HOLISTIC DECISION SUPPORT FOR BRIDGE REMEDIATION

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ABSTRACT: Bridges are essential and valuable elements in road and rail transportation networks. Bridge remediation is a top priority for asset managers, but identifying the nature of true defect deterioration and associated remediation treatments remains a complex task. Nowadays Decision Support Systems (DSS) are used extensively to assist in decision-making across a wide spectrum of unstructured decision environments. In this paper a *requirements-driven* framework is used to develop a risk based decision support model which has the ability to quantify the bridge condition and find the best remediation treatments using Multi Attribute Utility Theory (MAUT), with the aim of maintaining a bridge within acceptable limits of safety, serviceability and sustainability.

Keywords: Decision Support System (DSS), condition assessment, risk assessment, remediation, MAUT

1. INTRODUCTION

There are approximately 33,000 bridges in Australia [1]. Over 50% of these bridges are considered to be in a fair or poor state (40% fair and 15% in poor condition) [2]. 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 property. 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, remediation strategies have to be prioritised. A conservative bridge assessment will result in unnecessary actions, such as costly bridge strengthening or repairs [3]. 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 [2].

The service life of a bridge can be subdivided into four different phases [2]:
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 [4], one dollar spent in Phase A equals five dollars spent in Phase B; twenty-five dollars in Phase C equals hundred and twenty five dollars in Phase D.

Bridge design codes and specifications should be able to ensure good engineering quality in Phase A.

Bridge monitoring and maintenance must be accomplished during Phase B to prevent the structure from progressing into Phase C and D [2].

A pivotal responsibility for asset managers in charge of bridge remediation is to make transparent decisions which result in the lowest predicted losses in recognised constraint areas [5].

Decision-making in this field is more complicated than it was in the past due to two governing 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 competition typical of today's problems can result in a chain reaction magnification of costs if an error should occur [6].

The increasing level of decision support system implementation in organisations over the past two decades is strong proof that DSS are feasible and well accepted managerial tools [7]. These developed systems are now providing enormous benefits, both in time and cost savings [8].

A conventional decision support system 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 [6].

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 [6].

The research project presented in this paper deals with the development of a knowledge-based decision support model for bridge remediation. The working model includes a procedure for condition assessment in order to prioritise bridges in a network for maintenance fund allocation. The next step is classifying all the viable courses of action, and finally finding the best remediation strategy using Multi Attribute Utility Theory (MAUT).

2. THE BRIDGE REMEDIATION FRAMEWORK

The working framework for bridge remediation comprises the process which provides the system inputs (Condition Index, maintenance alternatives and decision constraints), the inference engine (Decision Analysis Tool) and the system output (Remediation Plan).

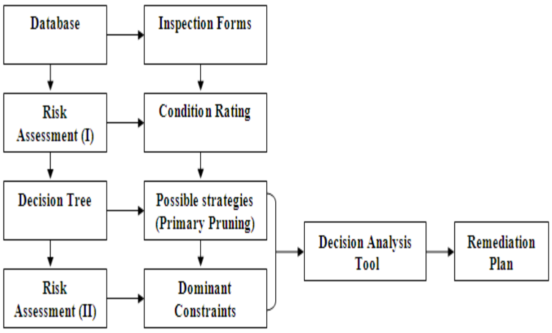

Figure 1. The Bridge Remediation Framework

2.1 The Database/ Inspection Forms

Due to increasing numbers of bridges in poor condition and higher traffic limits being carried on roads, many databases and inspection policies have been developed [2]. The effectiveness of a bridge monitoring system is related to its data storage and inspection information. The database stores 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. Inspections performed at fixed intervals are called periodic inspections, while special ones are referred to as non-periodic inspections [9].

2.2 Risk Assessment (I): Condition Rating

Bridge condition assessment based on field inspection is a fundamental step for providing the appropriate inputs for any condition rating system. Many bridge rating systems primarily use structural deficiency to assess the overall bridge condition rating. Bridge age, serviceability potential, environmental changes, client impact, historical value and strategic importance may not be specifically addressed using existing practices. The developing condition rating method described herein is an important step in adding more holism and objectivity to the current approaches. The main factors which should be addressed are described in the following sections. To quantify the parameters, numbers from 1 to 4 have been included which demonstrate the potential level of severity.

2.2.1 Age Factor (AF)

As bridges are designed to withstand fatigue loading (which increases with time), age is a useful parameter for assessing risk. Generally, bridges in the last quarter of their design life (typically 100 years) require more serious remedial actions than in previous quarters.

Table 1. Age Factor

A.F	Recently built	New	Old	Very old
	1	2	3	4

2.2.2 Structural Deficiency Factor (SDF)

This refers to the rate of deterioration or decay of constituent bridge material (e.g. cracking, corrosion and delamination, failure of joints and bearing).

Table 2. Structural Deficiency Factor

S.F	No Defect	Minor Defects	Medium Damage	Severe Damage
	1	2	3	4

2.2.3 Serviceability Potential Factor (SPF)

This parameter indicates the potential level of service and operation efficiency of a bridge. Load carrying capacity is a critical aspect of serviceability. Bridge width, overhead clearance and provision for pedestrians and cyclists are also determining issues. A poor SPF may trigger substantial remediation, bridge modifications or even bridge replacement.

Table 3. Serviceability Potential Factor

SP.F	Excellent	Good	Fair	Poor
	1	2	3	4

2.2.4 Road/Rail Type Factor (RF)

This factor can clearly depict a bridge's importance. Table 4 offers a functional classification system for *roads*, and builds on the work of Mulholland [10] and Talvitie [11].

Table 4. Road Type Factor

R.F	Minor	Local Access	Collectors	Arterials
	1	2	3	4

2.2.5 Environmental Change Factor (ECF)

This parameter considers post-design changes in climatic conditions, e.g. freeze and thaw; introduced aggressive factors such as chlorides, sulphates, carbon dioxide and other pollutants; substantial increases in traffic flow; increases of the bridge dead load due to repeated repaving; closing of joints; potential abutment rotation due to differential and/or excessive backfill material expansion; and non-anticipated alkali silica reaction [9].

Table 5. Environmental Change Factor

EC.F	Low	Medium	High	Very High
	1	2	3	4

Measuring the level of risk introduced by environmental change is often based on a bridge inspector’s experience or laboratory tests which are conducted within the detailed inspection phase.

2.2.6 Client Impact Factor (CIF)

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 [2] 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, as this factor can be systematically weighted and considered along with the other condition rating factors. Alternatively, it can be ignored by assigning it a weight of zero during decision making.

Table 6. Client Impact Factor

CI.F	Low	Medium	High	Very High
	1	2	3	4

2.2.7 Historical Factor (HF)

Some bridges have historical value and some are also heritage-listed. Generally, heritage-listed bridges are rarely used by the public, but some bridges with noted historical significance may need to remain in service.

Table 7. Historical Factor

H.F	Low Value	Medium	High	Very High
	1	2	3	4

2.2.8 Calculating the Condition Index (CI):

Since the importance of the above-mentioned factors is not the same, summing up all the values is not a rational way for finding the Condition Index (CI). Therefore some weight factors should be assigned by the decision makers and maintenance experts that reflect the importance of each condition index factor.

Importance weighting should be guided by organisational policy. A weighting of zero means that a specific condition factor is judged to have no bearing on the decision making environment, whilst a rating of 4 means that the factor is extremely important. If all of the seven listed condition rating factors are assigned weights greater than zero, the relevant *weighted* condition index equation is as follows:

$$\text{CI}=\frac{\sum_i (w_i \times F_i)}{28} \qquad \text{(Equation 1)}$$

w_i is the weight of the i th factor $\in [0,4]$

F_i is the assigned value of this factor $\in [1,4]$

According to the defined thresholds for the above factors, the Condition Index (CI) will be between 0 and 4 ($\text{CI} \in [0,4]$).

2.3 Risk Assessment (II): Dominant Constraint

Bridge risk evaluation often serves as the basis for bridge remediation priority ranking, and is conducted periodically for the purpose of safety and functionality [12]. The user is therefore required to assign a weighting for each constraint for individual bridges within their jurisdiction. Major risks and client constraints for bridge maintenance are categorised in Table 8.

Table 8. Major Risks and Client Constraints for Bridge Remediation

Criterion	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/ Load bearing capacity
	Closure of a strategic/ regional route	Minimal traffic disruption
Sustainability	Excessive remediation cost	Minimal cost
	Excessive work implication	Minimal work implication
Environment	Environmental damage	Minimal environmental damage
	Not aesthetically pleasing	Maximum aestheticism
Legal/ Political	Major changes in standards	Minimum vulnerability to political pressures
	Major changes in governance strategies	

2.4 Decision Tree: Possible 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 'satisficing' solutions [13, 14]. To define and categorise all the possible alternatives, a comprehensive classification should be defined. A decision tree is an appropriate decision analysis tool for this purpose. Figure 2 represents a decision tree which includes all the major courses of action for bridge remediation (Level 1 and 2) and some specific treatment options for concrete bridges (Level 3).

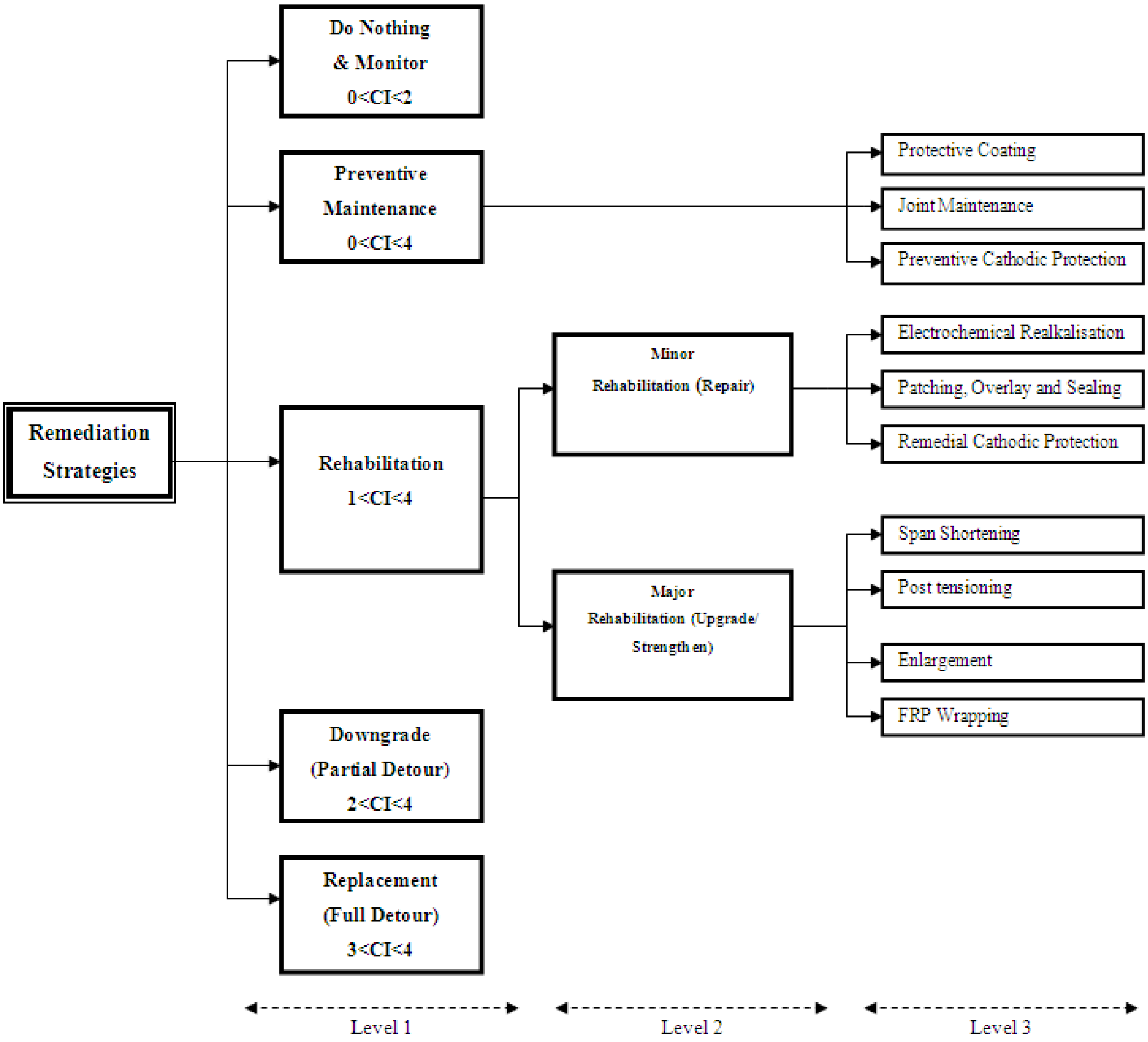

Figure 2. Decision Tree for Possible Bridge Remediation Courses of Action

For each of those treatment options in Level 3, there are a few sub branches which have not been addressed at this level.

Preventive and routine maintenance can be conducted as a supportive action for all the minor and major rehabilitation alternatives.

"*Do nothing*" is a very common course of action. In many instances, enough funds are not available and the bridge managers have to allocate the budget for the structures of higher priority.

2.5 Decision Analysis Tool

The ranking method in this research is based on Multi Attribute Utility Theory (MAUT). The Analytical Hierarchy Process (AHP) method [15] has also been primarily examined. After the comparison, the advantages and limitations of the two methods were analysed to select the most appropriate method for decision making. The advantages of the AHP method are that it supplies a systematic approach through a hierarchy and it has an 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 again.

The advantages of the MAUT approach are 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.

However the determination of the maximum and minimum ranges of the attributes and deriving work from the utility functions are perceived limitations [16]. After the analysis of the two methods it has been concluded from industry case studies that the MAUT is more practical for this applied research. Through the MAUT process, firstly, the problem under consideration is broken down into a hierarchy (Figure 3).

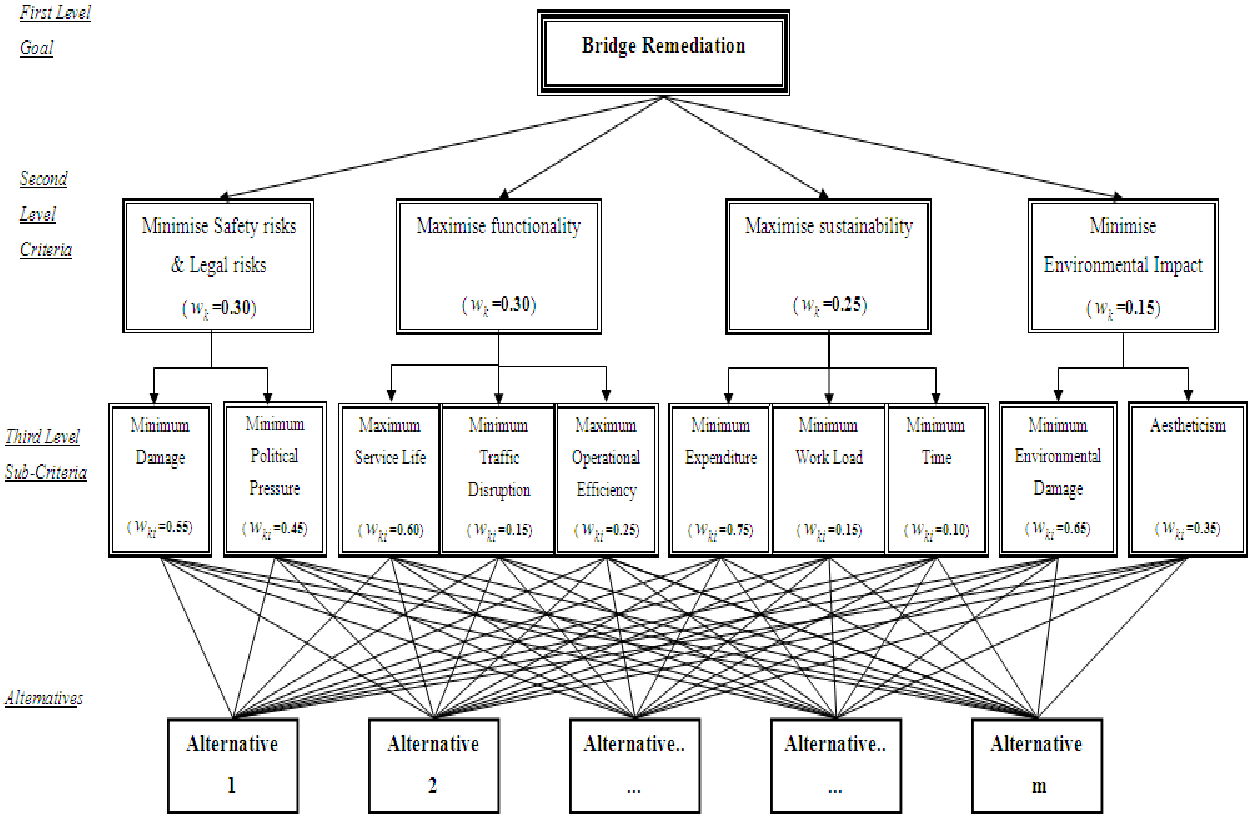

Figure 3. A Typical Hierarchy Structure for Bridge Remediation

Decision criteria are collected during interviews with bridge engineers and asset managers. All the elements (goal, objectives and constraints) are organized into a four-level hierarchy structure, which consider all the main aspects of the problem. This approach deals with identifying the overall goal and proceeding downward until the measure of value is included. 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 constraints (sub criteria) to be employed for assessing the objectives. The last level is added for the remediation treatment alternatives. Each criterion has a weight indicating its importance which is defined by the decision maker [17].

In the majority of cases based on the MAUT, the weights associated with the criteria can clearly reflect the relative importance of the criteria if the scores a_{ij} are from a dimensionless scale. The basic step of MAUT is the application of utility functions to transform the raw performance values of the alternatives against the constraints, both objective and subjective to a common dimensionless scale so that a more favoured option gains a higher utility value [18].

Weights of the criteria and sub criteria are usually defined based on the expert's judgments (which should reflect organisational policy) extracted during the problem solving. Final weights are obtained through normalising the sum of the scores to one [17].

2.5.1 Simple Multi Attribute Rating Technique (SMART)

SMART is a form of MAUT. In order to simplify the process, the utility function can be replaced by some scores which indicate the relative importance level of each treatment alternative with respect to the decision criteria.

The overall ranking value of each alternative x_j is expressed as follows:

$$x_j = \sum_{i=1}^{m} w_k w_{ki} a_{ij} \qquad j=1,\dots,m \qquad \text{(Equation 2)}$$

W_k and Wki are the weights of criteria and sub criteria

a_{ij} is the importance level of jth alternative in respect to the ith sub criterion and kth criterion.

The chosen alternative is normally the option with the highest overall score.

3. MODEL TESTING

Verification is concerned with establishing the internal correctness of a model. It is conducted by the model builder/expert to detect and eliminate any errors made in early prototypes and to confirm critical variable ranges for which the model can be applied [19].

In this research, model verification is accomplished through a literature review and case studies. In order to verify the application of SMART, concrete bridges located in New South Wales have been chosen. Model verification to date suggests that the model is technically correct and extends on current practice to make decision making more holistic, while a series of semi-structured field interviews are ongoing for system validation.

4. CONCLUSION

A Decision Support model for remediation planning of bridges has been achieved through an extensive literature review and expert judgment derived during case studies with bridge engineers and asset managers. The framework includes the Condition Index (CI) evaluation of the bridge as the primary sieve for selecting the major courses of action such as ‘Do nothing & monitor’, ‘Preventive maintenance’, ‘Rehabilitation (minor or major) and ‘Downgrading’. This index addresses various factors which have different weights in terms of their influence on the condition of the bridge. Generally, the most important parameters are related to structural and functional performance. Possible remediation treatment alternatives are sub categories of the major courses of action which are ranked through 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 modelling approach which distinguishes it from other decision analysis tools such as AHP.

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