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Multi-Objective Maintenance Optimization Model to Minimize Maintenance Costs While Maximizing Performance of Bridges

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Proper maintenance planning for bridges is necessary as it impacts the performance, safety, and maintenance costs. Implementing less costly interventions on time can reduce the deterioration of components, enhance performance of bridges, and prevent necessity of costly interventions. However, maintenance of bridges is often delayed due to lack of proper planning and limitations of recourses such as funds. This paper presents the development of a multi-objective maintenance optimization model for bridges that can identify optimum trade-offs between two important objectives of minimizing maintenance costs and maximizing performance of bridges. To this end, a multi-objective model is developed in three main steps: (i) formulation step where decision variables, objective function, and constraints are identified and formulated; (ii) implementation step that performs the model computations; and (iii) performance evaluation step where a case study is analyzed to illustrate the capabilities of the developed model. The computations of the optimization model are implemented using epsilon-constraint method and binary linear programing due to their capability of identifying optimal solutions in a short computational time. The case study results illustrated that the developed model identified pareto-optimal solutions of the above optimization objectives for a study period of 50 years.

Key Words: Multi-objective optimization, Bridge Performance, Bridge Condition, Bridge Maintenance Optimization, Bridge Maintenance Costs

Introduction and the Need

Proper maintenance planning for bridges is necessary as it impacts the performance, safety, and maintenance costs. Implementing less costly interventions on time can reduce the deterioration of components, enhance performance of bridges, and prevent necessity of costly interventions. However, maintenance of bridges is often delayed due to lack of proper planning and limitations of recourses such as funds. To address this problem, a number of studies presented budgeting methods for bridge maintenance prioritization to support decision makers in planning and prioritizing maintenance and

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renovation activities. For example, Zhang et al. presented a bridge network model to prioritize maintenance interventions for a network of bridges while considering budget constraints. They presented two performance indexes: (1) static priority index (SPI) that measures the performance of networks based on travel time between all possible origin-destination points in networks, and (2) dynamic priority index (DPI) that measures the performance of networks while considering uncertainties governing the performance of the transportation network. The results of the case study showed that the DPI is a more effective ranking mechanism compared to SPI (Zhang and Wang 2017). Similarly, Contreras-Nieto et al. presented a Multi-criteria Decision Making Model (MCDM) for prioritizing bridge maintenance activities and budget allocation. They applied Analytic Hierarchy Process (AHP) to rank the maintenance activities based on bridge experts' opinion on relative importance of maintenance interventions on deck, substructure, superstructure, and scour with respect to bridge resiliency, riding comfort, safety, and serviceability. The results of the case study showed that bridge decks are the most critical component while considering safety, serviceability, and comfort. Moreover, substructure have the highest importance while considering the resiliency criterion (Contreras-Nieto et al. 2019). Using technique for order of preference by similarity to ideal solution (TOPSIS), Das et al. presented a MCDM for prioritizing bridge maintenance interventions based on criteria such as bridge condition index, delay cost, and accessibility. The results of the case study showed that failure of higher priority bridges can lead to higher social costs (Das and Nakano 2021). Other studies considered maintenance and social costs along with the environmental impacts to bridge prioritize maintenance interventions. For example, Gokasar et al. presented a hybrid MCDM to rank bridge maintenance projects while considering various criteria, including cost effectiveness, physical condition, social impact for travelers, and CO_2 emissions. To this end, they integrated fuzzy weighted aggregated sum product assessment and TOPSIS to prioritize bridges maintenance projects. The results of the case study showed that environmental impacts of bridge maintenance projects can dominate the ranking of the maintenance alternatives (Gokasar, Deveci, and Kalan 2022). Despite the contributions of these studies in presenting models for maintenance prioritization, they focus on the short term bridge maintenance and are not capable of generating long term maintenance plans to maximize the performance of bridges within available budgets.

A number of studies focused on developing maintenance optimization models to identify optimal maintenance interventions for bridges to minimize life-cycle-costs (Jaafaru and Agbelie 2022; Nili, Taghaddos, and Zahraie 2021). For example, Ghodoosi et al. presented an optimization model to minimize life cycle costs of bridge structures. The presented model integrated databases of asset inventory, maintenance actions list, reliability–based deterioration model, an intervention effect model, and an optimization model using genetic algorithms to identify optimal intervention scenarios. They applied the model on a simply supported bridge superstructure. The case study showed that undertaking less costly minor repair actions results in 4.5 times more cost saving compared to conventional scenario where only major repairs are performed (Ghodoosi et al. 2018). In a similar study, Abdelkader et al. presented a multi-objective differential evolution optimization model to minimize maintenance time, cost, and greenhouse gases. They applied a discrete event simulation model to simulate the bridge deck replacement process and used a neural-network model to predict time, cost, greenhouse gases, and resource utilization of different intervention plans. The results of the case study showed up to 71%, 28%, and 39% reduction in time, cost, and greenhouse gases compared to conventional methods, respectively (Abdelkader et al. 2021). Nili et al. presented a simulation-based bridge maintenance optimization model that can identify optimum maintenance intervention plans to minimize agency and user costs in bridge repair projects while considering workspace limitations and predecessor relationships. They applied a discrete event simulation to identify optimum sequence of repair-activities for each repair intervention. The result of the case study showed 11% and 4% reduction in user costs and crew cost compared to conventional methods, respectively (Nili et al. 2021). Other studies in the literature showed that implementation of preventive maintenance (PM) reduces the frequency of major maintenance interventions and results in significant reduction in maintenance costs as well as environmental impacts. For example, Xie et al. presented a multi-objective optimization model using genetic algorithm to maximize safety and minimize life cycle cost and life cycle environmental impact. The model is designed to identify optimum timing of preventive maintenance interventions for existing bridges. The result of the case study revealed up to 25% reduction in life cycle environmental impacts compared to conventional methods (Xie, Wu, and Wang 2018). Although the aforementioned studies presented significant contributions to existing knowledge in identifying optimal maintenance interventions, the generated results are constrained by solution quality and/or computational efforts. Specifically, there is limited or no reported studies that focused on identifying optimum trade-offs between minimizing maintenance costs and maximizing performance of bridges.

Research Objectives and Methodology

The present study focuses on developing a new bridge maintenance optimization model that is capable of identifying optimal trade-offs between two primary objectives: (1) minimizing maintenance costs and (2) maximizing performance of bridges. The present model is designed to evaluate cost effectiveness of various maintenance interventions based on maintenance costs, performance index, and specified interest rate. To this end, present value method is used to analyze the maintenance costs over a period of study with respect to a specified interest rate. The present model is expected to support bridge operators in identifying an optimal schedule of maintenance interventions based on available budgets. Epsilon-constraint method and binary linear programing are used to perform the model computations due to their capability of identifying optimal solution in short computational time. The model is developed in three main steps: (i) formulation step where decision variables, objective function, and constraints are identified and formulated; (ii) implementation step that performs the model computations; and (iii) performance evaluation step where a case study is analyzed to illustrate the capabilities of the developed model. The following section describes these steps in details.

Model Development

The decision variables of the optimization model are designed to represent all feasible alternative plans for maintenance of bridge components for a predefined period of study. To linearize the problem and before performing the optimization computations, the model generates all feasible maintenance plans for each of bridge components. Each alternative plan specifies each intervention that should take place in each year. These alternative plans cover all the feasible maintenance plans for bridge components including deck, girder/beam, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings. These maintenance plan alternatives are modeled using “$M_{c,p}$” which is a binary decision variable that represents the selection of maintenance plan number “p” for component “c” from a set of feasible alternatives.

The objective functions of the developed optimization model are designed to generate optimal trade-offs among two optimization objectives: (1) minimizing maintenance costs, and (2) maximizing the performance index of bridges. Bridge maintenance cost can be calculated by adding up maintenance costs during a predefined study period for bridge components including deck, girder/beam, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings, as shown in Equation (1). Similarly, bridge performance can be calculated by weighted average of performance index of the above components during the predefined study period, as shown in Equation (2). Performance indexes of components in each year are calculated using Weibull probability method, as shown in Equation (3). Weibull probability method is widely used in the literature to model deterioration of buildings and infrastructure systems (Ghafoori and Abdallah 2022c, 2022b, 2022a; Toasa Caiza et al. 2020). Moreover, for each bridge in National Bridge Inventory (NBI), National Bridge Elements (NBE) contains data on bridge elements, their quantity, and percentage of each element quantity that are in good, fair, poor, and severe conditions (FHWA 2022). Based on the quantity of each element and cost references such as RSMeans (RSMeans 2020), cost of elements replacement can be calculated. Elements’ maintenance cost is estimated based on the cost of elements’ replacement, and improvements in condition of elements due to maintenance interventions (Grussing and Marrano 2007), as shown in Equation (4).

$$TBMC = \sum_{\mathrm{c}=1}^{\mathrm{C}} \sum_{p=1}^{P_C} \sum_{y=1}^{Y} M_{c,p} \times MC_{c,p,y} \tag{1}$$

Where: “$TBMC$” is total bridge maintenance cost; “C” is number of the bridge components; “P_C” is total number of alternative maintenance plans for component “c”; “Y” is number of years in study period; “$MC_{c,p,y}$” is maintenance cost of alternative plan “p”, in year “y”.

$$BPI = \frac{\sum_{\mathrm{c}=1}^{\mathrm{C}} \sum_{p=1}^{PC} \sum_{y=1}^{Y} M_{c,p} \times CPI_{c,p,y} \times W_c}{\sum_{\mathrm{c}=1}^{\mathrm{C}} \sum_{y=1}^{Y} W_c} \tag{2}$$

Where: “BPI” is bridge performance index; “$CPI_{c,p,y}$” is performance index of component “c” in alternative plan “p”, in year “y”. “W_c” is user specified weight for component “c”.

$$CPI_{c,p,y} = IP_c \times \left(\frac{100}{MP_c}\right)^{-\left(\frac{y}{\beta_c}\right)^{\alpha_c}} + ME_{c,p,y} \tag{3}$$

Where: $CPI_{c,p,y}$ is performance index of component “c” in alternative plan “p” in year “y”; $IP_c$is initial performance index of component “c”; $MP_c$is minimum acceptable performance index for component

"c"; β_c and α_c are Weibull deterioration function parameters for deterioration of component "c" which depend on operational and environmental condition of components and are determined based on previous data and expert's opinion; and $ME_{c,p,y}$ is improvement in performance index due to maintenance intervention in alternative plan "p" for component "c" in year "y".

$$MC_{c,p,y} = RC_c \times \left(\frac{100 - CPI_{c,p,y}}{100 - MP_c} \right) \tag{4}$$

Where: $MC_{c,p,y}$ is the estimated maintenance cost for component "c" in alternative plan "p" in year "y", and RC_c is cost of replacement of component c.

To ensure that the developed model provides feasible and practical solutions, the optimization model integrates two types of constraints: (i) maintenance plan alternative selection, and (ii) minimum performance indexes for each of components. The maintenance plan alternative selection constraints are integrated in the model due to the use of linear programming to limit the optimization model to select only one plan from the set of feasible plans, as shown in Equation (5). Moreover, the minimum performance indexes constraints are integrated in the model to ensure that maintenance intervention are performed on bridge components before their performance index fall blew the specified limit.

$$\sum_{p=1}^{P_c} M_{c,p} = 1 \qquad \forall\, c = 1, \dots, C \tag{5}$$

Where: "P_C" is total number of alternative maintenance plans for component "c"; and "c" ranges from one to total number of components "C".

Input data of the developed model is fed through a spreadsheet that includes data on: (i) bridge general information such as specifications of deck, girder/beams, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings; (ii) maintenance data such as possible intervention for each of the components; (iii) maintenance cost data for each of components estimated based on NBI and NBE; (iv) performance index data including existing performance, minimum acceptable performance index, and Weibull deterioration parameters for each of components.

The optimization model is implemented in MATLAB environment where it can read bridge data from spreadsheet to identify existing components. Next, based on the existing performance indexes of bridge components, the model generates a set of maintenance plans for each bridge component. Next, maintenance costs along with performance indexes of plans are calculated and stored in a database to be used during the optimization process.

Epsilon-constraint method (Haimes, Lasdon, and Wismer 1971) is used to perform the model computations due to its capability of (1) identifying pareto-optimal solutions for both convex and nonconvex problems, and (2) generating pareto-optimal trade-offs for the two optimization objectives in short computational time (Ehrgott 2005). This method converts one of the objective functions to a constraint that ranges from minimum and maximum values of the converted objective function where the full range is divided into "N" number of intervals. N+1 single objective optimization problems are generated and solved based on different values of the converted objective function to generate Pareto solutions of the two objective functions. Binary linear programing is used to solve the converted single-objective optimization problems since it is capable of identifying global optimal solutions in short computational time.

Case Study

A case study of a concrete bridge is performed to evaluate the performance of the model and demonstrate its capabilities. The case study bridge is located in Larimer County, Colorado, and was constructed in 1966 and has a deck area of 26,609 square feet and Average Daily Traffic (ADT) of 12514 vehicles. This bridge consists of a reinforced concrete deck, prestressed concrete girder, reinforced concrete columns, reinforced concrete abutment, reinforced concrete pier cap, strip seal expansion joint, and reinforced concrete bridge rail. The input data is collected based on NBI and NBE, as shown in Table 1.

The present model is used to identify optimal trade-offs among the two optimization objectives: (1) minimizing total maintenance cost, and (2) maximizing bridge performance. The minimum and maximum value of the first objective function, maintenance costs, were calculated by removing the second objective function and solving two single-objective optimization problems as follows: (1) minimizing total maintenance cost and (2) maximizing total maintenance cost. Next, the first objective function, total maintenance cost, was converted to a constraint that ranged from minimum value of \$15,040K to maximum value of \$24,660K with epsilon increments of 10K. Accordingly, the multi-objective problem was converted to 963 single-objective optimization problems. For each of these single-objective optimization problems, the model performed the calculations and identified optimal maintenance interventions to maximize the performance index of the bridge. The computations resulted in 963 pareto-optimal solutions with respect to the two objective functions, as shown in Figure 1.

The present model can generate detailed recommendations for maintenance interventions for each of the identified points on the pareto-optimal solutions. For example, the model identified maintenance intervention plan to achieve maximum performance index of 81 within maintenance cost of \$19,850K, as shown in Figure 1 and Table 2.

The optimization computations were performed on a personal computer with Intel Core i7-10510U M, CPU 2.3 GHz processor, and 8GB RAM. Based on the specified epsilon increments, 963 single-objective optimization computations were executed averagely in 6 seconds. Moreover, the model performed the total computations to achieve the pareto optimal solutions in 96 minutes.

Table 1

Input data of the case study

Element Group	Element Name	Unit	Total Quantity	Existing Performance Index
Deck	Reinforced Concrete Deck	Square Feet	26,609	99.81
Superstructure	Prestressed Concrete Girder	Linear Feet	2,255	97.07
Substructure	Reinforced Concrete Column	Count	6	100
Substructure	Reinforced Concrete Abutment	Linear Feet	236	97.2
Substructure	Reinforced Concrete Pier Cap	Linear Feet	112	100
Joint	Strip Seal Expansion Joint	Linear Feet	336	84.29
Bridge Rail	Reinforced Concrete Bridge Rail	Linear Feet	472	100
Wearing Surfaces and Protective Coatings	Steel Protective Coating	Square Feet	160	100

Table 2

Action Report for the maintenance budget of 19,850K

Element Group	Element Name	Interventions			
		Year	Action	Year	Action
Deck	Reinforced Concrete Deck	10	Seal deck overlays	20	Seal deck overlays
Superstructure	Prestressed Concrete Girder/Beam	12	Repair concrete	28	Repair concrete
Substructure	Reinforced Concrete Column	14	Repair concrete	30	Repair concrete
Substructure	Reinforced Concrete Abutment	12	Repair concrete	28	Repair concrete
Substructure	Reinforced Concrete Pier Cap	16	Repair concrete	32	Repair concrete
Joint	Strip Seal Expansion Joint	12	Sealing deck joints	28	Sealing deck joints
Bridge Rail	Reinforced Concrete Bridge Rail	16	Repair concrete	32	Repair concrete
Wearing Surfaces and Protective Coatings	Steel Protective Coating	16	Repair Steel Protective Coating	32	Repair Steel Protective Coating

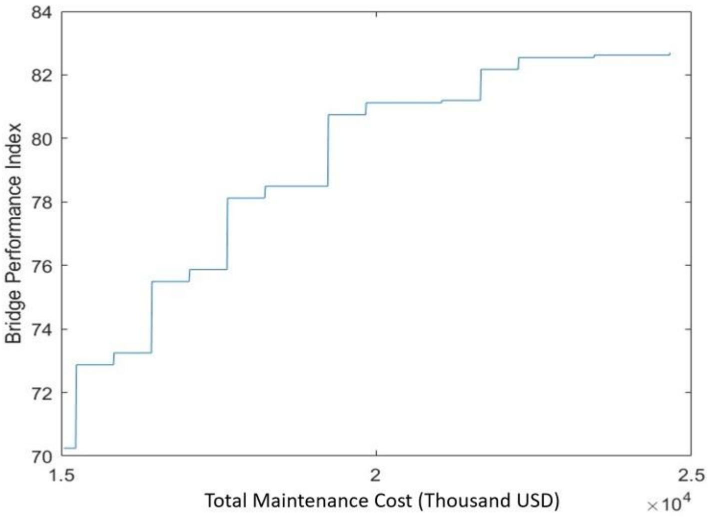

Figure 1. Pareto-optimal solutions for trade-offs among the two optimization objectives

Conclusions and Future Research

This study presented the development of a new model that is capable of identifying optimal trade-offs between two primary objectives of minimizing maintenance costs while maximizing bridge performance. The present model is designed to evaluate cost effectiveness of various maintenance interventions based on maintenance costs, performance index, and specified interest rate. The computations of the optimization model were implemented using epsilon-constraint method and binary linear programing due to their capability of identifying optimal solutions in a short computational time. Based on the epsilon-constraint method, total maintenance cost was converted to a constraint that ranged from the minimum value of $15,040K to the maximum value of $24,660K with epsilon increments of 10K. Accordingly, the multi-objective problem was converted to 963 single-objective optimization problems. For each of these single-objective optimization problems, the model performed the calculations and identified optimal maintenance interventions to maximize the performance index of the bridge. The case study results illustrated that the developed model identified pareto-optimal solutions of the two optimization objectives for a study period of 50 years. The present model can generate detailed recommendations for maintenance interventions for each of the identified points on the pareto-optimal solutions. The optimization model provides new and practical capabilities that enables decision makers to identify an optimal schedule of bridge maintenance interventions based on available annual budgets. It should be noted that the present case study focused on a bridge with reinforced concrete structure in the state of Colorado; and additional research is needed to evaluate other types of structures such as steel structures, and bridges located in other climates. Moreover, the present model applies the Weibull deterioration estimation method, which is subjective, as it relies on expert judgments of deterioration parameters. Therefore, other approaches such as data driven methods can be applied to objectively estimate the deterioration of elements condition. Based on the aforementioned limitations, future research and expansion of the present model include: (1) integrating data driven methods such as machine leaning and deep learning to identify deterioration of bridge components, and (2) evaluating additional case studies of bridges with different structure types and locations.

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