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A model for concurrent maintenance of bridge elements

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ABSTRACT

Maintenance activities on existing bridges are important for bridge safety and management. However, maintenance activities cause traffic jams and detours, and thus increase user costs. To reduce user costs resulting from maintenance activities while maintaining bridge elements in good condition, we introduce the concept of "concurrent element maintenance." The concurrent maintenance concept attempts to integrate maintenance timings of different elements of a bridge to reduce user costs over the bridge's life cycle. The proposed model adopts constraint programming as the search algorithm for optimizing the maintenance strategy of any bridge. An example using real data for a reinforced concrete highway bridge is presented. Sensitivity analysis of the discount rate investigates its influence on the life-cycle cost. The results demonstrate that the proposed model is effective for reducing the user costs as well as the total life-cycle costs.

1. Introduction

The construction of the transportation network is the most basic and key contribution to the nation's economy. All countries put their best resources and efforts into building up their own transportation network. After years of construction, concerns are less and less related to new construction projects but are more and more dramatically related to the maintenance of existing transportation facilities. Bridges play an important role in the transportation facilities. Some serious cases of old bridge collapses causing huge loss of life and blockages in the transportation network, such as the Silver Bridge in Ohio, USA in 1967 and the Feng-Gang Bridge in Taiwan in 2005, have drawn more and more attention to bridge maintenance issues, especially on aging bridges.

A maintenance plan for aging structure is essential to ensure a bridge's safety and serviceability. However, the impact of maintenance actions on the transportation network is much greater than before because of the increased usage of transportation with increased economic and business development. The social cost resulting from the traffic, environmental, and commercial impacts of construction was found to be about 5.5 times the total construction cost [1]. The number of vehicles is increasing, and the traffic impact of construction or maintenance is growing quickly. Thus, arrangement of maintenance activities to reduce the related user impact and cost is essential to society and to decision makers.

Recent research has taken user costs into consideration in construction and maintenance planning. Carr [2] used construction congestion cost systems to estimate the impacts of different traffic maintenance and construction methods in construction projects, as well as to provide decision makers with a better understanding of projects and of drivers' behaviors. Lee and Ibbs [3] simulated traffic volumes for several pavement maintenance strategies and calculated user costs as references for decision makers. Lee et al. [4] investigated the influence of maintenance strategies in the I-710 rehabilitation project on user costs. Related research concluded that the huge social costs of construction or maintenance should be considered in the decision-making process.

To reduce the user costs caused by essential bridge maintenance activities, we propose the concept of "concurrent element maintenance," in which we try to schedule the maintenance of bridge elements at the same time where possible to reduce the length of disruptions required to perform maintenance activities. A concurrent maintenance model that minimizes the life-cycle costs including agency costs and user costs of a bridge is established.

An example of a bridge considering maintenance activities for three elements is utilized to assess the capability and to validate the proposed model. Moreover, the sensitivity of life-cycle costs to the discount rate is analyzed. The model established provides decision makers with another maintenance strategy to assist in decision making from both users' and agencies' viewpoints.

2. Maintenance management

An essential function for bridge managers is the allocation of limited resources for maintaining deteriorating bridges. Studies of optimal maintenance planning have been conducted with different considerations. Most of the existing research is aimed at minimizing the expected cumulative maintenance cost over the analysis period. Other performance aspects are considered as constraints to ensure

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satisfactory lifetime safety and serviceability levels for deteriorating bridges. Research efforts on single-objective maintenance planning optimization include: Kong and Frangopol [5], who presented a reliability-based life-cycle cost optimization for deteriorating bridges; Morcous and Lounis [6], who minimized the life-cycle cost of an infrastructure network while fulfilling reliability and functionality requirements; Jha and Abdullah [7], who minimized the maintenance cost of roadside appurtenances for an improved highway life cycle; and Nishijima and Faber [8], who aimed to optimize the allocation of budgets for maintaining the operation of a portfolio of structures.

Another approach is to form a multiobjective optimization problem considering all related performance aspects as separate objective functions. Research efforts on multiobjective optimization problems of maintenance planning include: Miyamoto et al. [9], who considered minimization of maintenance cost and maximization of bridge durability and load-carrying capacity for existing bridges; Furuta et al. [10], who treated life-cycle cost, target safety level and service life as separate objective functions for civil infrastructure systems; Liu and Frangopol [11], who constructed a multiobjective optimization model considering trade-offs among life-cycle maintenance cost, condition, and safety levels of deteriorating bridges; and Lee and Kim [12], who considered maximizing recovery effect, maximizing applicability, and minimizing the maintenance cost for deteriorating bridge decks.

In this paper, optimization of the maintenance timing of different elements of a bridge is solved with respect to the objective of minimizing the life-cycle costs, including agency costs and the costs to users of a bridge. From the users' point of view, we attempt to integrate the timing of maintenance of elements through the proposed concept, “concurrent element maintenance,” to reduce the impact on road users. An example using real data for a reinforced concrete highway bridge is presented to demonstrate the effectiveness of the proposed concept.

3. Life-cycle cost analysis

Life-cycle cost analysis is an engineering economic analysis tool useful in comparing the relative merit of competing project implementation alternatives. By considering all the costs incurred during the service life of an asset, this analytical process helps decision makers to select the lowest cost option [13]. Life-cycle cost analysis has been widely applied for selecting maintenance strategies [5–11,14–17]. For example, Zayed et al. [14] applied economic analysis using present value and equivalent uniform annual cost to compare several steel bridge painting systems. Kong and Frangopol [15] evaluated maintenance cost dynamically by using cost functions incorporating time-dependent variables related to the quality of maintenance, and used these functions to obtain the optimal life-cycle maintenance scenario.

This study establishes a bridge maintenance planning model implementing the proposed concept of concurrent element maintenance as well as life-cycle cost analysis. Both direct and indirect costs are considered in the model. The direct costs, often called agency costs, include costs of material and labor, among others. The indirect cost is the user cost obtained by quantifying service losses such as traffic delays. The most common method for calculating life-cycle cost is the present value method:

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} \tag{1}$$

where LCC: life-cycle cost; C_t: cost in year t; i: discount rate; and T: analysis period.

4. Concept of concurrent maintenance

The concept of concurrent maintenance attempts to integrate the timings of maintenance of different elements of a bridge to reduce the user impacts and costs caused by maintenance activities. Maintenance activities are implemented for bridge safety while the elements are deteriorating to a threshold; i.e., the minimum acceptable condition of the elements set by the maintenance agencies or decision makers. Usually, maintenance activities are planned element by element to schedule on-time maintenance for each element. For example, two elements, A and B, of a bridge have their own initial condition states and deterioration rates, as shown in Fig. 1(a). Condition states range from 0 to 100, with 100 representing the best condition and 0 the worst condition. As they deteriorate to reach the maintenance

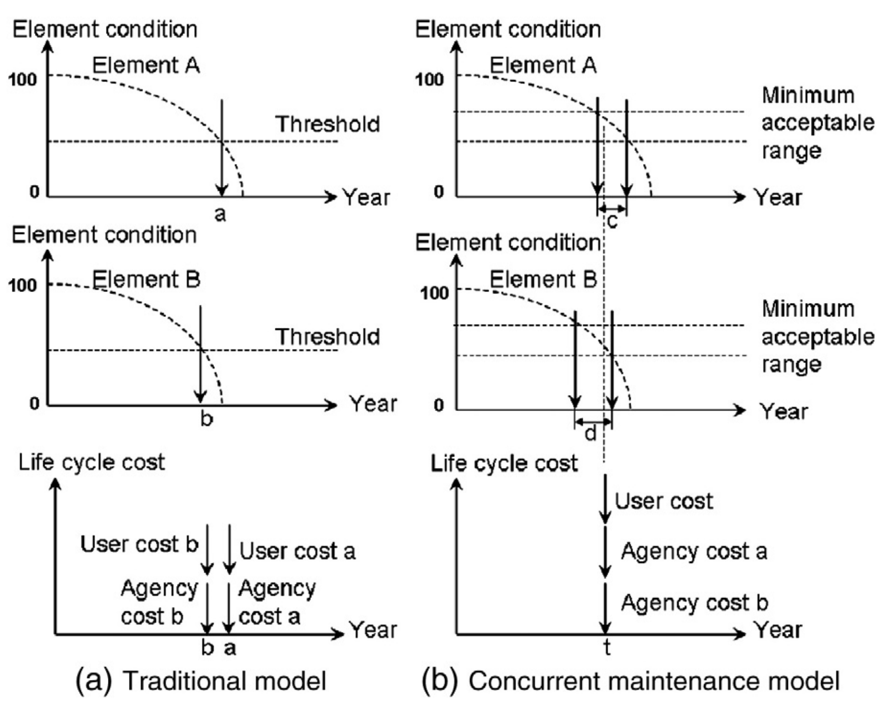

Fig. 1. Concepts of maintenance models.