asset managers in charge of bridge remediation is to make viable decisions with lowest predicted losses in recognised constraint areas (Rashidi et al., 2010).

As a matter of fact, decision-making in this field is more complicated than it was in the past for two governing reasons. Firstly, growing technology and communication systems have spawned a greater number of feasible solution alternatives from which a decision-maker can select.

Secondly, the increased level of structural complexity of today's problems can result in a chain reaction of magnification of costs if an error should occur (Lemass, 2004).

Turban and Aronson (2001) examined what they consider to be the major factors that affect decision-making, and have drawn conclusions regarding current trends and corresponding results/impacts on decision-making (Table 3.1).

Table 3.1 Factors Affecting Decision-Making (Turban and Aronson, 2001)

FACTOR	**TREND**		**RESULTS**
Technology	Increasing	→	More alternatives to choose from
Information/computers	Increasing	→	
Structural complexity	Increasing	→	Larger cost of making errors
Competition	Increasing	→	
International markets	Increasing	→	More uncertainty regarding the future
Political stability	Decreasing	→	
Consumerism	Increasing	→	
Government intervention	Increasing	→	

In general, managerial decisions are derived from human judgment which includes deductive reasoning supported by experience, information and knowledge (Faiz and Edirisinghe, 2009). To compensate the effect of human error, the decision making process can be partially supplemented by computer aided automation. The final system can not be fully automated, unless perfectly processed information and an optimum model is provided.

DSS is used to model human reasoning and the decision-making process; both are capable of accepting facts from users, processing these facts, and suggesting the solutions that are close to the solutions that are presented by human experts (Yehia et al., 2008). DSS can considerably support in evaluating different maintenance decisions in order to select the most robust and cost-effective answers in a systematic and transparent way (Zoeteman, 2001).

The growing level of decision support system accomplishment in organisations over the recent decades is strong proof that DSS is a viable and well accepted managerial tool.

3.3 Decision Support Systems

3.3.1 A Brief History

Over the past fifty-plus years, the field of Information Systems (IS) has undergone a considerable progression of growth. Each expansion has built on its predecessors and supplemented them in the process (Burstein and Holsapple, 2008).

Before 1965, it was extremely expensive to build a large-scale information system. Around this time, the establishment of the IBM System 360 and other more powerful processor systems made it more practical and cost-effective to build Management Information Systems (MIS) in large corporations. MIS was concentrated on providing managers with well structured, periodic reports which were mainly from accounting and transaction systems (Power, 2002). The pre-specified reports (eg. budget, cumulative cost and progress statements) output from MIS are data-oriented and restrict decision-makers to gathering the necessary information for making choices, but do not supply a framework to model decision problems. At that point, it was recognised that technological support for decision-making must facilitate ad hoc (problem-specific) recovery of data and managerial control over model manipulation. Decision-makers did not wish to be locked into systems they could not control (Silver, 1991).

In the late 1960s, model-oriented DSS or management decision systems became practical. Two DSS pioneers, Peter Keen and Charles Stabell, stated the concept of decision support which was extracted from the theoretical studies of organisational decision making during the late 1950s and early ‘60s and the technical work on interactive computer systems that mostly carried out in the 1960s (Keen and Scott Morton, 1978).

In 1961, Michael S. Scott Morton published “*Management Decision Systems: Computer-Based Support for Decision Making*”. Later, in 1968-1969, he studied the effect of computers and analytical models in critical decision making. His research played a *“key role in launching the DSS movement”* (Lemass, 2004).

In 1980, Steven Alter published an important book titled “*Decision Support Systems: Current Practice and Continuing Challenge”*. His research founded a structure for identifying management DSS (Power, 2002).

(Bonczek et al., 2007) established a theory based on knowledge-based DSS. Their research presented how Artificial Intelligence and Expert System technologies were applicable to developing DSS. They also introduced four essential “aspects” or components of all DSS (Power, 2002), these are:

1. A Language System (LS) which includes all the recognisable messages.

2. A Presentation System (PS) for all messages emitted by DSS.

3. A Knowledge System (KS) addressing all the imbedded knowledge in a DSS.

4. A Problem-Processing System (PPS) that tries to diagnose and solve problems.

In the early 1990, business intelligence, data warehousing and On-Line Analytical Processing (OLAP) software began expanding the potential of DSS (Dhar and Stein; Power, 2002). Around 1997, the data warehouse became the cornerstone of an integrated knowledge environment that granted a higher level of information sharing, facilitating faster and better decision making (Powell, 2001; Power, 2002).

Decision support systems have experienced a noticeable growth in scholarly attention over the past two decades. In according to Google Scholar (October 2007), the rate has increased from less than three publications per week in 1980 to over 20 publications per day twenty-five years later (Burstein and Holsapple, 2008). The Internet and Web have also accelerated developments in decision support and have provided a new way of capturing and documenting the development of knowledge in this research area (Power, 2002).

3.3.2 DSS Definitions

The early definition of DSS introduced it as a system that intended to support decision makers in semi-structured problems that could not be completely supported by algorithms. DSSs were planned to be an accessory for managers to expand their capabilities but not to replace them. The primary definition was based on the notion that the system would be computer-based, operate interactively online, and preferably have graphical outputs. According to Mora et al. (2003), in a typical DSS, the relevant data and models are captured and stored as inputs in the system. The decision maker employs computer technology to: (a) organise the information into problem parameters, (b) attach all the parameters to a model, (c) use the model to simulate events and alternatives, and (d) select the best solution to the problem. The outcomes are reported as parameter conditions, experimental forecasts, and/or recommended actions. Feedback from the user guides the decision maker to a problem solution, and created data and knowledge are stored as additional inputs for future or further processing. A typical architecture of DSS provided by Mora et al. (2003) is shown in Figure 3.1.

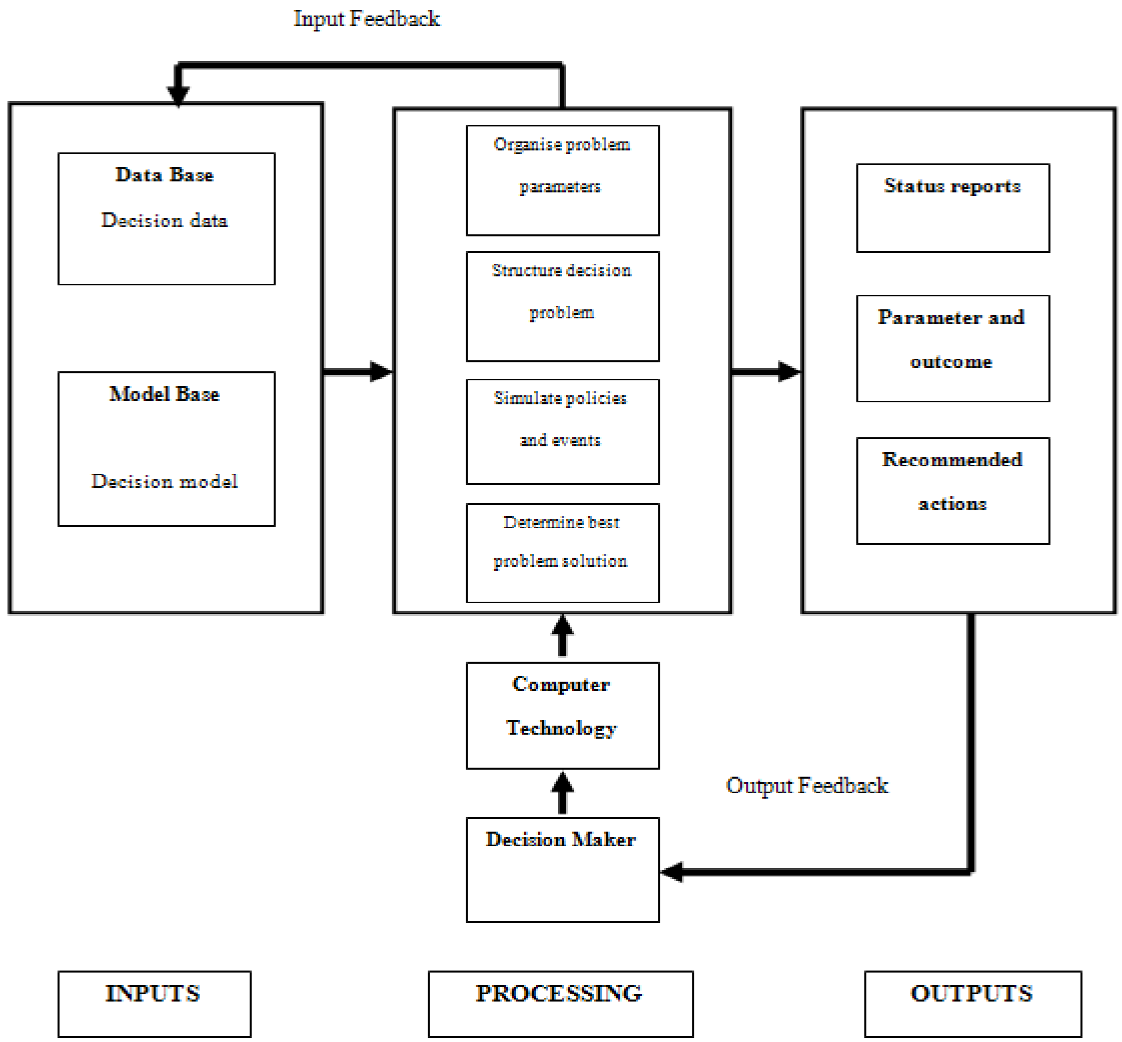


Figure 3.1 Typical Architecture of Decision Support System (Mora et al., 2003)

3.3.3 DSS Ideal Characteristics and Capabilities

Defining standard characteristics of DSS is not viable but the major features that distinguish DSS from other previously established systems can be summarised from Turban and Aronson (2001) as follows:

- DSS assists decision makers in semi-structured and unstructured problems (which can not be solved by standard procedural methods or tools), employing human judgment and computers.
- It covers a vast spectrum of managerial levels, from *top executive to line managers*.
- Support is provided to both individuals and groups. Less structured situations often require the intervention of several individuals from different divisions and organisational levels or sometimes even from different organisations.
- DSS facilitates several *interdependent and/or sequential* decisions that *may be made once, several times, or repeatedly.*
- DSS carries out all parts of the decision-making process: *intelligence, design, choice and implementation.*
- It covers a variety of decision analysis tools.
- DSS is adaptive and flexible, and so users can add, change, delete, or re-organise basic elements.
- DSS should be user friendly and have strong graphical interfaces.
- DSS tries to improve the *effectiveness* of decision making (appropriateness and quality) rather than its *efficiency* (the cost of decision making).
- DSS attempts to support the decision makers not to replace them. Therefore they will have control over all levels of the process.

- End users should be able to build (and modify) simple systems. Complicated systems can be constructed with assistance from information system (IS) experts.

- A DSS generally employs models for analysing problems since modeling enables experimenting with different strategies under different configurations.

- DSS should be able to supply access to a variety of data sources and formats.

- A DSS can be integrated with other systems and/or applications, and it can be distributed through networking and web technologies.

Figure 3.2 demonstrates an extension of an ideal set of DSS characteristics; based on the work of Turban and Aronson (2001).

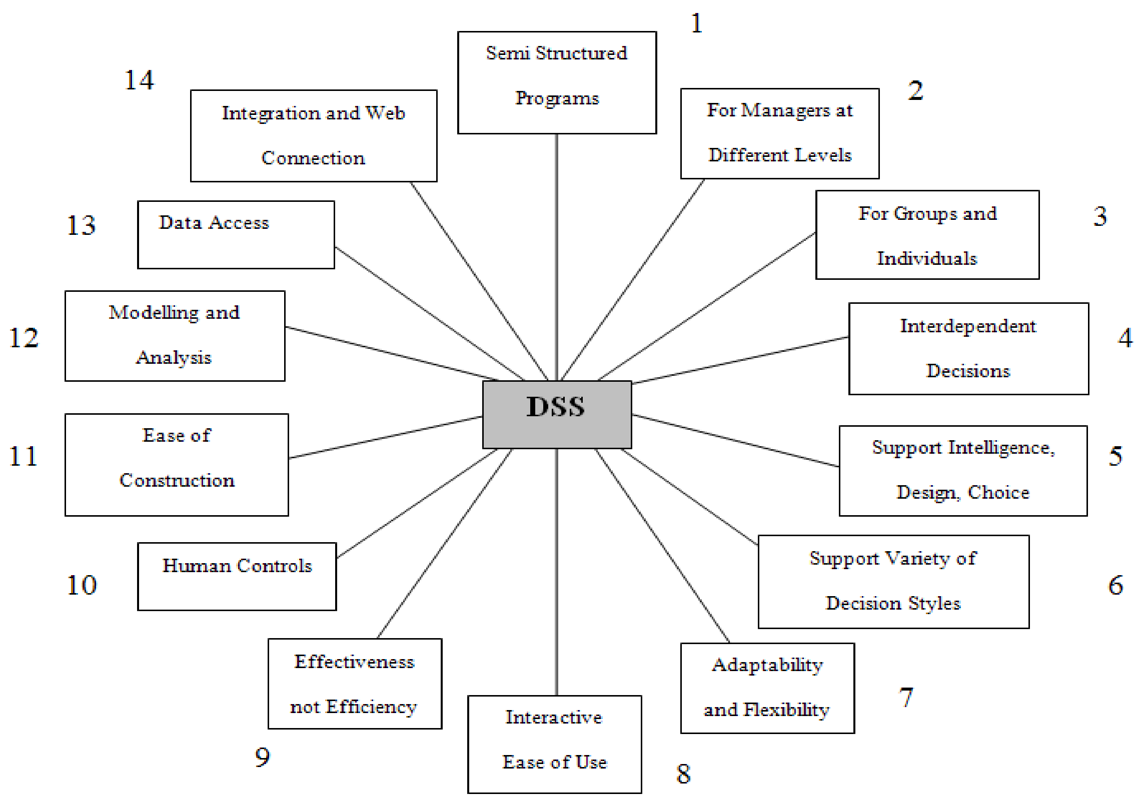


Figure 3.2 The Desirable Characteristics and Capabilities of DSS

Lemass (2004) also emphasises that a DSS should improve both the **effectiveness and efficiency** of decision-making. Effectiveness is the degree to which identified goals are achieved, whilst efficiency is a measure of the application of resources to attain the goals. The effectiveness and efficiency of a DSS can be measured by its ability to enable decision-makers to:

-define difficult problems earlier;

-rapidly identify viable solutions;

-equitably compare the consequences of each solution;

-stylise an interface for displaying problem-specific (ad hoc) data collection and results presentation (eg. tables, forms, graphics, etc); and

-run sensitivity analyses to check model assumptions and hence help to defend proposed solutions more convincingly.

3.4 An Introduction to Decision Making

Traditionally, a decision is defined as being a choice: *a choice about a course of action* (Costello and Zalkind, 1963)*, the choice of a strategy for action* (Fishburn, 1964)*, a choice leading to a certain desired objective* (Churchman, 1968). It can be clearly understood that decision making as *a non-random activity* concluding in the selection of one course of action among multiple strategies and DSS is a prevailing system that can ease this process (Burstein and Holsapple, 2008).

According to Harris (1998):

"Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to

be considered, and in such a case we want not only to identify as many of these alternatives as possible but to choose the one that best fits with our goals, objectives, desires and values."

Simon (1977) stated that the process of making the decision includes three basic phases: intelligence, design, and choice. Turban (1993) described how implementation, is also required over and above a "paper" solution , as the fourth phase, in order to solve the original problem.

The intelligence phase, or problem identification, involves gaining awareness that inconsistencies exist between the current state of a situation and the desired circumstances. At this level the decision maker tries to diagnose the problems that need to be addressed and/or opportunities that needto be tracked (Srinivasan et al., 2000).

In the design phase, a decision maker attempts to generate alternatives, and analyses the options to provide knowledge about their relevant implications. During this phase, the decision maker may find that supplementary knowledge is required. This leads to a return to the intelligence stage to clarify the problems before continuing with the design activity (Holsapple, 2005).

During the choice phase, the decision maker selects one of the proposed alternatives that have been explored in the design phase. The outcome depends on the nature of the *decision context* and the *decision maker's own traits and idiosyncrasies.* It may be that none of the alternatives are satisfying (return to the design phase), that several competing alternatives gain high scores, or that the state of the context has changed dramatically after analysis of alternatives (return to the intelligence phase). However, one option must be chosen for implementation (Burstein and Holsapple, 2008).

The fourth and final step is implementation. This phase includes a set of chosen solutions that need to be approved by stakeholders and put into action over time (Srinivasan et al., 2000). This requires cautious planning and sensitivity to those involved in the process and/or those affected by it. The resolution must then be monitored to guarantee that the problem has been corrected. If the problem has been rectified, then the decision-making procedure is finalised (Bartol et al., 2007). Generally, the outcome of successful implementation is solving the *real* problem while any failure results in returning to a former phase of the process (Turban and Aronson, 2001).

3.4.1 The Structure of Decisions

There is a variety of decision types which can be classified based on specific factors. An appreciation of decision types can assist decision makers understand what knowledge and knowledge manipulation features would be required in decision support system (Burstein and Holsapple, 2008). The level of '*programmability*' or structuredness is a helpful aspect for understanding and classifying decisions. Simon (1977) argued that decisions could be placed along a spectrum from highly structured to completely unstructured (Srinivasan et al., 2000). Decisions may also be further classified as single-stage and multiple-stage, with either risk, certainty or uncertainty of outcome.

Structured decisions are made when well known procedures can be readily applied to all the phases of decision-making to provide standard solutions for repetitive problems. They are characterised by definite decision criteria, a limited number of precise alternatives whose consequences can be worked out without any complexity (Srinivasan et al., 2000).

A semi-structured decision is made when some, but not all, of the phases of decision-making are structured. While some standard solution procedures may be applicable, human judgment is also called upon to develop decisions which tend to be adaptive in nature (Lemass, 2004).

When none of the phases of decision-making are structured, the resulting decisions are classified as **unstructured**. Lack of clear decision criterion and the difficulty in identifying a finite set of alternatives and high levels of uncertainty concerning the consequences of the known alternatives at most of the decision levels, are all symptoms of this unstructuredness (ibid).

Semi-structured and unstructured decisions are made when problems are **ill-defined (ill-structured).** Srinivasan et al. (2000) notes that most real-world problems fall towards the unstructured end of this spectrum. Table 3.2 demonstrates the characteristics of structured and unstructured decisions.

Table 3.2 Decision Structuredness (Burstein and Holsapple, 2008)

Structured decisions	**Unstructured decisions**
Routine, repetitive	Unexpected, infrequent
Established & stable context	Emergent & turbulent contexts
Alternatives clear	Alternatives unclear
Implications of alternatives straightforward	Implications of alternatives indeterminate
Criteria for choosing well defined	Criteria for choosing ambiguous
Specific knowledge needs known	Specific knowledge needs unknown
Needed knowledge readily available	Needed knowledge unavailable
Result from specialised strategies (i.e., procedures that explicitly pre-specify full set of steps to follow in order to reach decisions)	Result from general strategies (e.g., analogy, lateral thinking, brainstorming, synthesis used in the course of reaching decisions)
Reliance on tradition	Reliance on exploration, creativity, insight, ingenuity

Decision support systems can give valuable aids in semi-structured and unstructured decisions (keen and Scott Morton 1978). Burstein and Holsapple (2005; 2008) clearly defined the role of DSS for making decisions over a wide spectrum of problems:

> "*To support the making of unstructured decisions, a DSS can be designed to facilitate the exploration of knowledge, help synthesise methods for reaching decisions, catalog and examine the results of brainstorming, provide multiple perspectives on issues, or stimulate a decision-maker's creative capabilities. A DSS intended for supporting the production of semi-structured decisions may also possess such capabilities. Additionally, it may carry out some pre-specified procedures to partially contribute to reaching a decision. DSSs can also be valuable aids in the manufacture of structured decisions, by automatically carrying out some subset of the full prespecified procedure used. The chief benefits of this sort of DSS are more efficiency and less likelihood of human error in the decision process. Of course, if the system were to perform all steps of a full program for decision making, we would call it a decision-making system (not a decision support system).*"

(Burstein and Holsapple, 2008)

3.5 Multi Attribute Decision Making Methods

Engineering or management decisions are generally made through available data and information that are mostly vague, imprecise, and uncertain by nature (Devi et al., 2009). The decision-making process in bridge remediation is one of these **ill-structured** occasions, which usually need a rigorous approach which applies explicit subject domain knowledge to ill-structured (adaptive) problems in order to reformulate them as **structured** problems. Multi-Attribute Decision Making (MADM) is an efficient tool for dealing with uncertainties.

A standard feature of multi-attribute decision making methodology is the decision matrix with m criteria and n alternative as shown in Figure 3.3. In the matrix $\mathbf{C}_1,...,\mathbf{C}m$ and $\mathbf{A}_1,..,\mathbf{A}_n$ indicate the criteria and alternatives respectively: each row belongs to a criterion and each column describes the performance of an alternative. The score a_{ij} describes the performance of alternative $\mathbf{A}_j$ against criterion $\mathbf{C}_i$. It has been conventionally assumed that a higher score value means a better performance (Fülöp, 2005).

		x_1	·	·	x_n
		$\mathbf{A}_1$	·	·	$\mathbf{A}_n$
w_1	$\mathbf{C}_1$	a_{11}	·	·	a_{m1}
·	·	·	·	·	·
·	·	·	·	·	·
w_m	$\mathbf{C}_m$	a_{m1}	·	·	a_{mn}

Figure 3.3 The Decision matrix

As shown in Figure 3.3, weights $W_1,...,W_m$ are assigned to the criteria. Weight W_i reflects the relative importance of criteria $\mathbf{C}i$ to the decision, and is assumed to be positive. The weights of the criteria are typically defined on subjective basis. The values $X_1,...,X_n$ associated with the alternatives in the decision table are used in the Multi-Attribute Utility Theory (MAUT) methods (see below) and are the final ranking values of the alternatives. Usually, higher ranking value means a better performance of the alternative, so the alternative with the highest ranking value is the best of the alternatives (Fülöp, 2005).

In addition to some monetary based and elementary methods, the two main families in the multi-attribute decision making methods are those founded on the MAUT and Outranking Methods.

3.6 Elementary Methods of MADM

These elementary approaches are characterised by their simplicity and their independence to computational support. They are suitable for problems with a single decision maker, limited alternatives and criteria which can rarely occur in engineering decision making (Linkov et al., 2005). Maximin and Maximax methods, Pros and Cons analysis, Conjunctive and Disjunctive methods and the Lexicographic method are all in this category (UKDTLR, 2001; Baker et al., 2002).

3.6.1 Maximin and Maximax Methods

The maximin method's strategy is to avoid the worst possible performance, maximising the minimal performing criterion. The alternative, for which the score of its weakest crierion is the highest, is preferred (Linkov et al., 2005). For example a weight of one is given to the criterion which is least best achieved by that choice and a weight of zero to all other criteria. The strategy with the maximum minimum score will be the optimum choice. In contrast to the Maximin method, The Maximax method selects an alternative by its best attribute rather than its worst. This method is particularly useful when the alternatives can be specialised in use based upon one attribute and decision maker has no prior requirement as to which attribute this is (Yoon and Hwang, 1995).

3.6.2 Pros and Cons Analysis

Pros and Cons analysis is a qualitative comparison method in which positive and negative aspect of each alternative are assessed and compared. It is easy to implement since no mathematical skill is required (Baker et al., 2002; Fülöp, 2005).

3.6.3 Conjunctive and Disjunctive Methods

The conjunctive and disjunctive methods are non-compensatory, goal aspiration screening methods. They do not need attributes to be measured in commensurate units. These methods require satisfactory (in comparison with a predefined threshold) rather than best possible performance in each criterion i.e. if an alternative passes the screening, it is adequate (Zavadskas et al., 2007).

In Conjunctive method, an alternative must meet a minimal threshold for all attributes while in disjunctive method; the alternative should exceed the given threshold for at least one attribute. Any option that does not meet the rules is deleted from the further consideration (Linkov et al., 2005).

3.6.4 Decision Tree Analysis

Decision trees provide a useful schematic representation of decision and outcome events, provided the number of courses of action, a_i, and the number of possible outcomes, O_{ij}, not large. Decision trees are most useful in simple situations where chance events are dependant on the courses of action considered, making the chance events (states of nature) synonymous with outcomes (Lemass and Carmichael, 2008).

Square nodes correspond to decision events. Possible courses of action are represented by action lines which link decision events and outcome (chance) events. Circular nodes differentiate the outcome events from the decision events in order to underline that the decision-maker does not have control when chance or Nature determines an outcome.

Outcomes for each action, with outcome probability quantified, originates from the chance nodes and terminate in a partitioned payoff/expected value node. The expected value for each course of action is achieved by summing the expected values of each branch associated with the action (Lemass and Carmichael, 2008).

A decision tree representation of the bridge problem is shown below as an example. Three strategies (courses of action) are investigated (See Figure 3.4):

a_1: replace the distressed bridge section (it would soon be unsafe)

a_2: rehabilitate the bridge (repair costs will not be prohibitive)

a_3: do nothing (the symptoms are more superficial than structural)

The estimated costs of replacement and rehabilitation are \$6.3M and \$1.1M respectively. If the road section is replaced, it is assumed that no further capital costs will be incurred. If the road is rehabilitated and repairs are not satisfactory, an additional \$6.3M replacement cost will result. If no action is taken and the road consequently requires major repairs or becomes totally unserviceable, respective costs of \$6.3M and \$18M will apply (Lemass, 2004).

In this example, states of nature are the same as possible outcomes. The outcomes and associated negative payoffs (costs in millions of dollars) can be considered as follows:

Payoff

$S_1 = O_{11}$: the bridge section is successfully replaced $u_{11} = -\$ 6.3$

$S_2 = O_{22}$: the repairs are satisfactory u_{22} = - $ 1.1

$S_3 = O_{23}$: the repairs are unsatisfactory u_{23} = - $ 7.4

$S_4 = O_{34}$: the bridge section fails, becoming unserviceable u_{34} = - $ 18.0

$S_5 = O_{35}$: the bridge section requires major repairs u_{35} = - $ 6.3

$S_6 = O_{36}$: the bridge section remains satisfactory u_{36} = - $ 0.0

The expected value (cost) of action a_2 is the lowest, based on the probability (likelihood of occurrence) assigned for each outcome, p_{ij} and this course of action can be followed (Lemass, 2004).

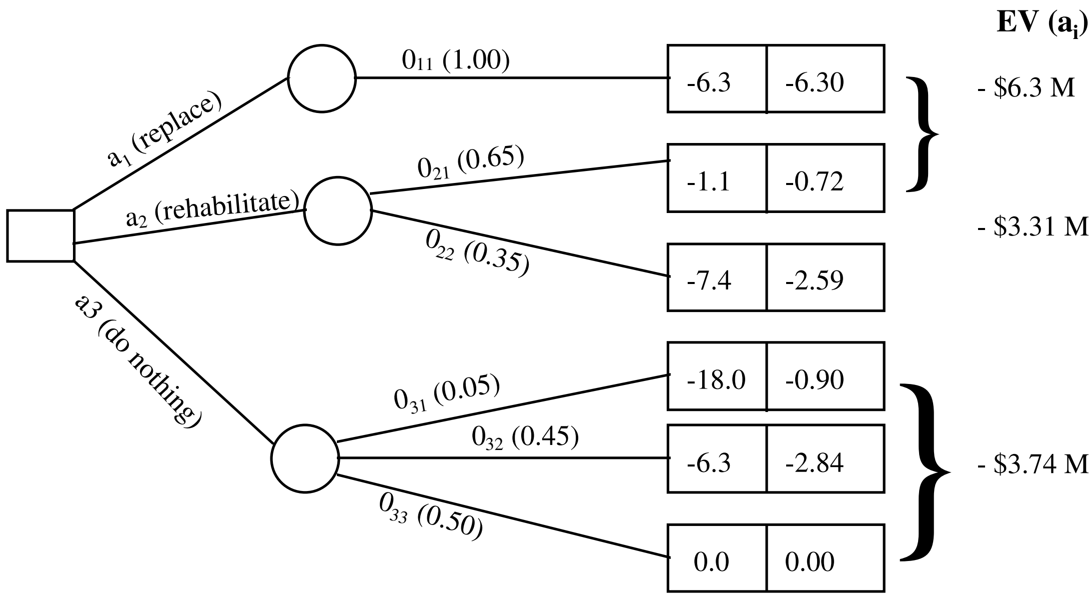


Figure 3.4 A Decision Tree for Selecting the Best Remediation Strategy of a Bridge

3.6.5 Lexicographic Method

In lexicographic analysis of problems, a chronological elimination process is continued until either a single solution is found or all the problems are solved (Ustinovichius et al., 2008). In this method criteria are first rank-ordered in terms of importance. The alternative with the best performance score on the most important criterion is selected. If there are ties related to this attribute, the performance of the joined option on the next most important factor will be compared until the unique alternative is chosen (Zavadskas et al., 2007).

3.6.6 Cost-benefit analysis (CBA) and Cost-effectiveness analysis (CEA)

The concept of cost-benefit analysis (CBA) originated in the United States in the 1930s where it was used to find a solution to problems of water provision. This method is used to estimate all the costs and benefits associated with a particular project which is usually defined in money terms, in order to weigh up whether a project will bring a net benefit to the public and to be able to compare the possible options for limited resources. It is one of the most comprehensive and at the same time the most difficult technique for decision making (Williams, 2008).

Cost−effectiveness analysis (CEA) is another tool which attempts to find the best activity, process, or intervention that minimises the costs of achieving a desired result. Analysts and agencies perform CEAs when the objectives of the public policy have been recognised and the only remaining question is to find the cheapest alternative of arriving at these objectives. CEA, therefore, does not ask, nor attempts to solve the problem of whether the policy is justified, in the sense that its overall benefits exceed its costs (Kuik et al., 1992; Fülöp, 2005).

According to Kuik et al. (1992) the application of CBA and CEA in an integrated assessment causes the following concerns:

- First, CBA measures costs and benefits on the basis of subjective preferences given objective resource constraints and technological possibilities and should probably be evaluated on a case−by−case basis as an open question.
- Second, certain costs and benefits which are in the social and environmental domains might be difficult to quantify in monetary terms.

3.7 Multi Attribute Utility Theory (MAUT)

MAUT is based upon the use of utility functions. Utility functions are employed to quantify the preference of the decision-maker by allocating a numerical index to different degrees of satisfaction as the attribute under consideration takes values between the most and least defined limits (Marzouk, 2006). They are considered a compliant tool of representing how much an attribute (or a measure) satisfies the decision-maker objectives to transform the raw performance values of the alternatives against diverse criteria, both factual (quantitative) and judgmental (qualitative), to a general dimensionless scale (Fülöp, 2005). They represent a means to translate attributes units into utility units. Utility functions can be specified in terms of a graph, table or mathematical expression. Mathematical expressions of utility functions include: straight-line, logarithmic, or exponential functions (Marzouk and Moselhi, 2003).

The utility values of performance measures are calculated by normalising the output of the simulation experiments. Normalisation of performance measures is carried out utilising the maximum and minimum limits of those measures. These limits are obtained from the pilot simulation runs. In addition, they are checked against the outputs measures gained from the simulation experiments and replaced if there are values beyond these limits. It has been suggested that utility functions be monotonic (Keeney and Raiffa, 1993; Marzouk, 2006) in such a way that the least desirable scenario corresponds to the lowest utility [U(xi) =0] while the most desirable scenario matches with the highest utility [U(xi) =1.0], the interval [0,100] can also be used for this purpose.

3.7.1 Simple Multi-Attribute Rating Technique (SMART)

Simple Multi Attribute Rating Technique (SMART) is a method that used to determine the weights of the attributes. This method was initially developed by Edwards (1971) and is based on direct numerical rating values that are aggregated additively. There are now many derivates of SMART, also including non-additive approaches. In a very basic format of SMART, there is a rank-ordering of alternatives for each attribute setting the best to 100 and the worst to zero and interpolating between. By refining the performance values with relative weights for all attributes a utility value for each alternative is calculated (Wolfslehner, 2005).

SMART is independent of the alternatives. While the introduction of value functions somewhat make the decision modeling process complex, the advantage of this method is that the ratings of alternatives are not relative, so that shifting the number of alternatives considered will not in itself alter the decision scores of the original alternatives. If new alternatives are probable to be added to the model after its primary construction, and the alternatives are acquiescent to a direct rating approach (not so qualitative as to require pair wise comparison), then SMART can be a superior choice (Valiris et al., 2005).

One of the limitations of this technique is that it disregards the interrelationships between parameters. However, SMART is a valuable technique since it is uncomplicated, easy and quick which is quite important for decision makers. In SMART, changing the number of alternatives will not change the decision scores of the original alternatives and this is useful when new alternatives are added (Valiris et al., 2005). He also argued that using SMART in performance measures can be a better alternative than other methods.

Adelman et al. (1984) noted that SMART has high levels of accuracy in certain tasks even though there is no formal mechanism for checking reliability of judgments between pairs of alternatives (Wang and Yang, 1999).

3.7.2 Analytical Hierarchy Process (AHP)

AHP is a multi attribute decision making method which belongs to the broader class of methods known as “additive weighting methods”. The AHP was proposed by Saaty (1977) and employs an objective function to aggregate the different features of a decision problem (Linkov et al., 2006; Bello-Dambatta et al., 2009) where the main aim is to choose the decision alternative that has the highest value of the objective function. The AHP is based on four clearly defined axioms (Saaty, 1991). Similar to MAU/VT and SMART, the AHP is classed as a compensatory method, where criteria with low scores are compensated for by higher scores on other criteria, but contrasting the utilitarian methods, the AHP exploits pair wise comparisons of criteria rather than utility or value functions where all individual criteria are paired with all other criteria and the end results accumulated into a decision matrix (Bello-Dambatta et al., 2009).

The process of AHP consists of three phases: decomposition, comparative judgments, and synthesis of priority. Through the AHP, decision problems are decomposed into a hierarchical structure, and both qualitative and quantitative information can be used to derive ratio scales between the decision elements at each hierarchical level by means of pair wise comparisons. The top level of hierarchy represents overall objectives and the lower levels correspond to criteria, sub-criteria, and alternatives. With comparative judgments, users are requested to set up a comparison matrix at each hierarchy by comparing pairs of criteria or sub-criteria. A scale of values -ranging from 1 (indifference) to 9 (extreme preference) is used to express the users preference. Finally, in the synthesis of priority stage, each comparison matrix is then solved by an eigenvector method for determining the criteria importance and alternative performance (Cheng et al., 2007).

The comparisons are generally documented in a comparative matrix A, which must be both transitive such that if, i > j and j > k then i > k where i, j, and k are alternatives; for all j > k > i and reciprocal, $a_{ij} = 1/a_{ji}$. Priorities are then calculated from the comparison matrix by normalising each column of the matrix, to derive the normalised primary right eigenvector, the priority vector, by A.W=λmax.W; where A is the comparison matrix; W is the principal eigen vector and λmax is the maximal Eigen value of matrix A (Saaty, 2004; Bello-Dambatta et al., 2009).

Through the AHP process, decision-makers' inconsistency can be calculated via consistency index (CI) which is used to find out whether decisions break the transitivity rule, and by how much. A threshold value of 0.10 is considered acceptable, but if it is more than that then the CI is calculated by using the consistency ratio CR= CI/RI where RI is the ratio index. CI is further defined as $CI = (\lambda_{max} - n)/(n - 1)$; where λmax as above; n is the dimension (Bello-Dambatta et al., 2009). The average consistencies of RI from random matrices are shown in Table 3.3.

Table 3.3 Random Inconsistency Index, Adapted from Ishizaka (2004)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The advantages of the AHP method are that it presents a systematic approach (through a hierarchy) and it has an objectivity and reliability for calculating weighting factors for criteria (Kim and Song, 2009). It can also provide a well-tested method which allows analysts to include multiple, conflicting, non-monetary attributes of alternatives into their decision making.

On the other hand, the disadvantages are that the calculation of a pair-wise comparison matrix for each attribute is quite complicated and as the number of criteria and/or alternatives increases, the complexity of the calculations increases considerably. Moreover if a new alternative is added after finishing an evaluation calculation, it is very troublesome because all the calculation processes have to be restarted again (Kim and Song, 2009).

The limitations of AHP are of a more theoretical nature, and have been the subject of some debate in the technical literature. Many analysts have pointed out that, the attribute weighting questions must be answered with respect to the average performance levels of the alternatives. Others have noted the possibility for ranking reversal among remaining alternatives after one is deleted from consideration. Finally, some theorists go so far as to state that as currently practiced, “the rankings of [AHP] are arbitrary”. Defenders of AHP, such as Saaty himself, answered that rank reversal is not a fault because real-world decision-making shows this characteristic as well (Norris and Marshall, 1995).

3.8 Outranking Methods

The most important outranking methods assume data availability roughly similar to what required for the MAUT methods. Fundamental problems with most MAUT and MAUT-related methods are handling uncertain or fuzzy information and dealing with information stated in other than ratio or interval scale. In some conditions, instead of quantitative measures descriptive expressions are frequently faced (Kangas et al., 2001). The outranking method acts as one alternative for approaching complex choice problems with multiple criteria and multiple participants. Outranking shows the degree of domination of one alternative over another and facilitates the employment of incomplete value information and, for example, judgments on ordinal measurement scale. They provide the (partial) preference ranking of the alternatives, not a principal measure of the preference relation (Kangas et al., 2001). Here the two most famous categories of the outranking methods, the ELECTRE and the PROMETHEE methods are briefly explained.

3.8.1 The ELECTRE Methods

The ELECTRE method is a part of MCDA (multi criteria decision-aid). The main aim of the ELECTRE method is to choose alternative that unites two conditions from the preference concordance on many evaluations with the competitor and preference discordance was supervised by many options of the comparison. The starting point is the data of the decision matrix assuming the sum of the weights of all criteria equals to 1 (Chih Huang and Hua Chen, 2005). For an ordered pair of alternatives (A_j, A_k), the concordance index C_{jk} is the sum of all the weights for those criteria where the performance score of A_j is least as high as that of A_k i .e.

$$C_{jk} = \sum_{a_{ij} \geq a_{ik}} w_i \qquad j,k=1,...,n, \qquad j \neq k \qquad \text{(Equation 3.1)}$$

The concordance index must lies between 0 and 1.

The calculation of the discordance index d_{jk} is more complex. If A_j performs better than A_k on all criteria, the discordance index will be zero. Otherwise,

$$d_{jk} = \max \frac{a_{ik} - a_{ij}}{\max a_{ij} - \min a_{ij}} \quad j,k=1,...,n, \qquad j \neq k \qquad \text{(Equation 3.2)}$$

Therefore for each attribute where A_k outperforms A_j, the ratio is computed between the difference in performance level between A_k and A_j and the maximum difference in score on the criterion concerned between any pair of alternatives. The maximum of these ratios (must be between 0 and 1) is the discordance index (Fülöp, 2005).

This method determines a partial raking on the alternatives. The set of all options that outrank at least one other alternative and are themselves not outranked.

3.8.2 The PROMETHEE Methods

This method was introduced by Brans and Vincke (1985) and Brans et al (1986). The scores of the decision table need not necessarily be normalised or transformed into a dimensionless scale. Higher score value indicates a better performance. It is also assumed that a preference function is associated to each attribute. For this aim, a preference function $P_i(A_j, A_k)$ is defined showing the degree of the preference of option A_j over A_k for criterion C_i:

$0 \leq P_i(A_j, A_k) \leq 1$ and

$P_i(A_j, A_k) = 0$ means no indifference pr preference,

$P_i(A_j, A_k) \approx 0$ means weak preference,

$P_i(A_j, A_k) \approx 1$ means strong preference, and

$P_i(A_j, A_k) = 1$ means strict preference.

In most realistic cases *Pi* is a function of the deviation $d=a_{ij}-a_{ik}$ i.e. *Pi(Aj,Ak)=Pi(aij-aik)*, where *Pi* is a non decreasing function, *Pi(d)=0* for d≤0 and $0 \leq P_i(d) < 1$ for d>0. A set of six functions was proposed by Brans and Vincke (1985) and Brans et al (1986). The main advantage of these preferences functions is the simplicity since there are no more than two parameters in each case.

A multi criteria preference index $\pi(A_j, A_k)$ of A_j over A_k can then be calculated considering all the attributes:

$$\pi(A_j, A_k) = \sum_{i=1}^{m} w_i \, P_i(A_j, A_k) \qquad \text{(Equation 3.3)}$$

The value of this index is between 0 and 1, and characterises the global intensity of preference between the couples of choices (Fülöp, 2005).

For ranking the alternatives, the following outranking flows are classified:

Positive outranking flow:

$$\varphi^{+}(A_j) = \frac{1}{n-1} \sum_{k=1}^{n} \pi(A_j, A_k) \qquad \text{(Equation 3.4)}$$

Negative outranking flow:

$$\varphi^{-}(A_j) = \frac{1}{n-1} \sum_{k=1}^{n} \pi(A_k, A_j) \qquad \text{(Equation 3.5)}$$

The positive outranking flow describes how much each alternative is outranking the other options. The higher $\varphi^{+}(A_j)$, the better the alternative. The negative outranking flow shows the power of A_j its outranking character.

The negative outranking flow shows how much each alternative is outranked by the others. The smaller $\varphi^{-}(A_j)$, the better the alternative. $\varphi^{-}(A_j)$ depicts the weakness of A_j its outranked character (ibid).

3.8.3 TOPSIS Methods

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) which was firstly proposed by Hwang and Yoon (1981) is one of the mostly used multi-criteria decision making techniques. The basic concept of TOPSIS is that the selected option should have the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution in a geometrical sense. Within the process an index called "similarity index" (or relative closeness) is defined to the positive-ideal solution by combining the proximity to the positive-ideal solution and the remoteness from the negative- ideal option. Then the method selects a solution with the maximum similarity to the positive-ideal solution. The default assumption is that the larger the outcome, the greater the preference for benefit attributes and the less the preference for cost attributes (Kilic, 2012). The idea of TOPSIS can be expressed in a series of steps:

Step 1: Identify performance data for *n* alternatives over *m* attributes. Raw measurements are normalised by converting raw measures x_{ij} into normalised measures r_{ij} as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{x_{ij}^2}} \quad i = 1, \ldots, m, j = 1, \ldots, n \quad \text{(Equation 3.6)}$$

Step 2: Estimate weighted normalised ratings:

$$\textit{Weighted } r_{ij} = w_j r_{ij} \quad \text{(Equation 3.7)}$$

w_j is the weight of the jth attribute. The basis for the weights is usually an *ad hoc* reflective of relative importance. If normalising was accomplished in Step 1, scale is not an issue.

Step 3: Obtain the positive-ideal alternative (extreme performance on each criterion) A^+.

Step 4: Find the negative-ideal alternative (reverse extreme performance on each criterion) A^-.

Step 5: Develop a distance measure for each decisive factor to both positive-ideal ($Si+$) and negative-ideal (Si^-).

Step 6: For each alternative, find out a ratio $Ci+$ equal to the distance to the negative-ideal divided by the summation of the distance to the negative-ideal and the distance to the positive-ideal:

$$C_{i+} = \frac{S_{i-}}{(S^{i-} + S^{i+})} \qquad \text{(Equation 3.8)}$$

Step 7: Rank order all the options by maximizing the ratio in Step 6.

3.9 Sensitivity Analysis

Sensitivity analysis is the method used to find whether a particular utility or probability is essential in determining the preferred alternative. There are always some uncertainties for the weights of the criteria and the scores of the alternatives against the subjective (judgmental) criteria. As a result an important question is how the final ranking or the ranking values of the alternatives is sensitive to the changes of some input parameters of the decision model.

A general and inclusive methodology was proposed by Mészáros and Rapcsák (1996) for MAUT models. In this approach, the weights and the scores of the alternatives against the criteria can change simultaneously, in given intervals. The following questions are addressed (Fülöp, 2005):

"What are the intervals of the final ranking values of the alternatives with the restriction that the intervals of the weights and scores are given?

-What are the intervals of the weights and scores with the restriction that the final ranking of the alternatives does not change?

-Consider a subset of alternatives whose ranking values are allowed to change in an interval. In what intervals are the weights and scores allowed to vary, and how will these modifications affect the ranking values of the entire set of alternatives?"

3.10 Summary

The current decision-making problems is more complex than it was in the past, prompting the need for decision support. Most "real-world" decision making situations are subject to bounded rationality; whereby the technical and economic evaluation of all solution alternatives (branches) is bounded by the consideration of dominant subjective constraints.

Bridge remediation is a decision-based process that is dependent upon both hard (scientific) and soft (experiential) knowledge. Intelligent decision support systems (controlled by humans) could provide the means to complement asset managers and bridge engineers by quantitatively supporting managerial decisions that could otherwise be based on personal intuition and experience. In addition to the traditional DSS characteristics (i.e. data and model orientation, interactivity), the inclusion of an intelligent knowledge base would be required to quantify the impacts of both technical (hard) and subjective (soft) constraints.

This chapter covers the definition of decision support system, it's ideal characteristics and it's background history. Different decision analysis methods including elementary methods, multi attribute utility theory and outranking methods have also been introduced and compared.

4 SYSTEM METHODOLOGY

4.1 Introduction

As discussed in Chapter 2, bridges are capital-intensive long life cycle assets. Normally, they involve small percent of the total length, but their share in the value of the network is ten times higher. Due to increasing traffic volumes and deterioration of existing bridges maintaining such assets and keeping them in an optimal condition is a complex task for authorities. This situation magnifies the importance of this research along with developing decision support methodologies that can assist asset managers and decision makers with the multifaceted task of bridge management.

The presented research was initiated to develop a decision support methodology for remediation of concrete bridges. Since required information for bridge management can be scares and not available, the system methodology is developed based on data collected during interviews with bridge engineers and experts.

In this chapter, the system methodology and the conceptual framework of the proposed DSS is presented. The details of the constituents will be discussed throughout the thesis.

4.2 Data Collection and Analysis

The information required for this research was gained through an extensive literature review, semi-structured interviews and review of the real cases to determine the information requirements, including decision points, dominant constraints and other relevant information considering the limitation of subjectivity and inability of users to verbalise their practice. The most important part of data collection was to extract and incorporate experts' judgement in a vigorous manner. In this study, semi-structured interview has been chosen as the main methodology for data collection. This method is flexible, allowing new questions to be brought up throughout the interview (as a result of the discussion between the interviewee and the interviewer) while a structured interview includes limited formalised questions. The interviewer in a semi-structured interview usually has a framework of themes to be discovered. The following areas are addressed through semi-structured interview:

-Bridge management in practice

-Bridge inspection strategies (inspection intervals, forms, methods,...)

-Condition assessment and priority ranking of bridges

-Remediation planning at both project level and network level

A questionnaire addressing the main research objectives has been designed and presented in Appendix B.

Interviews were carried out with male and female experts from both the public and private sectors in the following categories: (1) Consultants, (2) Government Agencies and (3) Researchers. Table 4.1 presents the list of participants consisted of roughly equal numbers of representatives from each of the categories.

Table 4.1 List of Interview Participants

Ref No	Organisation / Category	Ref No	Organisation / Category
1	RTA (Wollongong)	16	Gemena (Sydney)
2	RTA (Sydney)	17	Infratech Systems & Services
3	RailCorp (Wollongong)	18	Rocla (Sydney)
4	RailCorp (Sydney)	19	ARRB (Sydney)
5	Wollongong Council	20	ARRB (Melbourne)
6	Shellharbour Council	21	URETEK (Sydney)
7	Shoalhaven City Council	22	GBG Australia (Sydney)
8	Campbelltown City Council	23	PTS Consulting (Adelaide)
9	Sutherland Shire Council	24	Pitt& Sherry (Sydney)
10	GHD (Sydney)	25	University of Sydney
11	GHD (Wollongong)	26	SMART (Wollongong University)
12	COMPLETE (Sydney)	27	University of Newcastle
13	Savcor (Sydney)	28	University of Griffith
14	McDonald International (Nowra)	29	Monash University (Melbourne)
15	Thomas and Coffey (Wollongong)	30	University of Technology Sydney

4.3 Limitation of Existing BMSs

Worldwide many bridge management systems are being developed. Most systems adopt the element based inspection technique and employ life cycle cost for selecting the best course of action. For example, Points utilises dynamic programming to formulate the optimal policy with minimum life cycle costs considering the element out of the risk of failure (Rashidi and Lemass, 2011a).

Abu Dabous et al. (2008) noted that the optimised life cycle cost method causes some practical difficulties, particularly when the offered fund does not match the estimated life cycle cost. It has also been discussed that some indirect cost components such as failure costs and user delays should be considered as well as the agency cost.

Most of the bridge condition rating systems are based on a very subjective procedure and are associated with uncertainty and personal bias. Lack of a generic method for quantifying the overall condition index of bridges (following inspection) is one of the major issues that has been emphasised and consequently addressed by this author. The following limitations have also been investigated:

-Lack of a structured approach for inspection (some condition parameters are not usually addressed in inspection forms) and insufficient inspection records.

-Lack of a consistent taxonomy for defect categorisation and treatment selection.

-Lack of an objective condition assessment methodology which can quantify all the parameters involved in the serviceability and reliability of bridges.

-Ignoring some human factors (political/social constraints) as decision criteria.

-Ignoring the combined project and network level decisions (most of the existing models deal separately with the network level and project level problems).

The developed model in this research is proposed to overcome the decision-related limitations of the existing systems by integrating quantitative and qualitative data through the decision making procedure.

4.4 Conceptual Framework

As discussed in the literature review, the bridge management system as a comprehensive tool, requires processing a considerable amount of data and information to make decisions with the aim of maintaining a bridge network.

The system methodology presented here deals with the development of a knowledge-based decision support model for bridge remediation as a solution for the problems and limitations of the existing models. The proposed model is expected to be flexible and capable of handling multi-layer of data and dealing with multi-objective nature of the decision.

The working model includes a procedure for condition assessment in order to prioritise bridges in a network for any necessary intervention and maintenance fund allocation. The collected data through inspection (using specifically designed forms) is an input for the CBR-DSS. The system processes the inputs (inspection data) and calculates the condition index for each bridge in the network. The detailed estimation procedure is presented in Chapter5.

Classifying all the possible actions (including MR&R strategies and/or treatment options), finding the main constraints (decision criteria) and finally employing a suitable decision analysis tool are the main tasks/milestones for the proposed system. This process facilitates the decision making by analysing the most viable alternatives and suggesting proper actions for the different bridge projects. Chapter 6 discusses the remediation planning at both at the project level and network level and finally Chapter7 presents a prototype system as proof of the functionality of the proposed concept.

Figure 4.1 shows the overall working framework including two main phases which will finally end with two major outputs: 1) Project Ranking and 2) Remediation Planning.

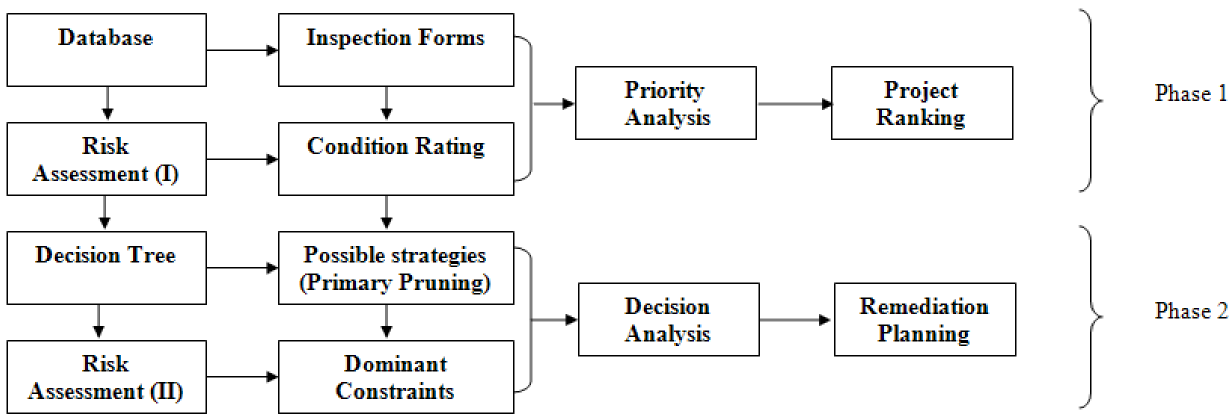


Figure 4.1 Conceptual Framework for Bridge Remediation (Rashidi and Lemass, 2011b)

The main system components, including inspection forms, condition rating, decision tree (possible strategies), dominant constraints, priority analysis and decision analysis are introduced and briefly discussed in the following sections.

4.4.1 The Database/Inspection Forms

The effectiveness of a bridge monitoring system is related to its data storage and inspection information. The periodic condition inspection of each bridge is an essential step to achieve continuous and reliable outcomes from the project- and network-level BMS analysis. Bridge datasets are imperative resources but the most time consuming to obtain. They are also fundamental input requirements for the accurate operation of BMS software (Lee, 2007). Branco and de Brito (2004) classified the bridge database into three types of information: static, semi-static, or upgradeable. Static information includes items such as administrative data, inspection manuals, structural reliability and graphic information. Semi-static information covers cost files, annual budgets, load-bearing capacity and reference state forms. The upgradable information addresses inspection forms which are based on a number of visits to a bridge at specific intervals, balanced by visits under certain circumstances (Rashidi and Lemass, 2011b). Inspections performed at fixed intervals are called periodic inspections, while special ones are referred to as non-periodic inspections. When serious structural defects are detected, a structural assessment is necessary to be performed. This type of inspection is focused on the localised affected section of the bridge in order to clarify the outcomes of the detailed inspection.

Data base designers are often accountable for choosing the best data model which most properly suits the data structure. Elmasri and Navathe (2000) pointed out that the most popular commercial management systems employ relational, hierarchical or network data models. In the relational model which is commonly used in engineering projects, the data is arranged in tables (Johnson, 1997; Abu Dabous and Alkass, 2008).

The Points bridge management system has been designed based on a relational database which stores data of the agency's physical bridge inventory and data associated with performing program simulations, a range of data definitions, and system parameters (AASHTO, 2005) .

The database selected for the proposed DSS is also relational, since this model is the best for storing bridge data and its design is usually represented using Entity Relationship (ER) diagrams.

For example, a bridge is a physical entity with a set of attributes such as the bridge name, length, location and number of spans and a set of values are assigned for the attributes (Dabous et al., 2008). The format of the developed database for the prototype DSS is presented in Chapter 7.

4.4.2 Risk Assessment (I): Condition Rating

Bridge condition assessment based on risk evaluation is a fundamental step for providing the appropriate inputs for any condition rating system. The reliability of decisions to find a remediation strategy or fund allocation is highly dependent upon the thoroughness of the condition assessment and diagnosis process (Rashidi and Lemass, 2011a). Many studies have been conducted to investigate risk assessment and bridge condition ratings. For example, Shetty et al. (1996) suggested a model for evaluation and prioritisation of bridges for remedial work, which involves risk assessment, ranking of bridges in a network based on risk, and selecting the best remedial strategies for each bridge. Stein et al. (1999) proposed a model for evaluating the risk related to scour threat to bridge foundations. Adey et al. (2003) developed a model for verifying the optimal intervention for a bridge subject to multiple hazards. Lounis (2004) developed an approach for maintenance optimisation of bridges which takes into account a few conflicting constraints, with focus on the risk of failure as a main criterion (Elhag and Wang, 2007). Most of these approaches are commonly based on subjective structural condition assessment. Parameters such as functionality and client prefrences may not be specifically addressed in them. As a result, one of the main objectives of this research was to propose an integrated index for the bridge rating, in a requirement driven context. The developing condition rating method described in Chapter 5 is an important step toward this aim and along with adding more holism and objectivity to the current approaches. Based on the proposed methodology Structural Efficiency (SE), Functional Efficiency (FE) and Client Impact Factor (CIF) as the main parameters involved in priority ranking of bridges are assessed and quantified separately. A general overview of the mentioned parameters is discussed in the following sections:

4.4.2.1 Structural Efficiency (SE)

As discussed in the Chapter 2, bridge condition rating is extracted from inspection data, which engages the use of techniques to evaluate the condition of each element and the amount of defects. Bridge inspections are conducted periodically. Level 2 (detailed) inspections are condition rating inspections that are performed by trained bridge inspectors almost every two years.

In order to be in harmony with the majority of inspection practices, the proposed system uses an element level index based on four condition states characterised in the Road and Maritime Services (RMS) of New South Wales in which the bridge element condition varies from 1 to 4 in rising order. The general description of the condition states for reinforced concrete bridge elements is presented in Table 5.1 (in Chapter 5). In this methodology the bridge is divided into elements normally made of similar material (Most bridges have about ten to twelve elements and bridge sized culverts typically have three to five elements). The bridge inspector estimates and records the quantities of the elements in each condition state independently. The total quantity must be calculated in the correct units for the elements. The units of measurement are square meters (deck, pile, and pier), meters (joints and railings) or each (waterway, bearing pad, etc) (Rashidi and Gibson, 2011). Each element contributes in a different way to the overall structural integrity in terms of material vulnerability and (/or) structural significance. Therefore it is necessary to clarify these factors for each element (Table 5.4 and 5.5 illustrated in Chapter 5).

The critical parameters that influence structural efficiency of bridges are identified as age, environment, road type and inspection. The weight of each of those factors should also be evaluated. Analytical Hierarchy Process (AHP) method which is a common tool for criteria weighting has been applied for this purpose, and finally the Causal Factor (CF) which represents the overall influence of the fore mentioned parameters, is implemented as a coefficient to the current structural condition index (Rashidi and Gibson, 2011).

4.4.2.2 Functional Efficiency (FE)

In the modern BMS the quality of service (functional efficiency) should be considered in addition to structural efficiency. Yanev (2007) stated that "the functional life of bridges is usually less than the structural life," e.g., 25 to 50 years (in high traffic growth), compared to 50 to 100 years (excepting disasters).

The main factors that affect the functional level of service of a bridge include:

-load capacity;

-overhead clearance;

-width;

-adequacy of bridge barriers;

-bridge drainage system;

The functional level of service of a bridge is deficient if any of the above mentioned factors does not meet the standard criteria for the road network where the bridge belongs to that.

In this study all the involved parameters have been re-defined in a quantitative manner and rated from 1-4 based on some defined intervals (See Table 5.9). At the next level all the factors have been weighted through the experts' judgment process considering their relative importance. The outcome introduced as Functional Efficiency factor (FE) that is calculated using equation (5.7) representing the serviceability level of the bridge (Rashidi and Gibson, 2012).

4.4.2.3 Client Impact Factor (CIF)

Sometimes parameters, such as heritage issues, social, economical or even political factors influence the decision making process in terms of priority ranking and budget allocation. Client impact factor (CIF) helps to build the social implications of remediation into the risk assessment process. It is a vast improvement on the "do nothing" course of action. On the other hand, bridge importance for economic activity can accelerate the decision making process toward the "replacement" or "rehabilitation" (Rashidi and Lemass, 2011b). This factor can be ranked based on the level of bridge criticality in terms of socio-economic, political and historical considerations (See Section 5.7). This part of the evaluation is relatively subjective but significant to notice, therefore the key decision maker or bridge maintenance planner should get involved to assign the appropriate rate for this parameter.

4.4.3 Priority Ranking of Bridges

In this study, the priority ranking is performed using an indicator named as Priority Index (PI) which integrates all the critical factors (and their associated weights) that will influence decision making. This enables bridge/funding agencies to make decisions and set objectives supported by strong logic. Figure 4.3 shows a summary of all the objectives involved in the ranking process.

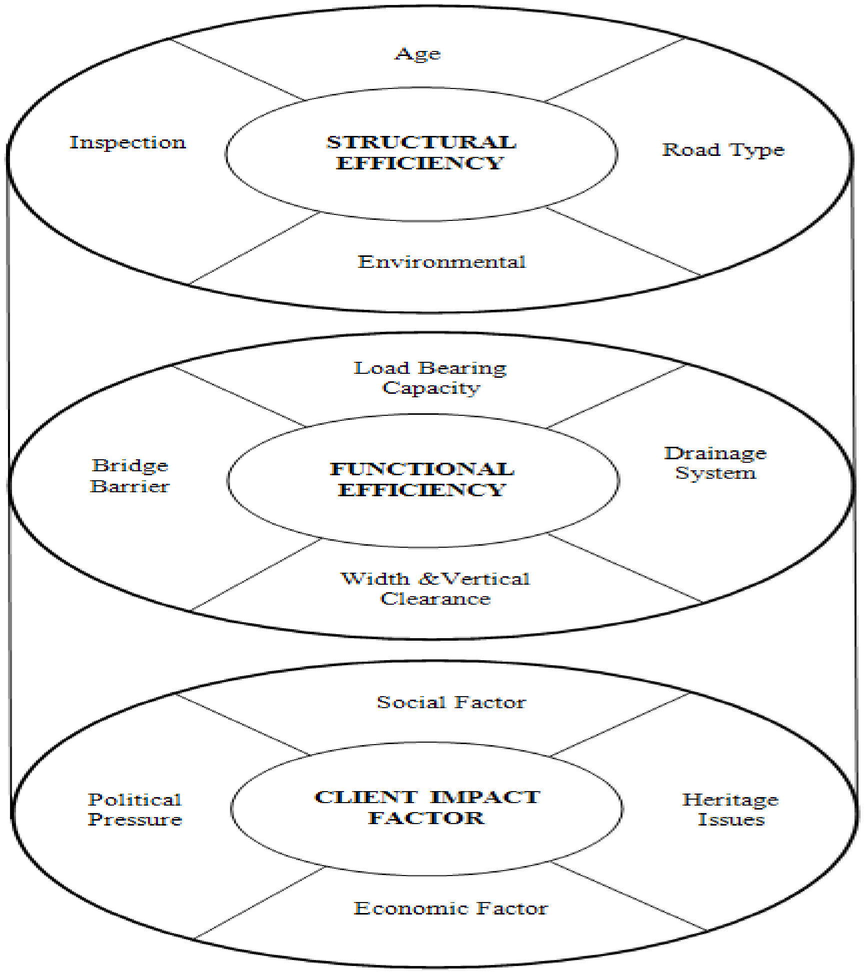


Figure 4.2 Factors Involved in the Priority Ranking Process (Rashidi and Gibson, 2011)

In fact structural efficiency is a representative of bridge condition considering the contributed causal factors (detailed explanations in section 5.5.1).

As shown in this figure, many parameters are involved in the ranking process, either directly or indirectly. On the other hand all the sub-parameters have been subjected to the ranking/weighting process so far and for each of them a rational weight has been assigned based on a heuristic methodology.

4.4.4 Decision Tree: Major Strategies

Most real-world decisions are not limited to singular, unique solutions. The decisions are usually less than optimal and are drawn from a set of feasible solutions that have been termed as 'satisfying' solutions (Lemass and Carmichael, 2008). To define and categorise all the possible alternatives, an inclusive classification should be defined. As discussed in Chapter 3, the decision tree is an appropriate tool for this purpose which provides a useful schematic representation of decision and outcome events. Figure 4.3 shows a decision tree which includes the common courses of action for bridge remediation and some specific treatment options for concrete bridges. For each of those treatment options in the last branches, there are again a few sub-branches based on some specific characteristics.

"*Do nothing"* is a very common course of action. In many cases, adequate funds are not available and the bridge managers have to allocate the budget for the structures of higher priority. Many engineers believe that a deteriorated bridge can be remained in service until a major rehabilitation or replacement decision is made.

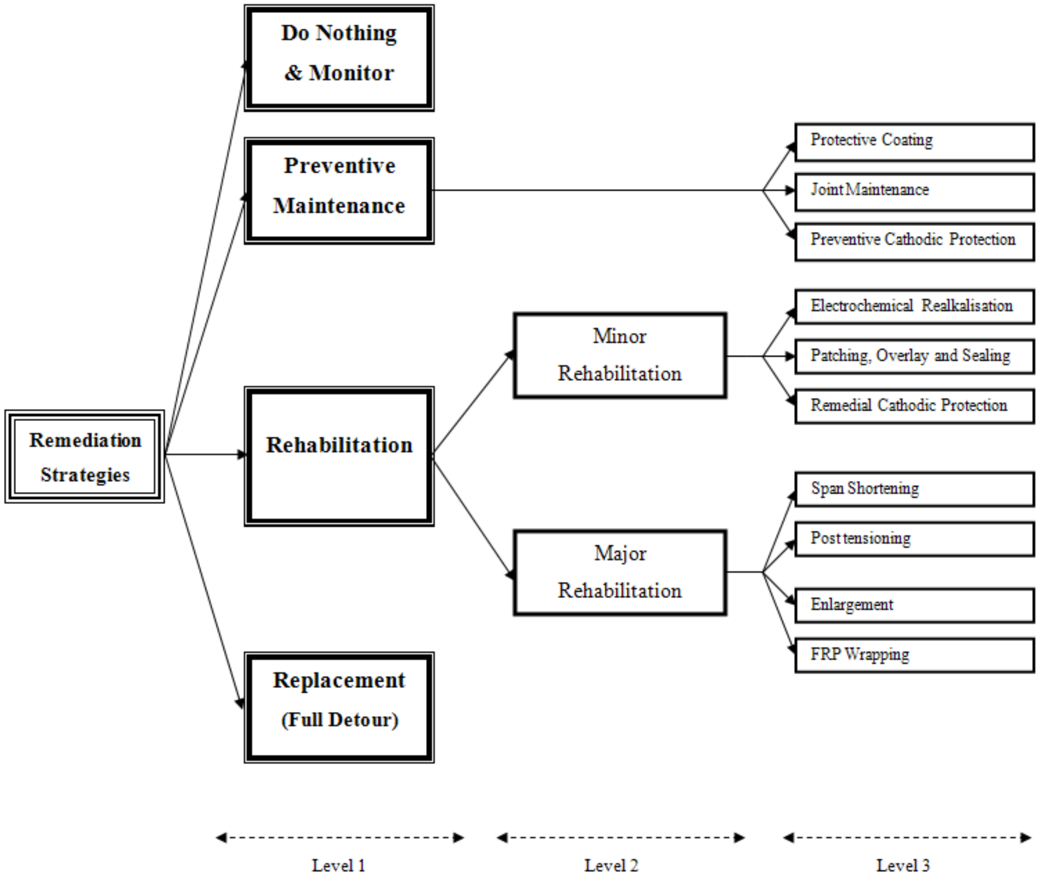


Figure 4.3 Decision Tree: All the possible courses of actions for bridge remediation

"Preventive and routine maintenance" represents the work required to be done to preserve the intended load carrying capacity of the bridge. It can be conducted as a supportive action for all the rehabilitation alternatives. Without suitable maintenance, bridges will deteriorate prematurely during their service life. Material damage and defects often accelerate this deterioration.

"*Rehabilitation*" refers to the maintenance work of greater "Scope" and "Cost" than simple routine maintenance (Raina, 2005). It can be selected as a long-term solution (Upgrade/Strengthening) or as a temporary fix (Repair) for structures suffering from structural deficiency, poor serviceability performance or aesthetic problems. Repair aims at rehabilitating the bridge to the service level it originally had or was intended to have while strengthening refers to improving the existing load carrying capacity of the bridge to the value it originally had or was planned to have (Raina, 2005).

“Replacement” is a course of action refers to reconstruction of the whole bridge or of its major elements taken for serious conditions in which the cost and/or the extent of repair or strengthening may be beyond the acceptable thresholds. In this case a full detour might be provided. Extending the service life of an existing bridge at an adequate level of service often has a preference over replacement because bridge closure for construction of a new bridge has significant impact upon regional traffic and consequently may affect the efficiency of the network that bridge belongs to. In addition it requires considerable capital, and usually causes political issues to be more determining.

4.4.5 Risk Assessment (II): Dominant Constraint

The selection of remediation options usually requires a case-by-case assessment, to ascertain the potential risks or benefits related to any given course of action. Practically, cost has always been the most significant factor in determining the most suitable remedial measures, but nowadays there is a welcome move towards the involvement of life-cycle costing instead of focusing on just the initial cost (Ryall, 2001). This notion can be extended to cover new policies and legislations to ensure bridges are maintained with historic preservation, and environmentally considerate methods at the front position.

Risks and their associated constraints with considerable impact on the selection process have been complied and reviewed by Rashidi and Lemass (2011b). Safety, functionality, sustainability, environment and legal/political constraints have been identified as the main categories of common client objectives for bridge remediation.

-Safety is related to the structural safety of the bridge elements under traffic and environmental loads which is highly related to design and material properties;

-Functionality is associated with the traffic characteristics and pertains to the parameters such as load bearing capacity, vertical clearance and deck width. It also covers items related to durability such as drainage system or deck waterproofing;

-Sustainability is related to the most economic solution taking to account the safety conditions;

-Environment is mainly associated with a set of procedures in order to analyse aspects such as protection against pollutions, soil excavation and so forth;

-Legal/political, includes any changes in standards and regulation or any probable political pressure toward a specific decision.

It is important to note that the proposed list is by no means inclusive, with other project specific criteria recognised during the remediation process. However, for the intention of system development, a generic list of dominant constraints will be used. The available options will also be compared, for the development of concept compliance ratings in Chapter 6.

4.4.6 Decision Analysis Tool

Deciding on the priorities for carrying out the remediation of bridges is the most challenging task in BMSs. The cost of MR&R consumes most of the accessible funding for bridge improvements. As a result, the budget for these activities should be carefully allocated. Setting priorities for MR&R activities is a multiple criteria decision making problem which requires simultaneous assessment at both the network level (i.e., which bridge to repair), and the project level (i.e., which repair alternative for a given bridge) (Elbehairy et al., 2006b).

Multiple criteria decision making is a complex procedure that involves expert judgment and knowledge to rank and prioritise all the possible alternatives. Decision analysis methods are procedures that employ data, information and experience to facilitate the decision-making process in a systematic approach (Dabous et al., 2008). As discussed in Chapter 3, several decision-making tools have been developed in a variety of purposes. Some of them are simple qualitative procedures for assessing the advantages and disadvantages of each alternative and ranking them accordingly. Other methods are quantitative procedures to utilise data and experience to rank a group of choices.

The decision making in this research is based on the modified Simple Multi Attribute Rating Technique (SMART) in which the eigenvector method of the analytical hierarchy process (AHP) is used for criteria weighting. It is a useful tool for evaluating remediation strategies using multiple criteria while incorporating expert judgment. The advantages of the selected approach is that the implicated judgments are made explicitly, the value information can be used in many ways to help simplify a decision process, and a decision maker typically learns a great deal through these joint efforts to construct their views on their priorities.

4.4.7 Remediation Plan

Selection of an optimal remediation plan is one of the main objectives of any BMS which can be conducted at both project level and network level. The project level decisions which focus on remediation strategy selection of individual bridges is based on the assumption that enough fund is available for any MR&R strategy. Real decisions, in practice involve the network level criteria considering the fact that the budget is limited.

As discussed earlier, the proposed methodology specifies which bridge has the highest priority and what action should be taken for that bridge (assuming that enough fund is available). In order to optimise decisions and maximise benefits to the agencies and the users, the budget allocation process need to be expanded to the network level using a viable structured approach.

A methodology is developed based on analysing the various combinations of MR&R alternatives for top ranked bridge projects. Simulation is a very useful tool to perform a large number of scenarios, and develop all the possible combinations between projects and MR&R strategies. Each combination is a possible remediation plan and the total cost of any combination must not exceed the available budget.

Firstly bridge projects will be ranked according to the overall priority index addressing their structural and functional efficiency, considering the client impact factor. Projects are included in the budget allocation program based on the priority assigned for each one from the suggested method. The project with the highest priority will be included first, followed by the bridge with the second highest priority, and so on.

Through the method which is conducted for strategy selection a score is allocated (indicating the relative importance based on the degree that each strategy satisfies certain criteria defined by the decision maker) for each action. The simulation uses these scores to compare the different nominee combinations. For instance, if the score for maintenance is 25, the score for repair is 40 and the score for reconstruction/replacement is 35 and the assigned budget is enough to cover only two of these alternatives on two different bridges, the best selection is to perform a repair on one project and a replacement for the other (because it will include the maximum sum of scores of 75). If a program suggests maintenance for one bridge and replacement for the other, it will produce a sum of scores of 60 that is less than 75. Therefore, the program recommends replacing one and repairing one as the maximum sum of scores indicates the maximum benefits. An illustrative example will be presented in chapter 6 showing the credibility of the proposed model.

4.5 Summary

A decision support model for remediation planning of bridges has been achieved through an extensive literature review and expert judgment derived during case studies and interviews with bridge engineers and asset managers. The framework includes two main phases: 1) Priority ranking of bridges using Priority Index (PI), considering the Structural Efficiency (SE), Functional Efficiency (FE) and Client Impact Factor (CIF). 2) Selecting the best MR&R (Maintenance, Repair and Replacement) remediation strategy with the aim of improving the bridge condition at both project and network level or at least keeping the condition in a steady state. Possible remediation alternatives are ranked through the modified Simple Multi Attribute Rating Techniques (SMART) in which the decision criteria should be drawn from the secondary risk analysis process. Simplicity and flexibility are the main attributes of this modeling approach which distinguishes it from other decision analysis tools.

Interviews with thirty experts have been conducted to determine information requirements, decision points, dominant constraints and other relevant information considering the limitation of subjectivity and inability of users to verbalise their practice. Classifications and information presented in the following chapters have been supported by the literature review and data collected through semi-structured interview with the potential decision makers.

Real case studies are used to validate the proposed decision support model. Through the analysis of the case studies, the validity of decisions regarding selecting a solution for bridge improvement can be examined. Successful validation enables the decision makers to rely on the proposed model. It can also support the applicability of the model for other civil infrastructures.

5 CONDITION ASSESSMENT AND RANKING OF BRIDGES

5.1 Introduction

As discussed in previous chapters, deficiencies related to aging bridges have become a major concern for asset managers and society globally and particularly in Australia. Due to the substantial role of bridges in transportation networks and in accordance with the limited funding for bridge management, remediation strategies have to be prioritised.

Bridge condition assessment is the evaluation of the differences between the as-designed, as-built, and as-is states of the structures. The subject can be a bridge component, a group of similar elements within a span, or in all spans, components, and eventually the entire bridge. The outcome determines the sufficiency of monitoring and maintenance and the effects of traffic and the environment and defining the present and future needs (Yanev, 2007).

A conservative bridge evaluation will result in unnecessary action, such as, costly bridge rehabilitation or even replacement. On the other hand, any negligence or delayed actions in bridge maintenance may lead to heavy future costs or degraded assets (Rashidi and Lemass, 2011a). The accuracy of decisions developed by any manager or bridge engineer relies on the accuracy of the bridge condition assessment which emanates from visual inspection. It is indeed a fundamental step for providing the appropriate inputs for any bridge management system and the reliability of decisions to find remediation strategy or fund allocation is highly dependent upon the exactness of the diagnosis process. Most of bridge rating systems are based on a very subjective procedure and are associated with uncertainty and personal bias. Many bridge agencies commonly use only structural condition. Parameters such as functionality and client impact may not be specifically addressed in the existing practices. The developing condition rating method described in this chapter is an important step in adding more holism and objectivity to the current approaches.

To achieve this goal, all the important parameters have been identified, weighted and finally synthesised in an index introduced as Priority Index (PI). Weights were initially set based on experience and then adjusted by a trial-and-error method. Although quantification of the findings is repeatedly emphasised but involving the subjective judgments, in some area, seems to be inevitable.

5.2 Bridge Inspection

Bridge inspection is an essential element of BMS (particularly for aged and deteriorated bridges) and a path to condition rating. The accuracy of condition assessment is highly reliant on the quality of the inspection. Historically, the inspection of existing bridges has been assumed as a secondary priority of a semi-random nature. The inspections were usually done as a consequence of warnings received from sources very often outside the bridge network system; or as a result of an obvious inadequacy of the bridge that did not allow it to fulfill the expected function (Branco and de Brito, 2004).

An international literature search on inspection type/frequency aspect of bridge maintenance has not revealed any well established method. Current bridge inspection methodologies have limitations generally empirical and mostly based on field experience and engineering assessments.

The inspection methods in Australia have followed that of the American Association of State Highway and Transportation Officials (AASHTO) there were then modified by the road authorities. However, many bridge agencies use their own strategies for inspection and condition rating nevertheless the element based inspection is regarded as the most reliable technique for condition assessment and possible treatment/maintenance cost estimation.

5.3 General Knowledge Based Inspection System

An inspection system is often organised at the bridge network level instead of at the single bridge level to reduce fixed costs and enhance efficiency. The functionality of the management system is based on the standardised inspection plan. It includes a periodic set of inspections based on a fixed timetable, in which some flexibility is allowed to take into account a reasonable global allocation of inspection resources, complemented by special inspections when something serious is detected or suspected. The quality of the inspection is strongly related to the knowledge and experience of the inspectors and their compliance with prescribed procedures.

The main focus of bridge management is at the network level, based on statistical parameters (eg element condition state, bridge vertical clearance, etc) rather than physical parameters (eg, coating thickness for steel, crack width in concrete, , etc). However, these statistical parameters are derived from detailed information from observations or technical information (Rashidi and Gibson, 2011).

An inspection report is completed for every bridge inspection performed. This report is crucial as it provides specific details about the inspection and about the bridge itself. Standard report forms have been developed for most inspection types. These forms provide a mean for recording standard information relevant to all bridges and special information unique to a particular bridge. Photographs, sketches, and detailed measurements should be included to quantify any problem areas found. A detailed sketch of the whole bridge may be needed in order to allocate numbers and identify particular bridge elements (Little, 1990). A variety of inspections may be required on a bridge during its service life. The main types of inspection are addressed in the following sections:

5.3.1 Initial (inventory) Inspection

Initial inspections are performed on new bridges or when existing bridges are first entered into the database. This inspection provides a basis for all future bridge inspections or their modification. Inventory inspection provides structure inventory and appraisal data along with bridge element information and baseline structural condition. Inventory inspections usually start in the office with the construction plans and route information then proceed to the field for verification of the as-built conditions. Initial defects are noted which might not have been present at the time of construction. Changes in the condition of the site, such as erosion, scour and re-grading of slopes are also considered (Rashidi and Gibson, 2011).

5.3.2 Routine Inspection

The routine inspection is a diagnostic method with the greatest potential, generally based on direct visual observation of the most exposed areas and relies profoundly on subjective evaluations made by the bridge inspectors. No significant structural defect is expected during an inspection, and the work recommended falls within the range of maintenance.

A period of 12-15 months between routine inspections is usually recommended so that the influence of the weather on the general condition and degradation of the bridge can be assessed. A routine inspection must be planned in advance to facilitate the best assured conditions (e.g. weather conditions, traffic) that may permit detection of defects (Branco and de Brito, 2004).

5.3.3 Detailed Inspection

Easy and fast nondestructive in situ tests are performed in detailed inspection in addition to direct visual observation as a way of exploring every detail that may potentially lead to future problems. There is a possibility that special means of access may be used if such is considered indispensable. The period recommended for a detailed inspection is 5 years and replaces a routine inspection if their calendars agree. A preliminary visit to the bridge site may be useful to evaluate existing conditions. If there is a need to follow up the evolution of certain defects with greater frequency, however, the period between visits may be reduced to 1 year, especially for local areas of the bridge (Watson and Everett, 2011).

Planning a detailed inspection includes a careful study of the bridge dossier to identify the reasons and evolution of the defects detected in the previous inspections and the specific points to be assessed closely. Based on previous inspection forms and a preliminary visit to the site, the eventual special means of needed access are planned. The following files must be brought to the site and/or prepared beforehand: a list of all single points to be checked, schematics with reference grids of the most relevant elements, and the last periodic inspection forms and the inspection manual (Rashidi and Gibson, 2011).

According to the outcomes obtained, the inspection may possibly have one of the following consequences: the organisation of a structural assessment or of complementary surveillance measurements; the preparation of a list with particular aspects to follow especially carefully in the next inspection; the organisation of maintenance work needed; and the establishment of a medium-term maintenance plan.

5.3.4 Structural Assessment

A structural assessment is normally the consequence of the detection of a major structural or functional deficiency during a routine or detailed inspection. It may also be necessary if widening the deck or strengthening the structure is under consideration. The expected results from this inspection are: the characterisation of the structural shortcomings, the remaining service life estimation by using degradation mathematical models, and also evaluating of its current load-bearing capacity. It is not easy to predict the required means because a wide range of situations can initiate a structural assessment.

The static and dynamic load tests and also laboratory tests can be valuable complements to the information collected in situ. Nevertheless, they must be used with some parsimony since, as well as being expensive, they force the total interruption of traffic over the bridge for uncertain periods of time (Branco and de Brito, 2004).

5.3.5 Special Inspection

This could be undertaken to cover special conditions such as occurrences of earthquakes, unusual floods, passage of high intensity loading, etc. These inspections should be supplemented by testing as well as structural analysis. For that reason the inspection team should include an experienced bridge design engineer (Raina, 2005).

An underwater inspection is also a special inspection performed on bridges with structural elements partially located under water that are not easily accessible for inspection, and generally the inspection interval should not exceed sixty months. Inspections are undertaken by experienced divers to assess the material condition specific material type taking under water photographs/videos as necessary.

5.4 Development of a Unified Bridge Condition Rating

As discussed in Chapter 2, there are various methodologies for condition assessment of bridges which are mostly based on the structural aspects. To address the multi-objective nature of the work, all the observations and facts obtained from the inspection can be integrated in an index indicating the overall efficiency of the structure in terms of safety and serviceability issues. This index is finally used for priority ranking of bridges in the network. In this research a requirement–driven framework for developing an integrated bridge condition index, as a support for risk assessment and prioritisation is proposed. The proposed model comprises three important parameters including structural efficiency, functional efficiency and client impact factor which are explained in the following sections.

5.5 Structural Efficiency Assessment

Bridges are a complex mixture of parallel and series systems, but almost all BMS use the evaluation of members or elements as input to calculate the overall structural reliability (Yanev, 2007).

With the purpose of being consistent within the current bridge inspection practices in Australia the recommended methodology is based on four condition states defined in the Roads and Maritime Services (RMS) of New South (formerly Road and Traffic Authority) in which the bridge element condition ranges from 1 to 4 in rising order. The general description of the four condition states for reinforced concrete bridge elements is presented in Table 5.1 below.

In this system the bridge is divided into elements generally made of a similar material (most bridges have about ten to twelve elements and bridge sized culverts usually have three to five elements). The inspector estimates and records the quantities of the bridge element in each condition state independently. The total quantity must be measured in the correct units for the elements. The units of measurement are square meters (deck, pier, and pile), meters (joints and railings) or each (bearing pad, waterway, etc).

Table 5.1 Condition States for Concrete Bridge Elements (RTA, 2007)

Condition State	**Description of defects**
1	The element shows no deterioration. There may be discolouration, efflorescence and/or superficial cracking but without effect on strength and/ or serviceability.
2	Minor cracks and spalls may be present but there is no evidence of corrosion of non-prestressed reinforcement or deterioration of the prestressed system.
3	Some delaminations and/or spalls may be present. No evidence of deterioration of the prestress system. Corrosion of non-prestressed reinforcement may be present but loss of section is minor and does not significantly affect the strength and/or serviceability of either the element or the bridge.
4	Delaminations, spalls and corrosion of non-prestressed reinforcement are prevalent. There may also be exposure and deterioration of the prestress system (manifested by loss of bond, broken strands or wire, failed anchorages, etc). There is sufficient concern to warrant an analysis to ascertain the impact on the strength and/or serviceability of either the element or the bridge.

The following example shows the bridge element condition concept. The data used in this example has been extracted from a bridge inspection report provided by the RMS for a concrete bridge in the Illawarra NSW region. The condition inspection result of the pile element with a total area of 695 m^2 are presented in Table 5.2.

Table 5.2 Bridge Pile Condition Rating Results

Condition Rate	Area (m^2)
1	618
2	3
3	74
4	0

The overall condition of piles = [(618×1) + (3×2) + (74×3) + (0×4)] / [695×1] =1.22

As shown above, the element condition index can be calculated as the current value divided by the initial value of the bridge element. Quantities can also be used for the cost estimation of required maintenance works. To describe the overall condition status of structural elements, the Element Structural Condition Index (ESCI) is introduced as:

$$\text{ESCI}=\frac{\sum(qi\times ci)}{\sum qi} \qquad \text{(Equation 5.1)}$$

- qi is the quantity of elements reported in condition index ci

- ci is the condition of sub-element i $ci \in (1,2,3,4)$

As shown in the ESCI estimation process, deterministic values are used as an approximation for the element value at each of the four condition states. This approximation may not be quite reliable, since data collected through the inspection process is usually associated with subjectivity and uncertainty (Rashidi and Gibson, 2012). Many attempts have been made to reduce the uncertainty. For example Colorado Department of Transportation (1995) suggested a frame work for condition rating of deck cracking which is shown in Table 5.3.

Table 5.3 Conditions Rating of Deck Cracking (Colorado, 1995; Abu Dabous and Alkass, 2010)

Crack Width (mm)	Spacing of Cracks in Concrete Deck (m)			
	> 3	**2-3**	**1-2**	**<1**
<1	1	1	2	3
1-2	1	2	3	4
2-3	2	3	4	4
>3	3	4	4	4

This study also attempts to identify subjective issues and reduce the associated uncertainty. According to Rashidi and Gibson (2011), some elements require more attention than the others in terms of *material vulnerability* and/or *structural significance*. For example reinforced concrete has more potential for damage than steel. A defective main beam will require more urgent attention than the bridge drainage outlets. One crack can be a flexural crack flagging a primary structural failure while the other may be the result of creep and shrinkage of concrete, which has limited structural importance. However the determination of structural/material vulnerability of various bridge elements is a difficult task. Sometimes conducting structural analysis such as a non-destructive testing program is unavoidable. Alternatively, bridge experts and inspectors can rely on their own experience and knowledge to determine these factors.

5.5.1 Structural Significance Factor

Generally, the prevailing condition (rating) of the particular element may cause some inaccuracies in the overall structural assessment. For example, a minor component with worse condition may unreasonably raise the rating value of element under which the component is grouped. This problem can be resolved with the introduction of an element structural significance factor which is not dependent on the prevailing condition of components (Sasmal and Ramanjaneyulu, 2008).

The evaluation incorporates many parameters and human judgments that may cause the procedure to be slightly uncertain and imprecise. Tee et al. (1988), Melhem and Aturaliya (1996), Sasmal and Ramanjaneyulu (2008) and Abu Dabous and Alkass (2010) tried to employ a systematic approach to quantify the structural importance of various bridge elements. Tee et al. (1988) defined the structural significance as the role of an element in comparison to the other components and quantified this factor for different elements at different condition rating based on the survey results responded by 46 inspectors and bridge experts. Abu Dabous and Alkass (2010) described the structural importance of a bridge component as the level the component contributes to the overall structural safety and integrity of the bridge and proposed the Analytical Hierarchy Process (AHP) to estimate the value of this parameter.

In this research the Element Structural Significance has been investigated through conducting semi-structured field interviews with bridge engineers/inspectors. The outcome of the processed expert judgments considering the results of previous research is summarised in Table 5.4. The higher numbers represent the superior importance of structurally critical members which have a great impact on the strength and safety of the structure and where failure of the member could lead to catastrophic collapse.

Table 5.4 Structural Significance Factor S_i

Element	Structural Significance Factor, S_i
Barrier, Footway, Kerbs, Joints	1
Foundation, Abutment, Wingwall	2
Deck, Bearings	3
Beams, Headstocks, Piers	4

5.5.2 Material Vulnerability Factor

Different materials have different contributions to the structural efficiency of a bridge. For example reinforced concrete is more vulnerable than steel and the structural vulnerability of precast concrete is more than reinforced concrete. Therefore material factor should be considered in the structural assessment of bridge elements. Table 5.5 presents the vulnerability factor of common materials used in concrete bridges introduced as m_i which is obtained from the work of Valenzuela et al. (2010) and validated by the judgements of structural engineers. Based on vulnerability of different materials it varies between 1 and 4 (Rashidi and Gibson, 2011).

Table 5.5 Material Vulnerability Factor M_i

Material of the element	Material Vulnerability Factor, M_i
Steel	1
Reinforced Concrete	2
Precast concrete	3
Pre stressed concrete	4

5.5.3 Causal Factors (CF)

Bridge elements deteriorate over an extended period of time and the rate of deterioration is a function of various parameters. Apart from some pre-existing factors such as design and construction, there are several post existing causes involved in the structural efficiency of bridges. These include the environment where the structure is located in, the length of time the structure has been in service (Age), the function the structure is required to perform (Road Class) and the quality of inspection and monitoring (See Figure 5.1).

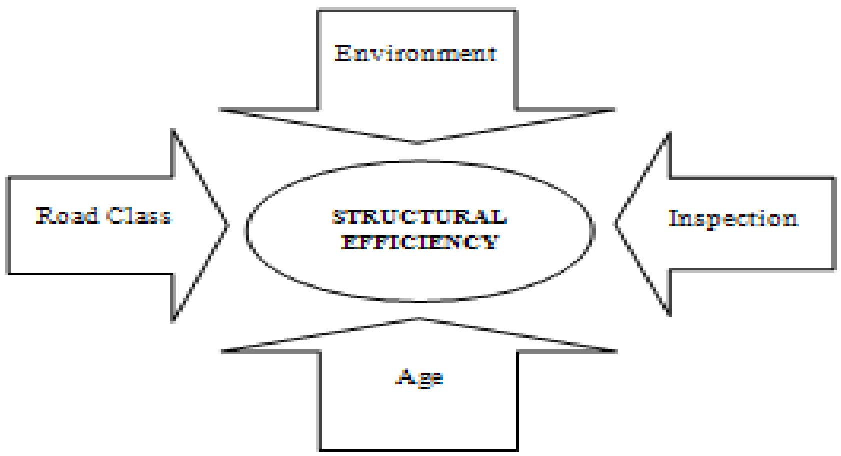


Figure 5.1 Causal Factor CF

5.5.3.1 Environmental Change Factors:

The environmental change factor includes natural/man caused environmental actions that cause chemical and physical deterioration of concrete. The degradation mechanisms are usually related to the interaction between the environment and the materials and controlling this interaction is the basis of durability design. The interactions with the environment are usually associated with:

climatic conditions: temperature, solar radiation, moisture, rain, ice, etc;

air and soil aggressive causes: air pollution, contact with sulphates, chlorides, etc;

chemical reactions within concrete: alkali-silica or sulphate reactions;

human actions: de-icing salts on roads, abrasion from traffic, fire, etc.

The most important degradation mechanisms in concrete structures occurs in the carbonation of concrete, chemically aggressive salts, freeze/thaw cycles and a chloride attack in a saline environment (Raina, 2005).

The initiation and rate of concrete deterioration may also be influenced by the presence of early-age defects, which originated at the time of construction, or in the very early stages of the structure's life. These defects accelerate deterioration by facilitating penetration of the concrete surface by the atmosphere and other environmental agents, which partake in the chemical and physical processes that cause damage (Raina, 2005; Buckley and Rashidi, 2013).

5.5.3.2 Age:

As bridges are designed to withstand fatigue loading (which increases with time), age is an important parameter involved in the structural condition assessment. The life expectancy of current bridges is about 50 years and for major concrete bridges around 100 years. In fact, for the structural safety of the bridge, the designers have the reference code actions, usually defined for a period of 50 years. They need to adopt durability measures for 100 years, but the code indications are usually referred to as 50 years. They need to consider that bridge bearings and other equipments capable of lasting at most 25 years. When service life is raised beyond the current 50 years, the study of major bridges requires that safety be reconsidered to integrate coherence into the design (Branco and de Brito, 2004; Rashidi and Gibson, 2012). The service life of a bridge may be brought to an end when one of the key components fails to function as designed.

The year of construction can be used as stratification criteria. Any groups of structures can be classified according to their years of construction. There are 4 main intervals defined by the RMS to provide a good separation of the information in the first attempt to understand a group of structures. The proposed time intervals by RMS are (Ariyaratne et al., 2009):

1836-1948

1948-1976

1976-2001

2001-2009

Rashidi and Gibson (2012) have defined 4 categories of age as follows and a score (1-4) is assigned for each interval (See Table 5.6):

Recently built (0-25 yrs)

New (25-50 yrs)

Old (50-75 yrs)

Very Old (75-100 yrs)

5.5.3.3 Inspection Factor:

Human related factors are also important aspects in the modelling. As known information required for condition rating are given by bridge inspectors, and consequently uncertainties and fuzziness of the inspection data would cause inaccuracies in the diagnosis of structural or functional defects (Wang et al., 2007; Wang and Foliente, 2008). There is strong evidence to prove that the condition index estimated from the inspection rating data is influenced by the judgement of individual inspectors. Some of the probable errors in the inspection process are as follows (Yanev, 2007):

Inadequacy of equipments

Exaggeration of some defects (loss of steel cross section to corrosion is usually overstated)

The inability to recognise structurally significant features, such as support condition, bridge skew, fracture-critical members, and fatigue-sensitive details.

Fear of traffic

Lack of proper inspection training

Inappropriate forms/check lists

Accessibility and visibility

Time constraints

Wind, rain and snow

The required frequency and quality of inspections must be evaluated by the asset managers and bridge engineers in order to achieve the optimum structural reliability. Four categories of inspection quality have been simply introduced by some linguistic terms as very high, high, medium and low.

5.5.3.4 Road Type Factor:

The bridge structures can be classified according to the road they are located on. There are two categories of classifications on which the bridge is built; (1) Road Number and (2) Road Type. Using the Road Number, all the bridges in that class (number) belong to that road, although a road carries a traffic characteristic that can be sought in the case of a class using the Road Number (Ariyaratne et al., 2009). The second road classification factor is the Road Type. This factor is involved based on usage and importance of the bridge to the network addressing the road type of the bridge including street, road, freeway (FWY) or highway (HWY), bridge environment such as rural or urban, and the feature crossed such as road, waterway and railway (Wang and Foliente, 2008).

In this study four categories of roads have been introduced based on the Annual Average Daily Traffic (AADT) as below and a score (1-4) has been allocated for each interval (See Table 5.6).

Minor (AADT≤150)

Local Access (150<AADT≤1000)

Collectors (1000<AADT≤3000)

Arterials (AADT>3000)

5.5.4 Rating and Priority Vector of the Causal Factors

As previously discussed, all the above mentioned factors have been classified based on some definitions and rated from 1 to 4 where the higher numbers are associated with the higher severity.

Table 5.6 Rating of the Causal Factors

Rating	Causal Factors			
	Age	Road Class	Aggressive Factor	Inspection Quality
1	Recently built	Minor	Low	Very High
2	New	Local access	Medium	High
3	Old	Collectors	High	Medium
4	Very old	Arterials	Very High	Low

Table 5.6 presents the rating of each individual factor based on the proposed classification and inspection reports.

For the purpose of finding the weight of the contributing factors, Analytical Hierarchy Process (AHP) developed by Saaty (1977) has been chosen. The detailed methodology of AHP has been described in Chapter 3 (See section 3.7.2).

Bridge experts engaged in this research project, have been asked to compare the involved parameters in pair and specify the quantity of the relative importance according to Table 5.7 below.

Table 5.7 Nine Scales of Relative Importance (Saaty, 1977)

Importance Intensity	Explanation
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Absolute importance of one over another
2,4,6,8	Intermediate values between the two judgments
Reciprocals	Reciprocal for inverse comparison

The results of pairwise comparison are entered in a reciprocal comparison matrix as shown in Table 5.8. The importance level of the causal factors is developed as a vector of priorities which is a normalised eigenvector estimated by dividing each element by the sum of that column and computing the average of each row that shows the priority weight of the corresponding element.

Table 5.8 Pairwise Comparison of the Causal Factors and the Final Weights

	Age	Environment	Road Class	Inspection	*Weights*
Age	1	3	5	1	*0.411*
Environment	1/3	1	1	1/3	*0.120*
Road Class	1/5	1	1	1/3	*0.107*
Inspection	1	3	3	1	*0.362*

As shown in the table, age and inspection achieved the highest weight. Environment and road class obtained the third and fourth priority respectively. This rating might not be generalised for all the situations as some post design changes can affect the conditions. Considering this fact the proposed model has been designed with optimum level of flexibility, so the decision makers can apply their own priorities.

Now the causal factor can be calculated using the ratings of the causal parameters (introduced in Table 5.6) and their associated weights (estimated via AHP) as shown in the following equation (Rashidi and Gibson, 2011):

$$CF = 0.411\boldsymbol{A} + 0.120\boldsymbol{E} + 0.107\boldsymbol{R} + 0.362\boldsymbol{I} \qquad \text{(Equation 5.2)}$$

-***A*** is the age factor

-***E*** is the environmental factor

-***R*** is the road type factor

-***I*** is the inspection factor

5.5.5 Structural Efficiency

The overall Structural Efficiency index (SE) integrates all of the abovementioned parameters that influence structural effectiveness and is estimated as follows (Rashidi and Gibson, 2012):

$$SE = \frac{CF \sum(Mi \times Si \times ESCI\, i)}{16n} \qquad \text{(Equation 5.3)}$$

-CF is the causal factor

-Mi is the material vulnerability factor

-Si is the structural importance factor

-ESCIi is the Element Structural Condition Index

-n is the number of element types

SE is a dimensionless factor indicating the relative judgement and its range is a numerical value that varies from 1 to 4. The priority for remedial action increases as the number increases.

5.6 Functional Efficiency Assessment

The modern BMS considers the quality of service (functional efficiency) in addition to structural efficiency. Yanev (2007) stated that “the functional life of bridges is less than the structural life,” e.g., 25 to 50 years (in high traffic growth), compared to 50 to 100 years (excepting disasters). According to Rashidi and Lemass (2011a), the bridge functional efficiency is dependent on the traffic volume that it can withstand, which is mainly related to the load bearing capacity of the bridge, existing number of lanes or the width of the deck, vertical clearance and the barriers. The drainage system, provisions for pedestrians and cyclists and any post design changes should also be carefully considered in the assessment process.

Any deficiency associated with the above items can reduce the level of service and accelerate the deterioration process. For this reason, it is advantageous to consider the elimination of these deficiencies within the decision making process. Five main deficiencies that can seriously affect bridge safety and serviceability are chosen to be included in the framework of the developed assessment method: Load bearing capacity, vertical clearance, width, barriers and the drainage system which are described in the following sections.

5.6.1 Load Bearing Capacity

For bridge sufficiency rating, it is required to consider the actual loading on the bridge and its components. The load factor to be used for any component of loading shall be defined on the basis of the uncertainty associated with its nominal magnitude, allowing for the degree to which it has been the subject of direct measurement. Austroads has adopted the load rating procedures in Section 3 in the Australian Bridge Design Standard AS 5100.7. The procedure rates the live load capacity of a bridge compared to one of three nominated rating vehicle arrangements. Bridges with live load capacity less than the legal requirement are subjected to special considerations for safety concerns.

According to the Australian Bridge Design Code (5100.7, 2004) inspections of the loadings on the bridge should consider:

Whether there is any increase in the dead load or superimposed loads, for instance altered deck materials and thickness, increased pavement thickness, increased depth of ballast, Whether there has been any change in the weight or other applied loadings due to increased service provisions,

Whether the loading is applied as anticipated in the design, or whether eccentricities have been defined,

Whether loadings are being applied as anticipated to individual elements or to details, nothing such things as unequal loading in pairs of members, crooked and bent members, damaged and cracked members, worn pins, loose rivets, etc

Whether any components are subject to problems in regard to vibration or wind loading,

The efficiency of the bearings to permit movement and articulation as intended, including a check to ensure that movements are not impeded by the buildup of material etc., and

Whether there has been any foundation movement or any change to the ground conditions which has influenced the loadings in the bridge.

In this study, load bearing capacity factor (Lc) is introduced as the proportion of actual live load capacity to initial designed capacity. If the Lc equals 1 then the structure can bear exactly the required load and if it is less than one the structure is substandard. The Lc greater than 1 represents a more reliable bridge in terms of the live load bearing capacity.

5.6.2 Bridge Vertical Clearance

The vertical clearance is the height above and below the bridge deck. This can be a critical safety factor as vehicles or trains passing under or on the bridge must have sufficient vertical clearance to pass safely. Each bridge/road agency independently specifies a target vertical clearance, based on the local circumstances and the defined strategy for the route (Austroads, 2004). The minimum vertical clearance at structures over roadways and railways and also pedestrian bridges can be referred to the Australian Standard for bridge design (AS 5100.1), unless otherwise specified or agreed by the authorities. The bridge attribute that can be used to evaluate this item is the percentage of difference between the existing vertical clearance and the mandatory one. This can be calculated using the following equation:

$$Vc = \left|\frac{\mathrm{Ht} - \mathrm{H}}{\mathrm{H}}\right| * 100 \qquad \text{(Equation 5.4)}$$

Where H is the bridge vertical clearance and Ht is the target vertical clearance.

5.6.3 Bridge Width

Each bridge agency independently specifies target trafficable carriageway width, based on the road agency's general strategy for the route and local conditions taking into account the route's geometry, traffic volumes and composition, climatic conditions and the bridge locality (Austroads, 2004).

This factor can be defined as the percentage of difference between the existing width and the target trafficable carriageway width (mandatory one) of the bridge:

$$Wb = \left|\frac{\mathrm{Wt} - \mathrm{W}}{\mathrm{W}}\right| * 100 \qquad \text{(Equation 5.5)}$$

Where W is the bridge width and Wt is the target width.

5.6.4 Bridge Barrier

A bridge barrier is a longitudinal structure installed to prevent a wayward vehicle from running off the edge of a bridge or culvert. While this is similar to the function of a roadside barrier, a bridge barrier is generally designed to have nearly no deflection upon impact. They are generally constructed from metal posts or railings, concrete safety shape or a combination of both. According to the Australian Standard for bridge design (AS 5100.1), the performance level and barrier type constraints for each bridge or relevant site should be determined by the relevant authority.

Sufficiency indicator for this factor is suggested to be the percentage of the bridge barrier systems not conforming to the defined target level:

$$Bb = \left|\frac{\mathrm{Bt} - \mathrm{B}}{\mathrm{B}}\right| * 100 \qquad \text{(Equation 5.6)}$$

Where B is the bridge barrier's length and Bt is the barrier's length satisfying the defined target.

5.6.5 Bridge Drainage System

One of the most important bridge deficiencies is related to the reduced performance of the drainage system. The drainage system might not be adequate to drain the accumulated water. It is necessary to evaluate the performance of the drainage system during an inspection. Poor drainage will accelerate corrosion of the reinforcement and deterioration process; therefore, it can directly affect the safety of the passengers and the durability of the bridge. Based on the inspectors' assessment, one of four linguistic condition states (Poor, Fair, Good or Excellent) representing the bridge efficiency level can be assigned.

5.6.6 Functional Efficiency Index

The contributing parameters in bridge functional efficiency and their associated condition states are summarised in Table 5.9 below. As a result of expert judgements Lc less than 70% and Vc, Wb and Bb over 20% are assumed as critically substandard.

Table 5.9 Rating of the Functionality Factors

	1	2	3	4
Load Bearing Capacity (Lc)	$Lc \geq 1$	$0.9 \leq Lc < 1.0$	$0.7 \leq Lc < 0.9$	$Lc < 0.7$
Vertical Clearance (Vc)	$Vc \leq 5$	$5 < Vc \leq 12$	$12 < Vc \leq 20$	$Vc > 20$
Width (Wb)	$W \leq 5$	$5 < W \leq 12$	$12 < W \leq 20$	$W > 20$
Bridge Barrier (Bb)	$Bb \leq 5$	$5 < Bb \leq 12$	$12 < Bb \leq 20$	$Bb > 20$
Drainage System (Ds)	Excellent	Good	Fair	Poor

Rating of the drainage system (Ds) is expressed by some linguistic terms and can be specified by the inspector/bridge engineer.

To evaluate the overall functional efficiency all these elements should be weighted. Again the potential decision makers' judgment regarding the relative importance of the various factors has been used. The result is as follows:

Table 5.10 Importance Weighting of Each Functionality Factor

Lc	Vc	Wb	Bb	Ds
70%	10%	10%	5%	5%

Load bearing capacity which assures safety and serviceability of the structure has got the highest weight (70%). The overall functional efficiency factor (a dimensionless parameter) can be calculated using the ratings and the weights:

$$FE = 0.7Lc + 0.1Vc + 0.1Wb + 0.05Bb + 0.05Ds \qquad \text{(Equation 5.7)}$$

- Lc is the load bearing capacity
- Vc is the vertical clearance
- Wb is the width
- Bb is the barrier
- Ds is the drainage System

The range is a numerical value that varies from 1 to 4. The priority for remedial actions increases as the number increases.

5.7 Client Impact Factor

The nature of a bridge site and the extent of the bridge remediation treatment may cause decision makers to close bridge lanes or create alternative routes or bypasses to control the traffic flow. Excessive traffic delay times often result in negative feedback from both the road users and their political representatives. This factor helps build the social implications of remediation into the risk assessment process. It is a vast improvement on the 'do nothing' course of action. On the other hand, the bridge’s importance for economic activity can accelerate the decision making process toward ‘replacement’ or ‘rehabilitation’ (Rashidi and Lemass, 2011b). This factor can be ranked based on the level of bridge criticality in terms of socio-economic, political and historical considerations as shown in Table 5.11. This part of evaluation is quite subjective but significant enough to be noticed, therefore the key decision maker or bridge maintenance planner should be involved in assigning the appropriate rate in regard to this managerial parameter.

Table 5.11 Rating of the Client Impact Factor

Rating	1	2	3	4
Client Impact Factor (CIF)	Low	Medium	High	Very High

5.8 Bridge Prioritisation and Ranking

Bridge management systems are required to generate the ranking of various projects in a network. If unlimited funds are available, all the maintenance and rehabilitation requirements are addressed as they happen and the bridge infrastructure can be maintained in an excellent condition. However, as discussed in the literature review, transportation authorities must cope with limited budget and resources. Therefore, priorities have to be clarified for the fund distribution among the different projects in a network. Generally, priorities are set based on the ranking of the available bridge projects in a network. Many bridge management systems grade the projects based on a benefit-to-cost ratio analysis and the average Health Index (HI) for each project

In the benefit-to-cost ratio methodology, priority is given to projects that have more benefits and incur less cost. Kulkarni et al. (2004) noted that concerns arise when the benefit concept is used to apprise a large number of different projects with diverse locations, as opposed to a small quantity of projects. Fairness in selecting projects is an important issue, since the decision maker may select a bridge with a lower need ahead of another bridge with a higher need because of the lower cost for the first project. On the other hand, an excessive amount of effort is demanded to use the concept for a network with a large number of projects.

HI is a performance measure for bridges which has been developed for the California Department of Transportation (Roberts and Shepard, 2000). The HI evaluates the structural condition of a single bridge or a network of bridges by employing quantitative condition information collected through the bridge inspection process. This index estimates the remaining bridge asset value and assumes that the asset value reduces as the structure deteriorates over time. The HI is an average of the conditions of the bridge components. Abu Dabous et al. (2008) discussed that the HI is an overall representation of a bridge or a network condition and may not reflect the conditions of particular bridge elements properly.

Many road and bridge authorities in Australia, including the Road and Maritime Services (RMS) of NSW are using a single criterion based on the structural condition for ranking and prioritising bridges. Other constraints such as sufficiency and client impact factors are used in an isolated fashion. Expanding the approach to address additional criteria will improve the outcomes in terms of safety, functionality and sustainability of the bridge networks.

5.8.1 Bridge Overall Priority Index

In this study, the ranking is suggested to be performed according to an overall score estimated using the above mentioned criteria which have been identified throughout the data collection and model verification phase of this study. This function, which is introduced as the Priority Index (PI), is a simple tool that integrates all the critical factors that will influence decision making. This enables bridge/funding agencies to make decisions and set objectives backed up by strong logic. By using this technique all bridges are sorted in descending order starting with the bridge with the highest ranking index, the required actions are carried out until the allocated funds are exhausted.

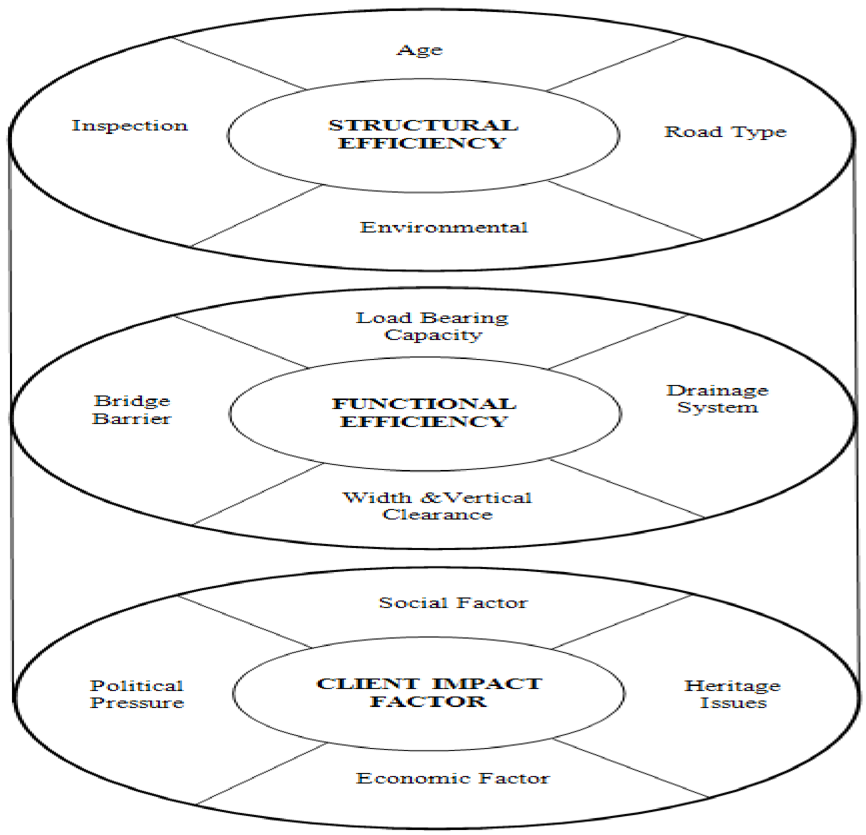


Figure 5.2 Parameters Involved in the Priority Ranking Process

Figure 5.2 shows a summary of all major and minor objectives involved in the ranking process. As shown in this figure, many parameters are involved in the ranking process, either directly or indirectly. On the other hand, all the sub-parameters have been subjected to the ranking/weighting process so far and for each of them a rational weight has been assigned based on a heuristic methodology.

The final stage is to weigh up the major categories: Structural efficiency, functional efficiency and the client impact factor. A few asset managers and bridge engineers noted that the client impact factor has a potential to be a key factor; sometimes it can interfere strongly. For example when some political pressure incurs, priorities are changed and an unqualified bridge may become a top priority. Many experts believe that the non-technical items such as social/political issues should not be underestimated or exaggerated, because the safety of the structure to the public is vital. The results of the expert judgement are illustrated in Figure 5.3 below. Structural Efficiency (SE) has achieved the highest score with 60% importance and both Functional Efficiency (FE) and the Client Impact Factor (CIF) acquired 20% of the total weight.

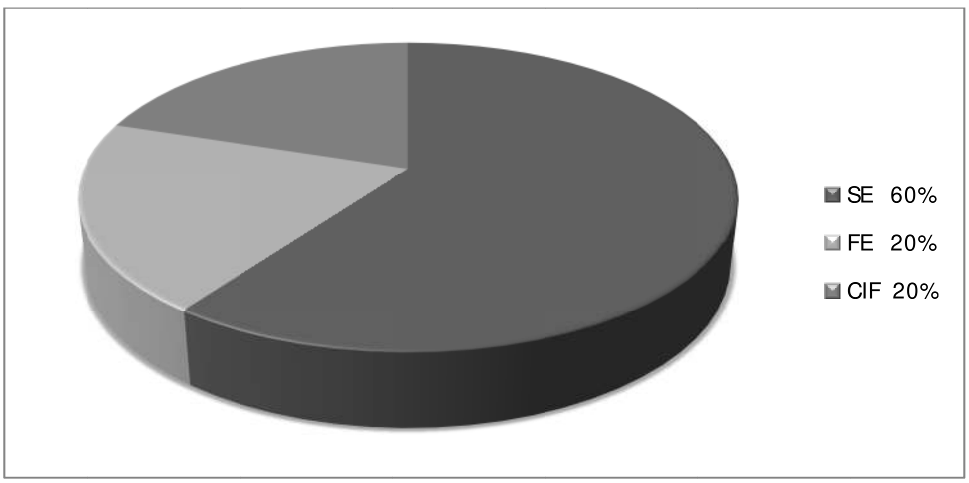


Figure 5.3 Weighting of the Major Factors

The Priority Index (PI) can be estimated employing the following equation:

$$PI = 0.6SE + 0.2FE + 0.2CIF \qquad \text{(Equation 5.8)}$$

It is important to notice that all the assigned weights so far are based on the expert judgements. Figure 5.4 presents flow chart of the ranking procedure based on computing the PI. The procedure uses the default parameters and attributes and their associated weights developed in this chapter, and at the same time provides flexibility to decision makers to offer their inputs to the system to modify these elements based on their priorities and judgments.

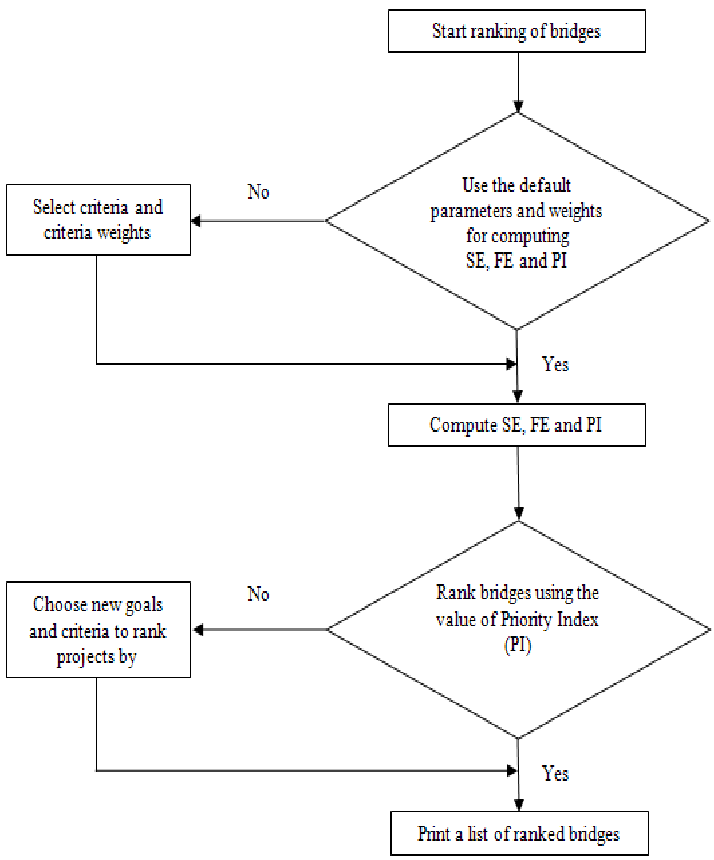


Figure 5.4 Bridge Ranking Procedure

Priority ranking can be achieved through the prototype system in which the weight of parameters have been stored. The user/decision maker inputs the required data for each bridge and the PI is automatically calculated. The program then starts sorting the bridges in descending order of the priority index.

5.9 The Proposed Inspection Form

Along with the objectives defined in Chapter 4 and the methodology developed within the current chapter, a new inspection form has been designed and proposed. In this form all the required data for computing the main priority parameters have been included. The decision makers' comments are designed to be considered as the authorities may manipulate all the structured process of the system with a specific reason. For this reason the system is called a decision support system since it is not a substitution for a human being. One of the advantages of this form is that the cost of treatment options would be easier to estimate since all the element types are measured seperately.

Table 5.12 Proposed Bridge Inspection Form

Bridge Code:	Bridge Name:	Bridge Type:	Location:
Inspection Type:	Inspection Date:	Inspector's Name:	Proposed date of next inspection

I) <u>Structural Efficiency Assessment:</u>

Element Code	**Element Description**	**Total Quantity**	**Units**	**Estimated Quantity in Condition State**			
				1	**2**	**3**	**4**

Table 5.12 Cont' Proposed Bridge Inspection Form

	Causal Factors (CF)							
Age	Recently Built	☐	New	☐	Old	☐	Very Old	☐
Road Type	Minor	☐	Local Access	☐	Collectors	☐	Arterials	☐
Environment	Low	☐	Medium	☐	High	☐	Very High	☐
Inspection Quality	Very High	☐	High	☐	Medium	☐	Low	☐
	II) <u>Functional Efficiency Assessment:</u>							
Load Bearing (Lf)	$LF \geq 1$	☐	$0.9 \leq LF \leq 1.0$	☐	$0.7 \leq LF < 0.9$	☐	$0.5 \leq LF < 0.7$	☐
Vertical Clearance (Vc)	$Vc \leq 5$	☐	$5 < Vc \leq 12$	☐	$12 < Vc \leq 20$	☐	$Vc > 20$	☐
Width (Wb)	$Wb \leq 5$	☐	$5 < Wb \leq 12$	☐	$12 < W \leq 20$	☐	$W > 20$	☐
Barriers (Bb)	$Bb \leq 5$	☐	$5 < Bb \leq 12$	☐	$12 < Bb \leq 20$	☐	$Bb > 20$	☐
Drainage System (Ds)	Excellent	☐	Poor	☐	Fair	☐	Poor	☐

LF is introduced as the proportion of actual live load capacity to initial designed capacity.

Vc is the percentage of difference between the existing vertical clearance and the mandatory one.

Wb is the percentage of difference between the existing width and the the target trafficable carriageway width

Bb is the percentage of bridge barrier systems not conforming to the defined target level.

Ds represent the performance of the drainage system.

Table 5.12 Cont' Proposed Bridge Inspection Form

Inspector's Comment: ....Inspector's Signature:

…………………………………………………………Date:………………………………………………………………..........

III) <u>Client Impact Factor (CIF):</u>

Low ☐ Medium ☐ High ☐ Very High ☐

CIF is the level of bridge criticality in terms of socio-economic, political and historical considerations.

Asset Manager's Comment:

………

Asset Manager's Signature:

…………………………………………………………Date:…………………………………………………………...

5.10 Summary

Bridges have a high asset value but only limited financial resources are available to maintain them at a high working standard. It is therefore important to put considerable effort into the risk assessment process to ensure that the structures are analysed carefully and any defects are rectified early, before they become a significant issue.

In this Chapter, a methodology for priority ranking of bridges is proposed. Following a multi-criteria type of analysis, a priority index (PI) is computed for each bridge. PI is expressed as a number which enables the decision makers to simply understand and compare the condition of a variety of bridges in the network. Because of the multi objective nature of the work, various factors are involved that required to be identified and weighted properly. The proposed system provides flexibility for the decision makers in stating their degree of satisfaction with each criterion and alerts the decision makers toward the expected risks.

6 BRIDGE REMEDIATION STRATEGY SELECTION

6.1 Introduction

Chapter five discussed a method developed for condition assessment and prioritisation of bridge projects. The asset manager (or bridge maintenance planner) can recognise bridges with the highest priority for intervention through evaluating structural and functional efficiency considering client impact factor. For each of the prioritised bridges, the decision maker should select a remediation strategy to improve the bridge condition. Generally, managerial decisions are based upon rules of thumb achieved over many years of experience. Apart from the knowledge and proficiency of bridge managers, rules of thumb are prone to potential inaccuracy and may lack sufficient reliability and compulsion to influence authorities and community. Not unexpectedly, this situation aggravates dilemmas related to infrastructure funding system. Therefore, the bridge asset managers need tools that can support them to identify appropriate actions and enhance their credibility with potential stakeholders (Wu, 2008). The present work is aimed to provide such a tool when evaluating alternative strategies for a collection of bridges.

As discussed in Chapter 4 and presented in Figure 6.1, the secondary phase of the project is focused on the strategy selection. Identifying the possible course of actions, major criteria and selecting the best decision analysis tool with the aim of proposing a rational remediation plan are discussed in this chapter.

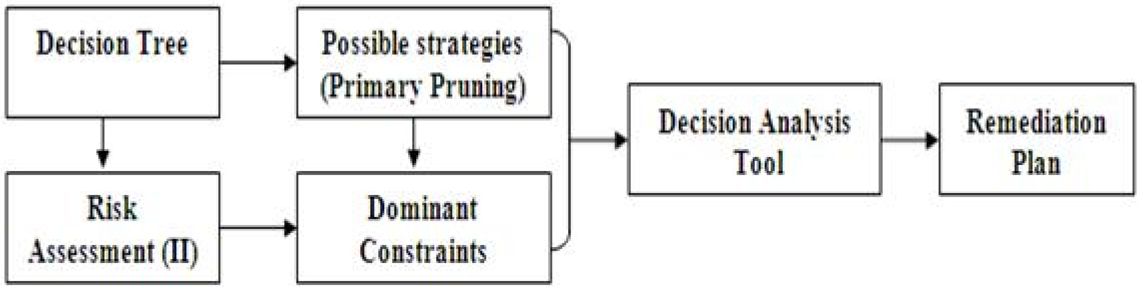


Figure 6.1 Secondary Phase of the Project

6.2 Decision Tree: Possible alternatives

Most real-world decisions are not limited to single, unique solutions. The decisions are usually less than optimal and are drawn from a set of feasible solutions that have been termed as 'satisficing' solutions (Lemass and Carmichael, 2008). Therefore, the potential range of satisficing solutions should be identified and classified.

For each bridge that needs intervention, a number of strategies are available. These strategies can range from “do nothing” to “complete replacement”. In interviews, engineers from Roads and Maritime Services (RMS), NSW and local councils noted that a deteriorated bridge can be left in service until a major rehabilitation or even replacement decision is made.

A decision tree is a useful tool for classification of all the possible alternatives as well as decision making. The decision tree presented in Figure 6.2 is proposed by Rashidi and Lemass (2011b) It includes some branches representing a number of potential major strategies (Level 1 and Level2) which could be further narrowed to sub branches as minor strategies (such as Level 3) when other managerial constraints are imposed. It should be noted that the mentioned items in Level 3 are just examples to show a few sub-branches of each category.

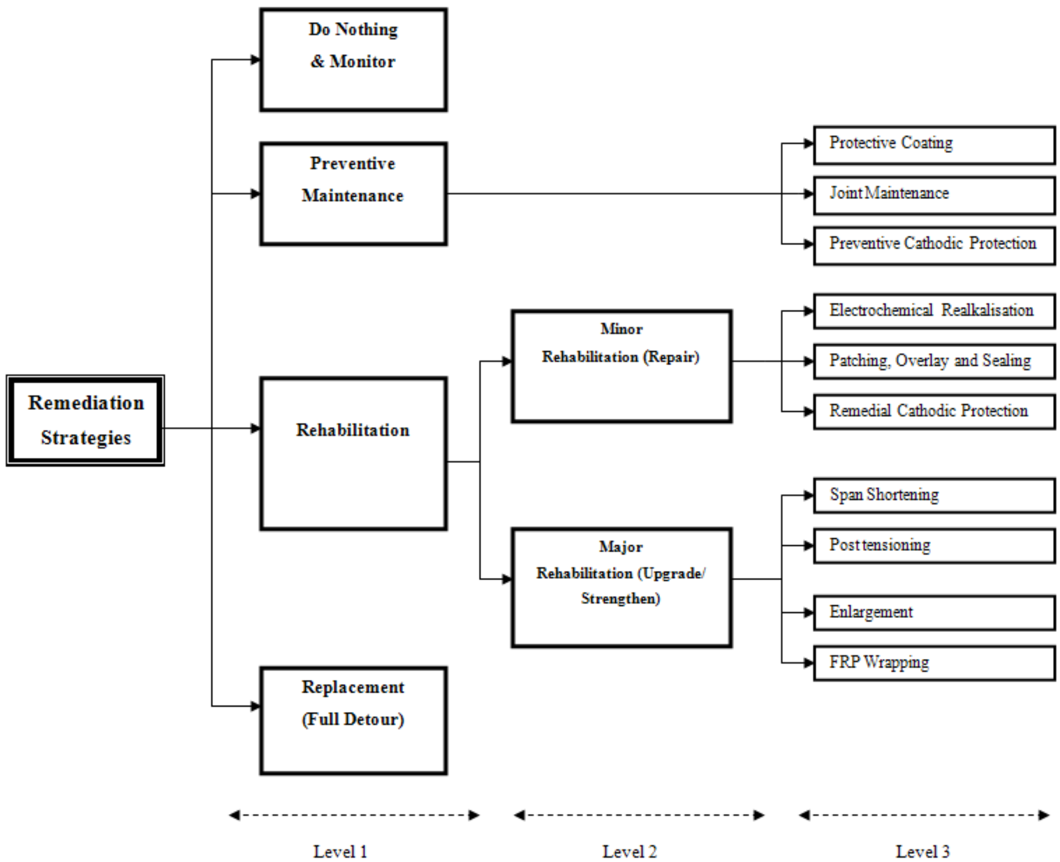


Figure 6.2 Decision Tree for Remediation Courses of Action (Rashidi and Lemass, 2011a)

6.2.1 Major Strategies (Level 1 and 2)

As shown in Figure 6.2, major alternatives are branches known as level 1 and level 2 of the introduced decision tree including "*Do Nothing and Monitor*", "*Preventive Maintenance*", "*Rehabilitation (Minor and Major: Repair and Strengthening respectively)*" and "*Replacement*".

In many instances, adequate funds are not available and the bridge managers have to allocate the budget for the structures of highest priority. In this case, "*Do nothing"* is a very common course of action with no need of investment. This alternative is associated with monitoring the general condition of elements while keeping them in service until a major action such as rehabilitation or replacement is required.

"Preventive and routine maintenance" represents the actions required to be conducted to preserve the planned structural and functional efficiency of the bridge. Routine bridge maintenance includes those activities, identified primarily through Level 1 inspection, which maintain the serviceability of the structure. In general, they do not change condition and are comprised of the clearing of drainage, minor repairs to the road surface, adjusting deck joints and debris removal. This is usually conducted as a supportive action for all the minor and major rehabilitation strategies. Without appropriate maintenance, bridges will deteriorate prematurely during their service life. Material damage and defects often accelerate this deterioration process.

"*Rehabilitation*" refers to the maintenance work of greater "Scope" and "Cost" than simple routine maintenance. It may be selected as a long-term solution (Upgrade/ Strengthening) or as a temporary fix (Repair) for structures suffering from structural deficiency, poor serviceability performance or aesthetic problems.

Repair aims at rehabilitating the bridge to its original service level or what it was intended to have while strengthening refers to improving the existing functionality of the bridge to the value it originally had or was planned to have (Raina, 2005).

"*Replacement*" refers to reconstruction of the whole bridge or of its major elements. This is for serious conditions in which the cost and/or the extent of repair or strengthening may be beyond the acceptable thresholds. In this case a full detour might be required.

Extending the service life of an existing bridge at an adequate level of service often has a preference over replacement because bridge closure for construction of a new bridge has a significant impact upon regional traffic and may consequently affect the efficiency of the network to what the bridge belongs. In addition, it requires considerable capital, and usually causes legal and political issues.

6.2.2 Minor Strategies (Level 3)

Major strategies addressed in section 6.2.1 include a few options, but according to the variety of treatment options for each of those main alternatives in level 1 and 2, selecting the appropriate course of actions needs to be more structured. However, practically finding the solutions is usually based on the experience of inspectors/asset managers. In order to add more certainty and objectivity to the problem solving approach, it is fundamental to create some "*fit to purpose*" classification systems that can address all the common defects that may be detected in the bridge, causes of defects and finally treatment options considering correlations between those parameters.

The first attempt to relate the defects with their respective repair techniques was made within the Brite 3091 Project where, in which only corrosion related defects were included. Possible repair techniques were divided into preventive repair techniques and defect repair techniques. The resultant list thus prepared was turned into a correlation matrix, but it included only the corrosion-related defects (de Brito et al., 1997).

Table 6.1 illustrates a schematic correlation matrix which links defects (D) and repair techniques (R). In the intersection of each line (representing a defect) and each column (characterising the repair technique), a coefficient representing the knowledge based correlation degree between the defect and the repair technique has been introduced.

Table 6.1 Schematic Correlation Matrix: Defect vs Repair Technique

	R_1	R_2	R_3	R_4	R_5	…	…	…	R_n
D_1	0	1	1	2	0	…	…	…	0
D_2	0	1	2	1	2	…	…	…	2
D_3	0	2	1	1	0	…	…	…	0
D_4	1	2	0	1	0	…	…	…	0
D_5	0	2	2	0	…	…	…	…	1
…	…	…	…	…	…	…	…	…	1
…	…	…	…	…	…	…	…	…	0
…	…	…	…	…	…	…	…	…	0
D_n	2	0	1	0	1	…	…	…	2

The criteria adapted for that coefficient are:

0- NO CORRELATION: no relationship whatsoever between the defect repair technique and the repair technique.
1- LOW CORRELATION: preventive repair technique aimed at eliminating the causes of the defects but not the defect itself.
2- HIGH CORRELATION: defect repair technique aimed at eliminating the deterioration of the area in which the defect was detected but not necessarily its cause.

For example, R3, R5 and Rn have the highest correlation with the defect type D2; therefore the decision maker should consider them in the priority of selections.

As discussed in Chapter 2, there are various taxonomies existing in practice but since expanding technology is spawning an even greater number of feasible alternative solutions, the classification systems should be updated within a certain period of time. Table 6.1 shows a very simple, but comprehensive classification of treatment options for concrete components provided by Buckley and Rashidi (2013).

6.3 Risk Assessment II: Decision Criteria

The selection of remediation options involves a case-by-case evaluation, to determine the potential risks associated with any given course of action. Bridge maintenance planners have various criteria and constraints that must be coped with when endeavouring to propose the best possible solution for bridges. The main idea of using criteria is to measure the performance of alternatives in relation to the objectives of the decision maker based on a numeric scale.

Table 6.2 Treatment Options for Concrete Elements (Rashidi et al., 2010)

Principle	Technique	Principle	Technique
Ingress Protection	Protective coating Crack sealing & repair	**Control of Anodic Areas**	Apply Barrier to reinforcement Apply Chemical to reinforcement Apply Sacrificial coating to reinforcement
Restoring Passivity	Chloride extraction Replacement of contaminated concrete	**Strengthening**	Add external reinforcement Post- tension Plate bond Enlarge component Span shortening techniques Resin or grout injection of voids or cracks
Moisture Control/ Increase Resistivity	Surface coating Over cladding		
Cathodic Control	Saturation (saline treatment) Surface coating Cathodic inhibitors	**Concrete restoration by replacement**	Hand applied mortar Recasting with concrete Sprayed concrete (shot-crete)
Replacement	Replace the element		

According to Lemass and Carmichael (2008), as a result of incomplete information, misinformation, uncertainty and the changing preferences of decision makers, the list of technical constraints imposed by rational models of choice should be bounded by the inclusion of subjective constraints such as safety and reliability. However, for the purpose of system development, five generic categories of dominant risks and their associated constraints are proposed and listed in Table 6.3 below.

Table 6.3 Major Risks and Client Constraints for Concrete Bridge Maintenance

Criteria	Risks	Client Constraint
Safety	Potential injury/fatality	Minimal damage/Maximum safety of the public
	Damage to property	
Functionality	Low level of service	Maximum service life/durability
	Lack of operational efficiency	Maximum operational efficiency
	Closure of a strategic/regional route	Minimal traffic disruption
Sustainability	Excessive rehabilitation/replacement cost	Minimal cost*
	Excessive work implications	Minimal work implications
Environment	Environmental damage	Minimal environmental damage
	Not aesthetically pleasing	Maximum aestheticism
Legal/ Political	Major changes in standards	Minimum vulnerability to legal (regulations)/political pressures
	Major changes in governance strategies	

*The cost includes design, traffic management, supervision, and user cost.

These important variables and their interrelationships were identified through the comprehensive literature review and a series of interviews with experts from transportation agencies introduced as the level two of risk assessment in the current model. This list is by no means inclusive, with other project specific criteria identified during the risk assessment process (Rashidi and Lemass, 2011b).

6.4 Decision Analysis Tool

As discussed in Chapter 3, engineering or management decisions are commonly made through available data which are mostly vague, imprecise, and uncertain by nature. The decision-making process in bridge remediation strategy selection is one of these ill-structured occasions, that usually need a rigorous approach which applies explicit subject domain knowledge to ill-structured (adaptive) problems to reformulate them as structured problems (Rashidi et al., 2010). Multi Criteria Decision Making (MCDM) methods are employed in order to deal with problems that engage various criteria simultaneously and to attain greater transparency of the decision making process. MCDMs seek to go deeper along a holistic point of view, aggregating all the available data including that of a subjective nature.

Various categories of MCDM techniques including monetary based and elementary methods, multi-attribute utility techniques and outranking methods have been introduced and discussed within Chapter 3 extensively. It has been attempted here to find the best tool which can satisfy the required robustness. AHP, ELECTRE and PROMETHEE, SMART and TOPSIS have been found to be more applicable to the bridge management systems (See Sections 3.7.1, 3.7.2, 3.8.1, 3.8.2 and 3.8.3). A short summary of these tools presented in the following sections.

6.4.1 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is a multi attribute decision making method which belongs to a broader class of methods known as “additive weighting methods”. The AHP was proposed by Saaty (1977) and employs an objective function to aggregate the different features of a decision problem where the main aim is to choose the decision alternative that has the highest value of the objective function. AHP is classed as a compensatory methods, in which criteria with low scores are compensated for by higher scores on other criteria, but contrast to the utilitarian methods, the AHP exploits pair wise comparisons of criteria rather than utility or value functions where all individual criteria are paired with all other criteria and the end results accumulated into a decision matrix (See Section 3.7.2 for more details).

The advantages of the AHP method are that it supplies a systematic approach through a hierarchy and it has objectivity and consistency. On the other hand, the limitations are that calculation of a pair-wise comparison matrix for each criterion is quite complex and as the number of constraints and/or alternatives increases, the number of calculations for a pair-wise comparison matrix rises considerably. Moreover if a new alternative is added, all the calculation processes have to be restarted (Rashidi and Lemass, 2011a).

6.4.2 ELimination Et Choix Traduisant la REalité (ELECTRE)

ELECTRE is a part of the MCDM family which originated in France in the mid-1960s and is usually classified as an "outranking method" of decision making. The character of the recommendation depends on the problem being addressed: selecting, ranking or sorting.

The major purpose of the ELECTRE method is to choose alternatives that unite two conditions from preference concordance on many evaluations with the competitor and preference discordance was supervised by many options of the comparison. This method determines a partial raking on the alternatives. The set of all options that outrank at least one other alternative and are themselves not outranked (See Section 3.8.1).

6.4.3 Single Multi Attribute Rating Technique (SMART)

Simple Multi Attribute Rating Technique (SMART) is a form of MAUT in which the utility functions can be replaced by some scores which indicate the relative importance level of each treatment alternative with respect to the decision criteria. This method is based on direct numerical rating values that are aggregated additively (See Section 3.7.1). Currently there are many derivates of SMART which, also include non-additive approaches. In a very basic format of SMART, there is a rank-ordering of alternatives for each attribute setting the best to 100 and the worst to zero and interpolating between. By refining the performance values with relative weights for all attributes a utility value for each alternative is calculated (Fülöp, 2005).

SMART is independent of the alternatives. While the introduction of value functions makes the decision modelling process somewhat complex, the advantage of this method is that the ratings of alternatives are not relative, so that shifting the number of alternatives considered will not in itself alter the decision scores of the original alternatives. If new alternatives are probable to be added to the model after its primary construction, and the alternatives are acquiescent to a direct rating approach (not so qualitative as to require pair wise comparison), then SMART can be a superior choice (Valiris et al., 2005)

Adelman *et al*. (1984) noted that SMART has high levels of accuracy in certain tasks even though there is no formal mechanism for checking reliability of judgments between pairs of alternatives.

6.4.4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) which was firstly proposed by Hwang and Yoon (1981) is one of the mostly used multi-criteria decision making techniques. The basic concept of TOPSIS is that the selected option should have the shortest distance from the positive ideal solution and the farthest distance from the negative-ideal solution in a geometrical sense. Within the process an index called "similarity index" (or relative closeness) is defined to the positive-ideal solution by combining the proximity to the positive-ideal solution and the remoteness from the negative-ideal option. Then by this method a solution is selected with the maximum similarity to the positive-ideal solution. The default assumption is that the larger the outcome, the greater the preference for benefit attributes and the less the preference for cost attributes (more details are presented in Section 3.8.3).

6.5 Selection of the Best Method through Comparison

The key characteristics of the above techniques have been investigated and the advantages and disadvantages compared. Table 6.4 below presents the advantages and disadvantages of the abovementioned tools. SMART and AHP seem to be more advantageous than other techniques in terms of simplicity and robustness respectively

There are two main quantities indicating the level of importance which are involved in the decision evaluation: 1) weight of criteria and 2) rate of each alternative associated with each criterion. Through the SMART process, both values are selected based on cardinal numbers representing the level of importance, but in the AHP technique the quantities have been drawn from a set of pair wise comparisons that makes it more reliable and the same time more complex.

Table 6.4 Advantages and Disadvantages of the Selected MCDM Tools

Tool	Advantages	Disadvantages
AHP	-Widely accepted and applied in different areas (E.g. engineering, economic, social, political, etc.) (Bello-Dambatta et al., 2009). -Consistency assessment enables the decision maker to identify those judgements that require reassessment (Triantaphyllou, 2000). -Over-specifying inputs through explicit pair-wise comparisons (Triantaphyllou, 2000).	-If a new option is added after finishing an evaluation, all the calculation processes have to be re-started again (Kim and Song, 2009). -Calculation of pair-wise comparison matrix is complicated and as the number of criteria and/or alternatives increases the number of the calculations enhances rapidly (Kim and Song, 2009).
ELECTRE	-Widely applied for many practical problems, especially in French speaking societies (Triantaphyllou, 2000) -It is totally non compensatory. The weights allocated to each criterion are independent of the scale of criterion (Adolphe and Rousval, 2007). -Outranking methods have the potential to deal with more than 80 alternatives (Rogers and Bruen, 2000). ELECTRE models allow for incomparability (Rogers and Bruen, 2000).	-The decision maker does not intend to provide weights to the decision criteria, so the numbers are accepted unchallenged as inputs to a complicated procedure (Rogers and Bruen, 2000). -It is difficult to investigate the robustness and sensitivity of the method in any automated or interactive way (Belton and Stewart, 2002) -It can compare alternatives but is not able to produce a single index of performance (Eisenführ et al., 2010).
SMART	-SMART is robust and simple in terms of both the responses required of the decision maker and the manner in which the responses are analysed (Goodwin and Wright, 2004). -SMART has high levels of accuracy in certain tasks even though there is no official mechanism for checking reliability of judgments between pairs of alternatives (Wang and Yang, 1999). -Weights elicitation can be done via various methods which lead to identical results in at least 80% of the cases (Kabli, 2009). -The ratings of alternatives are not relative, so that shifting the number of alternatives will not in itself alter the decision scores of the original alternatives (Fülöp, 2005). -Using SMART in performance measures can be a better alternative than other methods (Valiris et al., 2005).	-It disregards the interrelationships between parameters (Goodwin and Wright, 2004). -The cost of its simplicity is that the method may not consider all the details and complexities of the real problem (Valiris et al., 2005).
TOPSIS	-The purpose of the decision made is not only to make as much profit as possible, but also to avid as much risk as possible (Kabli, 2009). -Simplicity, rationality, comprehensibility (Triantaphyllou, 2000).	-Other alternative distance measures can be used instead of Euclidean distance, in which case different answers may be found for the same problem (Triantaphyllou, 2000). -It is more difficult to determine weight and keep the consistency of judgment matrix, especially when it is used with more attributes (Dong-Sheng et al., 2007) - The algorithm doesn't consider the correlation of attributes (Dong-Sheng et al., 2007). - The subjectivity of weights (Kabli, 2009).

A reasonable balance has to be made between the simplicity of SMART and the complexity of AHP. In this study identifying the appropriate criteria (through risk analysis) and weighting the criteria have been highly emphasised. The eigenvector approach of AHP is a suitable way to provide reliable judgements and its strength justifies the complexity of using that. The proposed method is a combination of these two techniques, introduced as modified SMART which will be explained in the following section.

6.6 Strategy Selection Using Modified SMART

Through the SMART process, firstly, the problem under consideration is broken down into a hierarchy, including at least three main levels: goal, criteria and alternatives. The decision criteria might be general and they may therefore require to be broken down into more specific sub-criteria introduced as attributes in an extra level of hierarchy.

This approach deals with identifying the overall goal and proceeding downward until the measure of value is included. Figure 6.3 shows a four-level hierarchy structure considering the general aspects of the problem. The first level of the structure is the overall goal of the ranking. The second level contains the objectives (criteria) defined to achieve the main goal. The third level holds the sub criteria to be employed for assessing the objectives. The final level is added for the remediation treatment alternatives. Each criterion has a weight indicating its importance and reflecting the organisational policy. These weights are defined by the decision makers employing the pair wise comparison approach embedded in the AHP and will vary for different projects with different decision makers (Rashidi and Lemass, 2011b). The AHP has the major benefit of allowing the decision makers to carry out a consistency check for the developed judgment in regard to its relative importance among the decision making components. Therefore, the decision maker(s) can modify their judgments to improve the consistency and to supply more-informed judgments under consideration. The assigned weights in Figure 6.3 are based on an expert judgment for a typical BMS.

The procedure is also able to provide flexibility in selecting the criteria to be used to evaluate the rehabilitation strategies and even increasing or decreasing the numbers of levels (associated with the criteria) in the hierarchy.

The overall ranking value of each alternative for a four level hierarchy (as shown in Figure 6.3) x_j is expressed as follows:

$$x_j = \sum_{i=1}^{m} W_k W_{ki} \, a_{ij} \qquad j=1,...,m \qquad \text{(Equation 6.1)}$$

-W_k is the weight of criterion k

-W_{ki} is the weight of the i^{th} sub-criterion in the category of criterion k

-a_{ij} is the importance level of *j*th alternative in respect to the *i*th sub criterion and *k*th criterion.

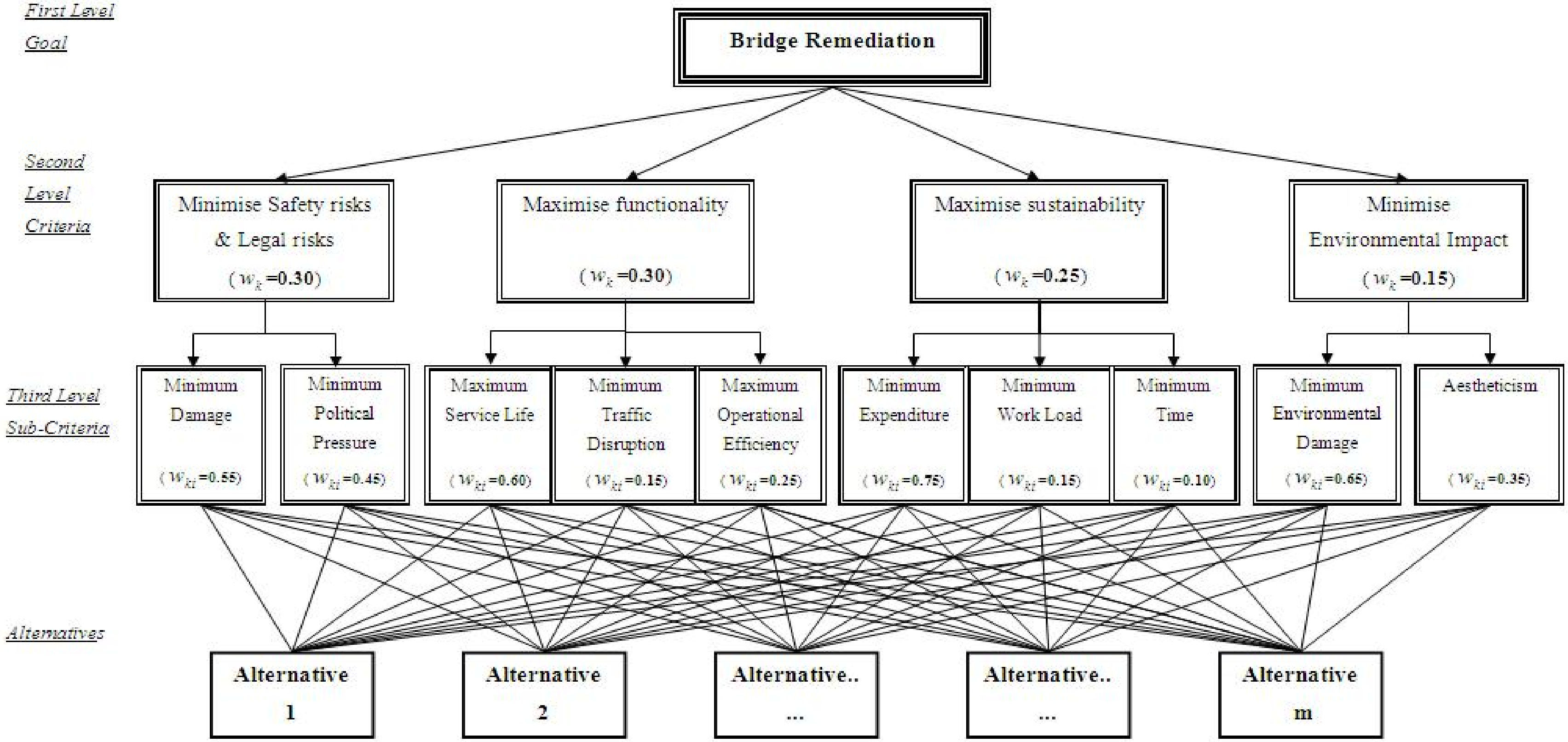


Figure 6.3 Typical Hierarchy Structure for Bridge Remediation (Rashidi and Lemass, 2011b)

6.6.1 Procedures for Major/Minor Remediation Strategy Selection

Figure 6.4 presents a flow chart of the proposed ranking procedure for major strategy selection, which can be applied for each bridge that requires intervention.

It begins with the primary condition assessment considering all the factors that have been discussed in Chapter 5 in order to estimate the Priority Index (PI). The bridge with the highest ranking will be subjected to level two of risk assessment and ends with criteria selection. The eigenvector approach of AHP will be used in order to define the vector of constraints' priorities. Finally the SMART technique will be applied to rank the main options at level 1 and 2 including "Do nothing", "Preventive maintenance", "Rehabilitation" and "Replacement".

For any rehabilitation and/or maintenance outcomes, another decision may need to be taken, to select the treatment type for the individual elements. Generally, because of budget limitation, bridge asset managers have to define the level of satisfaction for the different elements, considering the structural significance and material vulnerability of those components. For example, a bridge manager may decide to leave a barrier with the ESCI of 3 in service for a long period of time contenting to some general routine maintenance. The system does not have any default for that and the system user (decision maker) should assign the target values for the acceptable threshold of element condition.

Figure 6.5 shows the procedure for minor strategy selection. The most applicable alternatives are primarily proposed by the inspector(s) mainly based on technical considerations and further refined by the bridge maintenance planner.

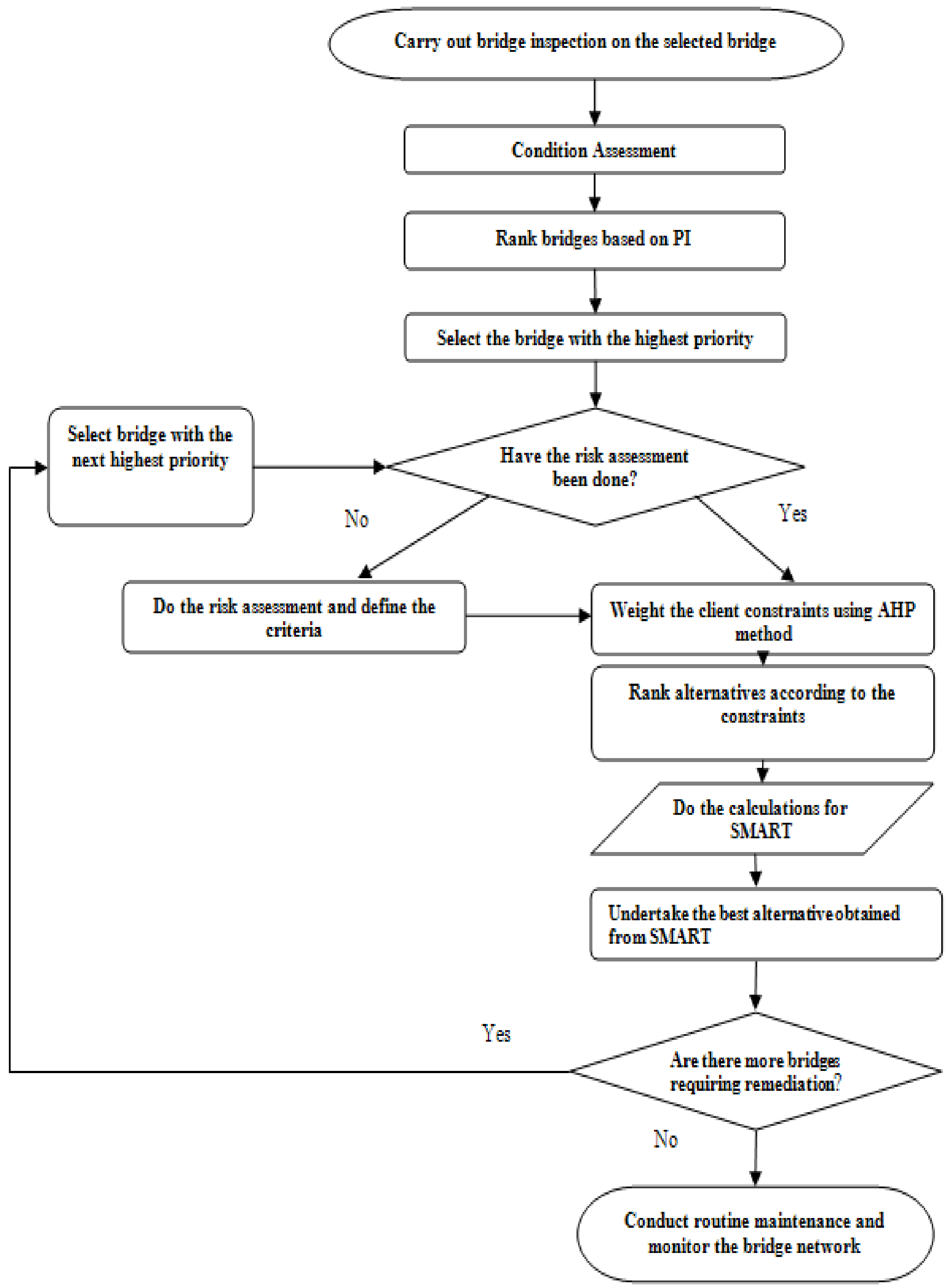


Figure 6.4 Flow Chart of the Proposed Method for Strategy Selection at Project Level

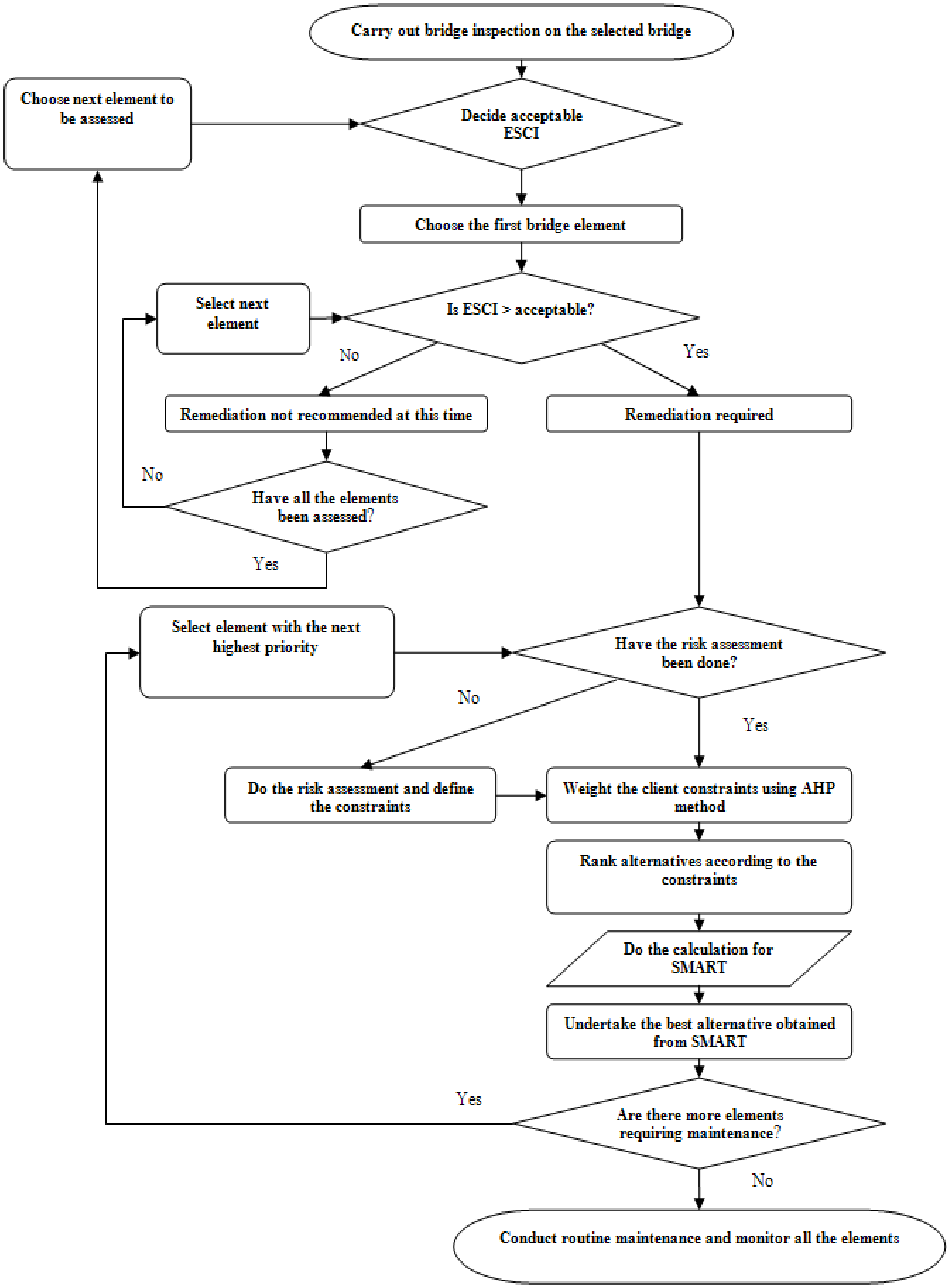


Figure 6.5 Flow Chart of the Proposed Method for Treatment Selection at Element Level

6.7 Priority Arrangement for Budget Allocation

If transportation authorities had unlimited funds, road and bridge networks could be monitored and maintained at high level of quality. However, in reality, limited budgets are assigned for bridge remediation projects. On the other hand bridge agencies are facing an increasing number of deficient bridges requiring intervention. This makes the challenge of bridge management more complex.

The limitation of budget availability and the high cost of remedial actions are the main constraints that should be taken into consideration for rational justification of decisions in regard to budget allocation.

As discussed earlier, the CBR-DSS specifies which bridge has the highest priority and what action to be taken for that bridge (assuming that enough funds are available). In order to optimise decisions and maximise benefits to the agencies and the users, the budget allocation process needs to be expanded to the network level using a viable structured approach.

A methodology has been developed based on analysing the various combinations of MR&R alternatives for top ranked bridge projects. According to Abu Dabous (2010), simulation is a very useful tool to perform a large number of scenarios, and develop all the possible combinations between projects and MR&R strategies. Each combination is a remediation alternative and the total cost of any combination must not exceed the available budget.

A set of constraints should be defined in order to compare the two alternatives. The simulation develops the first alternative and considers it to be the current best. Then it develops the second alternative and compares it with the first one based on the defined constraint. If the first is better than the second one, it still remains the current best. The procedure continues and develops a third program and compares it with the current best. The process continues until all the programs have been compared. The final current best will be the recommended course of action.

The proposed method in Chapter 5 ranks bridge projects based on the overall priority index addressing their structural and functional efficiency and considering the client impact factor. Projects are included in the budget allocation program based on the priority assigned for each one from the suggested method. The project with the highest priority will be included first, followed by the bridge with the second highest priority, and so on.

In the current chapter, a method for choosing a remediation strategy for bridges is presented. The method allocates a score (indicating its relative importance, based on the degree that each strategy satisfies certain criteria defined by the decision maker) for each action. The simulation uses these scores to compare the different nominee combinations. For instance, if the score for maintenance is 20, the score for repair is 45 and the score for reconstruction/replacement is 35 and the assigned budget is enough to cover only two of these alternatives on two different bridges, the best selection is to perform a repair on one project and a replacement for the other (because it will include the maximum sum of scores of 80). If a program suggests maintenance for one bridge and replacement for the other it will produce a sum of scores of 55 which is less than 80. Therefore, the program recommends replacing one and repairing one as the maximum sum of scores indicates the maximum benefits.

For the first three iterations of the simulation process, three projects with the highest priority are selected based on the overall priority index. The available remediation strategies are maintenance, rehabilitation and reconstruction of bridge projects. In the first iteration, if the budges is sufficient to perform any of these three options (the cost of each program is estimated before), the one with the highest score is selected as the best program.

In the second iteration, two bridges (with the highest and the second highest priority) will be considered. One of the available MR&R strategies can be carried out for each individual project. In this case, nine (=3^2) programs including (maintain1 and reconstruct2), (maintain1 and rehabilitate2), or (maintain1 and maintain2), (rehabilitate1 and reconstruct2), (rehabilitate 1 and rehabilitate 2), (rehabilitate 1 and maintain2) (reconstruct1 and reconstruct2), (reconstruct1 and rehabilitate 2), (reconstruct1 and maintain2) can be developed for assessment.

If the allocated fund can cover any of these programs, the combination with the highest score is selected as the best alternative, replacing the previous iteration. If the estimated cost for any of these nine combinations was over the available budget, the process stops and the program from the previous iteration will be the recommended program. It is also possible that a subset of the all programs be performed within the available funds (the one with the highest sum of scores becomes the best).

The third iteration will include the three highest priority bridges and will have twenty seven (=3^3) alternatives. Again if the available budget is enough for any of combinations, the one with the highest sum of scores for its remediation options is chosen to become the best alternative. The process continues until a program which includes bridges with the highest priority and maximum weight is developed.

The flowchart presented in Figure 6.6 shows the procedure of the remediation planning at network level.

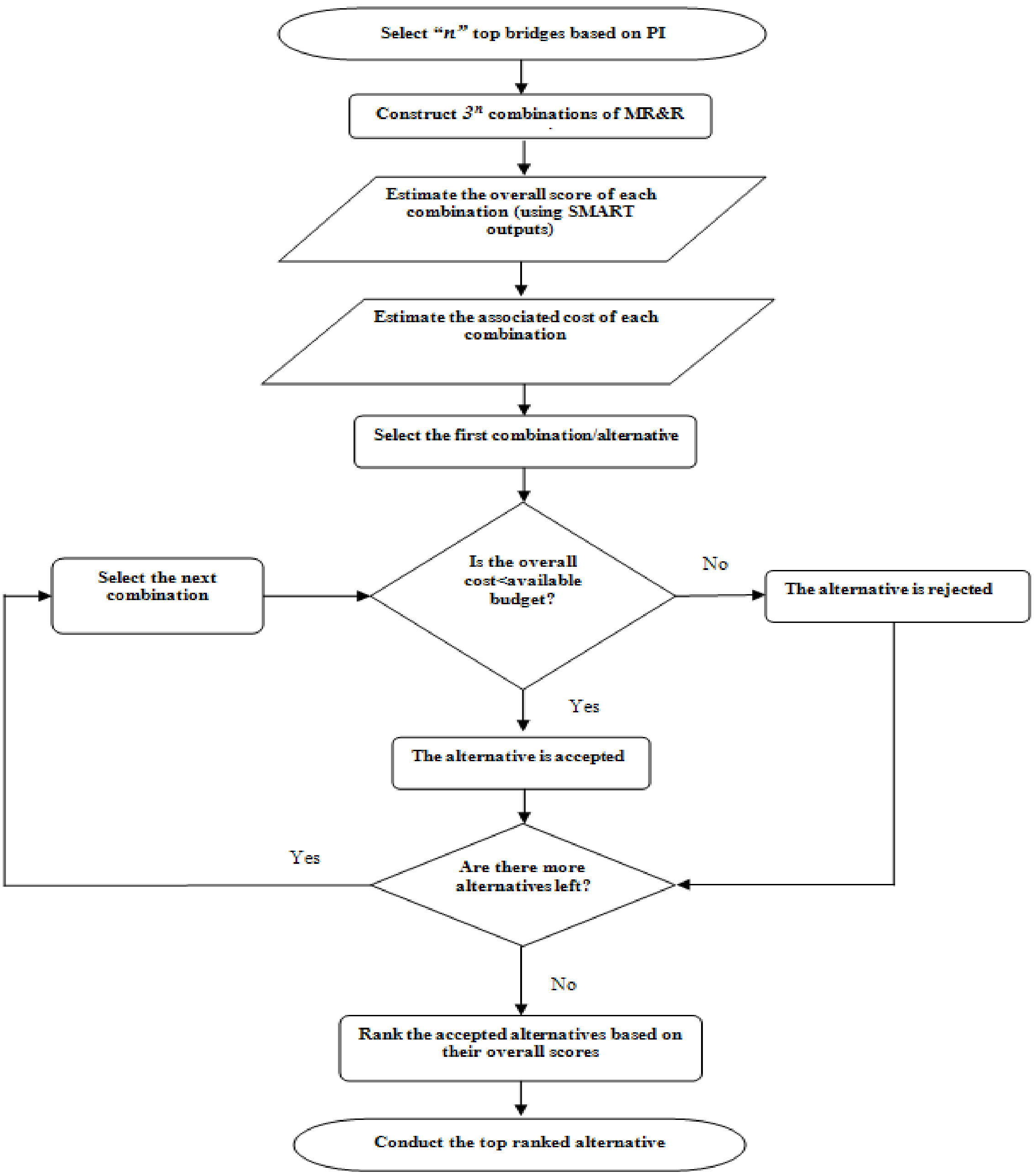


Figure 6.6 Flow Chart of the Remediation Planning at Network Level

6.8 Summary

In this chapter a review of bridge management decision making has been presented and the multiple-criteria nature of the problem discussed. Sound decision making requires including multiple and conflicting criteria in the process. Five major categories of criteria including safety, functionality, sustainability, environment and legal/political constraints have been identified through level two of risk assessment. Different decision analysis tools have been analysed and the modified Simple Multi Attribute Ranking Method (SMART) has been selected as the main frame work for strategy selection. In this method the eigenvector approach of the AHP based on pair wise comparison of the decision criteria is chosen for criteria weighting. The modified SMART accounts for the uncertainty associated with the values representing the intensity of the relative importance while producing a sensitive evaluation of the consistency in judgments.

This chapter has also presented a technique for priority arrangement of bridge projects in terms of budget allocation through combining the outputs of the developed model in Chapter 5 and the current chapter. The overall scores obtained from each rehabilitation strategy (estimated using the decision support method) are important inputs for developing a budget plan at network level.

7 IMPLEMENTATION AND VERIFICATION

7.1 Introduction

As discussed in Chapter 4, the last phase of the project is implementation which can be accomplished through the application of software as a representative of Decision Support System. Prototype software named CBR-DSS is developed to confirm the practicality of the proposed methodology. CBR-DSS specifies which bridge has more criticality to be considered as a priority and what strategy should be selected for remediation purposes at both project and network level. This aims to make the maximum benefits to the users and the agency within the available resources/budget. CBR-DSS has also a potential to be integrated with other systems and/or applications and it can be distributed through networking and Web technologies. Real case studies have been used to verify the application of the proposed model and the extent of its capabilities.

7.2 Prototype System

The CBR-DSS program has been developed using Microsoft Visual C# and includes all the elements of the proposed framework (designed in 10 tabs). The implementation codes are also presented in the appendix.

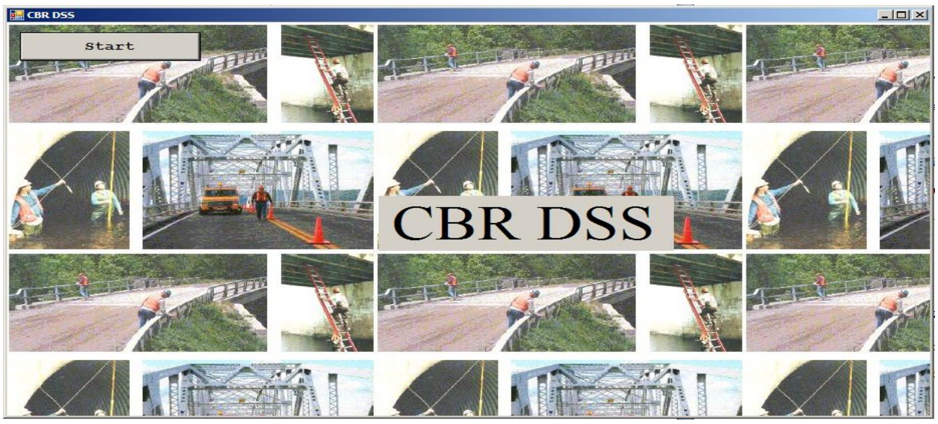


Figure 7.1 CBR-DSS: The Cover Page

7.2.1 Bridge General Data

As shown in Figure 7.2, the first screen (tab) is related to the bridge's general data. This screen enables the inspector/user to indicate certain information about it (e.g., name, code, year completed, etc) and also inspection related data (e.g., inspector's name, inspection date, weather condition, etc).

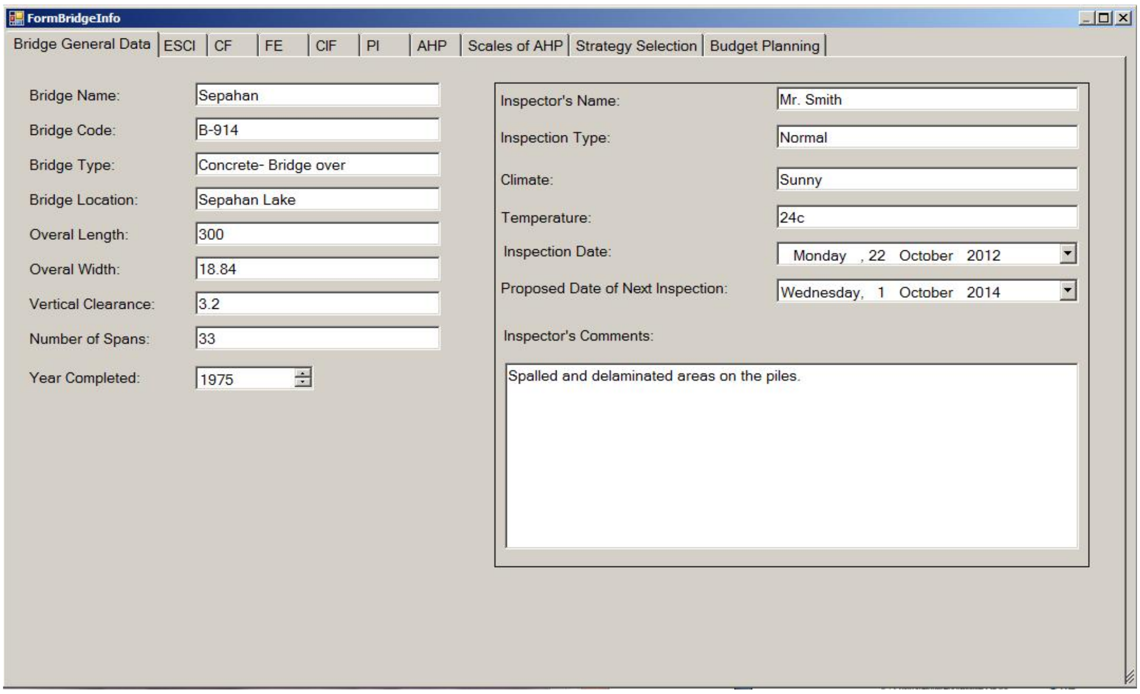
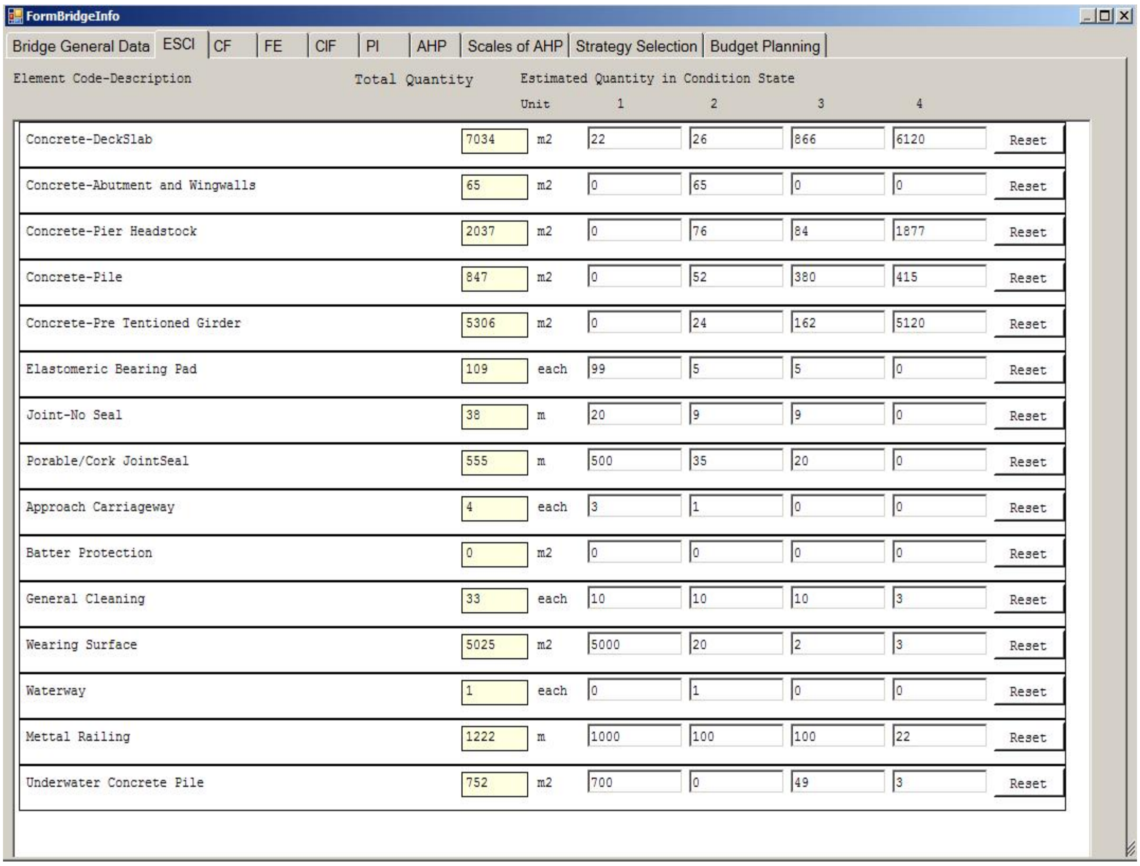


Figure 7.2 General Information

7.2.2 Element Structural Condition Index (ESCI)

The next step is to determine the element condition index (scaled 1 to 4) by the inspector to enter the quantities in each of the four condition states for each element. The Structural significance factor (si) and Material vulnerability factor (mi), introduced in Chapter 5, have been assigned as a default for each element. The program calculates the ESCI using Equation 5.1 (See Section 5.5) and proceeds to the next level which is the estimation of the causal factors in order to finalise the quantification of the Structural Efficiency (SE). Figure 7.3 below is the snapshot of structural condition information of a concrete bridge.



Element Code-Description	Total Quantity	Unit	1	2	3	4	
Concrete-DeckSlab	7034	m2	22	26	866	6120	Reset
Concrete-Abutment and Wingwalls	65	m2	0	65	0	0	Reset
Concrete-Pier Headstock	2037	m2	0	76	84	1877	Reset
Concrete-Pile	847	m2	0	52	380	415	Reset
Concrete-Pre Tentioned Girder	5306	m2	0	24	162	5120	Reset
Elastomeric Bearing Pad	109	each	99	5	5	0	Reset
Joint-No Seal	38	m	20	9	9	0	Reset
Porable/Cork JointSeal	555	m	500	35	20	0	Reset
Approach Carriageway	4	each	3	1	0	0	Reset
Batter Protection	0	m2	0	0	0	0	Reset
General Cleaning	33	each	10	10	10	3	Reset
Wearing Surface	5025	m2	5000	20	2	3	Reset
Waterway	1	each	0	1	0	0	Reset
Mettal Railing	1222	m	1000	100	100	22	Reset
Underwater Concrete Pile	752	m2	700	0	49	3	Reset

(Column heading over 1–4: Estimated Quantity in Condition State)

Figure 7.3 Bridge Elements Condition

7.2.3 Causal Factor (CF)

Once the ESCI evaluation has been finalised, the inspector/bridge maintenance planner is required to define the causal parameters introduced in Chapter 5 including age, environmental/aggressive factors, road type and inspection quality. Each choice is linked to a number from 1 to 4 (as shown in Figure 7.4) and the overall value of CF is calculated (by the program) using Equation 5.2 (See Section 5.5.1).

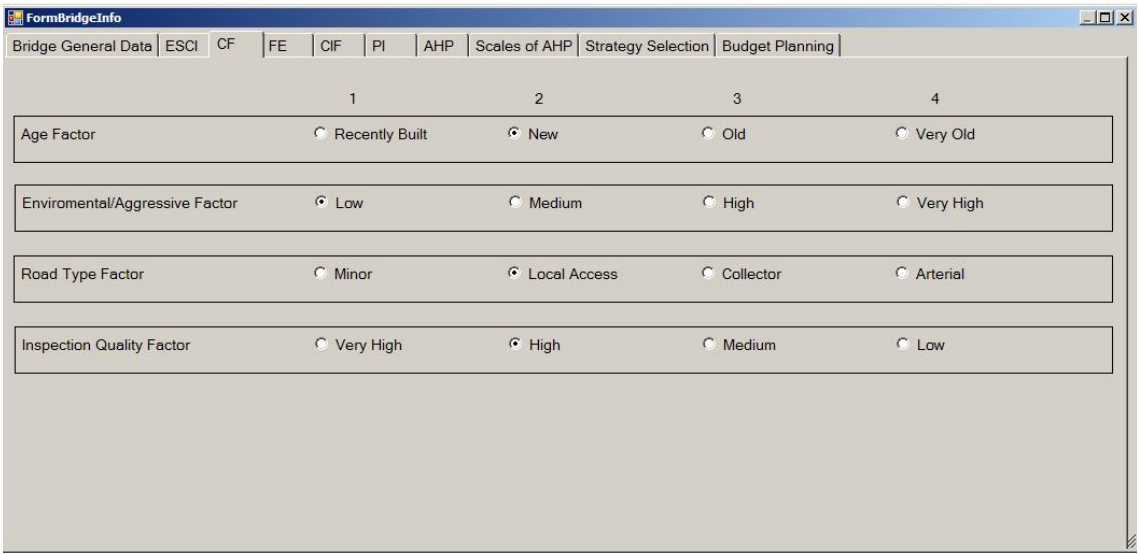


Figure 7.4 Causal Factors

7.2.4 Functional Efficiency (FE)

The fourth tab (presented in Figure 7.5) embraces the parameters involved in Functional Efficiency (FE) assessment including load bearing capacity (Lc), vertical clearance (Vc), width (Wb), bridge barrier (Bb) and drainage system (Ds).

Lc is the proportion of the actual live load capacity to initial design capacity.

Vc is the percentage of difference between the existing vertical clearance and the mandatory one.

Wb is the percentage of difference between the existing width and the target trafficable carriageway width of the bridge.

Bb is the percentage of bridge barrier systems not conforming to the defined target level.

Ds (Drainage System) is related to the performance of the bridge drainage system. According to the inspectors' judgment of one of the four linguistic condition states: Poor, Fair, Good or Excellent representing the bridge efficiency level should be selected.

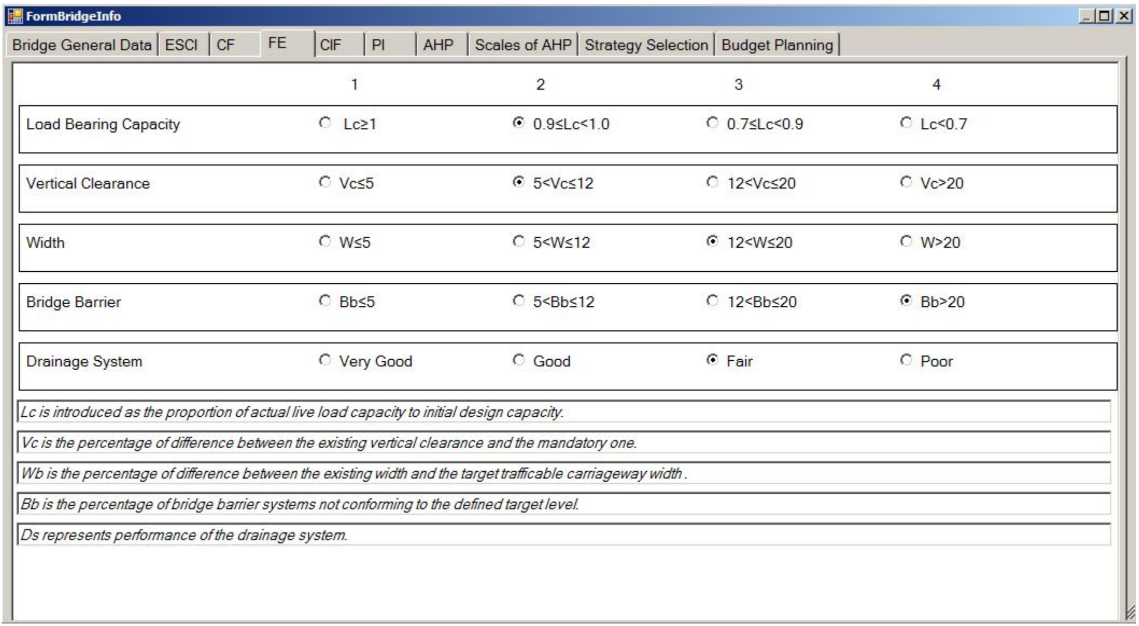


Figure 7.5 Functional Efficiency (FE) Factors

7.2.5 Client Impact Factor (CIF)

As shown in Figure 7.6, this tab simply provides a few option buttons addressing four linguistic conditions for evaluation of the client preferences in terms of socio-economic, political and historical considerations.

This part of assessment is quite subjective but significant enough to note, therefore the key decision maker or bridge maintenance planner should become involved to assign the appropriate rate in regard to this parameter.

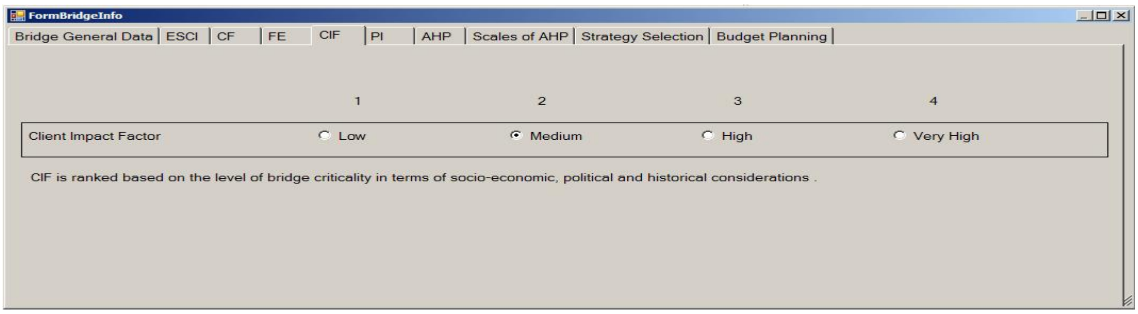


Figure 7.6 Client Impact Factors (CIF)

7.2.6 Priority Index (PI)

Structural Efficiency (SE), Functional Efficiency (FE) and Client Impact Factor (CIF) as the main parameters engaged in priority assessment of bridges have been estimated by the program using the relevant equations in Chapter 5. The outputs appear in the sixth screen (PI). The default weights have been defined as SE=0.6, FE=0.2 and CIF=0.2. However the program is flexible enough to allow the decision makers/maintenance planners to enter their own weights based on their own priorities. For example, one of the interviewees allocated 0% weight for CIF, 60% and 40% for SE and FE respectively.

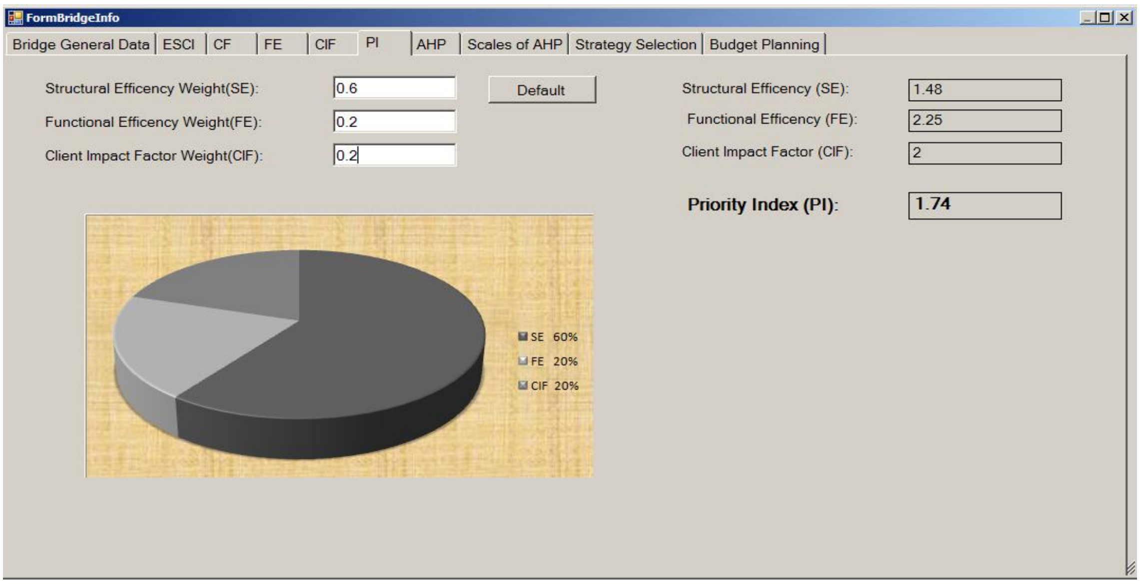


Figure 7.7 Priority Index (PI)

The Priority Index (PI) will be calculated through Equation 5.8 and the result will appear on the PI screen. The CBR-DSS saves the results for individual bridges and ranks them (based on the PI value) in descending order.

7.2.7 Criteria Weighting Using AHP

As previously discussed in Chapter 6, the eigenvector approach of AHP is employed for criteria weighting. The decision maker is required to compare the involved criteria in pairs and specify the quantity of judgments according to the scale for relative importance provided by Saaty (2004). Figure 7.8 presents the screen which has been added as a user guide for selecting the appropriate scale.

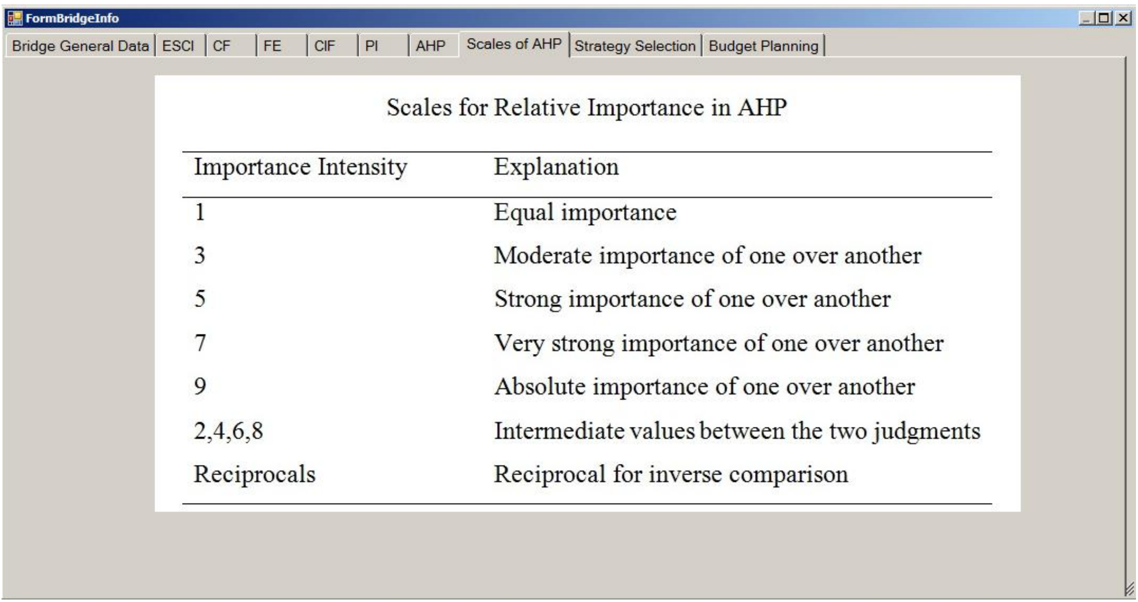


Figure 7.8 1-9 Scales for Relative Importance (Saaty 1980)

Six parameters, including “Service Life”, “Safety”, “Cost”, “Environmental Impact”, “Traffic Disruption” and “Legal/Political” have been selected as the main criteria and introduced as a default to CBR-DSS.

The next step is to construct the AHP matrix. The total number of each comparison matrix is n^2 (n = number of criteria). Excluding the diagonal elements representing the equal importance of each criterion compare to itself (=1) and also dependent upper or lower triangle elements for inverse comparisons, the required number of judgments will decrease to $(n^2-n)/2$. Therefore in the case of having six parameters, fifteen pair-wise comparisons are required to be performed by the user. Figure 7.9 shows the performance of CBR-DSS for AHP matrix construction.

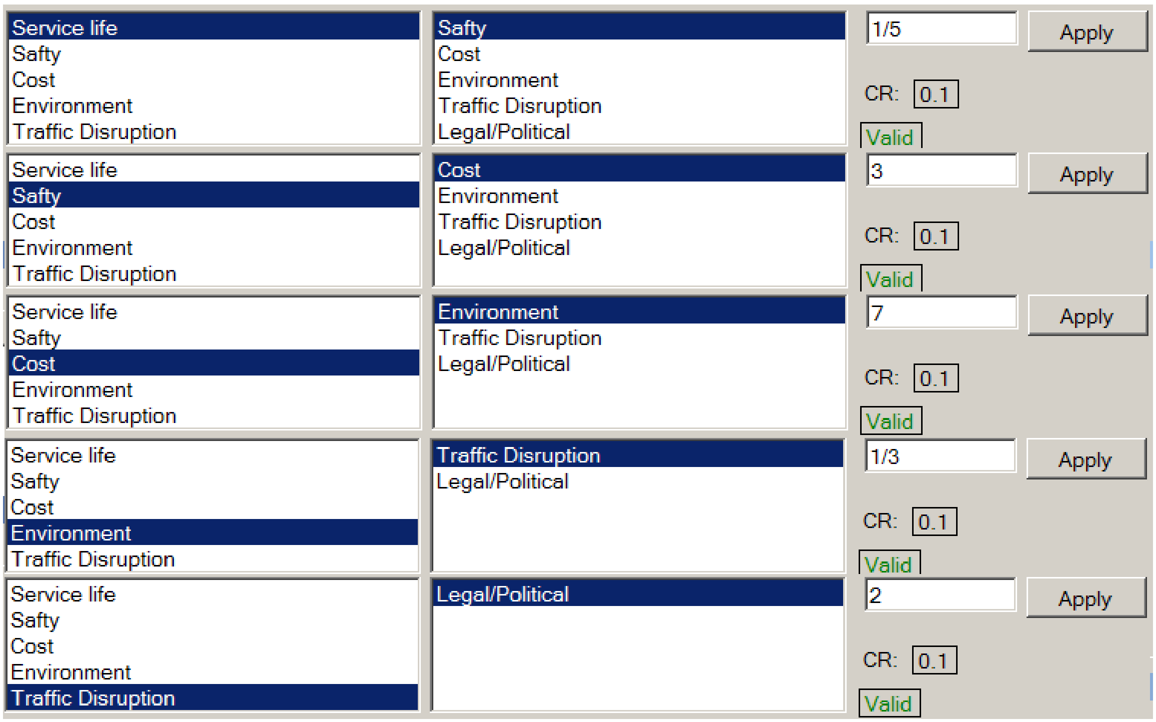


Figure 7.9 Fifteen Sets of Pair-Wise Comparisons

As previously discussed, the decision makers may be unable to provide completely consistent comparisons, it is therefore required that the pair-wise comparison matrix should have an adequate consistency, which can be checked by the consistency ratio (CR) introduced in Chapter 3 (section 3.7.2). If the CR is equal or less than 0.1, then the program will confirm the validity of judgments, otherwise another try will be required.

At the final level, the CBR-DSS program calculates the vector of weights (which are normalised to the sum to one) using the principal eigenvector of the comparison matrix. Figure 7.10 is a snap shot of CBR-DSS's interface for criteria weighting using AHP methodology. The AHP matrix is constructed by the program and the output (final weights) will appear in the upper right corner of the screen.

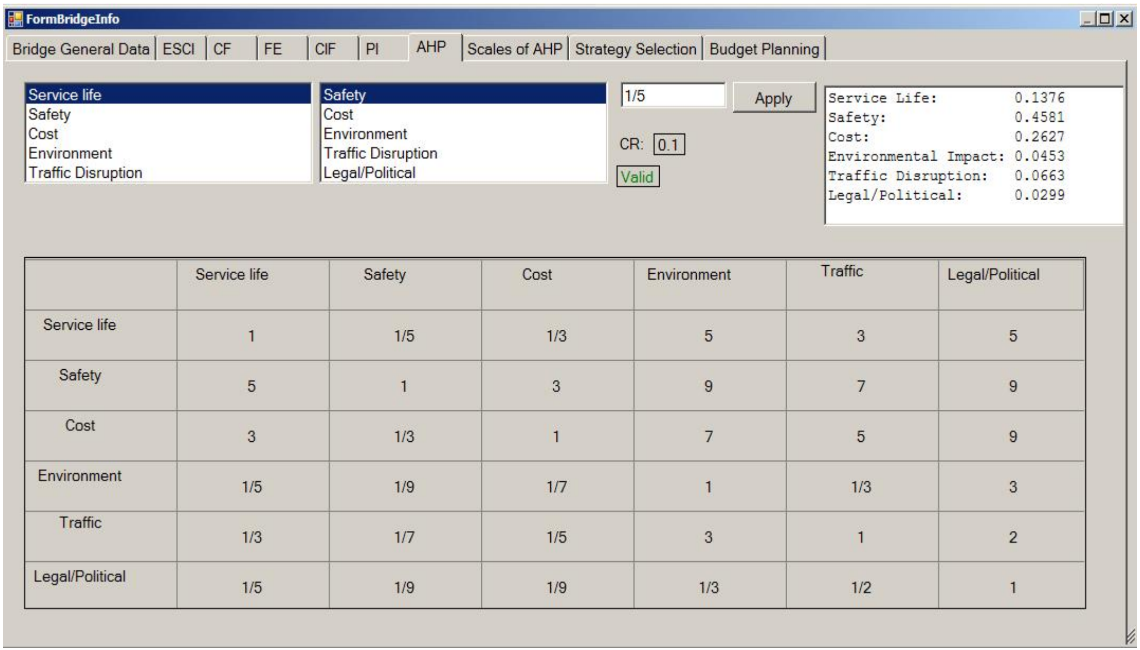


Figure 7.10 Criteria Weighting Using AHP Methodology

7.2.8 Strategy Selection

Once the criteria weighting has been finalised, the program proceeds to the next step which is the major strategy selection using modified SMART methodology. The decision outcome at this level is made at the project level for each individual bridge. The user/decision maker should rank the alternatives using some cardinal numbers (1-6) representing the score of each option in regards to each criteria. Figure 7.11 illustrates the decision matrix constructed in CBR-DSS that provides the best major strategy, based on the maximum score achieved, through the SMART tool. The weights are imported from the AHP outputs (previous tab) in a percentage (%).

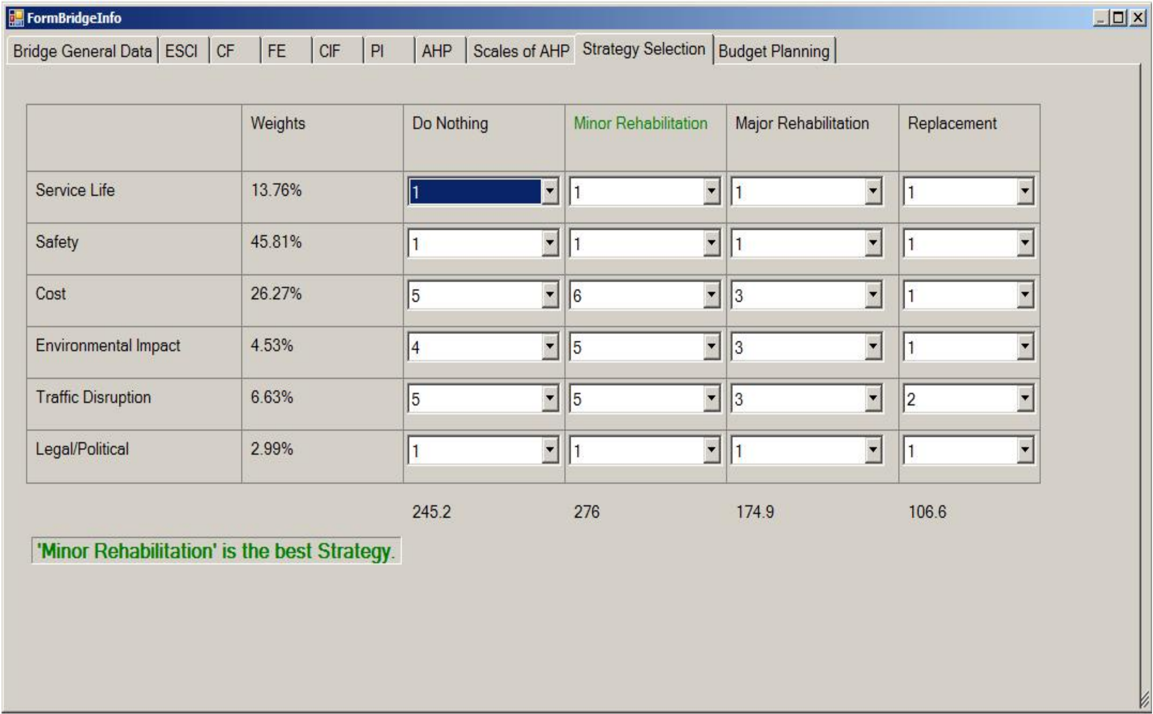


Figure 7.11 Strategy Selection

7.2.9 Budget Planning

The final screen presents the selection of the best remediation plan at the network level considering the budget limitation based on the methodology discussed in Chapter 6.

This method is developed based on analysing the various combinations of MR&R alternatives for top ranked bridge projects. Each combination is a nominee program and the total cost of any combination must not exceed the available budget.

CBR-DSS is programmed to develop a remediation plan for the two top bridge projects (with the highest overall PI) taking to account the overall score achieved through SMART and the available budget. Figure 7.12 presents the remediation plan and budget prioritisation procedure for the top critical projects. The unit costs for MR&R strategies and the available budget are specified and entered by the user. Other required data for this part of the project can be either imported from the database or entered by the user manually.

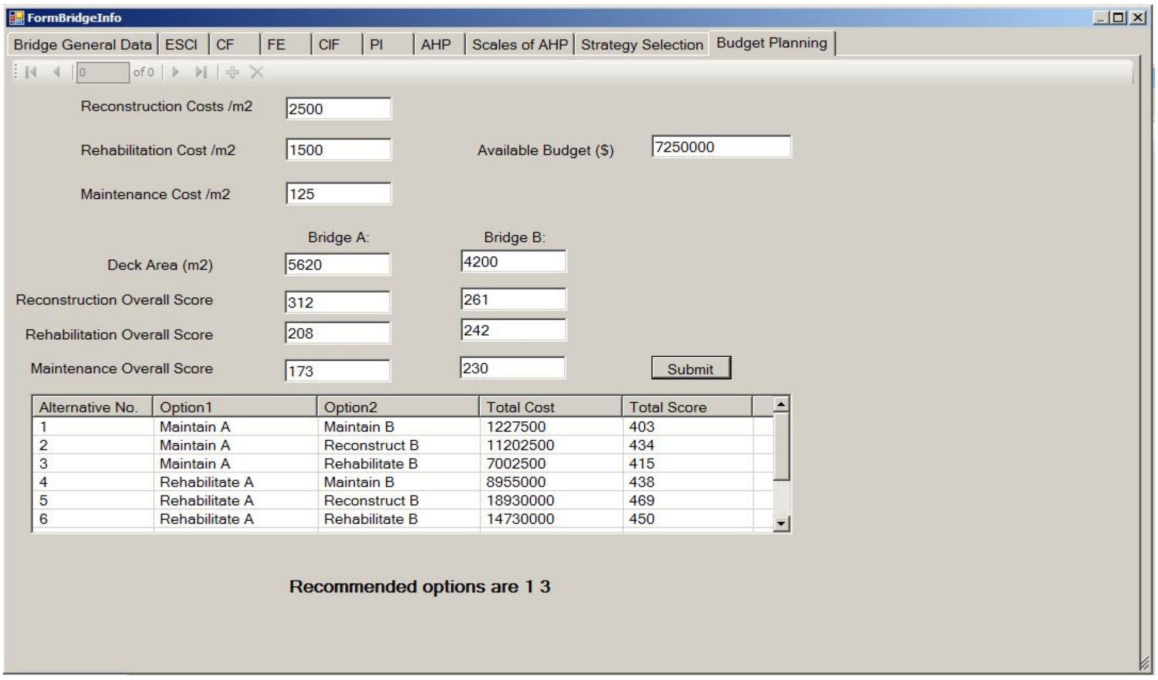


Figure 7.12 Budget Planning

7.3 Verification

Verification through case studies is accomplished to determine the utility of proposed model and the extent of its capabilities. Required data was extracted from the reports provided by the bridge management division of the Roads and Maritime Services (RMS). Missing data in the documented files was compensated by the inspectors/bridge maintenance planner's assessments. Case studies are presented in the following sub sections to test the validity of the proposed model. The bridges' names are not disclosed because of the author's commitment to privacy issues.

7.3.1 Case Study I: Condition Assessment and Priority Ranking

In order to verify the application of the first phase of CBR-DSS, a sample sub-network consisting of six bridge projects in New South Wales (N.S.W) has been chosen. Required data was extracted from the reports provided by the bridge management division of the Roads and Maritime Services (RMS). Some information was not found in the documented files, this was compensated by requesting bridge inspectors or bridge maintenance planners to provide their assessments for the missing data.

The Priority Index of all the bridges was calculated in order to rank them for any possible MR&R actions. In all cases, resource allocation starts from the bridges with the highest priorities. Table 7.1 represents the condition assessment procedure of a 39 year old bridge situated approximately 10 kilometres south of Wollongong, adjacent to the coastline (introduced as Bridge F in this study). According to the inspection reports all the piers are footed in saline water, and there is ongoing cracking of columns and headstocks. Testing revealed high chloride contamination levels. These levels implied that corrosion was past the acceptable threshold, and remediation was required. This could slow the degradation process.

The total quantity of each category of elements and the quantity associated with each condition state were estimated by the inspection team. The values of the causal factors including age (A), environmental aggressive factors (E), road type (R) and inspection (I) are identified by either the inspectors or the bridge maintenance planner. In this case, the bridge was built in 1972 and now has been in its second quarter of its service life (A=2). In terms of environmental condition this bridge has been exposed to severe pollutants and the highest value (E=4) has been assigned for that mean. The road which bridge was built over is a collector (R=3) and the inspection quality is reasonably high (I=2).

The Element Structural Condition Index (ESCI), the Causal Factor (CF) and finally the Structural Efficiency (SE) are then calculated using equation 5.1, 5.2 and 5.3 respectively.

Table 7.1 Evaluation of the Overall Bridge Priority Index (PI) for Bridge F

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state				ESCI (Eq1)	Si	Mi	ESCI*Si*Mi
					1	2	3	4				
1	**BELA**	Elastomeric Bearing Pad	109	ea	0	0	83	26	4.00	3	3	36.00
2	**CABW**	Concrete-Abutment and Wingwalls	65	m2	0	65	0	0	2.00	2	2	8.00
3	**CDSL**	Concrete-Deck Slab	7034	m2	22	26	866	6120	3.86	3	2	23.16
4	**CPHS**	Concrete-Pier Headstock	2037	m2	0	76	84	1877	3.88	4	3	46.61
5	**CPIL**	Concrete-Piles/Piers	847	m2	0	52	380	415	3.43	4	2	27.43
6	**CPRG**	Concrete-Pre-tensioned Girder	5306	m2	0	24	162	5120	3.96	4	4	63.37
7	**JNOS**	Joint - No Seal	38	m	0	0	12	26	3.68	1	1	3.68
8	**JPOS**	Pourable / Cork Joint Seal	555	m	0	0	125	430	3.77	1	1	3.77
9	**MAPP**	Approach Carriageway	4	ea	3	1	0	0	1.25	1	1	1.25
10	**MBAT**	Batter protection	158	m2	0	0	102	56	3.35	1	1	3.35
11	**MGCL**	General Cleaning	33	ea	0	0	33	0	3.00	1	1	3.00
12	**MWES**	Wearing surface	5025	m2	0	0	1214	3811	3.76	1	1	3.76
13	**MWWY**	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
14	**RMET**	Metal Railing	1222	m	0	70	63	1089	3.83	1	1	3.83
15	**RMIS**	Miscellaneous Railing	629	m	0	0	289	340	3.54	1	1	3.54
16	**RPNT**	Railing Paint Work	1216	m	0	0	13	1203	3.99	1	1	3.99
17	**UCPL**	Underwater CPIL - Concrete-Pile	752	m2	0	0	124	628	3.84	4	2	30.68
		∑(ESCI*Si*Mi)										***267.43***

Causal Factor			**A**	**E**	**R**	**I**				
CF= *0.411* **A**+0.120**E**+0.107**R**+0.362**I**			**2**	**4**	**3**	**2**				***2.35***

SE=CF * ∑(ESCI*Si*Mi)/16n	***SE=2.35*251.90/ (16*17)***	***2.31***

FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds		**L.C=2**	**Vc=1**	**Wb=2**	**Bb=2**	**D.S=2**		***1.90***
	FE=0.7(2)+0.1(1)+0.1(1)+0.05(2)+0.05(2)							

CIF		Low	**Medium**	High	Very High		***2.00***

PI= *0.6* ***SE+*** *0.2* ***FE+*** *0.2* ***CIF***	***PI=0.6(2.31)+0.2(1.9)+0.2(2.0)***	***2.16***

The overall Priority Index (PI) for Bridge F was 2.16. In comparison to the condition index of the other bridges in the network (presented in the Appendix C) it had the highest rate and therefore has been targeted as the top priority for remedial action (See Figure 5.5).

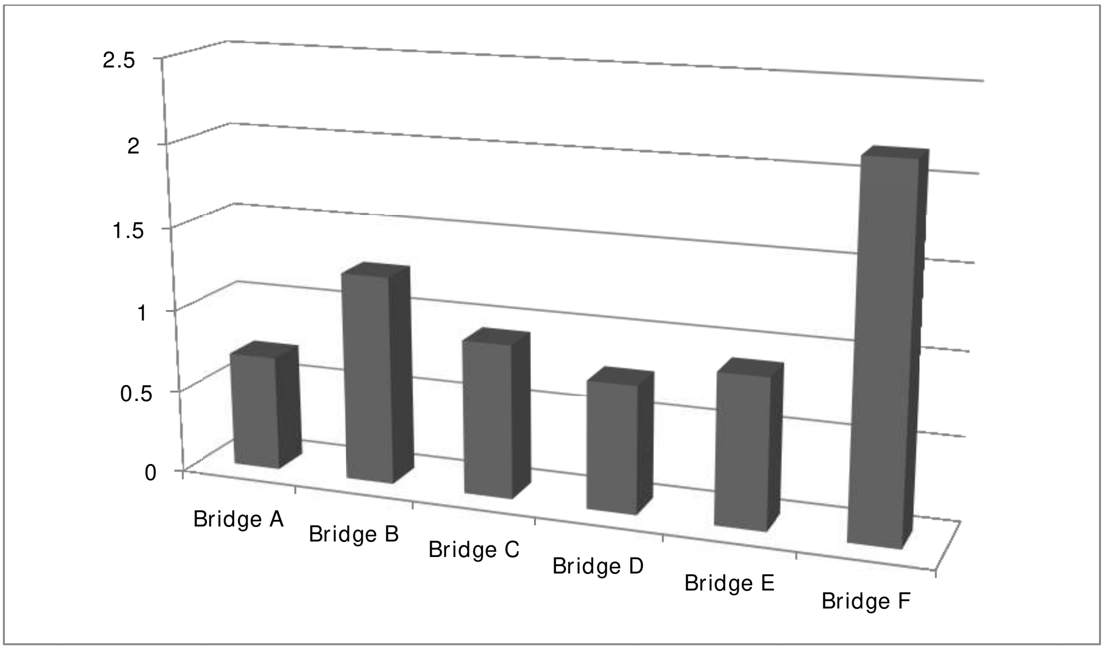


Figure 7.13 Charts Presenting the Priority Index of Six Bridges in a Network

7.3.2 Case Study II: Remediation Planning at Project Level

The rehabilitation project of Bridge N was chosen as a case study to demonstrate the applicability and validity of the proposed methodology. This bridge was designed and constructed in 1956. The overall length of the existing deck is 18.26 m with two spans of 9.14 m each. Following the detailed investigations in 2002 it was determined that the bridge is suffering from the on-going deterioration of the concrete piles and on-going scouring of the bridge abutments. Based on the analysis of asset management section of RMS, bridge replacement was found as the most effective strategy.

To support the current research, a detailed report for the bridge has been provided in order to test the proposed DSS method by comparing the results obtained from it against the actual decisions made for the bridge.

A site visit was conducted by the RMS bridge maintenance planner and project manager in conjunction with RMS bridge engineers from Parramatta. The primary objective of the site visit was to identify preliminary options to rehabilitate the bridge based on the options outlined in previous investigations and visual inspection of the bridges. Routine maintenance, minor rehabilitation (repair), major rehabilitation (strengthening) and replacement were examined as potential methods for bridge remediation:

The modified Simple Multi Attribute Rating Technique (SMART) has been employed to evaluate the major remediation strategies for the bridge. In this approach, as explained in Section 6.5, the limitations and constraints are expressed quantitatively by means of the weight of the objective values in the available pool of alternatives defined by the decision maker.

The first step is decomposing the problem into a hierarchy structure as is shown in (Figure 7.14). A three-level hierarchy structure is used, where the first level is the main goal of the ranking exercise, the second level includes the criteria and the third level holds the possible remediation strategies.

To perform this step, two experts from the industry who were involved in the management of this bridge were requested to provide the inputs. The experts were first required to determine the evaluation criteria (and sub-criteria if necessary). In their view many of the sub-criteria addressed in the hierarchy of Figure 6.7 such as aestheticism and work load were redundant and not necessary to be considered in the decision making procedure of this specific project. The final decision making criteria were identified as safety, cost, useful service life, traffic disruption, environmental impact and legal/political considerations.

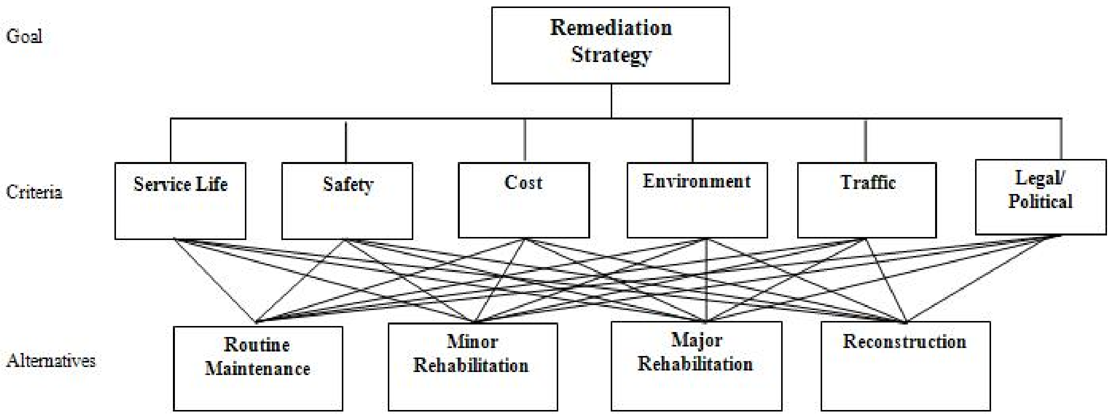


Figure 7.14 Three Level Hierarchy Structure: MCDM for Bridge N

The experts were then asked to compare the criteria in pairs with respect to the overall goal. The AHP method has been conducted to estimate the vector of priority (VOP) for the introduced criteria based on the experts' judgments. The provided matrix is presented in Figure 7.15 below.

	Service Life	Safety	Cost	Environmental Impact	Traffic Disruption	Legal/ Political
Service Life	1	1/5	1/3	5	3	5
Safety	5	1	3	9	7	9
Cost	3	1/3	1	7	5	9
Environmental Impact	1/5	1/9	1/7	1	1/3	3
Traffic Disruption	1/3	1/7	1/5	3	1	2
Legal/ Political	1/5	1/9	1/9	1/3	1/2	1
Σ	9.73	1.90	4.79	25.33	16.83	29.00

Figure 7.15 AHP Matrix for Bridge W

According to the obtained VOP presented below, safety has the highest weight and legal/political issues have the lowest contribution.

$$\text{VOP}=\begin{bmatrix}0.1376\\0.4581\\0.2627\\0.0453\\0.0663\\0.0299\end{bmatrix}=\begin{bmatrix}\text{Service Life}\\\text{Safety}\\\text{Cost}\\\text{Environment}\\\text{Traffic Disruption}\\\text{Legal/ Political}\end{bmatrix}$$

As discussed in chapter 3, since the decision makers may be unable to provide perfectly consistent pair wise comparisons, it is demanded that the pairwise comparison matrix should have an adequate consistency, which can be checked by the following consistency ratio (CR) which was primarily introduced in Section 3.7.2.

$$\text{CR}=\frac{(\lambda max-n)/\,(n-1)}{RI} \qquad \text{(Equation 7.1)}$$

Where,

λ_{max}=9.73(0.1376) + 1.9(0.4581) + 4.79(0.2627) + 25.33(0.0453) + 16.83(0.0663) + 29(0.0299)= 6.59

Random inconsistency index (RI) for 6 criteria is extracted from the following table provided by Ishizaka (2004).

Table 7.2 Random Inconsistency Index, Adapted from Ishizaka (2004)

N	1	2	3	4	5	**6**	7	8	9	10
RI	0	0	0.58	0.9	1.12	**1.24**	1.32	1.41	1.45	1.49

Now all the parameters are provided and CR is calculated based on Equation 6.1. Since the value of CR is less than 1, it can be concluded that the accomplished judgement is consistent.

$$\text{CR}=\frac{(\lambda max-n)/\,(n-1)}{RI}=0.095<0.1$$

Then the experts were asked to compare the major alternatives with respect to each criterion using SMART methodology. Finally, global priorities of the different major strategies were calculated by multiplying the weights of the alternative associated with each criterion by the criterion weight and finding the overall sum as shown in Table 7.3.

As shown in Table 6.6, "Replacement" has got the highest score in this analysis. The system performed well against past decisions undertaken by the RMS in 2009.

Table 7.3 Global Priorities of Different Major Strategies

Criteria \ Alternative	Weights %	Routine Maintenance	Minor Rehabilitation	Major Rehabilitation	Reconstruction
Service Life	**13.76**	1	1	3	6
Safety	**45.81**	1	1	3	5
Cost	**26.27**	5	5	3	1
Environmental Impact	**4.53**	4	3	3	1
Traffic Disruption	**6.63**	5	5	5	1
Legal/Political	**2.99**	1	1	2	3
Overall Score		245.2	240.7	310.3	**358**

RMS has completed the $3.7 million replacement of Bridge N. The safety concerns that were identified with the original bridge have been considered in the design of the new bridge. These safety concerns could not have been addressed with further maintenance or rehabilitation of the old bridge.

7.3.3 Case Study III: Remediation Planning at Element Level

Bridge W is situated south of Wollongong, adjacent to the coastline. This bridge has experienced ongoing cracking and spalling problems, probably due to spray carried by strong southerly winds, insufficient consolidation during construction, and the formation of inner cracks that transforms into spalls. The estimated ESCI of pier element was 3.80, which was well above the accepted threshold defined by the decision maker (ESCI=2).

Three options were primarily proposed by the inspectors: Recasting with concrete, Surface coating and Cathodic Protection (CP). Cost, service life, aesthetics, environmental damage and traffic disruption have been identified as the main client constraints. A three level hierarch structure addressing the goal, criteria and finally, the alternatives, has been constructed (Figure 7.16).

Two experts have been involved in pair wise comparison of the client constraints (through AHP methodology) in order to rank the criteria and also specifying the score of each alternative in regard to those parameters.

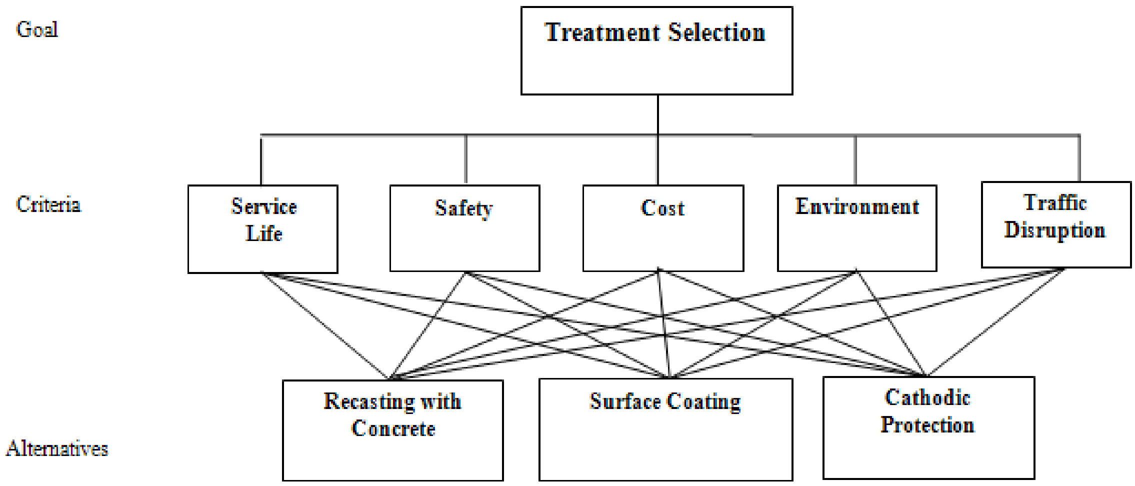


Figure 7.16 Three Level Hierarchy Structure: MCDM for Bridge W

The AHP matrix has been developed based on the pair wise comparison of the criteria performed by the bridge manager (Figure 7.17).

	Environmental Damage	Service Life	Cost	Aesthetics	Traffic Disruption
Environmental Damage	1	1/5	1/3	5	3
Service Life	5	1	3	9	7
Cost	3	1/3	1	7	5
Aesthetics	1/5	1/9	1/7	1	1/3
Traffic Disruption	1/3	1/7	1/5	3	1
Σ	9.53	1.79	4.68	25	16.33

Figure 7.17 AHP Matrix for Bridge W

At the next step the eigenvector of the AHP matrix indicating the VOP was found:

$$\text{VOP}=\begin{bmatrix}0.13\\0.50\\0.26\\0.03\\0.07\end{bmatrix}=\begin{bmatrix}\text{Environmental Damage}\\\text{Service Life}\\\text{Cost}\\\text{Aesthetics}\\\text{Traffic Disruption}\end{bmatrix}$$

Then the consistency of pair wise comparison matrix was checked through estimating the CR.

λmax (E1) =9.53 (0.13)+1.79 (0.50)+4.68 (0.26)+25(0.03)+16.33 (0.07)= 5.35

$$\text{CR}=\frac{(\lambda max-n)/\,(n-1)}{RI}=0.78<0.1 \qquad \text{OK}$$

The DSS calculated the best treatment option for the degradation of the concrete piers on Bridge W (See Table 7.4). The application of electrical potential (cathodic protection) received the highest ranking score (=418). This method ranked superior for minimal environmental damage and maximum life expectancy. The decision made by the RMS was the same; the concrete was patched and then cathodic protection was applied.

Table 7.4 Global Priorities of Different Major Strategies

Alternative / Criteria	Weights %	Recasting with Concrete	Surface Coating	Cathodic Protection
Environmental Damage	**13**	4	4	3
Service Life	**50**	3	3	6
Cost	**26**	3	4	2
Aesthetics	**3**	3	3	2
Traffic Disruption	**7**	3	4	3
Overall Score		310	343	418

7.3.4 Case Study IV: Remediation Planning at Network Level

To demonstrate the development of the proposed methodology for remediation planning at the network level, the following case study for prioritisation and strategy selection is presented. Those three projects with the highest priority index (F, B and C) are selected. The cost of the three courses of action (reconstruction, rehabilitation and maintenance) has been extracted from the existing cases in RMS and the costs per square meter considering the contingency was roughly estimated. Table 7.5 shows the cost information and the overall score associated with each option (based on the outputs of the modified SMART) for the top three bridges which have been ranked based on the priority index.

Table 7.5 Costs and Overall Scores of Remediation Strategies for Top Three Projects

Bridge	Deck Area (m2)	Reconstruction Cost	Rehabilitation Cost	Maintenance Cost	Reconstruction Overall Score	Rehabilitation Overall Score	Maintenance Overall Score
F	7,034	17,585,000	10,551,000	879,250	312	208	173
B	595	1,487,500	892,500	74,375	261	242	230
C	1,516	3,790,000	2,274,000	189,500	416	231	15

The 27 possible alternatives are obtained from all the viable combinations of projects and remediation options as illustrated in Table 7.6. The total cost is estimated by adding up the cost of all the remediation options involved in each combination. In the same way, the total score is obtained by calculating the sum of the overall scores of all the actions involved in each combination.

One of these alternatives should be chosen as the recommended strategy and the associated cost must be less than the available fund. For example if the available budget is $3.5 million, alternatives that cost more will be eliminated, that means alternatives 2, 3, 6 and 9 will remain. Among these, alternative 2 has the highest overall score of 634 and a total cost of $2,655,450 and alternative 6 has the second overall score of 449 and a cost of $1,915,000. Alternative 2 has a higher cost (within the budget) but can cause more improvement and development in the network. Therefore alternative 2 (Maintain A, Maintain B and Rehabilitate C) comes to the first priority.

Table 7.6 All the Possible Combinations, Associated Costs and the Overall Scores

Alternative No	Option1	Option2	Option3	Total Cost	Total Score
1	Maintain F	Maintain B	Reconstruct C	4,743,625.00	819.00
2	Maintain F	Maintain B	Rehabilitate C	3,227,625.00	634.00
3	Maintain F	Maintain B	Maintain C	1,143,125.00	418.00
4	Maintain F	Reconstruct B	Reconstruct C	6,156,750.00	850.00
5	Maintain F	Reconstruct B	Rehabilitate C	4,640,750.00	665.00
6	Maintain F	Reconstruct B	Maintain C	2,556,250.00	449.00
7	Maintain F	Rehabilitate B	Reconstruct C	5,561,750.00	831.00
8	Maintain F	Rehabilitate B	Rehabilitate C	4,045,750.00	646.00
9	Maintain F	Rehabilitate B	Maintain C	1,961,250.00	430.00
10	Rehabilitate F	Maintain B	Reconstruct C	14,415,375.00	854.00
11	Rehabilitate F	Maintain B	Rehabilitate C	12,899,375.00	669.00
12	Rehabilitate F	Maintain B	Maintain C	10,814,875.00	453.00
13	Rehabilitate F	Reconstruct B	Reconstruct C	15,828,500.00	885.00
14	Rehabilitate F	Reconstruct B	Rehabilitate C	14,312,500.00	700.00
15	Rehabilitate F	Reconstruct B	Maintain C	12,228,000.00	484.00
16	Rehabilitate F	Rehabilitate B	Reconstruct C	15,233,500.00	866.00
17	Rehabilitate F	Rehabilitate B	Rehabilitate C	13,717,500.00	681.00
18	Rehabilitate F	Rehabilitate B	Maintain C	11,633,000.00	465.00
19	Reconstruct F	Maintain B	Reconstruct C	21,449,375.00	958.00
20	Reconstruct F	Maintain B	Rehabilitate C	19,933,375.00	773.00
21	Reconstruct F	Maintain B	Maintain C	17,848,875.00	557.00
22	Reconstruct F	Reconstruct B	Reconstruct C	22,862,500.00	989.00
23	Reconstruct F	Reconstruct B	Rehabilitate C	21,346,500.00	804.00
24	Reconstruct F	Reconstruct B	Maintain C	19,262,000.00	588.00
25	Reconstruct F	Rehabilitate B	Reconstruct C	22,267,500.00	970.00
26	Reconstruct F	Rehabilitate B	Rehabilitate C	20,751,500.00	785.00
27	Reconstruct F	Rehabilitate B	Maintain C	18,667,000.00	569.00

7.4 Summary

In this Chapter the developed prototype system (CBR-DSS) that demonstrates the main functionalities of the proposed model has been presented. Snapshots of the different forms and reports produced by the prototype software are also included.

CBR-DSS has the major capabilities of a desired DSS as discussed in Chapter 3:

-It carries out all parts of the decision-making process: *intelligence, design, choice and implementation.*

-It is able to facilitate several *interdependent and/or sequential* decisions that *may be made once, several times, or repeatedly.*

-It is adaptive and flexible, and so users can add, change or re-organise basic elements.

-It is user friendly and has graphical interfaces.

Some case studies have been used to validate the developed decision support model. The analysis of the case studies show that the proposed decision support method produces applicable decisions regarding selection of the best alternative for bridge improvement projects.

8 SUMMARY, CONCLUSION AND FUTURE WORK

8.1 Summary

Bridges are critical components of the transportation infrastructure, since they connect highways and roadways as linking nodes and support an increasing amount of daily traffic. As bridges age, departments of transportation are faced with increasing pressure to keep their bridge networks healthy and operational with limited repair funds.

The main objective of this research, therefore, was to develop a practical and efficient decision support methodology for selecting and prioritising the actions necessary to maintain a bridge network within acceptable limits of safety, functionality and sustainability. The proposed framework is innovative in its ability to optimise decisions at the network level (which bridge should be repaired) as well as at the project level (best type of remediation strategy).

An extensive literature survey was performed to review the current practice in bridge management and the application of DSS as a strong support for decision making. The need to develop a unified bridge management practice was established based on the fact that many of the existing approaches are subjective and highly relied on the personal experience and use of organisational rules of thumb (heuristics). There were a few attempts to add more objectivity to the decision making process, but the multifaceted characteristics of the problem and multi objective nature of the decision have not been properly addressed. Moreover, the combined project and network level decisions were often ignored.

A conceptual framework for decision support system has been proposed as a result of the conducted research. The proposed decision support system consists of two main phases:

1) Condition assessment and priority ranking of bridges in the network.

2) Selection of the best remediation strategy at both project and network level based on decision criteria using reliable decision analysis tools.

A summary of the suggested model is presented in the following sections:

8.1.1 Condition Assessment and Priority Ranking of Bridges

A network level ranking method based on the evaluation of structural efficiency and functional efficiency of bridges taking into account the client impact factor was developed and presented as a dimensionless value introduced as Priority Index (PI).

Structural efficiency assessment is based on an element based condition evaluation, taking into account structural importance and material vulnerability of different elements, considering four main causal factors involved in the overall structural reliability of the components (including age, environmental aggressive factors, road type and inspection quality). An equation has been established for quantification of the Structural Efficiency (SE) that represents the overall structural reliability of a bridge.

Functional efficiency which indicates the quality of service has been considered in addition to structural efficiency. This attribute addresses the traffic volume that the bridge can withstand, which is mainly related to the load bearing capacity of the bridge, existing number of lanes or the width of the deck, vertical clearance and the barriers. Drainage system, provisions for pedestrians and cyclists and any post design changes are also included in this category of evaluation. Any deficiency associated with the above items can reduce the level of service and accelerate the deterioration process. Five main deficiencies that might be considered as threat for bridge safety and serviceability has been included in the framework of the developed assessment method: Load bearing capacity, vertical clearance, width, barriers and the drainage system. An equation has also been used for estimation of the functional efficiency.

Client impact factor builds the social implications of remediation into the risk assessment process. This factor can be ranked based on the level of bridge criticality in terms of socio-economic, political and historical considerations.

Priority Index (PI) integrates all the above mentioned factors that influence decision making. Using this index enables bridge/funding agencies to make decisions and set objectives backed up by strong logic.

8.1.2 Bridge Remediation Strategy Selection

A Multi Criteria Decision Making (MCDM) method was required to select the best alternative, while integrating both the qualitative criteria and quantitative measurements. There are two main quantities which should be properly addressed in the decision evaluation: 1) weight of the criteria and 2) rate of each alternative associated with each criterion.

SMART is robust and simple in terms of both the responses required of the decision maker and the manner in which the responses are analysed. The rating of alternatives is not relative, so that shifting the number of alternatives will not itself alter the decision scores of the original alternatives. In AHP pair wise comparison of the weights and alternatives and also consistency assessment (which enables the decision maker to identify those judgements that require reassessment) makes it more reliable.

Through the SMART process, both the above mentioned values are selected based on cardinal numbers representing the level of importance, but in AHP technique the quantities have been drawn from a set of pair wise comparisons that makes it more consistent and the same time more complex. A reasonable balance has to be set between the simplicity of SMART and complexity of AHP. In this study identifying the appropriate criteria (through risk analysis) and weighting the criteria have been highly emphasised. The eigenvector approach of AHP is a suitable way to provide accurate judgements and its strength justifies the complexity of using that. The proposed method is a combination of these two techniques, introduced as modified SMART which employs the eigenvector approach of Analytical Hierarchy Process (AHP) in order to extract experts' judgments and rate the criteria in a robust way.

Bridge maintenance planners have various criteria and constraints that must be coped with when endeavouring to propose the best possible solution for bridges. The main idea of using criteria is to measure the performance of alternatives in relation to the objectives of the decision maker based on a numeric scale. Five major categories of criteria including safety, functionality, sustainability, environment and legal/political constraints have been identified through level two of risk assessment.

The suggested method for remediation strategy selection at project level is based on the assumption that adequate fund is available for any MR&R action. Real decisions in practice use the network level objectives based on the fact that the budget is limited. To resolve this problem, a methodology is developed based on evaluating the various combinations of MR&R actions for top ranked bridge projects. The overall scores associated with each action which obtained through the strategy selection process (based on the degree that each strategy satisfies certain criteria) and the associated estimated costs are used to compare the different combinations. The alternative with the highest overall score and the estimated cost less than the available budget will be the recommended option.

8.2 Contributions

The main scope of this research was to develop a decision support methodology for bridge remediation that would improve knowledge in the area of infrastructure management. Based on the achieved developments, this research made a number of contributions which will be beneficial to transportation agencies, asset management consultants involved in the bridge infrastructure management. The main contributions are outlined as follows:

• An extensive review of the bridge management systems and their components and decision support models (Chapter 2 and 3). This knowledge was achieved by studying previous research and interviews with experts from transportation agencies.

• Development of a bridge condition assessment methodology and proposing an index (PI) for priority ranking of bridges in the network (Chapter 5).

• Development of a multi-criteria decision support method for remediation strategy selection and priority arrangement of a combination of bridge projects for budget allocation (Chapter 6).

• Development of an interactive and easy to use prototype decision support system known as CBR-DSS to implement the proposed methodology. CBR-DSS is able to facilitate several interdependent and/or sequential decisions that may be made once, several times, or repeatedly. It is adaptive and flexible, and so users can add, change or re-organise basic elements. It is user friendly and has graphical interfaces (Chapter 7).

• Validation of the developed method using case studies. The analysis of the case studies show that the proposed decision support method produces applicable decisions regarding selection of the best alternative for bridge improvement projects (Chapter 7).

8.3 Conclusion

Both the network ranking and the rehabilitation strategy selection method were developed and validated using case studies and information extracted during interviews with engineers from public organisations and consultants involved in the bridge rehabilitation projects. It has been concluded that the proposed model is able to add more objectivity and holism to the current approaches through considering the main aspects of the problem and attempting to quantify the major parameters. The analysis of case studies and the feedback received from the experts in regard to applicability of CBR-DSS has shown that the developed decision support methodology has the following benefits:

-Sufficiently flexible to allow decision makers to engage their judgments in the decision making process.

- Ability to deal with multi layers of data and multi criteria decision problems.

- Both the project and network levels of the bridge management process are considered.

- CBR-DSS has a potential to be used in practice and the general structure is also applicable for other types of infrastructures.

- Social/Political constraints are considered in addition to the technical conditions.

Despite the capabilities and benefits of the proposed methodology, it has some limitation and challenging issues that should be improved:

- The system is focused on bridge networks and ignores the interaction with roadways connected to the bridge.

-It has been assumed that the bridge condition rating will improve following the MR&R actions, but the system is not able to estimate the improvement in the condition rating.

-The risks associated with uncertainties in experts' judgement and data collection require further consideration and development.

-The system is not able to estimate the cost of alternative remediation strategies.

-Minor (Level 3) strategy selection has not been designed in the prototype system.

8.4 Recommendation for Future Works

Based on the above mentioned limitations, future research is recommended to be focused on the following items:

1- Developing methodologies for cost estimation of different remediation strategies considering all the engaged parameters.

2- Some of the uncertainties associated with experts' judgement could be taken into account as a risk and be considered in the formulas.

3- Expanding the prototype system to full-scale software which flexibly enables the decision maker to develop alternative hierarchy structures and to change decision elements.

4- Linking the bridge remediation decisions to the roadway repair decisions and arrive at optimal routing that minimises traffic interruptions.

5- Determining an estimate of the improvement in the condition rating because of a specific remediation plan.

6- Providing some correlation matrices that can select the level of association of defects with treatment techniques. The bridge maintenance planners can then select the most relevant alternatives as an input for comparison.

7- Expanding and generalising the current model for other types of bridges such as railway bridges.

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APPENDIX DEFECTS, CAUSE OF DEFECTS AND TREATMENT OPTIONS

Table A.1. Defects of Concrete Bridges (Adapted from Branco & de Brito, 2004)

A-A. Superstructure Global Behavior	
A-A1 Permanent deformation A-A2 Relative displacement	A-A3 Piers tilting A-A4 Vibration
A-B. Foundations/Abutments/Embankments	
A-B1 Scour A-B2 Settlement A-B3 Rotation A-B4 Settlement/ failure of the approach slab A-B5 Embankment erosion	A-B6 Embankment slippage A-B7 Heavy vegetation growth/burrows A-B8 Obstruction of the waterway by debris A-B9 Silting
A-C. Concrete Elements	
A-C1 Corrosion stain A-C2 Efflorescence/moisture stain A-C3 Concretion/swelling A-C4 Wear/scaling/disintegration A-C5 Voids/porous area/honeycombing/ aggregates nest A-C6 Stratification/segregation	A-C7 Delamination/spalling A-C8 Concrete crushing A-C9 Map cracking A-C10 Longitudinal crack A-C11 Transverse crack A-C12 Diagonal crack A-C13 Crack over/ under a bar
A-D. Reinforcement/Cables	
A-D1 Exposed bar (loss of cover) A-D2 Exposed duct (loss of cover) A-D3 Exposed strand/wire (loss of cover) A-D4 Corroded bar A-D5 Bar with reduced cross-section	A-D6 Broken bar A-D7 Broken strand/wire A-D8 Deficiently grouted duct A-D9 Faulty sealing of prestress anchorage A-D10 Corroded anchorage

A-E. Bearings	
A-E1 Obstruction due to debris/ vegetation A-E2 Obstruction due to rust A-E3 Broken retainer-bars A-E4 Cracked roller A-E5 Roller failure A-E6 Corrosion A-E7 Deteriorated base plate/pot	A-E8 Detachment/failure of anchor bolts/pins A-E9 Lead crushing A-E10 Elastometer creep A-E11 Elastometer crushing A-E12 Bearing displacement A-E13 Failure of the bearing seat A-E14 Moisture/trapped water
A-F. Joints	
A-F1 Vertical misalignment(traffic shock) A-F2 Loss of parallelism A-F3 Transverse shear cut A-F4 Obstruction due to debris A-F5 Obstruction due to rust A-F6 Corrosion A-F7 Detachment/ failure of anchorages	A-F8 Loosening/failure of bolts/pins A-F9 Cracking of the metallic components A-F10 Displacement/failure/deterioration of the filler/sealant A-F11 Moisture/trapped water/vegetation growth
A-G. Wearing Surface (Asphalts).Watertightness	
R-G1 Localised patching [m] R-G2 Waterproofing and asphalt repaving [m]R-G3 Patching, waterproofing and asphalt repaving [m]	R-G4 Latex modified concrete overlay [m] R-G5 Concrete overlay, waterproofing and asphalt repaving [m] R-G6 Cathodic protection [m]
A-H. Water Drainage	
R-H1 Removal of debris/obstructing asphalt from deck drain or gutter [m] R-H2 Gutter joint repair [m R-H3 Deck drain extension downwards/upwards [m]	R-H4 Diversion of point of discharge of deck drain [m] R-H5 Installation of new deck drains/void tubes [m] R-H6 Replacement of drain/gutter/void tubes [m]

A-I. Secondary Elements	
R-I1 Installation/replacement of traffic signs [m]	R-I6 Welding repair [m]
	R-I17 Replacement of sidewalks [m]
R-I2 Installation/replacement of curbs/traffic	R-I8 Replacement of utilities [m]
	R-I9 Installation/replacement of lighting [m]
barrier wall [m]	
R-I3 Replacement of hand railing [m]	R-I0 Replacement of edge beams [m]
R-I4 Blast cleaning/coating [m]	R-I11 Replacement of acroterium [m]
R-I5 Replacement/tightening of bolts/pins [m]	R-I12 Removal of vegetation growth [m]

Table A.2 Possible Causes of Defects for Concrete Bridges (Branco & Brito, 2004)

C-A. Design Errors	
C-A1 Deficient layout of the bridge C-A2 Deficient hydraulic design C-A3 Wrong choice of materials C-A4 Wrong/ missing design loads C-A5 Over-simplified structural modeling C-A6 Missing temperature effects on long or skewed decks C-A7 Non-consideration of long-term effects in the design of vertical elements C-A8 Non-consideration of instability effects in the design of vertical elements C-A9 Non-consideration of the building process C-A10 Wrong seismic/horizontal loads design C-A11 Non-detected computer analysis mistakes C-A12 Deficient foundation modelling C-A13 Deficient scour design/protection C-A14 Insufficient reinforcement/prestress design cover C-A15 Inadequate reinforcement/prestress spacing	C-A16 Other reinforcement/prestress detailing errors C-A17 Defficient metallic connections design/detailing C-A18 Defficient bearings design/positioning C-A19 Defficient joints design/positioning C-A20 Excessive exposed areas in structural elements /faulty geometric design C-A21 Inability to predict the replacement of heavily deteriorated elements C-A22 Difficulty/impossibility of inspection of parts of the structure C-A23 Non-prevision of a minimum slope in quasi-horizontal surfaces C-A24 Drainage directly over concrete, a joint, a bearing or an anchorage C-A25 Other drainage design faults C-A26 Lack of waterproofing membrane C-A27 Deficient design specifications C-A28 Incomplete/contradictory/over-compact drawings
C-B. Construction Errors	
C-B1 Wrong interpretation of drawings C-B2 Inexperienced personnel C-B3Deficient soil compaction C-B4 Deficient materials transport/ storing	C-B14 Early/faulty demoulding C-B15 Premature loading C-B16 Faulty patching C-B17 Faulty placing of waterproofing membrane

C-B5 Changes in prescribed materials mixing proportions C-B6 Use of inappropriate materials (contaminated water, over-reactive aggregates) C-B7 Faulty casting C-B8 Overuse of formwork/faulty formwork C-B9 Deficient concrete compaction/curing C-B10 Cold joint C-B11 Inaccurate reinforcement/prestress positioning/detailing C-B12 Inadequate prestressing C-B13 Deficient grouting of prestress cables ducts	C-B18 Deficient asphalt paving/repaving of the deck C-B19 Faulty asphalt patching C-B20 Obstruction of drains with asphalt C-B21 Faulty bolt/pin tightening C-B22 Defective welding C-B23 Faulty coating C-B24 Faulty construction/placing of joints C-B25 Deficient placing of bearings C-B26 Insufficient/ inexistent quality control
C-C. Natural Accidental Actions	
C-C1 Earthquake C-C2 Fire C-C3 Downpour C-C4 Flood C-C5 Earth sliding	C-C6 Snow avalanche C-C7 Tornado/cyclone C-C8 Tsunami C-C9 Thunderbolt C-C10 Volcano eruption
C-D. Man Caused Accidental Actions	
C-D1 Fire C-D2 Collision/traffic accident C-D3 Explosion/bombing	C-D4 Overload C-D5 Heavy objects dropped C-D6 Vandalism
C.E-Environmental Actions	
C-E1 Temperature C-E2 Humidity (wet/dry cycles) C-E3 Rain C-E4 Snow	C-E5 Ice (freeze/thaw cycles) C-E6 Wind C-E7 Direct solar radiation

C.F-Natural Aggressive Factors	
C-F1 Water (wet/dry cycles) C-F2 Carbon dioxide C-F3 Salt/salt water (chlorides) C-F4 Acid/soft water C-F5 Ammonium/magnesium salts C-F6 Sulphates	C-F7 Alkali-aggregate reaction C-F8 Abrasion (wind, sand, heavy objects suspended in a stream) C-F9 Cavitation C-F10 Biological action (algae, lichen, roots) C-F11 Evaporation of volatile components
C.G-Man Caused Aggressive Factors	
C-G1 Water C-G2 Carbon dioxide C-G3 De-icing salts C-G4 Pollution C-G5 Organic compounds (sugar, oils)	C-G6 Abrasion (traffic, transport of materials) C-G7 Cavitation C-G8 Biological action (sewers) properly still in service
C.H-Lack of Maintenance	
C-H1 Accumulation of rust/debris in the bearings C-H2 Bearing (or components of) not functioning properly still in service C-H3 Accumulation of rust/debris in the joints	C-H4 Joints (or components of) not functioning properly still in service C-H5 Gutter/drains obstructed by debris C-H6 Lack/loosening of pins/bolts C-H7 Defective metallic coatings C-H8 Heavy vegetation growth/burrows
C.I-Changes from Initially Planned Normal Use	
C-I1 Changes in upstream/downstream in the channel stream layout C-I2 Heavy increase in traffic flow C-I3 Increase in maximum allowed load C-I4 Increase of the dead load due to repeated repaving	C-I5 Excessive traffic speed C-I6 Inappropriate/ missing signs C-I7 Inappropriate/ missing lighting C-I8 Foundations settlement C-I9 Closing of joints

C-I10 Changes in the span distribution C-I11 Abnormal functioning of the bearings	C-I12 Strengthening works of certain elements but not all the necessary C-I13 Change in codes (live loads, seismic action)

Table A.3 Repair [r] and Maintenance[m] Techniques of Defects of Concrete Bridges

R-A. Superstructure Global Behavior	
R-A1 Release of internal/external connection [r] R-A2 Restraint of internal/external connection [r]	R-A3 Building a span support (new column) [r] R-A4 Additional exterior prestress [r]
R-B. Foundations/Abutments/Embankments	
R-B1 Scour repair (wedge foundations using calibrated material) [r] R-B2 Scour prevention (hydrodynamic protections, islet construction [r] R-B3 Foundation consolidation (Jack up and compaction) [r]	R-B4 Soil compaction under approach slab [r] R-B5 Replacement of the approach slab [r] R-B6 Embankment consolidation [r] R-B7 Removal of accumulated debris /vegetation growth/ burrows [m] R-B8 Removal of silting [m]
R-C. Concrete Elements	
R-C1 Cosmetic repair [m] R-C2 Concrete patching (with deteriorated concrete removal) [r] R-C3 Crack injection [r] R-C4 Crack grouting [r]	R-C5 Crack sealing [r] R-C6 Crack stapling [r] R-C7 Concrete refacing/encasing [r] R-C8 Partial/global replacement [r]
R-D. Reinforcement/Cables	
R-D1 Concrete patching (with reinforcement/prestress cleaning) [r] R-D2 Concrete patching (with reinforcement splicing/replacement) [r] R-D3 Concrete encasing (with reinforcement splicing/replacement) [r] R-D4 Glued steel plates [r]	R-D5 Incorporated steel profiles [r] R-D6 Additional/replacement of prestress R-D7 Grouting of void ducts R-D8 Corrosion treatment and sealing of anchorage [m] R-D9 Corrosion treatment and sealing of anchorage [r] R-D10 Replacement of anchorage [r]

R-E. Bearings	
R-E1 Removal of debris/moisture/trapped water /vegetation growth [m] R-E2 Replacement of the retainer-bars [r] R-E3 Replacement of the roller [r] R-E4 Blast cleaning/ coating [m] R-E5 Replacement of the base plate/ pot [r]	R-E6 Replacement of the anchor bolts/pins [r] R-E7 Replacement of the lead [r] R-E8 Replacement of the elastometer [r] R-E9 Concrete patching of the bearing seat R-E10 Repositioning of the bearing [r] R-E11 Replacement of the bearing [r]
R-F. Joints	
R-F1 Removal of debris/moisture/trapped water /vegetation growth [m] R-F2 Blast cleaning/coating [m] R-F3 Replacement of the anchorages [r]	R-F4 Replacement/tightening of bolts/pins [r] R-F5 Replacement of the filler/sealant [r] R-F6 Replacement of the joint [r]
R-G. Wearing Surface (Asphalts).Watertightness	
R-G1 Localised patching [m] R-G2 Waterproofing and asphalt repaving [m] R-G3 Patching, waterproofing and asphalt repaving [m]	R-G4 Latex modified concrete overlay [m] R-G5 Concrete overlay, waterproofing and asphalt repaving [m] R-G6 Cathodic protection [m]
R-H. Water Drainage	
R-H1 Removal of debris/obstructing asphalt from deck drain or gutter [m] R-H2 Gutter joint repair [m R-H3 Deck drain extension downwards/upwards [m]	R-H4 Diversion of point of discharge of deck drain [m] R-H5 Installation of new deck drains/void tubes [m] R-H6 Replacement of drain/gutter/void tubes [m]

R-I. Secondary Elements	
R-I1 Installation/replacement of traffic signs [m]	R-I6 Welding repair [m]
R-I2 Installation/replacement of curbs/traffic barrier wall [m]	R-I17 Replacement of sidewalks [m]
R-I3 Replacement of hand railing [m]	R-I8 Replacement of utilities [m]
R-I4 Blast cleaning/coating [m]	R-I9 Installation/replacement of lighting [m]
R-I5 Replacement/tightening of bolts/pins [m]	R-I0 Replacement of edge beams [m]
	R-I11 Replacement of acroterium [m]
	R-I12 Removal of vegetation growth [m]

Table A.4 Correlation Matrix Between the Defects and Cause of Defects (Adapted from Branco & Brito, 2004)

	C-A1	C-A2	C-A3	C-A4	C-A5	C-A6	C-A11	C-A12	C-A14
A-A1	0	1	1	1	0	0	1	1	0
A-A2	0	1	1	1	1	0	1	1	0
A-A3	0	1	1	1	1	1	1	1	0
A-B1	1	0	0	1	0	0	1	1	0
A-B2	0	2	2	0	0	0	0	0	0
A-B3	0	1	1	1	0	0	1	2	0
A-B4	0	1	1	1	0	0	1	2	0
A-B5	1	0	0	1	0	0	0	1	0
A-B6	0	0	1	0	0	0	0	1	0
A-B7	0	0	1	0	0	0	0	1	0
A-B8	0	0	0	0	0	0	0	0	0
A-B9	0	1	0	0	0	0	0	0	0
A-C1	0	2	0	0	0	0	0	0	2
A-C2	0	0	0	0	0	0	0	0	0
A-C3	0	0	0	0	0	0	0	0	0
A-C4	0	0	0	0	0	0	0	0	0
A-C5	0	0	1	0	0	0	0	0	0
A-C6	0	0	1	0	0	0	0	0	0
A-C7	0	0	0	0	0	0	0	0	1
A-C8	0	0	0	0	0	0	0	0	0
A-C9	0	0	1	1	0	0	0	0	0

0-no correlation; 1-low correlation; 2-high correlation

APPENDIX B FIELD INTERVIEW QUESTIONS

Name/Status: ....
Organisation: ....
Experience: ....

What is your ‘remediation/maintenance/renewal’ terminology?
....

Does your organisation manage bridge remediation/maintenance?
....

What type of bridge inspection procedures do you follow?
....
....
....

Who conducts the bridge inspections?
....

What type of bridge inspections are conducted and how often?

Routine inspections ....
Intensive inspections..................................
Structural inspections..................................
Other?..

How do your asset managers prioritise the bridges in a network (in terms of maintenance actions)?
....
....
....

Which parameters are involved in the priority ranking of bridges?
Structural efficiency
Functional efficiency (Serviceability Potential)
Client Preferences (Heritage, Political issues,...)
Other (please specify)
....
....
....

How much weight (percentage) do you assign for the foregoing parameters?
Structural efficiency..
Functional efficiency (Serviceability Potential)....................................

Client Preferences (Heritage, Political issues, ...)
Other (please specify) ....
....
....
....

Which factors are contributing to the structural efficiency of bridge elements?

Environmental aggressive factor
Road type
Inspection quality
Age
Other (please specify)
....
....
....

How much weight (percentage) do you assign for the above mentioned factors?..

Environmental aggressive factor
Road type
Inspection quality
Age
Other (please specify)
....
....
....

How do you rank the following elements (scaled 1-4) in terms of structural importance?

	1	2	3	4
Barrier	☐	☐	☐	☐
Footway	☐	☐	☐	☐
Kerbs	☐	☐	☐	☐
Joints	☐	☐	☐	☐
Foundation	☐	☐	☐	☐
Abutment	☐	☐	☐	☐
Wing Wall	☐	☐	☐	☐
Deck	☐	☐	☐	☐
Bearing	☐	☐	☐	☐
Beams	☐	☐	☐	☐
Headstocks	☐	☐	☐	☐
Piers	☐	☐	☐	☐

....
....
....

How do you rank the following materials (assign numbers from 1-4) in terms of their structural vulnerability?

	1	2	3	4
Precast concrete	☐	☐	☐	☐
Reinforced concrete	☐	☐	☐	☐
Prestressed concrete	☐	☐	☐	☐
Steel	☐	☐	☐	☐
Timber	☐	☐	☐	☐

....
....
....

*Which factors are contributing to the functional efficiency of bridge elements?

Load Bearing Capacity
Vertical Clearance
Width
Barriers
Other (please specify)

....
....
....

How much weight (percentage) do you assign for the above mentioned factors?

Load Bearing Capacity..
Vertical Clearance...
Width..
Barriers...
Other (please specify)

....
....
....

Do you consider social and political issues in the priority ranking of bridges? ....
If 'Yes' please specify the extent of it's importance in your decision making.

....
....

How do you consider heritage issues in the priority ranking of bridges?
....

How do your asset managers normally choose a remediation method?

* Reliance on personal experience, memory and intuition
* Critical review of previous methods or precedent lists
* Group brainstorming/synectics techniques
* Use of organisational rules of thumb (heuristics)
* Database/literature search techniques
* Use of knowledge-based system software (decision support systems)
* Other (please specify)

....
....

Are organisational/community constraint preferences factored into your decision making?
....

- If 'Yes' please specify the dominant constraints
-

....
....
....
How do you allocate budget (in terms of remediation plans) for a set of top ranked bridges at network level?
....
....
....

Are your asset managers required to manage other non-bridge assets?...............

- If 'Yes' please specify other asset types to be managed
-

....
....
....

Are commercial decision support systems used by your organisation for bridge maintenance/remediation?...

If 'Yes' are they comprehensive for your decision making?
....
....
....
How does your organisation undertake cost evaluation during maintenance?

Use of unit rates from case history experience
Use of published cost guide rates
Other (please specify)
....
....
....

Please give your views on the effectiveness of the Bridge Remediation DSS regarding its problem solving relevance and validity.

Relevance ....
....

Validity ....
....

Could the Bridge Remediation DSS or a similar systematic decision support tool prove useful to your organisation for:

(a) Engineer training? ....

(b) Incorporation as a risk management standard procedure? ....

(c) Other? (eg., TQM standard procedure?) (Please specify)

....
....
....

Please include any comments or suggestions for specific decision support topic applications or DSS system improvements
....
....
....

Through which medium would you suggest the Bridge Remediation DSS or similarly structured DSS applications should be developed?..........................
....
....
....

Thank you for your interest and time. Results of this survey will remain confidential.

APPENDIX C CASE STUDIES

Table C.1. Evaluation of the Overall Bridge Priority Index (PI) for Bridge A

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state 1	2	3	4	ESCI (Eq1)	*Si*	M*i*	ESCI*Si*Mi
1	BFIX	Metal Fixed Bearing	16	ea	16	0	0	0	1.00	3	1	3.00
2	CABW	Concrete-Abutment and Wingwalls	37	m2	37	0	0	0	1.00	2	2	4.00
3	CCGD	Concrete-Cross Girder / Diaphragm	45	m2	44	1	0	0	1.02	4	4	
4	CDSL	Concrete-Deck Slab	469	m2	468	1	0	0	1.00	3	2	6.01
5	CPHS	Concrete-Pier Headstock	28	m2	28	0	0	0	1.00	4	2	8.00
6	CPIL	Concrete-Pier (excl . Any Headstock or piles)	46	m2	46	0	0	0	1.00	4	2	8.00
7	CPRG	Concrete-Reinforced Beam	197	m2	195	2	0	0	1.01	4	2	8.08
8	JNOS	Joint - No Seal	14	m	14	0	0	0	1.00	1	1	1.00
9	JPOS	Pourable / Cork Joint Seal	7	m	7	0	0	0	1.00	1	1	1.00
10	MAPP	Approach Carriageway	2	ea	1	1	0	0	1.50	1	1	1.50
11	MBAT	Batter protection	134	m2	129	5	0	0	1.04	1	1	1.04
12	MGCL	General Cleaning	2	ea	0	2	0	0	2.00	1	1	2.00
13	MWES	Wearing surface	163	m2	163	0	0	0	1.00	1	1	1.00
14	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
15	RCON	Concrete Railing/ End Posts	47	m	47	0	0	0	1.00	1	2	2.00
16	UCPL	Underwater CPIL - Concrete-Pile	10	m2	10	0	0	0	1.00	4	2	8.00
		∑(ESCI*Si*Mi)										56.63

Causal Factor	A	E	R	I	
CF=0.411A+0.120E+0.107R+0.362I	3	3	2	2	2.53

*SE=CF * ∑(ESCI*Si*Mi)/16n*	*SE=2.53*56.63/ (16*16)*	*0.56*

	L.C=2	Vc=1	Wb=1	Bb=2	D.S=2	
FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds	*FE=0.7(2)+0.1(1)+0.1(1)+0.05(2)+0.05(2)*					*1.80*

	Low	Medium	High	Very High	
CIF					*1.00*

PI=0.6SE+0.2FE+0.2CIF	*PI=0.6(0.56)+0.2(1.8)+0.2(1.0)*	*0.90*

Table C.2. Evaluation of the Overall Bridge Priority Index (PI) for Bridge B

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state				ESCI (Eq1)	*Si*	*Mi*	ESCI*Si*Mi
					1	2	3	4				
1	BELA	Elastomeric Bearing Pad	12	ea	12	0	0	0	1.00	3	3	9.00
2	CABW	Concrete-Abutment and Wingwalls	19	m2	19	0	0	0	1.00	2	2	4.00
3	CDSL	Concrete-Deck Slab	595	m2	594	1	0	0	1.00	3	2	6.01
4	CPHS	Concrete-Pier Headstock	123	m2	118	0	5	0	1.08	4	3	12.98
5	CPIL	Concrete-Piles/Piers	64	m2	54	0	0	10	1.47	4	2	11.75
6	CPRG	Concrete-Pre-tensioned Girder	547	m2	546	0	0	1	1.01	4	4	16.09
7	JNOS	Joint - No Seal	44	m	0	44	0	0	2.00	1	1	2.00
8	JPOS	Pourable / Cork Joint Seal	11	m	11	0	0	0	1.00	1	1	1.00
9	MAPP	Approach Carriageway	2	ea	2	0	0	0	1.00	1	1	1.00
10	MGCL	General Cleaning	6	ea	0	0	6	0	3.00	1	1	3.00
11	MWES	Wearing surface	605	m2	605	0	0	0	1.00	1	1	1.00
12	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
13	MMAS	Brick/ Masonary/ Reinforced Earth	80	m2	70	0	10	0	1.25	1	2	2.50
14	RCON	Concrete Railing/ End Posts	113	m	112	0	1	0	1.02	1	2	2.04
15	RMIS	Miscellaneous Railing	55	m	55	0	0	0	1.00	1	2	2.00
		*∑(ESCI*Si*Mi)*										***76.36***

Causal Factor			**A**	**E**	**R**	**I**				
CF=*0.411***A***+0.120***E***+0.107***R***+0.362***I***			**3**	**3**	**2**	**2**				***2.53***

SE=CF * ∑(ESCI*Si*Mi)/16n	***SE=2.53*72.03/ (16*15)***	***0.81***

FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds		**L.C=2**	**Vc=2**	**Wb=1**	**Bb=2**	**D.S=2**	***1.90***
	FE=0.7(2)+0.1(2)+0.1(1)+0.05(2)+0.05(2)						

CIF		Low	Medium	High	Very High		***2.00***

PI=*0.6***SE+****0.2***FE+****0.2***CIF***	***PI=0.6(0.81)+0.2(1.9)+0.2(2.0)***	***1.26***

Table C.3. Evaluation of the Overall Bridge Priority Index (PI) for Bridge C

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state 1	2	3	4	ESCI (Eq1)	Si	Mi	ESCI*Si*Mi
1	BEXP	Metal Expansion Bearing	4	ea	4	0	0	0	4.00	3	1	12.00
2	CABW	Concrete-Abutment and Wingwalls	102	m2	99	3	0	0	1.03	2	2	4.12
3	CDSL	Concrete-Deck Slab	1516	m2	1375	141	0	0	1.09	3	2	6.56
4	CPIR	Concrete-Pier (excl . Any Headstock or piles)	128	m2	113	0	15	0	1.23	4	2	9.88
5	CPOG	Concrete - Post -Tensioned - Girder	1284	m2	1142	142	0	0	1.11	4	4	17.77
6	JASS	Assembly Joint - Seal	23	m	23	0	0	0	1.00	1	1	1.00
7	MAPP	Approach Carriageway	2	ea	0	2	0	0	2.00	1	1	2.00
8	MBAT	Batter Protection	14	m2	14	0	0	0	1.00	1	1	1.00
9	MGCL	General Cleaning	6	ea	0	6	0	0	2.00	1	1	2.00
10	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
11	RMET	Metal railing	292	m	292	0	0	0	1.00	1	1	1.00
12	RMIS	Miscellaneous Railing	157	m	157	0	0	0	1.00	1	1	1.00
13	UCPL	Railing Paint work	292	m	292	2	0	0	1.01	1	2	2.03
		∑(ESCI*Si*Mi)										62.35

Causal Factor			A	E	R	I				
CF=0.411A+0.120E+0.107R+0.362I			2	3	1	2				2.01

SE=CF * ∑(ESCI*Si*Mi)/16n	SE=2.12*62.35/ (16*13)	0.60
FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds	Lc=2 Vc=1 Wb=1 Bb=2 Ds=3 FE=0.7(2)+0.1(1)+0.1(1)+0.05(2)+0.05(2)	1.85
CIF	Low / Medium / High / Very High	1.00
PI=0.6SE+0.2FE+0.2CIF	PI=0.6(0.39)+0.2(1.8)+0.2(1.0)	0.93

Table C.4. Evaluation of the Overall Bridge Priority Index (PI) for Bridge D

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state				ESCI (Eq1)	Si	Mi	ESCI*Si*Mi
					1	2	3	4				
1	BELA	Elastomeric Bearing Pad	21	ea	21	0	0	0	1.00	3	1	3.00
2	BFIX	Metal Fixed Bearing	21	ea	21	0	0	0	1.00	3	1	3.00
3	CABW	Concrete-Abutment and Wingwalls	224	m2	222	2	0	0	1.01	2	2	4.04
4	CCGD	Concrete-Cross Girder / Diaphragm	848	m2	848	0	0	0		4	4	0.00
5	CDSL	Concrete-Deck Slab	2344	m2	2343	1	0	0	1.00	3	2	6.00
6	CPIR	Concrete-Pier (excl . Any Headstock or piles)	480	m2	440	30	10	0	1.10	4	2	8.83
7	CPRG	Concrete-Pre-tensioned Girder	3294	m2	3293	1	0	0	1.00	4	4	16.00
8	JASS	Assembly Joint / Seal	75	m	62	13	0	0	1.17	1	1	1.17
9	MAPP	Approach Carriageway	2	ea	1	1	0	0	1.50	1	1	1.50
10	MBAT	Batter protection	220	m2	220	0	0	0	1.00	1	1	1.00
11	MGCL	General Cleaning	7	ea	0	7	0	0	2.00	1	1	2.00
12	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
13	RCON	Concrete Railing/ End Posts	4	m	4	0	0	0	1.00	1	2	2.00
14	RMET	Metal Railing	504	m	194	310	0	0	1.62	1	1	1.62
		*∑(ESCI*Si*Mi)*										***52.16***

Causal Factor			A	E	R	I				
CF=0.411A+0.120E+0.107R+0.362I			2	2	2	2				***2.00***

*SE=CF * ∑(ESCI*Si*Mi)/16n*	*SE=2.53*56.63/ (16*14)*	***0.47***

FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds		L.C=1	Vc=1	Wb=1	Bb=2	D.S=2		***1.10***
	FE=0.7(1)+0.1(1)+0.1(1)+0.05(2)+0.05(2)							

CIF		Low	Medium	High	Very High		***1.00***

PI=0.6SE+0.2FE+0.2CIF	*PI=0.6(0.47)+0.2(1.1)+0.2(2.0)*	***0.70***

Table C.5. Evaluation of the Overall Bridge Priority Index (PI) for Bridge E

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state				ESCI (Eq1)	*Si*	*Mi*	ESCI*Si*Mi
					1	2	3	4				
1	BEXP	Metal Expansion Bearing	10	ea	10	0	0	0	4.00	3	1	12.00
2	CABW	Concrete-Abutment and Wingwalls	125	m2	124	1	0	0	1.01	2	2	4.03
3	CCGD	Concrete-Cross Girder / Diaphragm	96	m2	95	0	1	0	1.02	3	4	
4	CDSL	Concrete-Deck Slab	1162	m2	1109	53	0	0	1.05	3	2	6.27
5	CPHS	Concrete-Pier Headstock	38	m2	37	1	0	0	1.03	4	3	12.32
6	CPIR	Concrete-Pier (excl . Any Headstock or piles)	220	m2	214	0	6	0	1.05	4	2	8.44
7	CRBM	Concrete-Reinforced Beam	368	m2	365	2	1	0	1.01	4	2	8.09
8	JNOS	Joint - No Seal	19	m	19	0	0	0	1.00	1	1	1.00
9	JPOS	Pourable / Cork Joint Seal	7	m	7	0	0	0	1.00	1	1	1.00
10	MAPP	Approach Carriageway	2	ea	1	1	0	0	1.50	1	1	1.50
11	MGCL	General Cleaning	4	ea	0	4	0	0	2.00	1	1	2.00
12	MWWY	Waterway	1	ea	1	0	0	0	1.00	1	1	1.00
13	RMIS	Miscellaneous Railing	130	m	128	2	0	0	1.02	1	1	1.02
14	UCPL	Underwater CPIL - Concrete-Pile	74	m2	74	0	0	0	1.00	4	2	8.00
		∑(ESCI*Si*Mi)										**66.66**

Causal Factor			**A**	**E**	**R**	**I**				
***CF*=*0.411* A+0.120E+0.107R+0.362I**			**1**	**3**	**2**	**2**				***1.71***

SE=CF * ∑(ESCI*Si*Mi)/16n	***SE=1.71*66.66/ (16*14)***	***0.51***

FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds		L.C=1	Vc=1	Wb=2	Bb=2	D.S=4	***1.30***
	FE=0.7(1)+0.1(1)+0.1(2)+0.05(2)+0.05(4)						

CIF		Low	Medium	High	Very High		***1.00***

PI*=0.6*SE*+0.2*FE*+0.2*CIF	***PI=0.6(0.51)+0.2(1.3)+0.2(1.0)***	***0.77***

Table C.6. Evaluation of the Overall Bridge Priority Index (PI) for Bridge F

Item	Element Code	Element Description	Total Quantity	Units	Estimated Quantity in condition state 1	2	3	4	ESCI (Eq1)	Si	Mi	ESCI*Si*Mi
1	BELA	Elastomeric Bearing Pad	109	ea	0	0	83	26	4.00	3	3	36.00
2	CABW	Concrete-Abutment and Wingwalls	65	m2	0	65	0	0	2.00	2	2	8.00
3	CDSL	Concrete-Deck Slab	7034	m2	22	26	866	6120	3.86	3	2	23.16
4	CPHS	Concrete-Pier Headstock	2037	m2	0	76	84	1877	3.88	4	3	46.61
5	CPIL	Concrete-Piles/Piers	847	m2	0	52	380	415	3.43	4	2	27.43
6	CPRG	Concrete-Pre-tensioned Girder	5306	m2	0	24	162	5120	3.96	4	4	63.37
7	JNOS	Joint - No Seal	38	m	0	0	12	26	3.68	1	1	3.68
8	JPOS	Pourable / Cork Joint Seal	555	m	0	0	125	430	3.77	1	1	3.77
9	MAPP	Approach Carriageway	4	ea	3	1	0	0	1.25	1	1	1.25
10	MBAT	Batter protection	158	m2	0	0	102	56	3.35	1	1	3.35
11	MGCL	General Cleaning	33	ea	0	0	33	0	3.00	1	1	3.00
12	MWES	Wearing surface	5025	m2	0	0	1214	3811	3.76	1	1	3.76
13	MWWY	Waterway	1	ea	0	1	0	0	2.00	1	1	2.00
14	RMET	Metal Railing	1222	m	0	70	63	1089	3.83	1	1	3.83
15	RMIS	Miscellaneous Railing	629	m	0	0	289	340	3.54	1	1	3.54
16	RPNT	Railing Paint Work	1216	m	0	0	13	1203	3.99	1	1	3.99
17	UCPL	Underwater CPIL - Concrete-Pile	752	m2	0	0	124	628	3.84	4	2	30.68
		∑(ESCI*Si*Mi)										267.43

Causal Factor			A	E	R	I				
CF=0.411A+0.120E+0.107R+0.362I			2	4	3	2				2.35

SE=CF * ∑(ESCI*Si*Mi)/16n	SE=2.35*251.90/ (16*17)	2.31

FE=0.7Lc+0.1Vc+0.1Wb+0.05Bb+0.05Ds		L.C=2	Vc=1	Wb=2	Bb=2	D.S=2		1.90
	FE=0.7(2)+0.1(1)+0.1(1)+0.05(2)+0.05(2)							

CIF		Low	**Medium**	High	Very High		2.00

PI=0.6SE+0.2FE+0.2CIF	PI=0.6(2.31)+0.2(1.9)+0.2(2.0)	2.16

APPENDIX D THE IMPLEMENTATION CODES

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;
using CBR_DSS.Properties;

namespace CBR_DSS
{
    public partial class FormEditBridge : Form
    {
        Dictionary<string, int> factorsnames = new Dictionary<string, int> { { "Service life", 0 }, { "Safety", 1 }, { "Cost", 2 }, { "Environment", 3 }, { "Traffic Disruption", 4 }, { "Legal/Political", 5 } };
        Bridge bridge;
        Label[,] irLabels = new Label[6, 6];
        ComboBox[] DoNothing = null;
        ComboBox[] MinorReh = null;
        ComboBox[] MajorReh = null;
        ComboBox[] Replace = null;
        bool canApply = false;

        void ApplyChanges()
        {
            if (!canApply) return;
            //Tab Bridge Info ****************************************
            bridge.Name = textBoxName.Text;
            bridge.Code = textBoxCode.Text;
            bridge.Type = textBoxBridgeType.Text;
            bridge.Location = textBoxLoc.Text;

            bridge.OverallLenght = double.Parse(textBoxOvrLength.Text);
            bridge.OverallWidth = double.Parse(textBoxOvrWidth.Text);
            bridge.VerticalClearence = double.Parse(textBoxVerC.Text);
            bridge.YearCompleted = Convert.ToInt32(numYear.Value);
            bridge.Inspections[0].InspectorName = textBoxInsName.Text;
            bridge.Inspections[0].InspectionType = textBoxInsType.Text;
            bridge.Inspections[0].InspectionDate = dateTimeIns.Value;
            bridge.Inspections[0].ProposedNextInspection = dateTimeNextInsp.Value;

            Inspection inspection = bridge.Inspections[0];
            inspection.ConcereDeckSlab = Concrete_DeckSlab.Value;
            inspection.ConcereAbutmentAndWingwalls = ciConcere_Abutment_Wingwalls.Value;
            inspection.ConcerePierHeadstock = ciConcere_Pier_Headstock.Value;
            inspection.ConcerePile = ciConcere_Pile.Value;
```

```
            inspection.ConcerePre_tentionedGirder                                    =
ciConcere_Pre_Tentioned_Girder.Value;
            inspection.ElastomericBearingPad = ciElastomeric_Bearing_Pad.Value;
            inspection.JointNoSeal = ciJoint_No_Seal.Value;
            inspection.Porable_CorkJointSeal = ciPorable_Cork_JointSeal.Value;
            inspection.ApproachCarriageway = ciApproach_Carriageway.Value;
            inspection.BatterProtection = ciBatter_Protection.Value;
            inspection.GeneralCleaning = ciGeneral_Cleaning.Value;
            inspection.WearingSurface = ciWearing_Surface.Value;
            inspection.Waterway = ciWaterway.Value;
            inspection.Mettalrailing = ciMettal_Railing.Value;
            inspection.UnderwaterConcretePile = ciUnderwater_Concrete_Pile.Value;

            bridge.LoadBearingCapacityFacotr = cLoadBeaaringCapFact.Value;
            bridge.VerticalCleareneceFactor = cVerClearenceFact.Value;
            bridge.WidthFactor = cWidthFact.Value;
            bridge.BridgeBarrierFactor = cBridgeBarrierFact.Value;
            bridge.DrainageSystemFactor = cDrainageSystemFact.Value;
            bridge.ClientImpactFactor = cClientImpactFactor.Value;
            bridge.Inspections[0].AgeFactor = cAgeFactor.Value;
            bridge.Inspections[0].EnvAggressiveFactor = cEnvAggressiveFact.Value;
            bridge.Inspections[0].RoadTypeFactor = cRoadType.Value;
            bridge.Inspections[0].InspectionQualityFactor                            =
cInspectionQualityFac.Value;
            bridge.Inspections[0].Climate = textBoxClimate.Text;
            bridge.Inspections[0].Comments = richTextBoxComm.Text;
            bridge.Inspections[0].Temp = textBoxTemp.Text;

            bridge.wSE = Convert.ToSingle(textBoxSE.Text);
            bridge.wFE = Convert.ToSingle(textBoxFE.Text);
            bridge.wCIF = Convert.ToSingle(textBoxCIF.Text);
            bridge.NumOfSpans = Convert.ToInt16(textBoxSpans.Text);
            RecalculatePage();
        }

        public Bridge Bridge
        {
            get
            {
                return bridge;
            }

            set
            {
                canApply = false;
                bridge = value;
                var inspection = bridge.Inspections[0];
                //Tab Bridge Info ****************************************
                textBoxName.Text = bridge.Name;
                textBoxCode.Text = bridge.Code;
                textBoxBridgeType.Text = bridge.Type;
                textBoxLoc.Text = bridge.Location;
                textBoxOvrLength.Text = bridge.OverallLenght.ToString();
                textBoxOvrWidth.Text = bridge.OverallWidth.ToString();
                textBoxVerC.Text = bridge.VerticalClearence.ToString();
                numYear.Value = (decimal)bridge.YearCompleted;
```

```
                textBoxInsName.Text = bridge.Inspections[0].InspectorName;
                textBoxInsType.Text=bridge.Inspections[0].InspectionType;
                dateTimeIns.Value = bridge.Inspections[0].InspectionDate;
                dateTimeNextInsp.Value                                        =
bridge.Inspections[0].ProposedNextInspection;
                textBoxSpans.Text = bridge.NumOfSpans.ToString();
                cLoadBeaaringCapFact.Value = bridge.LoadBearingCapacityFacotr;
                cVerClearenceFact.Value = bridge.VerticalCleareneceFactor;
                cWidthFact.Value = bridge.WidthFactor;
                cBridgeBarrierFact.Value = bridge.BridgeBarrierFactor;
                cDrainageSystemFact.Value = bridge.DrainageSystemFactor;
                cClientImpactFactor.Value = bridge.ClientImpactFactor;
                cClientImpactFactor.Value = bridge.ClientImpactFactor;

                Concrete_DeckSlab.Value = inspection.ConcereDeckSlab;
                ciConcere_Abutment_Wingwalls.Value                            =
inspection.ConcereAbutmentAndWingwalls;
                ciConcere_Pier_Headstock.Value = inspection.ConcerePierHeadstock;
                ciConcere_Pile.Value = inspection.ConcerePile;
                ciConcere_Pre_Tentioned_Girder.Value                          =
inspection.ConcerePre_tentionedGirder;
                ciElastomeric_Bearing_Pad.Value                               =
inspection.ElastomericBearingPad;
                ciJoint_No_Seal.Value = inspection.JointNoSeal;
                ciPorable_Cork_JointSeal.Value = inspection.Porable_CorkJointSeal;
                ciApproach_Carriageway.Value = inspection.ApproachCarriageway;
                ciBatter_Protection.Value = inspection.BatterProtection;
                ciGeneral_Cleaning.Value = inspection.GeneralCleaning;
                ciWearing_Surface.Value = inspection.WearingSurface;
                ciWaterway.Value = inspection.Waterway;
                ciMettal_Railing.Value = inspection.Mettalrailing;
                ciUnderwater_Concrete_Pile.Value                              =
inspection.UnderwaterConcretePile;

                cAgeFactor.Value = inspection.AgeFactor;
                cEnvAggressiveFact.Value = inspection.EnvAggressiveFactor;
                cRoadType.Value = inspection.RoadTypeFactor;
                cInspectionQualityFac.Value = inspection.InspectionQualityFactor;
                textBoxSE.Text = bridge.wSE.ToString();
                textBoxFE.Text = bridge.wFE.ToString();
                textBoxCIF.Text = bridge.wCIF.ToString();
                textBoxClimate.Text=bridge.Inspections[0].Climate;
                richTextBoxComm.Text=bridge.Inspections[0].Comments;
                textBoxTemp.Text=bridge.Inspections[0].Temp;
                canApply = true;
            }
        }

        public FormEditBridge()
        {
            InitializeComponent();
        }

        private void buttonExit_Click(object sender, EventArgs e)
        {
```

```
            DialogResult = DialogResult.OK;
        }

        void InittlAHP()
        {
            for (int i = 0; i < tlAHP.RowCount; i++)
            {
                tlAHP.ColumnStyles[i].SizeType = SizeType.Absolute;
                tlAHP.ColumnStyles[i].Width = tlAHP.Width / tlAHP.ColumnCount;
                tlAHP.RowStyles[i].SizeType = SizeType.Absolute;
                tlAHP.RowStyles[i].Height = tlAHP.Height / tlAHP.RowCount;
            }
        }

        void setAHPText()
        {
            for (int i = 0; i < 6; i++)
            {
                for (int j = 0; j < 6; j++)
                {
                    irLabels[i, j] = new Label();
                    irLabels[i, j].AutoSize = false;
                    irLabels[i, j].TextAlign = ContentAlignment.MiddleCenter;
                    tlAHP.Controls.Add(irLabels[i, j], j + 1, i + 1);
                    irLabels[i, j].Dock = DockStyle.Fill;
                }
            }
            var en = factorsnames.GetEnumerator();

            for (int i = 0; i < factorsnames.Count; i++)
            {
                en.MoveNext();
                Label vtl = new Label();
                vtl.Text = en.Current.Key;
                vtl.AutoSize = false;
                vtl.TextAlign = ContentAlignment.MiddleCenter;
                tlAHP.Controls.Add(vtl, i + 1, 0);
                Label htl = new Label();
                htl.Text = en.Current.Key;
                htl.AutoSize = false;
                htl.TextAlign = ContentAlignment.MiddleCenter;
                tlAHP.Controls.Add(htl, 0, i + 1);
                if (i == factorsnames.Count - 1)
                    break;
                listBoxG1.Items.Add(en.Current.Key);
            }
            listBoxG1.SelectedIndex = 0;
        }

        void SetStSelCombos()
        {
            DoNothing = new ComboBox[] { comboBoxDoN0, comboBoxDoN1, comboBoxDoN2,
comboBoxDoN3, comboBoxDoN4, comboBoxDoN5 };
            MinorReh = new ComboBox[] { comboBoxMin0, comboBoxMin1, comboBoxMin2,
comboBoxMin3, comboBoxMin4, comboBoxMin5 };
```

```
            MajorReh = new ComboBox[] { comboBoxMaj0, comboBoxMaj1, comboBoxMaj2, 
comboBoxMaj3, comboBoxMaj4, comboBoxMaj5 };
            Replace = new ComboBox[] { comboBoxRep0, comboBoxRep1, comboBoxRep2, 
comboBoxRep3, comboBoxRep4, comboBoxRep5 };
            for (int i = 0; i < 6; i++)
            {
                DoNothing[i].SelectedIndex = 0;
                MinorReh[i].SelectedIndex = 0;
                MajorReh[i].SelectedIndex = 0;
                Replace[i].SelectedIndex = 0;
            }
        }

        private void FormEditBridge_Load(object sender, EventArgs e)
        {
            InittIAHP();
            setAHPText();
            SetStSelCombos();
            RecalculatePage();
        }

        private void ValidateSingle(object sender, CancelEventArgs e)
        {
            var tb = sender as TextBox;
            tb.ForeColor = SystemColors.WindowText;
            try
            {
                Convert.ToSingle(tb.Text);
            }
            catch
            {
                tb.ForeColor = Color.Red;
                e.Cancel = true;
            }
        }

        private void buttonSEDefault_Click(object sender, EventArgs e)
        {
            textBoxSE.Text = Settings.Default.SE_Weight_Default.ToString();
            textBoxFE.Text = Settings.Default.FE_Weight_Default.ToString();
            textBoxCIF.Text = Settings.Default.CIF_Weight_Default.ToString();
            bridge.wSE = Convert.ToSingle(textBoxSE.Text);
            bridge.wFE = Convert.ToSingle(textBoxFE.Text);
            bridge.wCIF = Convert.ToSingle(textBoxCIF.Text);
        }

        void RecalculatePage()
        {
            CheckSumFactor();
            ShowSEFECIF();
            ShowValue();
            ShowWeights();
        }

        void CheckSumFactor()
        {
```

```
            try
            {
                labelErrMessage.Text = "";
                float        sum        =        Convert.ToSingle(textBoxSE.Text)        +
Convert.ToSingle(textBoxFE.Text) + Convert.ToSingle(textBoxCIF.Text);
                if (sum != 1.0)
                {
                    labelErrMessage.Text = "Sum of factors must be equal to 1.0";
                }
            }
            catch
            {
                labelErrMessage.Text = "Not defined.";
            }
        }

        void ShowWeights()
        {
            Calculations cal = new Calculations();
            cal.CR(bridge);
            labelWServ.Text = Math.Round(100 * bridge.wf[0], 2).ToString() + "%";
            labelWSafe.Text = Math.Round(100 * bridge.wf[1], 2).ToString() + "%";
            labelWCost.Text = Math.Round(100 * bridge.wf[2], 2).ToString() + "%";
            labelWEnv.Text = Math.Round(100 * bridge.wf[3], 2).ToString() + "%";
            labelWTraff.Text = Math.Round(100 * bridge.wf[4], 2).ToString() + "%";
            labelWLeg.Text = Math.Round(100 * bridge.wf[5], 2).ToString() + "%";
            listBoxWs.Items.Clear();
            listBoxWs.Items.Add("Service Life:          "+ Math.Round(bridge.wf[0],
4).ToString());
            listBoxWs.Items.Add("Safety:                              " + Math.Round(
bridge.wf[1], 4).ToString());
            listBoxWs.Items.Add("Cost:                                " + Math.Round(
bridge.wf[2], 4).ToString());
            listBoxWs.Items.Add("Environmental     Impact:     "     +     Math.Round(
bridge.wf[3], 4).ToString());
            listBoxWs.Items.Add("Traffic       Disruption:                 "       +
Math.Round(bridge.wf[4], 4).ToString());
            listBoxWs.Items.Add("Legal/Political:                         "       +
Math.Round(bridge.wf[5], 4).ToString());

        }

        void ShowSEFECIF()
        {
            try
            {
                Calculations cal = new Calculations();
                double se = cal.SE(bridge);
                double fe = cal.FE(bridge);
                labelSE.Text = Math.Round(se, 2).ToString();
                labelFE.Text = Math.Round(fe, 2).ToString();
                labelCIF.Text = (cClientImpactFactor.Value).ToString();
                double   pi   =   se   *   bridge.wSE   +   fe   *   bridge.wFE   +
cClientImpactFactor.Value * bridge.wCIF;
                labelPI.Text = Math.Round(pi, 2).ToString();
            }
```

```
            catch
            {
                labelSE.Text = "";
                labelFE.Text = "";
                labelCIF.Text = "";
            }
        }

        private void listBoxG1_SelectedIndexChanged(object sender, EventArgs e)
        {
            listBoxG2.Items.Clear();
            var en = factorsnames.GetEnumerator();
            for (int i = 0; i < factorsnames.Count; i++)
            {
                en.MoveNext();
                if (i <= listBoxG1.SelectedIndex)
                    continue;
                listBoxG2.Items.Add(en.Current.Key);
            }
            listBoxG2.SelectedIndex = 0;
        }

        private void listBoxG2_SelectedIndexChanged(object sender, EventArgs e)
        {
            textBoxVal.Text =
bridge.GetImportanceRatio()[factorsnames[listBoxG1.Text],
factorsnames[listBoxG2.Text]];
        }

        void ShowValue()
        {
            var sarr = bridge.GetImportanceRatio();
            for (int row = 0; row < 6; row++)
            {
                for (int col = 0; col < 6; col++)
                {
                    irLabels[row, col].Text = sarr[row, col];
                }
            }
            ShowAHPCalc();
        }

        void ShowAHPCalc()
        {
            Calculations cal = new Calculations();
            double cr = Math.Round(cal.CR(bridge), 2);
            labelCRError.Text = "Valid";
            labelCRError.ForeColor = Color.Green;
            labelCR.Text = cr.ToString();
            if (cr > 0.1)
            {
                labelCRError.Text = "Pairwaise comparison is not consistent.
Please try again.";
                labelCRError.ForeColor = Color.Red;
            }
        }
```

```
        private void tabPageAHP_Enter(object sender, EventArgs e)
        {
        }

        private void tabPageStrategySelection_Enter(object sender, EventArgs e)
        {
            Calculations cal = new Calculations();
        }

        double CalcStrategy(ComboBox[] combos)
        {
            double sum = 0;
            for (int i = 0; i < combos.Length; i++)
            {
                if (combos[i].SelectedIndex < 0) return 0;
                sum += Convert.ToInt16(combos[i].Text) * bridge.wf[i]*100;
            }
            return Math.Round(sum, 1);

        }

        void FindBestStrategy()
        {
            double[] varr = new double[]{
                CalcStrategy(DoNothing),
                CalcStrategy(MinorReh),
                CalcStrategy(MajorReh),
                CalcStrategy(Replace)
            };
            int index = 0;
            for (int i = 1; i < 4; i++)
            {
                if (varr[i] > varr[index])
                {
                    index = i;
                }
            }
            label_DoNothing.ForeColor = SystemColors.WindowText;
            label_MinReh.ForeColor = SystemColors.WindowText;
            label_MajReh.ForeColor = SystemColors.WindowText;
            label_Rep.ForeColor = SystemColors.WindowText;
            switch (index)
            {
                case 0: label_DoNothing.ForeColor = Color.Green;
labelStrategyRes.Text = "Do Nothing"; break;
                case 1: label_MinReh.ForeColor = Color.Green;
labelStrategyRes.Text = "Minor Rehabilitation"; break;
                case 2: label_MajReh.ForeColor = Color.Green;
labelStrategyRes.Text = "Major Rehabilitation"; break;
                case 3: label_Rep.ForeColor = Color.Green; labelStrategyRes.Text =
"Replacement"; break;
            }
            labelStrategyRes.Text ="'"+ labelStrategyRes.Text + "' is the best
Strategy.";
            labelDoNothing.Text = varr[0].ToString();
```

```
            labelMinor.Text = varr[1].ToString();
            labelMajor.Text = varr[2].ToString();
            labelRep.Text = varr[3].ToString();
        }

        private void comboBoxDoN0_SelectedIndexChanged(object sender, EventArgs e)
        {
            FindBestStrategy();
        }

        private void comboBoxMin0_SelectedIndexChanged(object sender, EventArgs e)
        {
            FindBestStrategy();
        }

        private void comboBoxMaj0_SelectedIndexChanged(object sender, EventArgs e)
        {
            FindBestStrategy();
        }

        private void comboBoxRep0_SelectedIndexChanged(object sender, EventArgs e)
        {
            FindBestStrategy();
        }

        private void buttonApply_Click(object sender, EventArgs e)
        {
            if (!nR.CheckCompumber(textBoxVal.Text))
            {
                MessageBox.Show("Number is wrong");
                return;
            }
            string[,] sarr = bridge.GetImportanceRatio();
            sarr[factorsnames[listBoxG1.Text], factorsnames[listBoxG2.Text]] =
nR.S(textBoxVal.Text);
            sarr[factorsnames[listBoxG2.Text], factorsnames[listBoxG1.Text]] =
nR.rS(textBoxVal.Text);
            bridge.SetImportanceRatio(sarr);
            ApplyChanges();
        }

        bool IsValidSingle(TextBox tb)
        {
            try
            {
                Convert.ToSingle(tb.Text);
                return true;
            }
            catch
            {
                return false;
            }
        }

        private void OnTextChange(object sender, EventArgs e)
        {
```

```
    ApplyChanges();
}

private void OnSingleChanged(object sender, EventArgs e)
{
    if (IsValidSingle(sender as TextBox))
        ApplyChanges();
}

private void OnComboBoxChanged(object sender, EventArgs e)
{
    ApplyChanges();
}

private void dateTimeIns_ValueChanged(object sender, EventArgs e)
{
    ApplyChanges();
}

private void InspectionsValueChanged()
{
    ApplyChanges();
}

private void OptionValueChanged()
{
    ApplyChanges();
}

bool IsValidInt(string s)
{
    try
    {
        Convert.ToInt16(s);
        return true;
    }
    catch
    {
        return false;
    }
}
private void ValidatingInt(object sender, CancelEventArgs e)
{
    e.Cancel = !IsValidInt((sender as TextBox).Text.Trim());
}

private void textBoxSpans_TextChanged(object sender, EventArgs e)
{
    if (IsValidInt((sender as TextBox).Text.Trim()))
        ApplyChanges();
}

private void textBoxClimate_TextChanged(object sender, EventArgs e)
{
    ApplyChanges();
}
```

```
        private void ciConcere_DeckSlab_Load(object sender, EventArgs e)
        {

        }

        private void controlOption1_Load(object sender, EventArgs e)
        {

        }

        private void pictureBox1_Click(object sender, EventArgs e)
        {

        }

        private void Concere_DeckSlabTab_SelectedIndexChanged(object sender,
EventArgs e)
        {

        }

        private void textBox3_TextChanged(object sender, EventArgs e)
        {

        }

        private void textBox6_TextChanged(object sender, EventArgs e)
        {

        }

        private void label51_Click(object sender, EventArgs e)
        {

        }

        private void tabPage1_Click(object sender, EventArgs e)
        {

        }

        private void pictureBox2_Click(object sender, EventArgs e)
        {

        }

        private void tabPageStrategySelection_Click(object sender, EventArgs e)
        {

        }

        private void Tab_Budget_Planning_Click(object sender, EventArgs e)
        {

        }
```

```
        private void textBox_Available_TextChanged(object sender, EventArgs e)
        {

        }

        private void button_Submit_Click(object sender, EventArgs e)
        {
            //---------------------------//
            string str_reconstruction_cost = textBox_Reconstruction.Text;
            decimal reconstruction_cost;
            decimal.TryParse(str_reconstruction_cost,out reconstruction_cost);

            string str_rehabiliation_cost = textBox_Rehabiliation.Text;
            decimal rehabiliation_cost;
            decimal.TryParse(str_rehabiliation_cost, out rehabiliation_cost);

            string str_Maintenance_Cost = textBox_Maintanence.Text;
            decimal maintenance_Cost;
            decimal.TryParse(str_Maintenance_Cost, out maintenance_Cost);

            string str_Available_Budget = textBox_Available.Text;
            decimal available_budget;
            decimal.TryParse(str_Available_Budget, out available_budget);

            string str_deck_area_A = textBox_A_DeckArea.Text;
            decimal deck_area_A;
            decimal.TryParse(str_deck_area_A, out deck_area_A);

            string str_deck_area_B = textBox_B_DeckArea.Text;
            decimal deck_area_B;
            decimal.TryParse(str_deck_area_B, out deck_area_B);

            string                    str_reconstruction_overall_A                    =
textBox_A_Reconstruction_Overall.Text;
            decimal reconstruction_overall_A;
            decimal.TryParse(str_reconstruction_overall_A,                           out
reconstruction_overall_A);

            string                    str_reconstruction_overall_B                    =
textBox_B_Reconstruction_Overall.Text;
            decimal reconstruction_overall_B;
            decimal.TryParse(str_reconstruction_overall_B,                           out
reconstruction_overall_B);

            string                    str_rehabiliation_overall_A                     =
textBox_A_Rehabiliation_Overall.Text;
            decimal rehabiliation_overall_A;
            decimal.TryParse(str_rehabiliation_overall_A,                            out
rehabiliation_overall_A);

            string                    str_rehabiliation_overall_B                     =
textBox_B_Rehabiliation_Overall.Text;
            decimal rehabiliation_overall_B;
            decimal.TryParse(str_rehabiliation_overall_B,                            out
rehabiliation_overall_B);
```

```
            string                    str_Maintenance_Overall_Score_A                =
textBox_A_Maintenance_Overall.Text;
            decimal Maintenance_Overall_A;
            decimal.TryParse(str_Maintenance_Overall_Score_A,                 out
Maintenance_Overall_A);

            string                    str_Maintenance_Overall_Score_B                =
textBox_B_Maintenance_Overall.Text;
            decimal Maintenance_Overall_B;
            decimal.TryParse(str_Maintenance_Overall_Score_B,                 out
Maintenance_Overall_B);

            //-----------------------------------//
            decimal MaintainA = deck_area_A * maintenance_Cost;
            decimal MaintainB = deck_area_B * maintenance_Cost;

            decimal reconstructA = deck_area_A * reconstruction_cost;
            decimal reconstructB = deck_area_B * reconstruction_cost;

            decimal rehabilitateA = deck_area_A * rehabiliation_cost;
            decimal rehabilitateB = deck_area_B * rehabiliation_cost;

            decimal []totalcosts=new decimal[9];        //Array to store the total
costs

            listView1.Items.Clear();

            //Row 1 Attrib
            ListViewItem Row1 = new ListViewItem("1");
            Row1.SubItems.Add("Maintain A");
            Row1.SubItems.Add("Maintain B");
            totalcosts[0]=MaintainA+MaintainB;
            Row1.SubItems.Add(totalcosts[0].ToString());
            Row1.SubItems.Add((Maintenance_Overall_A                          +
Maintenance_Overall_B).ToString());

            listView1.Items.Add(Row1);

            //Row 2 Attrib
            ListViewItem Row2 = new ListViewItem("2");
            Row2.SubItems.Add("Maintain A");
            Row2.SubItems.Add("Reconstruct B");
            totalcosts[1]=MaintainA + reconstructB;
            Row2.SubItems.Add(totalcosts[1].ToString());

Row2.SubItems.Add((Maintenance_Overall_A+reconstruction_overall_B).ToString());

            listView1.Items.Add(Row2);

            //Row 3 Attrib
            ListViewItem Row3 = new ListViewItem("3");
            Row3.SubItems.Add("Maintain A");
            Row3.SubItems.Add("Rehabilitate B");
            totalcosts[2]=MaintainA + rehabilitateB;
            Row3.SubItems.Add(totalcosts[2].ToString());
```

```
            Row3.SubItems.Add((Maintenance_Overall_A                               +
rehabiliation_overall_B).ToString());

            listView1.Items.Add(Row3);

            //Row 4 Attrib
            ListViewItem Row4 = new ListViewItem("4");
            Row4.SubItems.Add("Rehabilitate A");
            Row4.SubItems.Add("Maintain B");
            totalcosts[3] = rehabilitateA + MaintainB;
            Row4.SubItems.Add(totalcosts[3].ToString());
            Row4.SubItems.Add((rehabiliation_overall_A                             +
Maintenance_Overall_B).ToString());

            listView1.Items.Add(Row4);

            //Row 5 Attrib
            ListViewItem Row5 = new ListViewItem("5");
            Row5.SubItems.Add("Rehabilitate A");
            Row5.SubItems.Add("Reconstruct B");
            totalcosts[4] = rehabilitateA + reconstructB;
            Row5.SubItems.Add(totalcosts[4].ToString());
            Row5.SubItems.Add((rehabiliation_overall_A                             +
reconstruction_overall_B).ToString());

            listView1.Items.Add(Row5);

            //Row 6 Attrib
            ListViewItem Row6 = new ListViewItem("6");
            Row6.SubItems.Add("Rehabilitate A");
            Row6.SubItems.Add("Rehabilitate B");
            totalcosts[5]=rehabilitateA + rehabilitateB;
            Row6.SubItems.Add(totalcosts[5].ToString());
            Row6.SubItems.Add((rehabiliation_overall_A                             +
rehabiliation_overall_B).ToString());

            listView1.Items.Add(Row6);

            //Row 7 Attrib
            ListViewItem Row7 = new ListViewItem("7");
            Row7.SubItems.Add("Reconstruct A");
            Row7.SubItems.Add("Maintain B");
            totalcosts[6] = reconstructA + MaintainB;
            Row7.SubItems.Add(totalcosts[6].ToString());
            Row7.SubItems.Add((reconstruction_overall_A                            +
Maintenance_Overall_B).ToString());

            listView1.Items.Add(Row7);

            //Row 8 Attrib
            ListViewItem Row8 = new ListViewItem("8");
            Row8.SubItems.Add("Reconstruct A");
            Row8.SubItems.Add("Reconstruct B");
            totalcosts[7] = reconstructA + reconstructB;
            Row8.SubItems.Add(totalcosts[7].ToString());
```

```
            Row8.SubItems.Add((reconstruction_overall_A +
reconstruction_overall_B).ToString());

            listView1.Items.Add(Row8);

            //Row 9 Attrib
            ListViewItem Row9 = new ListViewItem("9");
            Row9.SubItems.Add("Reconstruct A");
            Row9.SubItems.Add("Rehabilitate B");
            totalcosts[8] = reconstructA + rehabilitateB;
            Row9.SubItems.Add(totalcosts[8].ToString());
            Row9.SubItems.Add((reconstruction_overall_A +
rehabiliation_overall_B).ToString());

            listView1.Items.Add(Row9);

            string selected_options="";

            int temp;
            for (int i = 0; i < 9; i++)
            {
                if (totalcosts[i] <= available_budget)
                {
                    temp = i + 1;
                    selected_options+=temp.ToString()+" ";
                }
            }

            if (selected_options.Length == 0)
            {
                label63_selections.Text = "The budget is not enough for any of the
options";
            }
            else
            {
                label63_selections.Text = "Recommended options are " +
selected_options;
            }
        }
    }
}
```