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# NETWORK-LEVEL BRIDGE MANAGEMENT USING A MULTIOBJECTIVE OPTIMIZATION DECISION MODEL

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**ABSTRACT**: This paper presents an approach for network-level bridge maintenance optimization that prioritizes bridge structures for maintenance by considering several relevant objectives. Three relevant and conflicting objectives are selected in this study, namely: the minimization of maintenance costs, maximization of condition rating, and minimization of traffic disruption. The prediction of the condition rating of bridge structures is based on first-order Markov chain models that take into account the time-dependence and inherent uncertainty associated with the deterioration of bridge structures. The proposed approach can be used to rank a large number of different structures that are part of a large bridge network in terms of their priority or urgency for maintenance. The optimal solution is defined as the solution that achieves the best compromise between the selected optimization objectives. Compromise programming is used to determine the optimal ranking of bridge projects for maintenance in terms of their effectiveness in the minimization of maintenance costs and traffic disruption, and improvement of bridge network performance. A multi-criteria optimality index is proposed as a measure of the effectiveness of the optimal maintenance strategies in achieving a satisfactory trade-off between the above relevant and competing maintenance criteria for the network analyzed. The proposed approach is illustrated on a small network of ten bridge projects that are optimized for maintenance by considering the three criteria selected. The weighted and non-weighted multi-criteria indices are generated for these projects.

## 1. INTRODUCTION

Bridge owners expect a service life of 75 to100 years for new bridges with only routine maintenance. However, it is observed that in North America many of the existing bridges that are only 10 to 20 years old require costly and extensive rehabilitation (Aktan *et al.* 1996; Dunker and Rabbat 1990). Highway bridges deteriorate as a result of aging, aggressive environmental degradation factors, increased traffic load, inadequate design, protection, and maintenance. In North America, about 40% of the bridges are over 40 years old, with extensive structural deficiency and loss of functionality. Their rehabilitation and renewal is estimated at hundreds of billions of dollars that cannot be accommodated by highway agencies. The magnitude of the problem poses great technical and economic challenges, specifically concerning which projects should be given high priority for maintenance and what is the optimal maintenance strategy that will reduce the risk of failure and the life cycle cost of the rehabilitated bridges. It is estimated that on average, 2.1% of the value of each of the bridges in the16 OECD countries is spent annually on maintenance, repair and strengthening (OECD 1989).

In order to optimize the maintenance management process over the life cycle of a given bridge, highway agencies need effective models, techniques, and tools for condition assessment, performance prediction, and maintenance optimization. Furthermore, an effective policy for bridge management should aim at satisfying several relevant objectives that may be of conflicting nature such as improving safety and reliability, reducing maintenance costs, and minimizing traffic disruption.

This paper presents a systematic decision-making approach for bridge maintenance management that is based on a multi-objective optimization algorithm. It is based on finding the optimal solutions that achieve the best trade-off between the following competing objectives; (i) maximization of bridge condition or performance; (ii) minimization of maintenance costs; and (iii) minimization of traffic disruption. The merits of a multi-objective-based maintenance optimization are discussed. The prediction of the condition or performance of bridge structure is based on a stochastic deterioration model that captures the time-dependence and uncertainty associated bridge performance. The compromise programming approach is used to determine optimal solutions and a multi-criteria optimality index is proposed as a parameter for the prioritization of projects for maintenance. The proposed approach will be illustrated in an example of a small network of aging highway bridges that require maintenance and rehabilitation.

## 2. MULTIOBJECTIVE-BASED MAINTENANCE OPTIMIZATION

### 2.1 Approaches for Maintenance Optimization of Highway Bridges

Highway bridges constitute a class of safety-critical infrastructure systems that should be analyzed with rigor as their failure can have catastrophic consequences, including multiple fatalities and injuries, complete loss of service, major traffic disruption, and considerable socio-economic impacts. Different approaches to maintenance optimization have been implemented in the different bridge management systems ranging from simplified economic models to sophisticated Markovian decision processes. In most bridge management systems, the main criterion used for maintenance optimization is the minimization of life cycle cost, which represents the present value of all the costs incurred throughout the life cycle of a bridge structure, including, the costs of design, construction, maintenance, repair, rehabilitation, replacement, demolition, and in some instances users' costs, and possibly costs of failure (although much harder to quantify).

The prioritization for maintenance and the assessment of the effectiveness of different maintenance strategies are based on the conventional condition ratings of bridge elements. These ratings represent a qualitative assessment of the condition of bridge structures, which are obtained by mapping the level of observed damage in the structure during visual inspections and non-destructive evaluation (or predicted using empirical or statistical methods) to a discrete rating scale, e.g. 0 to 5 in *Pontis* (FHWA 1993). Such an approach is quite adequate for the long- and short-term analysis of maintenance needs for a network of hundreds or thousands of structures; however, it has serious shortcomings for the detailed analysis of individual bridge structures or a group of structures, especially safety-critical/high risk structures. Highway bridges consist of several components with multiple failure modes and different consequences of failure.

The actual maintenance optimization problem is multi-objective in nature as the bridge owner or manager seeks to satisfy simultaneously several criteria, such as the minimization of costs to owners and users, improvement of safety, improvement of serviceability and functionality, minimization of maintenance time, minimization of traffic disruption, etc. The solution of this maintenance management problem can be obtained using the techniques of multi-criteria or multi-objective optimization. Several approaches have been developed to solve multi-criteria optimization problems, including multi-attribute utility theory (Von Neumann and Morgenstern 1947; Keeney and Raiffa 1976), weighted sum approach (Zadeh 1963), compromise programming, ε-constraint approach, sequential optimization (Koski 1984; Duckstein 1984; Osyzcka 1984; Fu and Frangopol 1990; Eschenauer et al. 1990; Lounis and Cohn 1993, 1995). In this paper, the compromise programming approach is used to solve the multi-objective maintenance optimization problem.

As opposed to life cycle cost or cost-benefit criteria, the use of a risk of failure as a criterion for maintenance optimization is more rational and relevant, however its implementation is not easy given the complexity of assessing the consequences of failure in monetary terms This means that monetary values need to be assigned for fatalities, injuries, and social costs which are not easily quantified, and various methods have been developed. Given the difficulty of accepting the notion of placing any sort of value on human life, Starr (1969) evaluated the risk of death from various causes and identified two general categories for risk of death: (i) risk associated with voluntary activities in which the individual evaluates and adjusts his exposure to risk; and (ii) risk associated with involuntary activities, which are determined by regulations from governmental agencies. Starr (1969) indicated that the public typically was willing to accept voluntary risks 1,000 times greater than involuntary risks. Paté-Cornell (1994) proposed different ranges of acceptable levels of risks for the public and workers ranging from $10^{-8}$ to $10^{-3}$ per year.

Despite its shortcomings, the use of the qualitative condition rating for the assessment of bridge performance is very practical, especially when dealing with a large network of bridge structures (hundreds or thousands), which is the case for many highway agencies. The condition rating provides a qualitative assessment of the reliability of the structure and is adopted in this study for the case of network-level bridge management. It is generally obtained from a combination of visual inspection and non-destructive evaluation of the state of damage of the structure investigated. In general, the condition rating of a bridge structure decreases with time due to deterioration. Threshold condition ratings $CR_{min}$ (or minimum acceptable values) are defined by different highway agencies beyond which a maintenance action is required. After the implementation of the maintenance action (including repair and rehabilitation), the condition of the bridge structure is improved to $CR_{maint}$, as shown in figure 1.

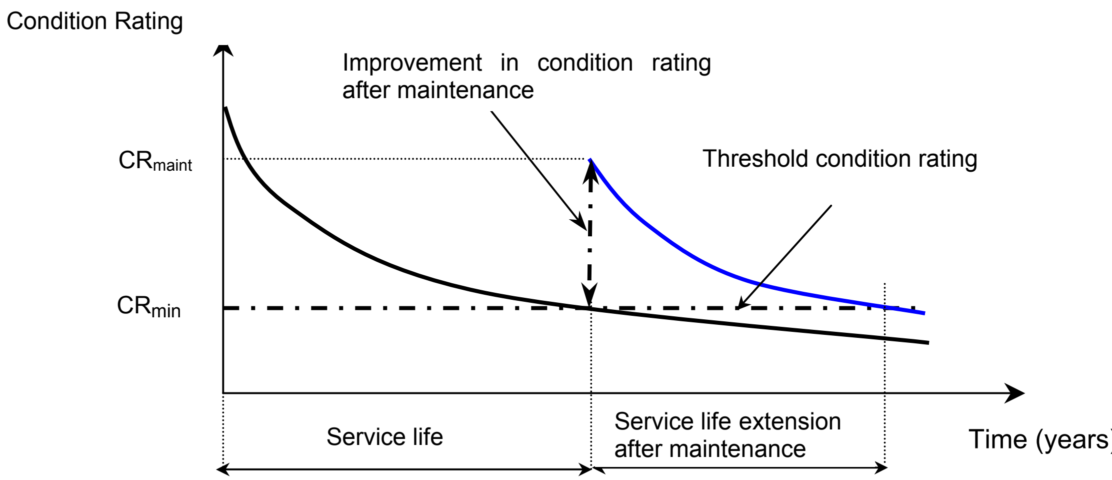


**Figure 1. Impact of maintenance on condition rating and service life of bridges**

At the network level of bridge maintenance management, decision support is needed to solve the following problems: (i) prioritization of bridge projects for maintenance, repair and replacement (MR&R); and (ii) optimization of maintenance strategy and time. In general, this is not a straightforward task given: (i) large number of deteriorated bridges; (ii) limited funds available for MR&R; (iii) uncertainty in bridge performance; and (iv) difference in importance risks of failure associated with different bridge components and systems. Hence, it is clear that the actual maintenance management problem is multi-objective in nature, and requires the determination of the optimal maintenance strategy that achieves the best trade-off between several conflicting objectives. In this paper, Specifically, the optimization objectives include: (1) minimization of maintenance costs; (2) maximization of network condition; and (3) minimization of traffic disruption failure. The solution of this maintenance management problem can be obtained using multi-objective optimization techniques, and more specifically the Pareto optimality concept and compromise programming (Lounis and Cohn 1995), which are presented in the following section.

## 2.2 Problem Formulation

For single-objective optimization problems, the notion of optimality is very well defined as the minimum or maximum value of some given objective function is sought. In multi-objective (or vector) optimization problems, the notion of optimality is not obvious because of the presence of multiple, incommensurable and conflicting objectives. In general, there is no single optimal (non-dominated or superior) solution that simultaneously yields a minimum (or maximum) for all objective functions. The Pareto optimality concept has been introduced as the solution to multi-objective optimization problems (Koski 1984; Eschenauer et al. 1990). A maintenance strategy $\mathbf{x}^*$ is said to be a Pareto optimum if and only if there exists no maintenance strategy in the feasible set of maintenance alternatives that may yield an improvement of some criterion without worsening at least one other criterion. The multi-criteria maintenance optimization problem can be mathematically stated as follows:

Find: $\mathbf{x}^*$ = Optimum

[1a] Such that: $\mathbf{f}(\mathbf{x}) = [\, f_1(\mathbf{x}) \;\; f_2(\mathbf{x}) \ldots\ldots\ldots f_m(\mathbf{x}) \,]^T$ = minimum $\quad x \in \boldsymbol{\Omega}$

[1b] $\sum C(\mathbf{x}) \leq B$

[1c] $\Omega = \{\mathbf{x} \in N: \ \beta_{min} \leq \beta(\mathbf{x}) \leq \ \beta_{th}\}$

where: **f** = vector of optimization criteria (e.g. condition rating, cost, traffic); C(x)= cost of maintenance strategy x; B= available budget; **Ω**= subset of the bridge or bridge network that at time t contains deficient bridge components/systems having a condition rating between a minimum value and a threshold value (very critical); N= entire set of bridge projects requiring maintenance.
The concept of Pareto optimality mentioned above, may be stated mathematically as follows (Koski 1984;Lounis and Cohn 1993): $x^*$ is a Pareto optimum if:

[2a] $f_i(\mathbf{x}) \leq f_i(\mathbf{x}^*)$ for i=1,2,…,m

[2b] with $f_k(\mathbf{x}) < f_k(\mathbf{x}^*)$ for at least one k.

In general, for a multi-objective optimization problem, there are several Pareto optima, and the problem is to select the solution that achieves the best compromise between all competing objectives. Such a solution is referred to in the optimization literature as "satisficing" solution in the multi-objective optimization literature (Koski 1984; Stadler 1988; Lounis and Cohn 1995). The determination of this satisficing solution is discussed in the next section. It is clear from the above that the existing approaches to decision making have serious limitations as they consider only one criterion at a time, i.e. life cycle cost (or cost-benefit) or condition. In this paper, a multi-objective approach for decision analysis, which incorporates cost and condition, is proposed to solve the maintenance optimization problem. Such an approach enables a better evaluation of the effectiveness of maintenance strategies in terms of several criteria and determines the optimal solution that achieves the best trade-off between all criteria (including conflicting ones, such as cost and risk).

The development and integration of the proposed decision support tools for maintenance optimization will lead to an effective approach to bridge maintenance management, which optimizes the allocation of maintenance funds and reliability, as well as improves the risk management in bridges.

### 2.3 Decision-Making under Multiple and Conflicting Objectives

In compromise programming, the "satisficing" solution is defined as the solution that minimizes the distance from the set of Pareto optima to the so-called "ideal solution". This ideal solution is defined as the solution that yields minimum (or maximum) values for all criteria. Such a solution does not exist, but is introduced in compromise programming as a target or a goal to get close to, although impossible to reach. The criterion used in compromise programming is the minimization of the deviation from the ideal solution **f*** measured by the family of $L_p$ metrics (Koski 1984; Lounis and Cohn 1993). In this paper, a multi-criteria optimality index, "MOI", is defined as the value of the weighted and normalized deviation from the ideal solution **f*** measured by the family of $L_p$ metrics:

[3] $$MOI(x) = \left[ \sum_{i=1}^{m} w_i^{\,p} \left| \frac{f_i(x) - \min f_i(x)}{\max f_i(x) - \min f_i(x)} \right|^p \right]^{1/p}$$

This family of Lp metrics is a measure of the closeness of the satisficing solution to the ideal solution. The value of the weighting factors $w_i$ of the optimization criteria $f_i$ (i=1,…,m) depends primarily on the attitude of the decision-maker towards risk. In this paper structural safety is considered as the governing criterion and a higher weight is placed on the reliability criterion, however, the optimization will also be carried out for equal weighting of all criteria to show the impact of weighting factors on the optimal decision. The choice of p indicates the importance given to different deviations from the ideal solution. For example, if p=1, all deviations from the ideal solution are considered in direct proportion to their magnitudes, which corresponds to a group utility (Duckstein 1984). However, for p ≥2, a greater weight is given to larger deviations from the ideal solution, and $L_2$ represents the Euclidian metric. For $p=\infty$, the largest deviation is the only one taken into account and is referred to as the Chebyshev metric or mini-max criterion and $L_\infty$ corresponds to a purely individual utility (Duckstein 1984; Koski 1984; Lounis and Cohn 1995). In this paper, the Euclidean metric is used to determine the multi-criteria optimality index and corresponding satisficing solution.

## 3. PERFORMANCE PREDICTION OF BRIDGE NETWORKS

Bridge structures deteriorate with time due to increased traffic loads, aggressive environmental factors, collision, inadequate design and workmanship, and lack of maintenance. For a given component or system and a given failure mode, the load effect and strength are time-dependent and present considerable uncertainty in their mean values as well as in their levels of scatter, which increase with time. In general, highway bridges are inspected every two years on average (FHWA 1995; MTO 1989). The inspector rates the condition of the deck, superstructure and substructure components of a bridge and assigns condition ratings for each component, the whole bridge, and possibly the entire network. This rating consists of mapping the assessed condition onto a 1 to 9, 1 to 7, or 1 to 5 rating scale (FHWA 1993, 1995; MTO 1989; Morcous *et al.* 2003) In this paper, the condition of a component, system, or network is based on a five-state rating scale.

The prediction of the network or component performance is based on a probabilistic discrete Markov chain that simultaneously takes into account the time-dependence and uncertainty of both deterioration and repair processes. The Markov chain is a stochastic process whose state space is finite or countable, that is described by $\{\mathbf{S}(t_n) = k, k =1, 2,\ldots, 5\}$, and such that the probability of a future state of the system $S(t_{n+1})$ at time $t_{n+1}$ is governed solely by its present state $S(t_n)$ at time $t_n$ and not its entire history. This represents the first-order type of stochastic process correlation underlying the Markovian process (Bogdanoff 1978;Ross 1996). The transition probability $p_{ij}$ represents the likelihood that the bridge condition will change from state i at time $t_n$ to state j at time $t_{n+1}$. In this project, a stationary stochastic process is first assumed which implies the time-invariance of the transition probability matrix.

Given the adopted condition rating scale and short transition time (1 or 2 years), the probability of decaying by more than one state in one year may be assumed negligible (FHWA 1993; Morcous et al. 2003). As a result, the deterioration of the bridge network can be modeled using a unit-jump deterioration model. The corresponding Markovian transition probability matrix consists only of two terms in each row, namely: $p_{ii}$, and $p_{ij}$ (with $j=i-1$ and $p_{ij}=1- p_{ii}$), which represent the probability of remaining at the same condition rating and the probability of deteriorating by one condition rating within one transition period, respectively. The proposed Markov chain model can be developed from a relatively limited amount of historical data on the network/component condition. However, the validity of the model should be investigated for its dependence on some explanatory variables, such as age, environmental conditions, structural system type, traffic loading, quality of design and protection, and maintenance level. This is confirmed by the study carried out by Dunker and Rabbat (1990) on the performance of highway bridges included in the U.S. *National Bridge Inventory (NBI*), which shows that bridge deterioration varies considerably from state to state with the highest deterioration in the central and southeastern states and the lowest in the southwestern states. This study also indicates that the states with aggressive environments and heavy truck traffic do not necessarily have higher percentages of bridge deficiency. This considerable difference in structural deficiency between states is attributed to differences in design, construction, inspection, funding and maintenance policies.

Once, the transition probability matrix is generated, the performance of the bridge network or component at any given time can be predicted from the n-step transition matrix as follows (Bogdanoff 1978; Ross 1996):

[4] $\mathbf{P}[S(t_n)] = \mathbf{P}[S(0)]\mathbf{P}^n$

in which $\mathbf{P}[S(t_n)]$ is the state probability matrix at time $t_n$ after n transitions; $\mathbf{P}[S(0)]$ is the initial state probability matrix; and $\mathbf{P}$ is the transition probability matrix. At the start of the bridge service life, the probability mass is near the highest condition rating, but with aging and deterioration, this probability mass shifts from states with high condition ratings to those with lower condition ratings. Ultimately, if no repairs are made, all the probability mass accumulates in the so-called "absorbing state" with condition rating 1.

## 4. ILLUSTRATIVE EXAMPLE

The approach presented in this paper is applied for the maintenance optimization of 10 deficient decks from different bridges within a network of a given highway agency. In this example, the feasible maintenance strategies are assumed optimized for the individual deficient structures based on the conventional life cycle cost minimization approach. The objective here is to optimize the prioritization of the 10 maintenance projects considering simultaneously their condition rating, maintenance cost, and average daily traffic subject to the constraint of a total available budget of $1.65 Million. The average daily traffic is a very relevant criterion as it indirectly provides a rating of the importance of the bridge relative to the service provided to the users and the socio-economic activity. If the bridge is posted or closed, users incur immediate economic impacts leading to higher travel costs due to longer travel time, higher fuel consumption, lost time, higher vehicle maintenance costs, and increased environmental impacts due to increased fuel consumption and gas emissions. It can be defined as a criterion for the control of traffic disruption.

Table 1, shows the values of the average condition rating, maintenance cost and average daily traffic associated with each bridge project, while figure 2 shows their normalized values (normalized with regard to the maximum value). Table 1 and figure 2 illustrate the conflicting nature of these criteria and the difficulty in prioritizing, as the project with the highest urgency in terms of condition (Project #3) is neither the same in terms of maintenance cost (Project #9) nor in terms of ADT (Project #5).

If a single-criterion prioritization is undertaken, the projects will be ranked as follows:

(i) Condition-based prioritization: the projects will be ranked in terms of increasing condition rating, i.e. the project with the lowest condition rating will given first priority, and end up with the project which exhausts the available budget. For the remaining deficient structures, posting or closing of the bridges should be investigated;

(ii) Maintenance cost-based prioritization: the projects will be ranked in terms of increasing cost, i.e. the project with the lowest life cycle cost will be given first priority, ending with the project at which the available budget is exhausted. For the remaining deficient structures, posting or closing of the bridge should be investigated; and

(iii) Traffic-based prioritization: the projects will be ranked in terms of decreasing average daily traffic (ADT), i.e. the project with the highest ADT will be given first priority, ending with the project at which the available budget is exhausted. For the remaining deficient structures, posting or closing of the bridge should be investigated.

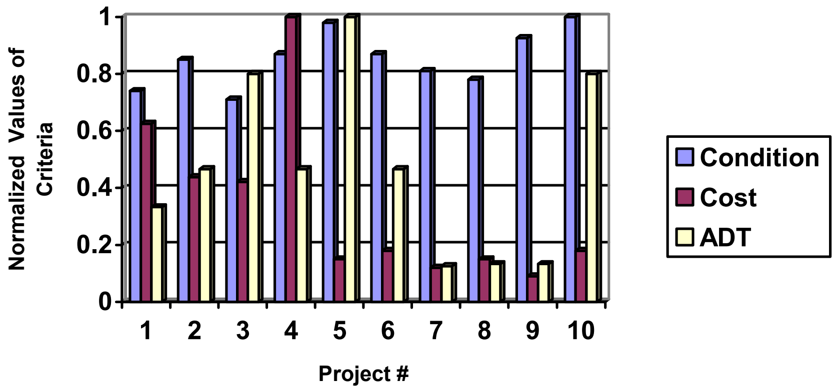


**Figure 2. Normalized Values of Optimization Objectives for Maintenance Projects**

Using the compromise programming and the $L_2$ metric, the proposed multi-objective optimality index (MOI) is determined for the bridge projects for two cases: (i) Case 1: Weighted MOI, in which weights of 0.5, 0.3, and 0.2 are assigned to condition rating, maintenance cost, and ADT, respectively.

**Table 1. Multi-criteria-based maintenance optimization of bridge structures**

| Maintenance Project # | Average Condition Rating | Maintenance Costs ($1,000) | Average Daily Traffic | Weighted Multi-Criteria Optimality Index (MOI) | Non-Weighted Multi-Criteria Optimality Index (MOI) |
|---|---|---|---|---|---|
| 1 | 2.00 | 520 | 5000 | 0.239 | 0.969 |
| 2 | 2.30 | 364 | 7000 | 0.296 | 0.869 |
| 3 | 1.92 | 350 | 12000 | 0.118 | 0.429 |
| 4 | 2.34 | 832 | 7000 | 0.421 | 1.290 |
| 5 | 2.65 | 125 | 15000 | 0.468 | 0.938 |
| 6 | 2.35 | 150 | 7000 | 0.303 | 0.828 |
| 7 | 2.18 | 100 | 1900 | 0.261 | 1.054 |
| 8 | 2.10 | 125 | 2000 | 0.230 | 1.020 |
| 9 | 2.50 | 75 | 2000 | 0.421 | 1.240 |
| 10 | 2.70 | 150 | 12000 | 0.503 | 1.031 |
| | | Total = 2,791 | | | |

The total maintenance costs for these 10 projects is $2.791 million, which is well in excess of the available budget of $1.65 million. From Table 1, the “ideal” (but non-existing) maintenance solution is associated with the following “ideal” criterion vector $\mathbf{f}^{*}=[f_{1min}\ \ f_{2min}\ \ f_{3max}]^{T}= [1.92,\ \ 75000,\ 15000]^{T}$. Using Equation (3), the values of MOI for the weighted and non-weighted cases are also shown in Table 1 and in figure 3. Using the weighted MOI, the satisficing solution is found to be Project # 3 for both weighted and non-weighted cases. Figure 5, however, illustrates the differences in the ranking for the other projects, for example the second highest priority is Project #9 for weighted MOI and Project # 6 for non-weighted MOI, which is due to the higher importance given to reliability. The difference in ranking between these two MOI indices varies from 0 for Project #3 to 5 for Project # 5.

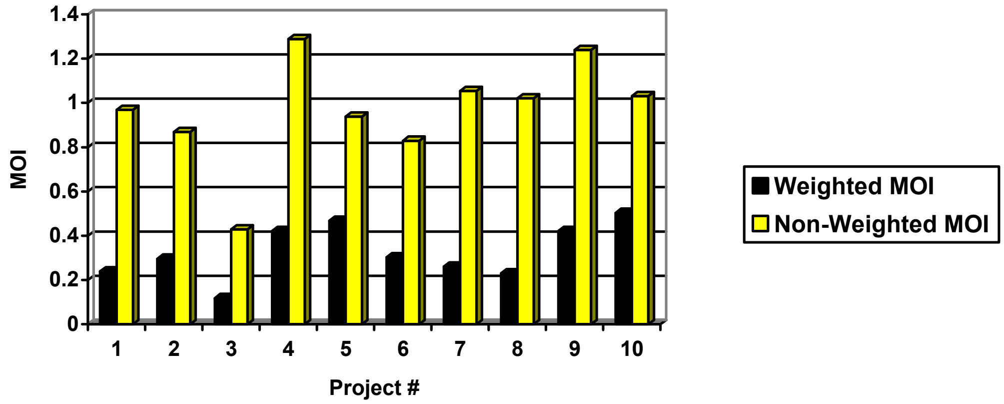


**Figure 3. Weighted and non-weighted multi-criteria optimality indices**

Considering now the budgetary constraint, the following projects will be scheduled for maintenance:

(i) Weighted MOI-Based Prioritization: Projects #3, #8, #1, #7, #2, and #4 for a total cost of $1.609 million. The other projects are delayed until the next year; however, a detailed analysis is required to assess if bridge postings or closures are required.

(ii) Non-Weighted MOI-Based Prioritization: Projects #3, #6, #2, #5, #1, and #8 for a total cost of $1.634 million. The other projects are delayed for a year, however, a detailed analysis is required to assess if bridge posting or closure are required.

## 5. SUMMARY AND CONCLUSIONS

The maintenance optimization approach presented in this paper demonstrates the potential of the multi-objective decision-analysis approach for the maintenance management of bridge structures The major merits of the approach are: (i) consideration of all possible (even conflicting) objective functions; (ii) ability to place more emphasis on condition improvement; and (iii) rational decision-making regarding the selection of bridge projects for maintenance. The prioritization of the bridges is based on the satisfaction of several conflicting objectives simultaneously, including structural condition, maintenance costs, and traffic flow. The use of multi-objective optimization is another step towards the development of more effective bridge management systems that will enable the decision-maker to select all relevant, including the conflicting, criteria and determine the corresponding optimal maintenance strategies.

This paper illustrated that the bridge maintenance management problem could be formulated as a multi-objective optimization problem. The solutions obtained achieved a satisfactory trade-off between several competing criteria, including the maximization of the bridge condition, minimization of maintenance costs and minimization of traffic disruption. The use of compromise programming and the proposed multi-criteria optimality index yield the optimal ranking of the deteriorated bridges in terms of their priority for maintenance.

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