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Maintenance optimization for transportation systems with demand responsiveness

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ABSTRACT

We present a quadratic programming framework to address the problem of finding optimal maintenance policies for multifacility transportation systems. The proposed model provides a computationally-appealing framework to support decision making, while accounting for functional interdependencies that link the facilities that comprise these systems. In particular, the formulation explicitly captures the bidirectional relationship between demand and deterioration. That is, the state of a facility, i.e., its condition or capacity, impacts the demand/traffic; while simultaneously, demand determines a facility's deterioration rate. The elements that comprise transportation systems are linked because the state of a facility can impact demand at other facilities. We provide a series of numerical examples to illustrate the advantages of the proposed framework. Specifically, we analyze simple network topologies and traffic patterns where it is optimal to coordinate (synchronize or alternate) interventions for clusters of facilities in transportation systems.

1. Introduction

Transportation infrastructure management refers to the process of making decisions concerning the allocation of resources for maintenance of the facilities that comprise transportation systems. The objective in making these decisions is to ensure that the systems are capable of performing the functions for which they were designed and built, while accounting for limited resource availability or level-of-service requirements. In this context, management decisions trade off user costs, which are associated with travel time, fuel consumption, vehicle depreciation and maintenance, and agency costs that are related to the type and intensity of maintenance activities, and include expenses for resource and personnel delivery, materials, etc. As facilities deteriorate, the rate at which user costs accrue increases. In turn, agency costs are incurred to improve condition, and thus, reverse the effects of deterioration.

The primary motivation for the work presented herein is that existing maintenance optimization models sacrifice important functional characteristics in favor of computational tractability/simplicity. In particular, models for multifacility transportation systems are usually formulated as constrained Markov Decision Processes (MDPs) using the notion of "randomized policies" and are solved as linear programs (Golabi et al., 1982; Golabi and Shepard, 1997; Murakami and Turnquist, 1997; Smilowitz and Madanat, 2000). In this framework, individual facilities are not identified and are assumed to be homogeneous. As a result, optimal policies specify the same set (probability distribution) of maintenance actions for all facilities that are in a given state, i.e., they are classified by their condition. Linear constraints can be included in these models to impose

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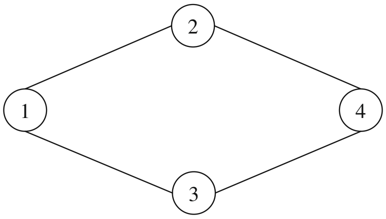

Fig. 1. Hypothetical transportation network.

restrictions that apply to the system, e.g., resource availability. These models are attractive because the computational effort to find optimal policies is independent of the number of facilities that comprise the system. However, omitting information that identifies the individual facilities makes it impossible to capture functional relationships that link them. This, in turn, constitutes an obstacle to providing effective decision support because significant benefits and costs in the management process can be directly attributed to interdependencies that link a system's facilities. To further emphasize this point consider the following example:

Fig. 1 represents a hypothetical transportation network with two paths between node 1 (origin) and node 4 (destination). We assume that the four links in the system are homogeneous with respect to their deterioration.

The fact that existing models classify facilities by their condition means that if links (1,2) and (1,3) are in the same condition, an optimal policy would specify the same action for both of them. Also, the homogeneous cost structure means that it costs exactly twice as much to apply an action to both links as it does to apply the action to either link individually. In practice, however, one expects maintenance policies to specify that (major) interventions on links (1,2) and (1,3) are performed at different times in order to minimize the disruption to the system. Such policies would account for a (user) cost structure in which disrupting the two links simultaneously costs much more than twice the cost of disrupting each link individually. Links (1,2) and (1,3) are said to exhibit a substitutable relationship. For analogous reasons, one also expects that interventions on links (1,2) and (2,4), or on links (1,3) and (3,4), would be synchronized. The links in each pair are said to exhibit a complementary relationship.

Recent advances in optimization theory, coupled with ever increasing availability of powerful computing platforms, make it possible to strike a more appealing and useful balance of capturing realism and ensuring tractability. In particular, as a step to address the limitations described in the preceding paragraphs, we formulate the problem of obtaining optimal maintenance policies for multifacility transportation systems as a quadratic program (QP). In the formulation, each facility's deterioration and demand/traffic are identified and represented as a linear system, i.e., an autoregressive moving average model with exogenous inputs (ARMAX) model. The model explicitly captures the bidirectional relationship between demand and deterioration. That is, the state of a facility, i.e., its condition or capacity, impacts the demand/traffic. The elements that comprise the system are linked because the state of a facility can impact the demand at other facilities. These relationships are captured by the specification of the cross-elasticities of demand. Simultaneously, demand/traffic determines a facility's deterioration rate. The quadratic objective can be used to capture nonlinearities in cost terms, which may, for example, reflect costs associated with congestion, vehicle wear and tear, and scale of maintenance activities. In addition to presenting the framework, we provide a series of numerical examples to illustrate its advantages. The numerical results illustrate how network topology and traffic patterns are key determinants of the structure of optimal maintenance policies.

The remainder of the paper is organized as follows: Section 2 provides an overview of maintenance optimization models for multifacility transportation systems. The proposed model is presented in Section 3. In Section 4, we provide numerical examples to illustrate the appealing features of the proposed model. Conclusions and directions for future work are discussed in Section 5.

2. Related work

The wide use and acceptance of finite (state and action) MDP formulations for periodic review maintenance optimization problems means that perhaps the most natural way to develop a framework for systems of interdependent facilities is to consider multidimensional MDP formulations for the problem. In the management science literature, these types of models are referred to as Parallel Machine/Equipment Replacement Problems (Vander Veen, 1985; Jones et al., 1991; McClurg and Chand, 2002; Chen, 1998; Childress and Durango-Cohen, 2005). These formulations provide an attractive framework to model interdependencies because the state and action space, as well as the deterioration process of each facility in the system is fully identified. In addition, there is a great deal of flexibility in terms of specifying M&R costs. Unfortunately, the fact that the state and action spaces are discrete, leads to significant computational problems in solving and analyzing such models. These difficulties are well-known and referred to as the "curse of dimensionality". The cause of these problems is that solution approaches for MDPs require enumerating all possible interventions for every system state and for every decision-making stage. Because the state and action spaces are discrete, the total numbers of possible system states and interventions