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The price of uncertainty in pavement infrastructure management planning: An integer programming approach

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ABSTRACT

Currently there is a true dichotomy in the pavement maintenance and rehabilitation (M&R) literature. On the one hand, there are integer programming-based models that assume that parameters are deterministically known. On the other extreme, there are stochastic models, with the most popular class being based on the theory of Markov decision processes that are able to account for various sources of uncertainties observed in the real-world. In this paper, we present an integer programming-based alternative to account for these uncertainties. A critical feature of the proposed models is that they provide – *a priori* – probabilistic guarantees that the prescribed M&R decisions would result in pavement condition scores that are above their critical service levels, using minimal assumptions regarding the sources of uncertainty. By construction of the models, we can easily determine the additional budget requirements when additional sources of uncertainty are considered, starting from a fully deterministic model. We have coined this additional budget requirement the price of uncertainty to distinguish from previous related work where additional budget requirements were studied due to parameter uncertainties in stochastic models. A numerical case study presents valuable insights into the price of uncertainty and shows that it can be large.

1. Introduction

An efficient maintenance and rehabilitation (M&R) policy for pavement infrastructure is critical for a safe and cost-effective transportation system. Researchers have developed numerous decision support systems to obtain optimal M&R policies. One popular class of models makes the assumption of determinism: Pavement deterioration and improvements in pavement conditions are known with complete certainty (e.g. Fwa et al., 1988, 1996; Wang et al., 2003; Ng et al., 2009). The resulting models are typically based on integer programming, with high computational requirements (although recent advances have reported increasingly larger problem instances that can be solved, e.g. see Dahl and Minken, 2008; Yoo and Garcia-Diaz, 2008). Clearly, the assumption of determinism is questionable in practice since pavement behavior depends on factors that are not completely known, such as environmental conditions, traffic loading and the structural properties of the pavement. Consequently, deterministic models cannot guarantee, in any sense, that pavement sections be maintained above their critical service levels, although most mathematical programming-based models have constraints that aim to "ensure" that the resulting pavement conditions are above a minimum level. Moreover, integer programming-based M&R models yield open-loop (i.e. non-condition-based) policies that are generally – from a managerial perspective – less desirable than

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condition-based, feedback policies common in stochastic models. For this reason, integer programming-based models are typically used on a rolling-horizon basis.

In order to incorporate stochasticity in the determination of optimal M&R policies, researchers have devised alternative models. The most popular class of models that explicitly accounts for the stochastic nature of the M&R problem is based on the theory of Markov Decision Processes (MDP). Unlike integer programming-based models, MDP models yield condition-based policies that are more attractive from a managerial perspective. Golabi et al. (1982) was the first to introduce the MDP approach to the pavement management problem. They determined a long-term M&R policy that was guaranteed to be optimal when the planning horizon is infinitely long. A short-term model was proposed to ensure that the steady-state condition is reached after a finite number of years. The same philosophy was adopted by Mbwana and Turnquist (1996). However, unlike Golabi et al. (1982), their model *explicitly* determined the optimal M&R action for *each* pavement section, whereas the output of the majority of MDP-based models only specifies the fraction of pavement sections in a particular state to which a certain M&R action is to be applied. The reason for this simplifying assumption is because of the well-known curse of dimensionality that makes the solution of large-scale MDP problems challenging, e.g. see Bertsekas (2001). Numerous other variations of the MDP-based pavement management problem have been proposed (e.g. Carnahan et al., 1987; Guignier and Madanat, 1999; Smilowitz and Madanat, 2000; Ferreira et al., 2002; Guillaumot et al., 2003; Boyles et al., 2010). The specification of the transition probabilities in MDP models is typically a result of statistical estimation (Madanat and Wan Ibrahim, 1995; Mishalani and Madanat, 2002). However, when there is a lack of historical data, the use of statistical procedures might not be feasible (Smilowitz and Madanat, 2000). Recently, Chu and Durango-Cohen (2007, 2008) presented an alternative to Markov transition probabilities with the use of state-space specifications of time series models to estimate infrastructure performance. Using this new approach, Durango-Cohen and co-workers have developed another class of infrastructure M&R models using continuous state and decision variables, thereby overcoming the computational and statistical limitations of the MDP models (Durango-Cohen and Tadepalli, 2006; Durango-Cohen, 2007; Durango-Cohen and Sarutipand, 2007, 2009).

Besides the use of determinism and stochasticity to classify the current infrastructure management literature, another possible criterion is whether one is examining a single facility versus an entire network. In terms of this alternative criterion, the current work focuses on the facility level budgeting problem (following Carnahan et al., 1987; Madanat, 1993a,b; Madanat and Ben-Akiva, 1994; Guillaumot et al., 2003; Boyles et al., 2010). The network level budget requirements can simply be obtained by solving the proposed budgeting problem for each facility in the system, as we shall demonstrate in Section 4. The related problem of network level budget allocation will be examined in future work (e.g. see Golabi et al., 1982; Fwa et al., 1988, 1996; Mbwana and Turnquist, 1996; Guignier and Madanat, 1999; Smilowitz and Madanat, 2000; Ferreira et al., 2002; Wang et al., 2003; Gao and Zhang, 2008; Ng et al., 2009).

From the above, it is clear that the predominant assumption in the current (stochastic) pavement management literature is that pavement conditions can be described by some discrete-time Markov chain, with known transition probabilities. To the best of our knowledge, we are only aware of one previous work that has addressed uncertainty in a non-MDP framework. Gao and Zhang (2008) developed a complex, linear, robust optimization model to determine optimal M&R decisions. Equations describing pavement deterioration and condition score improvements due to M&R actions were obtained based on linear regression. While they explicitly modeled the explanatory variables in the regression to be random, the regression coefficients were assumed to be deterministic, whereas sampling variation and measurement errors could easily lead to non-deterministic coefficients. A prominent feature of their model is that probabilistic guarantees can be given to the likelihood that pavement conditions get worse than their minimum acceptable levels, *for each pavement section individually*. We want to note that MDP models are also able to yield these probabilistic guarantees at the pavement section level (e.g., Mbwana and Turnquist, 1996), although most of these models impose probabilistic guarantees *at the network level*, i.e., they guarantee that a certain fraction of all pavement sections will be above their critical service levels.

There are two major contributions in this paper. First, we present two non-MDP models based on integer programming to incorporate uncertainty in the pavement management problem. They are simpler and more intuitive than the model proposed by Gao and Zhang (2008). Furthermore, we do not confine ourselves to the use of linear regression-based performance models. Our models only require the specification of some nominal parameter values and a set of intervals in which the parameters are hypothesized to reside. In our first model, we consider uncertainty in the pavement improvement due to M&R activities, whereas in the second model we also examine uncertainty in pavement deterioration rates. Second, we study the *price of uncertainty*, i.e., we present useful insights into the impact of uncertainty on M&R decision making (as compared to the case when uncertainty is completely ignored). In particular, we present some insightful results on the differences in budget requirements between planning in a deterministic world versus planning in an environment where parameters are allowed to be random. Note that due to the dichotomy in the current pavement management literature (a model is either fully deterministic or fully stochastic), the impact of uncertainty on M&R planning is not easily determined because of the fundamentally different assumptions in the two modeling paradigms. The models proposed in the current paper make such a comparison straightforward as they are gradual generalizations of each other.

In a number of related studies by Madanat (1993a,b), Madanat and Ben-Akiva (1994) and Kuhn and Madanat (2005, 2006) similar concepts as the price of uncertainty have been introduced. For example, Madanat (1993a,b) and Madanat and Ben-Akiva (1994) introduced the concept of "the value of more precise information" to quantify the cost savings that can be realized when infrastructure inspections are more accurate. Kuhn and Madanat (2005, 2006) examined the "cost of uncertainty", referring to the difference in maintenance cost when uncertainty in the Markov transition probabilities is explicitly consid-