Transportation Research Part B 78 (2015) 106–122

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

A joint bottom-up solution methodology for system-level pavement rehabilitation and reconstruction

Jinwoo Lee [a,*], Samer Madanat [b,1]

[a] Department of Civil and Environmental Engineering, University of California at Berkeley, 116 McLaughlin Hall, Berkeley, CA 94720-1720, United States
[b] Department of Civil and Environmental Engineering, University of California at Berkeley, 763 Davis Hall, Berkeley, CA 94720-1710, United States

ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 30 April 2015
Accepted 2 May 2015
Available online 18 May 2015

Keywords:
Bottom-up optimization
Pavement reconstruction
Pavement rehabilitation
History-dependent deterioration
Multiple constraints

ABSTRACT

We present a methodology for the joint optimization of rehabilitation and reconstruction activities for heterogeneous pavement systems under multiple budget constraints. The proposed bottom-up approach adopts an augmented condition state to account for the history-dependent properties of pavement deterioration, and solves for steady-state policies for an infinite horizon. Genetic algorithms (GAs) are implemented in the system-level optimization based on segment-specific optimization results. The complexity of the proposed algorithm is polynomial in the size of the system and the policy-related parameters. We provide graphical presentations of the optimal solutions for various budget situations. As a case study, a subset of California's highway system is analyzed. The case study results demonstrate the economic benefit of a combined rehabilitation and reconstruction budget compared to separate budgets.

1. Introduction

This paper addresses the problem of optimizing rehabilitation and reconstruction policies for large-scale pavement systems. We address situations where rehabilitation and reconstruction projects are funded from separate budgets as well as those where they share the same budget. For example, there can be two independent budgets: a capital budget for construction and reconstruction projects, and a maintenance budget for maintenance and rehabilitation activities.

We develop a bottom-up solution methodology for the system-level optimization. A bottom-up approach reflects pavement segment-specific characteristics, and provides individual optimal strategies for each segment. The performance and deterioration models are deterministic and follow Markovian properties, but consider history-dependent deterioration process. This is achieved by using augmented condition states that include history variables, such as the age of the pavement or the cumulative traffic loading, in addition to the current pavement condition, represented by pavement roughness.

The literature of pavement management optimization can be divided into two groups, in terms of the number of facilities considered: single facility problem and system-level problem. System-level problems consist of a lower level problem, the single pavement segment optimization, and an upper level problem.

For system-level optimization, the objective is to solve for optimal Maintenance, Rehabilitation and Reconstruction (MR&R) policies which minimize the expected lifecycle cost of systems, or maximize the reliability of systems, under limited monetary budgets. Two approaches exist to solve this optimization problem: the top-down approach and the bottom-up

* Corresponding author. Tel.: +1 510 898 8451.
E-mail addresses: jinwoolee@berkeley.edu (J. Lee), madanat@ce.berkeley.edu (S. Madanat).
[1] Tel.: +1 510 643 8739; fax: +1 510 643 3955.

http://dx.doi.org/10.1016/j.trb.2015.05.001
0191-2615/

approach. The most widely cited example of the top-down approach is the application in the state of Arizona (Golabi et al., 1982), which has been a notable success in achieving savings in road maintenance costs. The top-down approaches (Kuhn and Madanat, 2005; Durango-Cohen and Sarutipand, 2007) are computationally economical in comparison to the bottom-up approaches, but they are applicable only to homogenous systems, and they do not capture facility-specific features. The bottom-up approaches are beneficial in terms of incorporating heterogeneity among facilities in the system, but are more difficult from a computational perspective.

Robelin and Madanat (2008) solve the reliability-based problem for bridge system management with a bottom-up solution methodology. Sathaye and Madanat (2011, 2012) and Chu and Chen (2012) propose bottom-up approaches for system-level optimization of pavement management with threshold-based decision variables; decision variables are defined as trigger values for one or multiple treatments. The threshold structure allows for mathematical simplifications and makes the optimization approach applicable to the system-level problem. Reger et al. (2014) extend the work of Sathaye and Madanat (2012) to simultaneously incorporate the trade-off between costs and GHG emissions into the system-level pavement management problem. Genetic Algorithms (GAs) are widely used in infrastructure management (Fwa et al., 1994; Chan et al., 1994; Fwa et al., 1996; Cheu et al., 2004; Chootinan et al., 2006; Yeo et al., 2013) as bottom-up solution methodologies. In GAs, solution algorithms consist of iterative generation of offspring genotypes based upon the parent genotypes until a stopping criterion is satisfied. They take discrete activities as decision variables rather than continuous decision variables.

Single facility optimization problems are formulated in several ways. Much of the literature uses Markov Decision Processes (MDP), in which the condition state is discrete (Carnahan et al., 1987; Carnahan, 1988; Feighan et al., 1988; Gopal and Majidzadeh, 1991; Madanat, 1993; Madanat and Ben-Akiva, 1994). For problems formulated with continuous states, various solution approaches exist. Optimal control theory has been applied (Buttler and Shortreed, 1978; Friesz and Fernandez, 1979; Fernandez and Friesz, 1981; Markow and Balta, 1985; Markow et al., 1993; Tsunokawa and Schofer, 1994; Durango-Cohen and Sarutipand, 2007). Jido et al. (2008) extend the work of Madanat (1993) to a continuous-state framework. Li and Madanat (2002) determine the optimal pavement rehabilitation policies based upon the Markovian properties of the deterioration models which are continuous, deterministic and memoryless. Calculus of variations was utilized by Ouyang and Madanat (2006) to solve analytically for the optimal pavement rehabilitation schedule in a finite planning time horizon. Gu et al. (2012) improve on Ouyang and Madanat (2006) to consider multiple activities (maintenance and rehabilitation). In a similar manner, Rashid and Tsunokawa (2012) add decision variables for various treatments, building on Tsunokawa and Schofer (1994) which has a single decision variable (rehabilitation frequency). Lee and Madanat (2014a) jointly optimize pavement design and pavement MR&R policies in the continuous time and state frameworks.

Previous studies for infinite planning horizons that do not consider reconstruction policies are either unrealistic in general pavement cases (where reconstruction is mandatory because of accumulated permanent damage), or applicable only to the special case of perpetual pavements, where pavements are designed to have long lives (e.g. Nunn et al., 1997). As Guignier and Madanat (1999) have shown, joint optimization of reconstruction and periodic rehabilitation is beneficial in terms of lifecycle costs. In the latter paper, it is recognized that accounting for reconstruction in the maintenance and rehabilitation problem leads to steady-state solutions which consist of repeated cycles, where each cycle starts with a reconstruction and includes one or more rehabilitation events.

To determine the timing of reconstruction, augmented state MDP models have been proposed. The history-dependent bridge maintenance and reconstruction optimization problem is solved in Robelin and Madanat (2007) with an augmented state MDP. Lee and Madanat (2014b) solve the joint optimization problem of multiple pavement management activities including reconstruction based on a history dependent deterioration model.

The remainder of this paper is organized as following. In Section 2, the problem formulation, cost and performance models, and solution methodologies are presented. The proposed solution methodologies are utilized in a set of case studies in Section 3. Conclusions are presented in Section 4. The details of the mathematical solution are included in Appendix A.

2. Methodology

2.1. Basic formulation

The objective of the problem is to minimize the total discounted costs, subject to budget constraints. Consider a system of pavement which includes N segments numbered as $n \in \{1, \ldots, N\}$. The discounted cost-to-go of segment n at time t, $f_n(S_n(t), x_n)$, is defined as a function of the augmented condition state, $S_n(t)$, and segment-level MR&R actions, x_n. The multi-dimensional condition state $S_n(t)$ contains the pavement condition state and a history variable such as age. The system-level pavement management system (PMS) problem is formulated in (1). We focus on the infinite horizon problem and find the optimal steady state strategies. Thus, the objective function (1a) is not influenced by the current condition of the segments. A set of decision variables, x, is defined as $\{x_1, \ldots, x_N\}$, and a set of all possible x is noted as X. Two problems are separately defined by different budget constraints, (1b) and (1c). Monetary budget constraints for different types of activities (construction, rehabilitation, maintenance) are separately represented in (1b) and (1c) and indexed by $i \in \{1, \ldots, I\}$. The function $g_n^i(x_n)_j$ is the cost corresponding to budget i for segment n in the jth period when x_n is applied. For example, if B_1 is the available capital budget per unit period, then $g_n^1(x_n)_j$ is the reconstruction cost of the nth segment in the jth budget expenditure period. The unit budget expenditure period, denoted by θ, is the number of years that funds allocated in a time