DECISION SUPPORT SYSTEM FOR BRIDGE NETWORK MAINTENANCE PLANNING

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Introduction

Bridge maintenance planning as a part of public policy management is not only a scientific-analytic task (Heineman, 2002), but also involves political, subjective, and sometimes other factors. Decision-makers such as administrators, managers and/or politicians are the key players in the planning process, supported by policy analysts and other technical experts. The ultimate goal of bridge maintenance planning is to find the "best" strategies and/or operational plans that are not only technically feasible, but also are considered optimal by decision makers. This can be achieved by better understanding the real-world situations, identifying all possible objectives and conflicts, evaluating as many alternatives as possible, and finally reaching rational plans. Therefore, Decision Support System (DSS) is necessary for optimal bridge maintenance planning.

This paper presents a DSS for bridge network maintenance planning that involves a group of existing highway bridges with various remaining service lifetimes. The proposed DSS considers five bridge maintenance alternatives, including "do nothing", and the associated cost. Based on the annual bridge maintenance budget and the probabilities that each of the five maintenance alternatives may be conducted at that year on individual bridges in the network, the ultimate goal of this DSS is to find the best combination of the five maintenance alternatives applied to all bridges in the network during certain years. Since the mutual preferential independence requirement can be easily satisfied in this case, the additive form of the multiple attribute utility function can be used to establish the single-objective function for optimization with the weight assignment from the Reliability Importance Factor (RIF) of individual bridges in the network. The RIF reflects the sensitivity of the bridge network reliability in terms of the network connectivity to the change in the individual bridge system reliability due to maintenance actions. The optimization problem in the proposed DSS can be solved by either traditional mathematical programming for combinatorial optimization or the advanced heuristic search methods such as Genetic Algorithms (GAs).

Bridge Maintenance Alternatives and Associated Cost

The bridge maintenance alternatives presented in this paper include both preventive and essential maintenances with actual cost data, as well as "do nothing". The effects of the five different maintenance alternatives, namely, "minor concrete repair", "silane treatment", "cathodic protection", "rebuild" and "do nothing" on individual bridge condition and safety indices over time have been studied as shown in Tables 1 and 2 (Denton, 2002). For example, the "minor concrete repair" results in a decrease of bridge condition index (CI) between 2 and 3 with a triangular probability distribution. The mode of the triangular probability distribution is 2.5, indicating that the most likely decrease of the bridge condition index is 2.5 (see Table 1). Meanwhile, the "minor concrete repair" causes a delay in deterioration of bridge safety index (SI) when the bridge condition index is less than 1.0, in other words, there is no deterioration of the bridge safety index after the "minor concrete repair" maintenance action is applied, and the deterioration of the bridge safety index resumes after the bridge

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condition index reaches 1.0. The "silane treatment" affects only the deterioration rates during the maintenance effective duration that has a triangular probability distribution between 7.5 and 12.5 years. The bridge condition and safety indices will not change in the first 12.5 years after the "cathodic protection" maintenance action is applied. The "rebuild" is the only essential maintenance actions in this study. If this action is applied, the bridge condition index will be set to zero and the bridge safety index will be assigned to the safety index of the rebuilt bridge. Meanwhile, the deterioration of the bridge condition index will start between 10 and 30 years after "rebuild" with a triangular probability distribution mode of 15 years. The deterioration of the bridge safety index will begin when the bridge condition index reaches 1.0. Table 3 presents the associated cost of the five alternatives considered. Figures 1 to 4 shows the effects of the preventive ("minor concrete repair", "silane treatment" and "cathodic protection") and essential ("rebuild") maintenance alternatives on the mean values of bridge condition and safety indices over time.

Table 1: Effect of Bridge Maintenance Alternatives on Mean Condition Index (after Denton, 2002)

Bridge Maintenance Alternatives	Decrease in Condition Index	Delay in Deterioration (years)	Reduced Deterioration Rate ($year^{-1}$)	Maintenance Effective Duration (years)
Minor Concrete Repair	T(2.0, 2.5, 3.0)	-	-	-
Silane Treatment	-	-	T(0.00, 0.01, 0.03)	T(7.5, 10.0, 12.5)
Cathodic Protection	-	12.5	-	-
Rebuild	set to zero	T(10, 15, 30)	-	-
Do Nothing	-	-	-	-

Note: T (minimum value, mode, maximum value) represents the triangular probability distribution.

Table 2: Effect of Bridge Maintenance Alternatives on Mean Safety Index (after Denton, 2002)

Bridge Maintenance Alternatives	Increase in Safety Index	Delay in Deterioration (years)	Reduced Deterioration Rate ($year^{-1}$)	Maintenance Effective Duration (years)
Minor Concrete Repair	-	CI <1.0	-	-
Silane Treatment	-	-	T(0, 0.007, 0.018)	T(7.5, 10.0, 12.5)
Cathodic Protection	-	12.5	-	-
Rebuild	set to SI	CI <1.0	-	-
Do Nothing	-	-	-	-

Note: T (minimum value, mode, maximum value) represents the triangular probability distribution.

Table 3: Cost for Bridge Maintenance Alternatives (after Denton, 2002)

Bridge Maintenance Alternatives	Cost
Minor Concrete Repair	T(16, 3605, 14437)
Silane Treatment	T(0.3, 39,77)
Cathodic Protection	T(19, 2604, 5189)
Rebuild	T(247, 7410, 28898)
Do Nothing	0.0

Note: T (minimum value, mode, maximum value) represents the triangular probability distribution.

Dynamic Programming for Individual Bridge Maintenance Planning

Bridges without maintenance may not reach a targeted service lifetime due to the aging and deterioration. Therefore, bridge maintenance actions must be applied to extend the remaining service lifetime of individual bridges. Individual bridge maintenance planning needs to answer to questions such as what sequence of maintenance actions and when these maintenance actions should take place in order to minimize the life-cycle maintenance cost throughout the entire targeted lifetime period. The life-cycle maintenance cost can be either construction cost that bridge owners have to pay for or user's cost that includes the time delays and fuel consumption due to detour and/or congestion caused

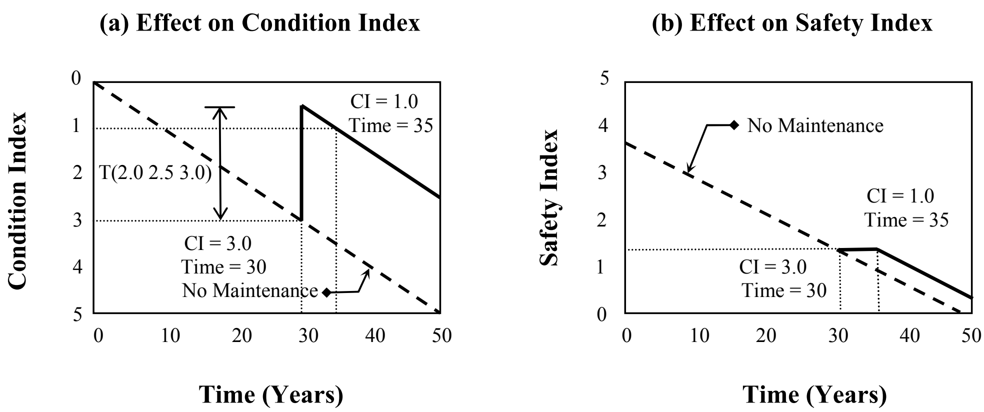

Figure 1: Effects of "Minor Concrete Repair" on Mean Condition and Safety Indices over Time

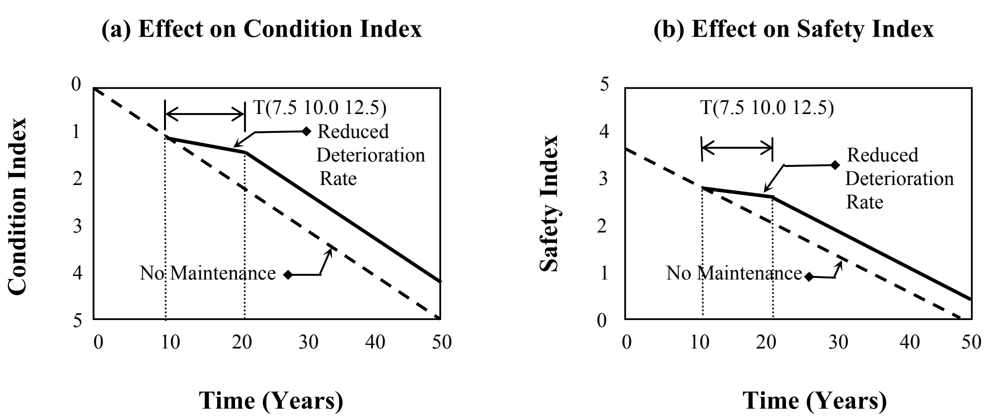

Figure 2: Effects of "Silane Treatment" on Mean Condition and Safety Indices over Time

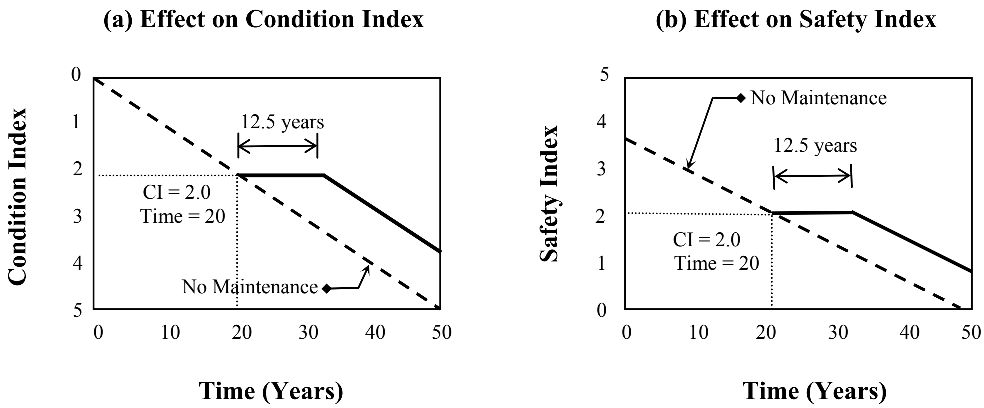

Figure 3: Effects of “Cathodic Protection” on Mean Condition and Safety Indices over Time

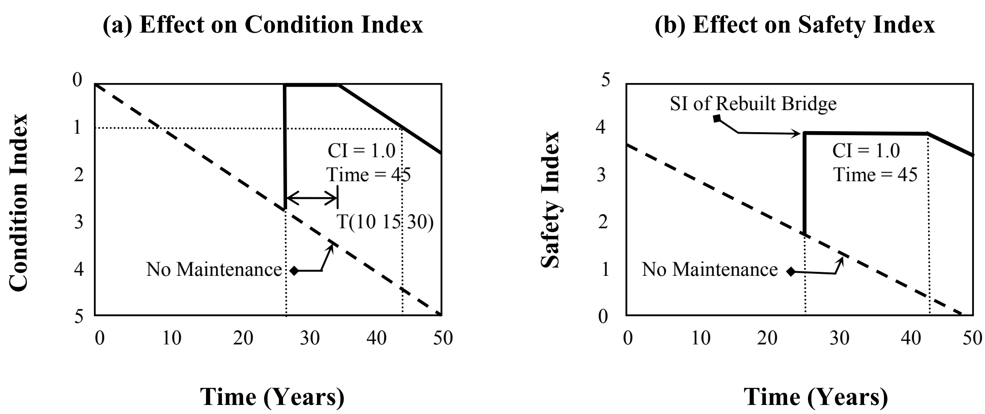

Figure 4: Effects of “Rebuild” on Mean Condition and Safety Indices over Time

by the maintenance actions or combination of both construction and user’s cost. In reality, bridge maintenance planning has to consider the maintenance funding limitation as well.

In this study, the prediction of the remaining service lifetime of individual bridges is based on both bridge condition and safety indices. The bridge condition index increases as the bridge deteriorates with time, while the bridge safety index decreases with time. The maximum condition index is set to be 3.0, and the minimum safety index is assigned to be 0.91 (Denton, 2002). In other words, an individual bridge should always have a condition index less than 3.0 and a safety index greater than 0.91 during the entire service lifetime period. The difference between the predicted remaining service lifetime and the targeted service lifetime of a bridge must be covered by applying maintenance alternatives. Any combination of the above five bridge maintenance alternatives that can extend the bridge service lifetime to the targeted level may be regarded as a feasible maintenance plan. These feasible maintenance plans may require performing different combinations of the above five maintenance actions at different application times, resulting in different life-cycle maintenance cost. The life-cycle maintenance cost for each feasible maintenance plan are converted to the net present values (NPV), using the discount rates ranging from 2% to 8%. Thus, an optimal bridge maintenance plan is the feasible plan that has a minimum life-cycle maintenance cost in terms of NPV. A dynamic programming (DP) procedure has been developed to identify the optimal bridge maintenance plans for individual bridges (Liu and Frangopol, 2006). Monte Carlo simulations are integrated within the DP procedure for sensitivity studies, considering the probability distributions of all random variables and parameters. As a result, the probabilities that each of the above five maintenance alternatives (including "Do Nothing") may be conducted at certain time (year) can be obtained for individual bridges. The details of the DP procedure combined with Monte Carlo simulations are presented in Liu and Frangopol (2006).

Multiple Criteria Decision-Making Process

Since almost all real-world decision problems must be addressed on the basis of multi-dimensional approaches, the Multiple Criteria Decision-Making (MCDM) process has been developed long time ago. Pareto first introduced the efficiency concept in 1896 (Doumpos and Zopounidis, 2002). A feasible solution is efficient if and only if there is no other feasible solution which dominates it (Ringuest, 1992). Von Neumann and Morgenstern (1944) developed the utility theory as one of the major methodologies in modern MCDM. The preference structures of a decision maker are represented by multiple attribute utility functions. Charnes and Cooper (1961) extended the traditional mathematical programming theory to the goal programming. In recent decades, more and more user-friendly software has been developed based on advances in information technology and computer science.

Basically, MCDM provides a set of criteria aggregation methodologies that focus on decision maker's preference structures, system values and judgment policy. Since the "optimal" solutions in the traditional mathematical programming usually do not exist in MCDM due to the potential conflicting nature of the multiple objects, MCDM could find an appropriate "compromise" solution that satisfies all of the decision maker's policy. MCDM general procedure consists of (1) identifying decision objectives, all feasible alternatives and participants; (2) developing evaluation criteria that measure the performance of each alternative on decision objectives; (3) modeling criteria aggregation; and (4) providing meaningful recommendations. MCDM approaches include multi-objective mathematical programming (MMP), multiple attribute utility theory (MAUT), outranking relation theory (ORT), interactive methods and preference disaggregation analysis (PDA) (Vincke, 1992; Pardalos et al., 1995).

Optimization for Bridge Network Maintenance Planning

Bridge network maintenance planning has to deal with multiple bridges in a highway network under limited annual maintenance budgets. Thus, MCDM approaches can be used to help bridge owners, authorizers and/or maintenance managers to make rational decisions on maintenance actions applied to each of individual bridges in the highway network. In this study, the multiple attribute utility theory (MAUT) is adopted. As a matter of fact, MAUT focuses on the development of the multiple attribute utility functions to model and represent the decision maker's preferential structures. The multiple attribute utility functions combine all of the marginal utility functions associated with individual attribute of each alternative. The marginal utility functions for each attribute can be built up by either direct interrogation with decision makers or by indirect methods, as well as by using the analytic hierarchy process (Saaty, 1980) that has been mainly used in USA. The decomposition forms of the multiple attribute utility functions may be (1) additive, (2) multiplicative and (3) multi-linear forms (Keeney and Raiffa, 1993). The additive form requires mutual preferential independence, that is, every subset of criteria is preferentially independent from the remaining criteria. A subset of criteria is considered to be preferentially independent form the remaining criteria if and only if the decision maker's preferences on the alternatives differ only with respect to the criteria, and are independent on the remaining other criteria. It must be noted that very complex decomposition forms are of not interest from a practical point of view (Vincke, 1992). MAUT also employs an interactive and iterative procedure involving policy analyst and decision makers to specify the weight and marginal utility function corresponding to each criterion. Finally, the total utility of each alternative can be used as an objective function in traditional mathematical programming in order to make final decisions (Doumpos and Zopounidis, 2002).

In this study, each of individual bridges in a highway network may be treated as a subset of criteria with a marginal utility function associated with the probabilities that each of the above five maintenance alternatives (including "do nothing") may be conducted at certain time (year). Since the mutual preferential independence requirement can be easily satisfied in this case, the additive form of the multiple attribute utility function is used to form a single-objective function for optimization. The objective function of multiple attribute utility may be also weighted by using RIF of individual bridges in the network, where RIF is defined as the sensitivity of the bridge network reliability to the change in the individual bridge system reliability (Liu and Frangopol, 2005). RIF in this paper reflects the sensitivity of the bridge network reliability in terms of the network connectivity to the change in the individual bridge system reliability due to maintenance actions, and must be developed as a function of the bridge system reliability profiles, network reliability, and network topology. RIF may also be expanded to include traffic capacity and impacts of bridge maintenance activities on economy, environment and society, when considering user's satisfaction and critical bridge performance of a bridge network (Liu and Frangopol, 2005). Consequently, the optimization problem in bridge network maintenance planning can be formulated as follows:

$$\text{Maximize} \quad \sum_i D_{ij} \times RIF_i \times P_{ij} \tag{1}$$

$$\text{Subject to:} \quad \sum_i C_i \le C_{budget} \tag{2}$$

where

D_{ij}	is a binary design variable, *i.e.* the value of D_{ij} can be either 0 or 1;
RIF_i	is the reliability importance factor for bridge *i*;
P_{ij}	is the probability of the maintenance alternative *j* applied to bridge *i*;
C_i	is the cost associated with the selected maintenance alternative for bridge *i*;
C_{budget}	is the annual maintenance budget at certain year;

The binary design variable, D_{ij} represents the decision on selecting the maintenance alternative *j* applied to bridge *i*, that is, D_{ij} = 0 means the maintenance alternative *j* will not be applied to bridge *i,* and D_{ij} = 1 means the maintenance alternative *j* is selected to be applied to bridge *i*. In addition, it should be noted that the values of RIF_i and P_{ij} usually vary during the entire service lifetime of bridge *i.* This is because RIF_i is normalized by considering all bridges in a highway network that experience the aging and deterioration with time (Liu and Frangopol, 2005). On the other hand, P_{ij} is normalized by considering all of the five maintenance alternatives applied to bridge *i* in a certain year, and is dependent on the results from the DP procedure that is combined with Monte Carlo simulations (Liu and Frangopol, 2006). Moreover, C_i is related to the cost in Table 3, but the actual values of C_i should be assigned in order to obtain an optimal bridge network maintenance planning. Finally, this combinatorial optimization problem can be easily solved by either traditional mathematical programming or the advanced heuristic search methods such as Genetic Algorithms (GAs).

Case Study

A numerical example involving five highway bridges is provided to demonstrate the application of the proposed DSS in bridge network maintenance planning. Table 4 presents the values of RIF_i , P_{ij} and C_i for combinatorial optimization that is subject to a budget constraint of C_{budget} = 10,000 The optimization results from a traditional mathematical programming are also summarized in Table 4.

Table 4: Example Values of RIF_i , P_{ij} and C_i

Maintenance Alternatives	Bridge E-17-HE (P_{1j})	Bridge E-17-HR (P_{2j})	Bridge E-17-LE (P_{3j})	Bridge E-16-MU (P_{4j})	Bridge E-16-NM (P_{5j})	Cost (C_i)
Minor Concrete Repair	0.40	0.30	0.15	0.20	0.15	4,500
Silane Treatment	0.20	0.20	0.40	0.10	0.35	48
Cathodic Protection	0.25	0.30	0.20	0.30	0.20	2,600
Rebuild	0.10	0.15	0.05	0.30	0.05	12,000
Do Nothing	0.05	0.05	0.20	0.10	0.25	0
Sum of P_{ij}	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	-
Reliability Importance Factor (RIF_i)	0.38	0.27	0.19	0.11	0.05	Sum of RIF_i *1.0*
Selected Maintenance Alternative	minor concrete repair	cathodic protection	silane treatment	cathodic protection	silane treatment	C_{budget} 10,000
Cost (C_i)	4,500	2,600	48	2,600	48	Sum of C_i *9,796*

Conclusions

This paper presented a decision support system (DSS) for bridge network maintenance planning using the multiple attribute utility theory (MAUT). The combinatorial optimization problem was developed with a single-objective function of the probabilities that the maintenance alternatives may be applied to each of the individual bridges in a highway network. The probabilities in the single-objective function had to be obtained from a Dynamic Programming (DP) procedure, considering individual bridge condition index, safety index and life-cycle maintenance cost. The single-objective function was also weighted by the Reliability Importance Factors (RIF), which had to be the functions of individual bridge system reliability profiles, bridge network reliability, and network topology. The constraint of the optimization problem was the limited annual maintenance budget. A numerical example was provided to demonstrate the application of the proposed DSS in bridge network maintenance planning.

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