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Network-Level Reliability-Based Bridge Inspection, Maintenance and Replacement Optimization Model

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ABSTRACT

This paper presents a reliability-based optimization model of inspection, maintenance and replacement for a system of several highway bridges. The objective in the formulation is to minimize the total expected social cost, including the expected cost of failure. The frequency of inspections is included as a decision variable. The probability of failure is explicitly taken into account in the constraints. A bottom-up approach is used, which allows for bridge-specific details to be taken into account. Most existing system level models assume that component deterioration is memoryless; however, this assumption is relaxed in this paper, and history-dependent deterioration models are used. The formulation is flexible enough to accommodate different types of facilities, deterioration processes and failure modes. A parametric study is conducted to demonstrate the model's response to different assumptions on the deterioration rates, maintenance costs and efficiency.

KEYWORDS: Bridge Inspection, Optimization, Model, Maintenance, Replacement, Bottom- up Approach.

1. INTRODUCTION

Infrastructure management is the process by which agencies monitor, maintain and replace deteriorating systems of facilities, within the constraints of available resources. More specifically, the management process refers to the set of decisions made by an infrastructure agency over time to maximize the system performance.

Based on the recent Status of the Nation's Highways, Bridges and Transit (FHWA, 2005), the average year of construction of the bridges in the United States was determined to be 1963. In 2002, 50% of the daily traffic utilized bridges were older than forty years. Of the nation's 586, 000 bridges, 28% were deficient, half of which were structurally deficient. The deteriorating bridge population, as well as the limited amount of funds available for maintenance and inspection, led to the development of bridge management systems to optimize the use of available funds, by helping agencies take maintenance and rehabilitation decisions.

Experience with infrastructure management systems in the United States shows that the benefits of systematic approaches to facilities' management have been substantial in practice. For example, the Arizona Department of Transportation reported that the implementation of its Pavement Management System (PMS) to optimize

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pavement rehabilitation expenditures has saved over $200 million in maintenance and rehabilitation costs over a five-year period (OECD, 1987). These savings were achieved because the maintenance and rehabilitation resource allocation decisions were made using the PMS with the objective of minimizing the life cycle costs of the pavement sections in the network.

As will be shown in the review of bridge management systems and optimization models, most system level models assume that the deterioration of facilities is memoryless, which may be unrealistic. On the other hand, most bridge management models using more realistic deterioration models are limited to one facility or to a group of similar facilities. The research presented in this paper aims at developing a bridge management model that can be applied to a system of several bridges while maintaining the identity of each bridge and considering history-dependent deterioration models.

Outline

The next section presents a review of existing bridge management systems and optimization models and discusses their limitations. The third section describes the development of a bottom-up reliability-based optimization model of deck inspection, maintenance and replacement for a system of several bridges. An implementation of the solution is also presented in that section. In the fourth section, a preliminary parametric study is conducted in order to assess the performance of the model. The last section presents extensions to the model developed in this paper.

2. REVIEW OF BRIDGE MANAGEMENT SYSTEMS AND OPTIMIZATION MODELS

Given the available resources, the history of facility conditions and the maintenance and repair decisions, the objective of infrastructure management is to determine the optimal maintenance decisions in the current year. The solution is based on the consequences of possible actions on the future condition of the system. Since information about the future condition is not available, deterioration models are used. This is a common framework in all existing bridge management systems and optimization models.

In the present section, the differences, characteristics and limitations of bridge management systems (BMS) implemented or designed to be implemented by agencies, will be presented. Optimization models of bridge maintenance and repair are also present in the literature. These models are not usually implemented, and they are developed to serve as a basis for future bridge management systems. These models will be reviewed in the second part of the present section.

Characteristics and Limitations of Existing Bridge Management Systems

Pontis (Golabi and Shepard, 1997), Bridgit (Hawk, 1994), the North Carolina Bridge Management System (Al-Subhi et al., 1990) and the Indiana Bridge Management System (Gion et al., 1992; Jiang and Sinha, 1989; Saito and Sinha, 1989a; Satio and Sinha, 1989b; Sinha et al., 1988), are four major bridge management systems in the United States. Their purpose is to help decision-makers with maintenance and repair (M&R) decisions for a system of several bridges, considering constraints of available budget and system performance. The types of deterioration models used in these four BMSs are almost similar; however, the optimization approach in Pontis differs from that in Bridgit, the North Carolina Bridge Management System (NCBMS) and the Indiana Bridge Management System (IBMS).

- In Pontis, the optimization approach is top-down. M&R optimization is performed at the system level. Actions are recommended for fractions of the bridge population. Actual bridges on which actions are performed are then selected, either manually or by a subroutine. This final selection may differ slightly from the optimization done earlier at the system level. This approach overcomes dimensionality problems in a very effective manner. It considers populations of bridge components rather than individual bridges, and that makes it well suited for large systems. However, some of the assumptions required in this approach are unrealistic. Parameters, recommendations and facility conditions must be aggregated over the bridge population. This may be problematic, as a group of bridges is usually less homogeneous than a system of pavement sections. Moreover, bridge-specific information or environmental factors cannot be taken into account. The version of Pontis described in Golabi and Shepard (1997) breaks down the bridges into components, and this does not allow the interactions between the components of a bridge to be considered, with the following two consequences: it leads to inaccurate modeling of deterioration and prevents the optimization model from favoring practical maintenance strategies. For example, if a bridge deck is to be maintained and its substructure will need maintenance in the near future, it is logical to group the maintenance actions in order to minimize the closure of the bridge. Based on conversations with engineers at the Federal Highway Administration and at the California Department of Transportation, the aforementioned facts are seen as the main reasons why bridge management systems such as Pontis are not used to their fullest capacity by State agencies in the United States.

- In Bridgit, the NCMBS and the IBMS, the optimization approach is bottom-up. M&R optimization is performed for every facility. Actions are evaluated for individual bridges. These recommendations are then aggregated and certain actions are selected to take into account system level constraints, such as budget or overall performance. The general layout of the optimization in both BMSs occurs in two steps. The first step is to define possible sets of actions at the bridge level, called life cycle activity profiles. The second step selects one life cycle activity profile for each bridge to maximize the total effectiveness, under constraints of budget and overall performance. The maintenance costs calculated in these BMS are called life cycle costs. However, the optimization is performed over a limited period, which we refer to as the optimization period (five years in the IBMS and twenty years in Bridgit). Beyond this period, maintenance actions are fixed. It is possible to address this issue by extending the optimization period. However, this would require increasing the number of alternatives for each bridge, and this may make the problem intractable.

Characteristics and Limitations of Optimization Models

Optimization models present in the literature typically have a higher degree of complexity than BMSs. However, they usually cannot be readily implemented and can be seen as prototypes for future BMSs. As was the case for the BMSs presented above, the objective of these models is to optimize M&R decisions, based on the knowledge of the current condition of the system through inspections, and on the prediction of future condition through the use of deterioration models. While the general framework of the optimization models is similar, these models differ in many aspects: scope of optimization, decision variables, layout of the optimization, deterioration models and assumptions about the knowledge of the current condition.

Scope of Optimization

The optimization is performed on a given system for a given planning horizon. The system can be composed of one facility or of several facilities. The facility level problem deals with only one bridge and is obviously less complex than a problem dealing with several facilities. It is also less realistic, especially in the presence of budget constraints; namely, a budget is usually provided for several facilities and not for a single facility.

Some models first developed at the facility level, such as in (Madanat and Ben AKival) and have later been extended to the system level (Smilowitz and Madanat, 2000). However, some other models, such as in (Kong and Frangopol, 2003), have been designed to illustrate the use of more complex and realistic deterioration models. These are facility level problems and have not been extended to the system level. Similarly, the reliability-based models of maintenance and inspection developed in

(Mori and Ellingwood, 1994; Chung et al., 2003) have not been extended to the system level.

Decision Variables

The main objective of the models is to optimize the maintenance of a bridge or of a system of several bridges, i.e. to help in the decision of which maintenance action is to apply on a given facility in a given year. More refined models also include the decision to inspect a facility in a given year as part of the decision variables (Madanat and Ben AKiva, 1994; Smilowitz and Madanat, 2000; Mori and Ellingwood, 1994; Chung et al., 2003).

Objective Function and Constraints

The optimization model can be set up in several ways. The first formulation described here is common to the problems posed as Markov decision processes, such as the model in at the facility level and the model in (Smilowitz and Madanat, 2000) at the system level. The objective of these models is to minimize the total cost under a budget constraint. The total costs are composed of the agency costs and the user costs. The agency costs represent the actual costs of maintenance, while the user costs are a translation of the condition of the facilities to monetary units. In (Madanat and Ben AKiva, 1994) and (Smilowitz and Madanat, 2000), the costs of maintenance also include the costs of inspection.

A different approach is presented in (Mori and Ellingwood, 1994). This facility level model minimizes the sum of the agency costs and the expected failure costs, under the following safety constraint: the probability of failure of the facility over the planning horizon must be kept under a specified value. In this model, agency costs also include inspection costs.

Deterioration Model

Deterioration models are used to predict the future condition of the system depending on maintenance actions performed on the facilities. A large proportion of the models present in the literature of maintenance optimization are time-independent: the models in (Kong and Frangopol, 2003), and in (Smilowitz and Madanat, 2000) (as well as all BMSs presented above). This means that the future condition of a facility only depends only on its current condition and is independent from its past condition. In other words, using states to represent the condition of a facility, the probability for an element to transition from an initial state A to a lower state B does not depend on the time spent in state A. This assumption is linked to the use of Markov chains to represent the deterioration of a facility, whereby a transition probability matrix is defined for each maintenance action. Although this assumption may be valid for certain bridge states, it has been shown empirically in (Mishalani and Madanat, 2002) that it is unrealistic for bridge states where the deterioration is primarily governed by chemical processes.

Other models use time-dependent deterioration models (Kong and Frangopol, 2003; Mori and Ellingwood, 1994).These models are based on physical properties of the facility considered.

Knowledge of Current Condition

The current condition of the system is estimated through inspections. In the United States, bridges are usually inspected every two years (FHWA, 2002b). In the model in (Kong and Frangpol, 2003), inspections are assumed to be periodically performed and are not part of the decision variables. In the presence of uncertainty with respect to the bridge elements' conditions, a conservative approach is to assume the worst possible condition. Such an approach may lead to unnecessary maintenance actions, thus yielding higher M&R costs. To reduce this uncertainty, it is possible to inspect the bridge components' conditions more frequently. Thus, a trade-off exists between M&R costs and inspection costs.

Improved models are presented in (Mori and Ellingwood, 1994) and (Chung et al., 2003). In these reliability-based models, inspections are part of the decision variables and are assumed to be error-free. The models developed in (Madanat and Ben AKiva, 1994) at the facility level and in Smilowitz and Madanat, 2000) at the system level jointly optimize inspections and maintenance. These models explicitly recognize the presence of random errors in the inspection results.

3. BOTTOM-UP FORMULATION

The limitations identified in the literature review point to the need for a model to optimize the maintenance of a system of bridges, with the following objectives:

- Bridge-specific attributes, including environmental factors and probability of failure, must be taken into account in the optimization.
- For each bridge or for each component of each bridge, a set of recommended actions must be determined.
- System level constraints (budget, overall performance) must be taken into account.
- Time-dependent deterioration models, whether physical or empirical, should be used.

Problem Formulation

Definitions and Assumptions

- **System**. The system considered in the basic model is a system of bridges. The system is managed by a single agency, such as the State Department of Transportation in the United States. While the condition of the bridges obviously changes over time, the system remains constant over the planning horizon: no bridges are built or decommissioned.
- **Budget**. For accounting and fiscal reasons, the agency usually has a yearly budget available for the maintenance of the system. In some cases, the available budget is broken down in parts that can be used only for a certain type of activities. For example, a portion of the budget can be used only for replacement of facilities, while another part may be reserved for routine maintenance. In our model, such refinements are not taken into account and the yearly budget is available for all activities. It is assumed that the budget available during a particular year can only be used during that year.
- **Costs**. The agency incurs costs when maintenance actions are performed. Moreover, maintenance actions on a bridge usually imply the closure of some or all of its lanes. This leads to delays to the users and/or costs associated with detours. This is particularly important in the case of bridges. In a highway network, bridges are usually capacity constraining, due to their high cost of construction relative to regular highway lanes. Moreover, convenient detours may not be available. Thus, user costs consist of delays, closures and detours associated with the performance of maintenance actions.
- **Modeling of bridges.** The only bridge component considered is the deck. The memoryless assumption made in all current system level models is relaxed; the deterioration model is continuous, stochastic and time-dependent. The probability of failure of the deck is part of the information provided by the deterioration model.

Formulation

The M&R actions considered in the model can be grouped into two general categories. The actions of the first category, which will be called *maintenance actions*, are performed according to a schedule, regardless of the condition of the facilities. The frequency of the performance of maintenance actions is a decision variable, for each bridge and each type of maintenance action. The actions of the second category, which will be called *repair actions*, are performed when the condition of a facility reaches a predefined level. The level at which a repair action is performed is a decision variable, for each bridge and each type of repair action. This distinction between time-based and condition-based trigger of M&R actions was first presented in [13](Kong and Frangopol, 2003). The following notation is used:

- N : Number of facilities in the system.
- T : Number of years in the planning horizon.
- M_n : Number of types of maintenance actions that can be applied on facility *n*.
- R_n : Number of types of repair actions that can be applied on facility *n*.

The decision variables are:

- $T_{n,m}^{\text{maintenance}}$: Time interval between two consecutive maintenance actions of type *m* scheduled for facility

n, $n = 1,...,N$, $m = 1,...,M_n$. $1_{n,t}^{\text{maintenance}}$ is also defined as 1 if maintenance action of type m is scheduled for facility n in year t, and 0 otherwise.

- $T_n^{\text{inspection}}$: Time interval between two consecutive inspections for facility n, $n = 1,...,N$. $1_{n,t}^{\text{inspection}}$ is defined as 1 if facility n is inspected in year t, and 0 otherwise. $1_{n,t}^{\text{inspection}} = 1$ if and only if the remainder of t divided by $T_n^{\text{inspection}}$ is equal to 0.
- $\beta_{n,t,r}^{\text{repair}}$: Target reliability index used for the repair action of type r on facility n in year t, $n = 1,...,N$, $r = 1,...,R_n$. For a given facility n in condition c at the beginning of year t, the repair action to be performed in year t is of type r such that $\beta_{n,t,r}^{\text{repair}} \geq c$ and for any $r' \neq r$ in $r = 1,...,R_n$, $\left[\beta_{n,t,r©}^{\text{repair}} < c\right.$ or $\left.\beta_{n,t,r©}^{\text{repair}} \geq \beta_{n,t,r}^{\text{repair}}\right]$. In other words, the type of the performed repair action is r such that $\beta_{n,t,r}^{\text{repair}}$ is the lowest target reliability index greater than the condition c of the facility.
- $I_{n,r,m}$: number of years after repair action r has been performed on facility n during which maintenance action m is not performed, regardless of whether maintenance action m is scheduled or not. The purpose of this variable is to prevent maintenance actions to be performed in a period of a few years following a repair action.

The formulation of the optimization problem is as follows:

$$\min \sum_{n=1}^{N} \left[F_n(T) C_n^F + \sum_{t=0}^{T-1} \alpha^t \left[1_{n,t}^{\text{inspection}} C_n^{\text{inspection}} + E\left[C_{n,t}^{\text{maintenance+repair}} \right] \right] \right] \tag{1}$$

subject to

$$F_n(T) \leq P_n^{\text{acceptable}}, n = 1,...,N \tag{2}$$

$$\beta_n(t_{\text{cont}}) = f_n\left(t_{\text{cont}}, t_n^{\text{repl}}(t_{\text{cont}}), \left\{actions_{n,t}, t = t_n^{\text{repl}}(t_{\text{cont}}),...,\text{int}(t_{\text{cont}})\right\}\right), \tag{3}$$

$$n = 1,...,N,\ t_{cont} \in [0,T]$$

$$1_{n,t}^{\text{inspection}} C_n^{\text{inspection}} + E\left[C_{n,t}^{\text{maintenance+repair}} \right] \leq B_t, t = 0,...,T-1 \tag{4}$$

The following notation is used:

- $F_n(T)$: Probability of failure of facility n over T years.
- C_n^F : cost of failure of facility n.
- α: Discount factor, $\alpha = 1/(1+r)$ where r is the interest rate.
- $C_n^{\text{inspection}}$: cost of inspection for facility n.
- $E\left[C_{n,t}^{\text{maintenance+repair}}\right]$: expected cost of maintenance and repair of facility n in year t. The expected value of the cost is used because of the probabilistic nature of the performance of maintenance and repair actions. Namely, repair actions are performed based on the deterioration, which is a probabilistic process; scheduled maintenance actions are performed only after a given period of time following a repair action. As the closed form of the expected cost is difficult to obtain in the general case, it will be determined through Monte-Carlo simulations, which are described later.
- $P_n^{\text{acceptable}}$: Acceptable probability of failure of facility n over the planning horizon.
- $\beta_n(t)$: Reliability index of facility n at time t. By definition of the reliability index, the instantaneous probability of failure of facility n at time t (given it has not failed yet) is $\Phi[-\beta_n(t)]$, where Φ is the

cumulative normal distribution.

- $t_n^{\text{repl}}\left(t_{\text{cont}}\right)$: Year of last replacement of facility *n* before time t_{cont}. If the facility *n* has not been replaced by time t_{cont}, then $t_n^{\text{repl}}\left(t_{\text{cont}}\right)=0$.

- $actions_{n,t}$: set of maintenance and repair actions performed on facility *n* in year *t*. This set may be empty. Due to the probabilistic nature of deterioration, this set is not deterministic. However, given a set of actual deterioration parameters and a repair policy, this set can be determined. This will be used in Monte-Carlo simulations, which are described later.

- $\text{int}\left(t_{\text{cont}}\right)$: Largest integer less than t_{cont}.

- B_t: Budget made available to the agency at the beginning of year *t*, to be used in year *t*.

The first constraint is a reliability constraint. The second constraint determines the deterioration pattern of the facilities. The third constraint is the budget constraint and is based on expected costs. Due to the large number of bridges in the system, the total cost for the system in a given year has a very low variance. Thus, if the expected system costs satisfy the budget constraint, the probability that the actual cost exceeds the budget constraint is very low. The validity of this assumption will be analyzed in case studies.

Due to the probabilistic nature of the application of repair actions, the complexity of determining a closed form of the deterioration and of the expected costs of maintenance and repair for a reasonably long planning horizon is very high. Thus, the expected costs, the deterioration profile and the probability of failure will be estimated using Monte-Carlo simulations. In order to decrease the complexity of the problem, the number of types of maintenance and repair actions may also be small, as is the case in Frangopol et al. (2001), where one type of maintenance actions is considered and replacement is the only type of repair.

Implementation of the Solution

A set of values of the decision variables for one bridge will be denoted as a policy. Based on the problem formulation, the solution can be determined in two distinct phases:

- **Facility level**. For each bridge, a list of possible policies is created. Using Monte-Carlo simulation, the cost of each possible policy for one bridge is determined, as well as the probability of failure of the bridge under this policy. If the probability of failure under a certain policy is lower than a predetermined threshold, this policy is kept for the second phase and is considered feasible at the facility level. Otherwise, it is considered infeasible and is not kept for the second phase.

- **System level**. At the beginning of this phase, a list of policies that are feasible at the facility level is available for each bridge, along with the costs of each policy. Then, one policy per bridge must be selected in order to minimize the total costs, while satisfying the budget constraint for every year of the planning horizon. The set containing one policy per bridge for all bridges will be called a combination of policies. If the numbers of bridges and feasible policies per bridge were small, the combinations of policies could be enumerated and the combination leading to the minimum costs could be determined. However, in this study, 20 bridges and approximately 200 policies per bridge are considered, which yields 200^{20} possible combinations. Such a large number of combinations cannot be enumerated in a reasonable amount of time. Fortunately, bounds for the minimum costs can be found. A lower bound of the minimum costs is achieved by the following combination C_{low_b} of policies P_n:

$$C_{\text{low\_b}} = \left\{ P_n, n=1,\ldots,N, \text{s.t. } P_n \text{ achieves } \min_{p\in\{\text{policies of bridge } n\}} total\cos t_{n,p} \right\} \quad (5)$$

where $total\cos t_{n,p}$ is the expected cost of maintenance, replacement, inspection and failure for bridge *n* under policy *p*, over the planning horizon. These minima can be determined in a reasonable amount of time. Moreover, if this combination of policies satisfies the budget constraint for every year of the planning horizon, it is the optimal solution. If it does not satisfy the budget constraint, one needs to find a combination of policies that satisfies the budget constraint to determine an upper bound of the minimum costs. A good candidate combination to satisfy the budget constraint is

$$C_{\text{up\_b}} = \left\{ P_n, n = 1,..., N, \text{s.t. } P_n \text{ achieves} \min_{p \in \{\text{policies of bridge } n\}} \left[\max_{t = 0,..., T-1} cost_{n,p,t} \right] \right\} \tag{6}$$

where $cost_{n,p,t}$ is the expected cost of maintenance, replacement and inspection of bridge *n* under policy *p* in year *t*. Let us explain the choice of this candidate using a simple example with one bridge and two policies over a planning horizon of three years. Let us assume that the first policy costs 400 (monetary units) in the first year and 0 in the following years and that the second policy costs 200 each year. If the budget made available each year is 200, the first policy is not feasible and the second policy is feasible, although the total cost of the first policy is lower than that of the second policy. This is due to the peaked cost of the first policy. Intuitively, policies with lower peaks in their cost per year are more likely to lead to a feasible combination.

If this combination does not satisfy the budget constraint, other combinations can be tried until one that satisfies the budget constraint is found. Exploration of other combinations was not implemented in this research.

The problem complexity is polynomial in the length of the planning horizon, with a degree not exceeding 2. Thus, the length of the planning horizon can be large without unreasonably increasing the needed computation time. The determination of the lower bound and candidate upper bound described above is linear in the number of bridges. However, there is no guarantee that $C_{\text{up\_b}}$ is actually an upper bound, nor that $C_{\text{low\_b}}$ is feasible, thus optimal. Finding a meaningful upper bound (i.e. an upper bound that is relatively close to the lower bound) in a systematic manner is not likely to be a polynomial time problem. A computer program was created in the C language to solve the optimization problem. With 20 bridges and approximately 200 policies per bridge, the computational time for the facility level portion is approximately 30 minutes on a standard personal computer, and the system level portion requires just a few seconds.

4. PARAMETRIC STUDY DATA

A deterioration model for highway bridges is presented in (Frangopol et al., 2001). The time evolution of the reliability index β is described, as well as the influence of a maintenance action on the reliability index. The following figures show the parameters that characterize the deterioration without maintenance (left) and the influence of a maintenance action (right).

The reliability index of a new bridge is β_0. Without maintenance, the reliability index is constant for a time period t_I, and then decreases with slope δ. If a maintenance action is performed, the reliability index immediately increases by γ, then decreases with slope θ for a time period t_{PD}. Beyond this period of influence of the maintenance action, the reliability index decreases with a slope δ. In (Frangopol et al., 2001), the time at which a maintenance action is performed is a random variable, whereas in this study, it is a decision variable. All the other parameters are random variables. Table 1 summarizes the distributions of the random variables from (Frangopol et al., 2001).

In (Frangopol et al., 2001), one bridge and one type of maintenance action are considered. The only repair action is replacement. The costs for maintenance and replacement, including user costs, are provided in (Kong and Frangopol, 2003). These values were used as a basis for the present study. However, the purpose of the present study is to demonstrate the capabilities of an optimization model in a more complex situation, both in terms of number of bridges and types of maintenance actions. Using the same distribution types, the parameters can be changed to represent slightly different bridges. A system of twenty bridges was created in this manner. One additional type of maintenance action was introduced, more costly and with a greater influence than the first one.

The objective of this preliminary case study is not to model a realistic system of bridge decks with high accuracy, but to verify that the developed optimization model provides reasonable results. Five groups of four bridges each were created. Within each group, the four bridge decks have the same deterioration parameters, but their unit costs of maintenance are different. All decks are assumed to have the same area (1, 000 square meters). Table 2 summarizes the parameters of the deterioration. β_0 and θ are not included in the table, since their values are not changed relative to Table 1.

The parameters for the first group of bridges (1-4) are the same as in (*18*), differing only in that maintenance of type 2 was not included in the paper. The other groups of bridges differ in their deterioration rates. Bridges 5-8 have faster deterioration rates than bridges 1-4, and bridges 9-12 have faster deterioration rates than bridges 5-8. Bridges 13-16 have slower deterioration rates than bridges 1-4, and bridges 17-20 have slower deterioration rates than bridges 13-16. The unit costs of maintenance and repair are summarized in Table 3.

The unit costs of maintenance of type 1 and replacement for the first bridge of each group are based on Kong and Frangopol (*13*). A higher unit cost was chosen for the maintenance of type 2, which is more effective than the maintenance of type 1. For the other alternatives, we changed the unit costs of maintenance in order to change the ratio between the unit costs of maintenance and replacement and the ratio between the unit costs of the two types of maintenance.

The planning horizon was chosen to be 75 years, and an interest rate of 2 percent was assumed. The target probability of failure is 10^{-5} over the planning horizon for each bridge.

5. RESULTS

Costs of failure up to five times the unit cost of replacement were tried and did not change the results of the optimization. For each bridge, only one type of maintenance action is to be performed. The policies leading to the minimum cost per bridge are described in Table 4.

The present value of the total cost associated with the combination $C_{\text{low\_b}}$ of policies is 2.0*10^7 dollars over the planning horizon of 75 years. This combination is feasible for any budget above 1, 286, 000 dollars per year. The present value of the total cost associated with the combination $C_{\text{up\_b}}$ of policies is 2.3*10^7 dollars over the planning horizon of 75 years. This combination is feasible for any budget above 646, 000 dollars per year. In this example, the total cost for the candidate upper bound is only 15 percent higher than the total cost for the lower bound, while the yearly budget required for the lower bound is twice as high as the budget for the candidate upper bound. The candidate upper bound shows that a relatively small premium on the total cost allows for more evenly distributed yearly costs. Further analysis would be required to extend these results to the general case. In this example, the optimization model provides logical and intuitive results:

- The faster the deterioration of a bridge, the shorter the recommended interval between maintenance actions is. For example, this can be seen by examining the second bridge in each group. The list of bridges in ascending order of interval between maintenance, and in descending order of deterioration rate, is: 10, 6, 2, 14 and 18.
- The faster the deterioration of a bridge, the shorter the recommended period of blocked maintenance.
- The smaller the ratio of the unit cost of repair to the unit cost of maintenance, the longer the recommended interval between maintenance. This can be seen for bridges 13 through 16; maintenance is less costly for bridges 13 and 14 than for bridges 15 and 16 and is thus recommended more frequently. Similarly, the

high cost of maintenance for bridges 19 and 20, associated with their slow deterioration, leads to the absence of recommended maintenance, whereas maintenance is recommended for bridges 17 and 18, since it is less costly.

- Maintenance of type 2 is more effective than maintenance of type 1. However, it is also more costly. The smaller the ratio of the unit cost of maintenance of type 2 to the unit cost of maintenance of type 1, the less likely maintenance of type 1 is recommended and the more likely maintenance of type 2 is recommended. This can be seen for bridges 5 through 8. For bridges 5 and 7, the ratio of the cost of maintenance of type 2 to the cost of maintenance of type 1 is 1.4, while for bridges 6 and 8, this ratio is 1.7. Maintenance of type 2 is recommended for bridges 5 and 7, while maintenance of type 1 is recommended for bridges 6 and 8.
- The faster the deterioration of a bridge, the shorter the recommended period between two consecutive inspections.

6. CONCLUSION

This paper presents a reliability-based optimization model of bridge maintenance for a system of bridge decks. The bridge decks do not need to have the same deterioration characteristics, and the deterioration models used are history-dependent. This optimization model can serve as the basis for more complex models, in which more elements than the decks are considered. Moreover, the techniques described in this paper provide a lower bound and a candidate upper bound of the optimal cost of maintenance and repair in a time proportional to the number of bridges in the system. As noted, the candidate upper bound determined in this research may not be feasible, and the determination of a meaningful upper bound in a systematic manner is not likely to be a polynomial time problem. This has motivated another approach where standard optimization techniques can be used, while maintaining the physical realism of models that take into account the history of deterioration and maintenance (*19*).

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Table (1): Deterioration Rates in (*18*).

Random variable	Distribution type	Characteristics
β_0	Lognormal	mean = 8.5, standard deviation = 1.5
t_I (years)	Lognormal	mean = 15, standard deviation = 5
δ (years^{-1})	Uniform	minimum = 0.005, maximum = 0.20
t_{PD} (years)	Lognormal	mean = 10, standard deviation = 2
θ (years^{-1})	Uniform	minimum = 0, maximum 0.05
γ	Lognormal	mean = 0.2, standard deviation = 0.04

Table (2): Deterioration Rates for the System of Bridge Decks.

Parameters		Bridges 1-4	Bridges 5-8	Bridges 9-12	Bridges 13-16	Bridges 17-20
t_I (years)	(mean)	10	6	3	12	14
	(standard deviation)	2	1.5	1	2	2
δ (years^{-1})		0.01	0.1	0.1	0.01	0.01
		0.3	0.4	0.5	0.2	0.1
Maintenance type 1						
γ	(mean)	0.2	0.2	0.2	0.2	0.2
	(standard deviation)	0.04	0.04	0.04	0.04	0.04
t_{PD} (years)	(mean)	10	8	5	12	14
	(standard deviation)	2	1.5	1	2	2
Maintenance type 2						
γ	(mean)	0.6	0.6	0.6	0.6	0.6
	(std. dev.)	0.04	0.04	0.04	0.04	0.04
t_{PD} (years)	(mean)	10	8	5	12	14
	(standard deviation)	2	1.5	1	2	2

Table (3): Unit Costs of Maintenance and Repair for the System of Bridge Decks (dollars per square meter).

	Bridges 1, 5, 9, 13, 17	Bridges 2, 6, 10, 14, 18	Bridges 3, 7, 11, 15, 19	Bridges 4, 8, 12, 16, 20
Maintenance type 1	216	216	259	259
Maintenance type 2	300	360	360	432
Replacement	2,818	2,818	2,818	2,818

Table (4): Optimal Policies for the System of Bridges.

Bridge (deterioration rate in parentheses)	Interval between inspections (years)	Threshold □ for replacement	Interval between maintenance of type 1 (years)	Interval between maintenance of type 2 (years)	Period of blocked maintenance (years)
1 (base)	5	4.5	10	none	10
2 (base)	5	4.5	10	none	10
3 (base)	5	4.5	10	none	10
4 (base)	5	4.5	10	none	10
5 (fast)	3	4.5	none	10	4
6 (fast)	3	4.5	7	none	6
7 (fast)	3	4.5	none	10	4
8 (fast)	3	4.5	7	none	6
9 (faster)	3	4.5	5	none	2
10 (faster)	3	4.5	5	none	2
11 (faster)	3	4.5	5	none	2
12 (faster)	3	4.5	5	none	2
13 (slow)	5	4.5	13	none	10
14 (slow)	5	4.5	13	none	10
15 (slow)	5	4.5	15	none	10
16 (slow)	5	4.5	15	none	10
17 (slower)	1	4.0	20	none	10
18 (slower)	5	4.5	24	none	10
19 (slower)	3	4.5	none	none	none
20 (slower)	3	4.5	none	none	none

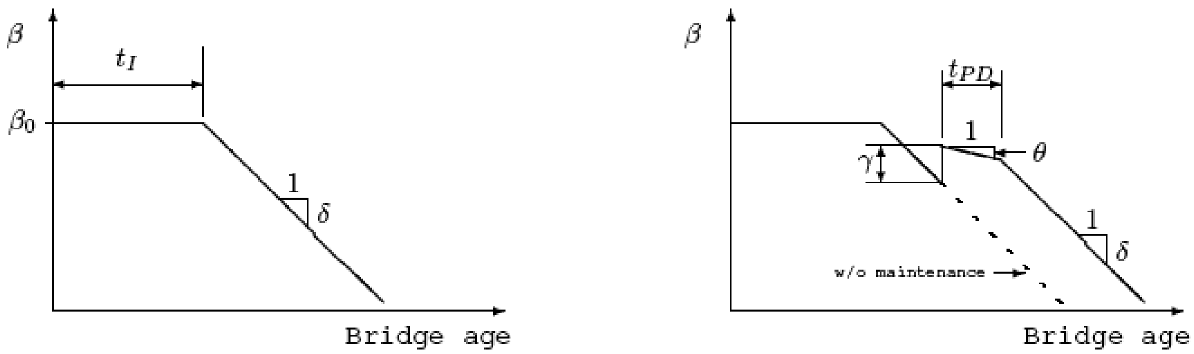

Fig. 1: Deterioration patterns in the absence of maintenance (left) and influence of maintenance actions (right).

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