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A Decision Support System for Concrete Bridge Maintenance

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Abstract: The maintenance of bridges as a key element in transportation infrastructure has become a major concern for asset managers and society due to increasing traffic volumes, deterioration of existing bridges and well-publicised bridge failures. A pivotal responsibility for asset managers in charge of bridge remediation is to identify the risks and assess the consequences of remediation programs to ensure that the decisions are transparent and lead to the lowest predicted losses in recognized constraint areas. The ranking of bridge remediation treatments can be quantitatively assessed using a weighted constraint approach to structure the otherwise ill-structured phases of problem definition, conceptualization and embodiment [1]. This Decision Support System helps asset managers in making the best decision with regards to financial limitations and other dominant constraints imposed upon the problem at hand. The risk management framework in this paper deals with the development of a quantitative intelligent decision support system for bridge maintenance which has the ability to provide a source for consistent decisions through selecting appropriate remediation treatments based upon cost, service life, product durability/sustainability, client preferences, legal and environmental constraints. Model verification and validation through industry case studies is ongoing.

Keywords: Concrete Bridge, Decision Support System, Risk, Maintenance, Weighted Constraint Matrix.

INTRODUCTION

There are approximately 2.5 million bridges on the global higher transportation network. In 2005 the US. Federal Highway Agency (FHWA) stated that 28% of their bridges are rated deficiently. In Europe this figure varies by around 10% [2]. Nevertheless, if we consider a rough average of 20% deficiency, almost 500,000 bridges require remediation and improvement.

Bridge management deals with all activities during a bridge's service life from construction to replacement, aiming to ensure its safety and functionality. It also addresses prioritization of protection needs, planning the maintenance systems, and optimization of the bridge life-cycle cost. An effective way for selecting the optimum maintenance strategy among all the solutions such as replacement, repair, rehabilitation, strengthening and preventive maintenance is the employment of a mathematical optimization and computerized system [3]. The development of a Decision Support System (DSS) for bridge maintenance can satisfy this objective and allow asset managers to select the best course of action for their needs under the constraints of each particular situation. A conventional DSS shall be broadly defined here as an interactive computer-based system that utilizes a model to identify and draw upon relevant data in order to aid decision-making [1]. In most cases it is not feasible to provide a fully automated process to achieve a conclusion. Only if an information processing task can be stated as an algorithm, the final structured decision development can be implemented in a computer program [2].

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APPLYING THE DECISION PROCESS TO BRIDGE MAINTENANCE

The decision support system discussed in this paper addresses the area of risk management for concrete bridges. This system partially comprises the knowledge base and model management components of Intelligent Decision Support Systems (IDSS). For simplification, this system is divided into two steps. The first step involves determining whether or not a particular element on a certain bridge requires maintenance. The second step is then developed by applying the various phases of the decision making process to choosing the optimal treatment option for components of concrete bridges requiring maintenance.

Step One: Determining if Maintenance Is Required

Concrete structures deteriorate gradually over an extended period of time. It is generally a medium to long-term process as the rate of deterioration is a function of relevant variables. These variables include: the length of time the structure has been in service, the function the structure is required to perform, the activities that are conducted within or upon the structure, the environment the structure is located in, and the physical properties of the concrete used to construct the structure. The most common problems in concrete bridges are corrosion of reinforcement, structural deficiency, chemical/acid attack, frost damage, fire damage, creep, internal reaction within the concrete, restrained movement, plastic cracking, and mechanical damage. In some cases more than one of these defects exist and make the situation more complex.

In Australia, the Road and Traffic Authority's Bridge Inspection Procedure (BIP) contains a process for determining quantitative condition ratings for bridge elements. Each element has four to five condition states listed with qualitative descriptions and viable maintenance actions [4]. An applicable pattern of the condition states and feasible actions for the concrete bridge elements is given in Table 1. Additionally, routine maintenance is a possible action for all condition states.

TABLE 1. Summary of Condition States and Feasible Actions for Concrete Bridge Elements (adapted from [4]).

Condition State	Condition State Description	Feasible Actions
1	No deterioration	_
2	Minor cracks and spalls No evidence of corrosion	Seal cracks, minor patch
3	Some delamination &/or spalls No evidence of deterioration of the prestress system Some corrosion of other reinforcement may be present, minor section loss	Clean reinforcement & patch (and/or seal)
4	Delamination, spalls and corrosion of reinforcement is prevalent Prestress system may also be exposed & deteriorated	Rehabilitate unit Replace unit

As an example, rehabilitation of a bridge element is recommended when the element is assessed as having a condition state of four. Replacement is also an additional option for this condition state.

Step Two: Choosing the Optimal Treatment Option

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. Numeric scoring models such as Weighted Constraint Matrix techniques have been developed to allow multiple constraints to be used for concept feasibility studies. These models can combine economic evaluation output with technical and subjective constraint to create a decision making environment that is more holistic (and realistic) in nature [5]. A Weighted Constraint Model is defined by a set of variables, their associated domains of values, and a set of binary constraints

governing the assignment of variables to values. Each constraint is associated with a positive integer weight. The output is an assignment which maximizes the weighted sum of satisfied constraints. The model generally adopts the form [5]:

$$S_i = \sum_{j=1}^{n} s_{ij} w_j \qquad j=1,2,3,\ldots\ldots,n \tag{1}$$

Where S_i =the total score of the ith treatment alternative

s_{ij} =the score of the i th treatment alternative on the j th constraint

W_j =the weight of the j th constraint

The treatment options that are available for concrete bridge components can be broadly defined as rehabilitation and replacement. These are defined by the principles covering them, which are further broken down into the techniques that are available in Table 2.

TABLE 2. Treatment Options for Concrete Components of Bridges.

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		

This decision support system requires that each treatment option be weighted according to the level of constraint satisfaction that exists for the technique.

Constraints have different levels of importance, and the relative level of importance of each constraint varies between bridges. Bridge risk evaluation often serves as the basis for bridge maintenance priority ranking and optimization, and is conducted periodically for the purpose of safety, functionality, and sustainability [6]. The user is therefore required to assign a weighting for each constraint for individual bridges within their jurisdiction. The levels of importance are ranked in a way that a larger number indicates a higher level of assessed constraint importance. Major risks and client constraints for concrete bridge maintenance are categorized in Table 3.

Table3. Risks and Client Constraints for Concrete Bridge Maintenance

Constraint Category	Risks	Client Constraint
FUNCTIONAL	Dysfunctional remediation method	Minimal complexity of maintenance method
	Road users confused by traffic control measures	Minimal complexity of traffic control
	Short period of service life	Maximum life expectancy (service life)
	Unable to get equipment to the work site	Easy access to site
	Difficult to access element	Easy access to element
	Lack of enough equipment	Maximum availability of equipment
	Lack of enough material	Maximum availability of materials
	Insufficient level of expertise	Maximum availability of skilled labour
ENVIRONMENTAL	Environmental damage	Minimal environmental damage
	Non-renewable energy resources are exhausted	Minimal non-renewable energy consumption
ECONOMICAL	Insufficient funds	Minimal repair cost
CLIENT PREFRENCES	Traffic disruption	Minimal traffic disruption
	Long construction time	Minimal construction time
	Not aesthetically pleasing	Maximum aestheticism

The choice phase involves: the valuation of the alternatives against the constraints, making a tentative choice, assessing its potential adverse consequences, and making a final selection. Table 4 is used to record the weightings of the criteria and treatment options, and to calculate the overall score for the treatment options. The process commences with the entry for the importance rating of each client constraint and of the weighting of the treatment option against the client criteria. The treatment option weightings are placed in the first column for that alternative. The second column for each alternative (shaded gray) carries the calculation of the importance rating of the criterion multiplied by the treatment option weighting. The total for each alternative is entered into the last cell. These cells represent the total rating for each of the treatment options. As previously mentioned, the option with the highest rating is selected as the optimal solution to the problem statement.

		CONCRETE TREATMENT ALTERNATIVES							
CLIENT CONSTRAINTS	Importance Level *Wj*	Coating *i=1*		Crack Sealing *i=2*		...		Post tension *i=m*	
Minimal complexity of maintenance method *j=1*	W_1	S_{11}	$S_{11} \cdot W_1$	S_{21}	$S_{21} \cdot W_1$	...	...	S_{m1}	$S_{m1} \cdot W_1$
Minimal complexity of traffic control j=2	W_2	S_{12}	$S_{12} \cdot W_2$	S_{22}	$S_{22} \cdot W_2$	...	...	S_{m2}	$S_{m2} \cdot W_2$
Maximum service life *j=3*	W_3	S_{13}	$S_{13} \cdot W_3$	S_{23}	$S_{23} \cdot W_3$	...	...	S_{m3}	$S_{m3} \cdot W_3$
...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...
Maximum aestheticism *j=n*	W_n	S_{1n}	$S_{1n} \cdot W_n$	S_{2n}	$S_{2n} \cdot W_n$	...	...	S_{mn}	$S_{mn} \cdot W_n$
TOTAL		$S_1 = \sum_{j=1}^{n} s_1 w_j$		$S_2 = \sum_{j=1}^{n} s_2 w_j$		$S_3 = \sum_{j=1}^{n} s_3 w_j$		$S_m = \sum_{j=1}^{n} s_m w_j$	

FIGURE 1. Weighted Constraint Table for Finding the Optimal Treatment Option.

CONCLUSION

Bridge maintenance is a very complex task and many studies were conducted to investigate methods for bridge condition ratings and risk analysis. Risks associated with bridge maintenance encompass human, environmental, economic, legal, operational and technical areas. Quantitative techniques are employed in the model management component of Intelligent Decision Support Systems (IDSS) to determine the optimal ranking of the maintenance strategies in terms of their efficiency in risk reduction, cost minimisation, and traffic control merits [6]. The system developed in this study is an IDSS whereby qualitative methods are used to input the data into a quantitative model. This method also considers the importance of the constraints (level of risk) and compares them against treatment options to determine appropriate courses of action. This is achieved by determining the level at which each option satisfies the criteria. The flowchart illustrated in Figure 1 illustrates the procedure used to determine and prioritise elements of the bridge network requiring maintenance (Step1) and the process of finding the optimal treatment solution (Step2).

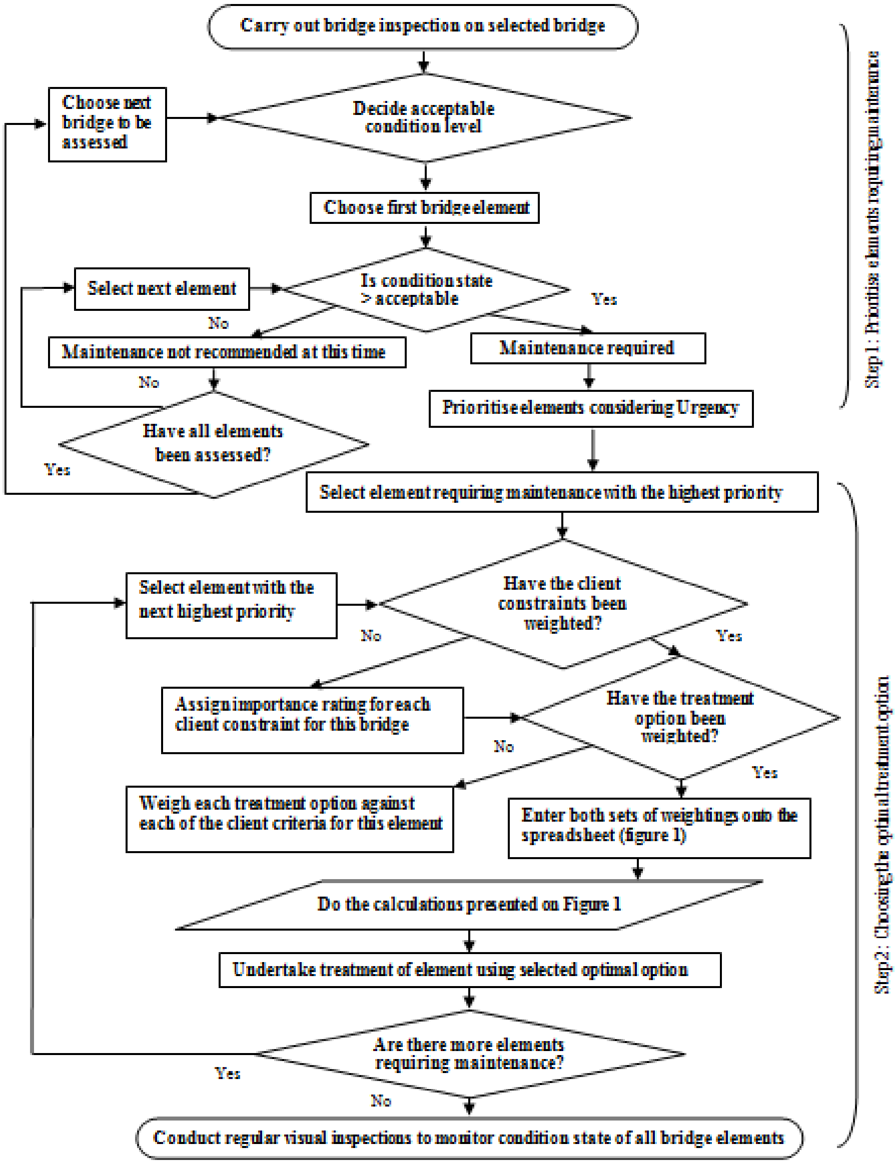

FIGURE 2. Flowchart for System Process.

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