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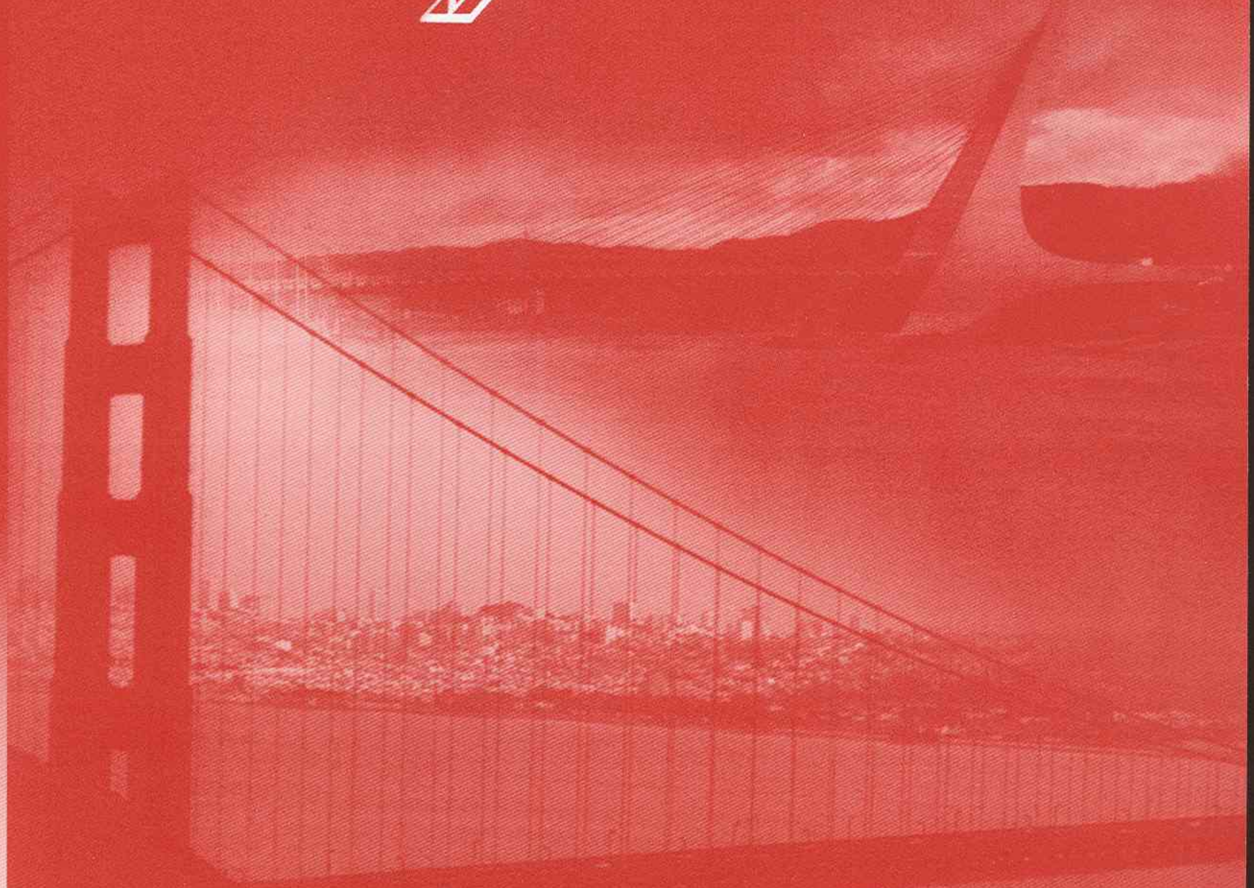

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LIFETIME MULTI-OBJECTIVE OPTIMIZATION OF MAINTENANCE OF EXISTING STEEL STRUCTURES

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Abstract

In this paper, the lifetime performance of deteriorating structures, defined by their time dependent condition index and reliability index, is analyzed. The effect of preventive and essential maintenance actions on performance and cost in predicted, and the optimal times of application of preventive and essential maintenance actions are found. Due to significant uncertainty in the initial performance, effects of deterioration and of maintenance actions, as well as, times of application and cost of maintenance actions, the analysis is performed in a probabilistic framework. The reduction in performance due to deterioration is simulated using an extension of the model proposed by Frangopol (1998). The probabilistic condition index, reliability index, and cumulative cost profiles are computed using Latin Hypercube simulation. Optimization of times of application is performed using genetic algorithms. Results show the significant importance of preventive maintenance actions in reducing the lifetime cost of existing structures, but also their fundamental role of essential maintenance action in keeping structures safe and serviceable during the entire lifetime.

1 INTRODUCTION

During the second half of the 20th century, most countries in Europe and North America, and Japan lived a period of intensive investment in transportation infrastructures, including highways, railways, ports and airports. In particular, the highway networks grew exponentially during this period. Few countries, however, planned to maintain these infrastructures or reserved funding for their repair or replacement. Structures were often built considering only the construction costs, disregarding or considering in very simplified manner the durability, maintenance cost and replacement cost.

As these structures aged, it became clear that the number of deteriorated structures is very large and will increase dramatically in the near future. Consequently, funding will be scarce for repairing and/or replace all structures that require improvement in performance.

For these reasons, methodologies that help decision makers in selecting maintenance policies leading to the best possible life-cycle performance and minimum cost are of paramount importance. This need, resulted, in the case of highway bridges, in the development of Bridge Management Systems, as Pontis (Thompson et al. 1998) and BRIDGIT (Hawk and Small 1998). These systems use the results of visual inspections, classified in terms of condition states, as the tool to evaluate the need to perform maintenance. In these systems, future performance is predicted in terms of current performance, using Markovian Chains.

Markovian Chains define probabilities for the future performance of a structure based only on current performance, disregarding the effect of the history of deterioration and maintenance, and the age of the structure, among other parameters. The use of condition states as the indicator of the need to perform maintenance is limited by the accuracy of visual inspections in assessing performance. Visual inspections are extremely useful is assessing the level of deterioration, such as cracking and spalling in reinforced concrete structures, and corrosion or paint distress in steel structures. However, early stages of several deterioration mechanism, such as fatigue, can not be identified by visual inspections. Furthermore, the impact of initial safety, existence of non-observable defects, and the time variation of loads, among others, can not be identified by visual inspections alone (Das 1998).

For this reason, several models were proposed for the life-cycle evaluation of the safety of deteriorating structures. Among these models, two different levels of detail must be distinguished. A more detailed analysis, based on realistic modelling of all significant deterioration mechanisms and loads time dependence was proposed, among others, by Enright and Frangopol (1998).

This type of analysis requires extremely large amount of information, and a time consuming analysis procedure, for each structure. For this reason, the cost of performing such evaluation for all structures in a network is too high, and its use is only reasonable for structures associated with significant deterioration, for which reduction of safety can be expected.

As a result, methods based on less detailed analysis, defining life-cycle performance independently of the deterioration mechanism were developed. These methods include the above describe Markov Chain methodology.

2 SIMPLIFIED LIFETIME ANALYSIS

The Markov Chain methodology, used in most current BMS, is the most current simplified method to assess future performance of deteriorating bridges. In this methodology, bridges are classified in discrete condition states. A probabilistic approach is employed, defining the probability of no change in state or change to a specific state in a given time period. This probability is computed using data collected over the years, on similar structures under similar environmental and use conditions. As exposed before, this methodology is limited by the accuracy of visual inspections and the shortcoming of Markov Chain.

Frangopol (1998) proposed a simplified model for the safety analysis of deteriorating structures under maintenance, considering the reliability index as measure of performance. The time-dependent reliability of a structure or element is defined using a probabilistic profile, based on a small number of parameters. In this manner, the future performance is calculated based on initial performance, deterioration rate, and history of maintenance (Frangopol et al. 2001).

Yang et al. (2005) defined performance in terms of the probability of finding a serious defect. The time dependent probability of failure is approximated by simple functions, taking into consideration the effects of the application of preventive and essential maintenance actions.

In both cases, a much more consistent measure of safety is used, resulting in more consistent results. However, none of these approaches includes the results of visual inspections, disregarding a large amount of information collected over the last three decades.

3 CONDITION, SAFETY, AND COST INTERACTION

In order to make use of the large amount of information gathered by highway agencies over the years in terms of condition states of bridges, the authors (Frangopol and Neves 2003) proposed a model defining performance based on three indicators: condition index, safety index, and cumulative cost.

The condition index is defined as an extension of the currently used condition states. Unlike these, however, the condition index is considered as a continuous variable. The safety index is defined as the reliability index of the structure or of an element. The cumulative cost includes the discounted costs of all maintenance actions.

All these indicators are probabilistic, defined in terms of a small number of random variables.

The condition and reliability indices under no maintenance are defined, based on the model proposed by Thoft-Christensen (1998) in terms of the following random variables: initial condition and reliability indices, C_0 and β_0, respectively, time to initiation of deterioration of condition and reliability, t_{ic} and t_i, respectively, and deterioration rate of condition and reliability, α_c and α, respectively. All these parameters can be deterministic or probabilistic, independent or correlated. Due to the relation of condition and reliability, it is also possible to state that the initiation of deterioration of reliability occurs when the condition index reaches a certain threshold.

A maintenance action is defined as causing one, several, or all of the following effects (Frangopol and Neves 2003): (a) increase in the condition index and/or reliability index immediately after application; (b) suppression of the deterioration in condition index and/or reliability index during a time interval after application; and (c) reduction of the deterioration rate of condition index and/or reliability index during a time interval after application. The random variables defining these effects are: (a) increase in condition and reliability index immediately after application, γ_c and γ respectively; (b) time interval during which the deterioration process of condition and reliability is eliminated, t_{dc} and t_d, respectively; (c) time during which the deterioration rate in condition and reliability is eliminated or reduced, t_{pdc} and t_{pd}, respectively; and (d) deterioration rate reduction of condition and reliability, δ_c and δ, respectively. Alternatively, the reduction in deterioration of the condition index and reliability index can be defined by the deterioration rate during the effect of maintenance, θ_c and θ, respectively. The meaning of each of these parameters is represented in Figure 1.

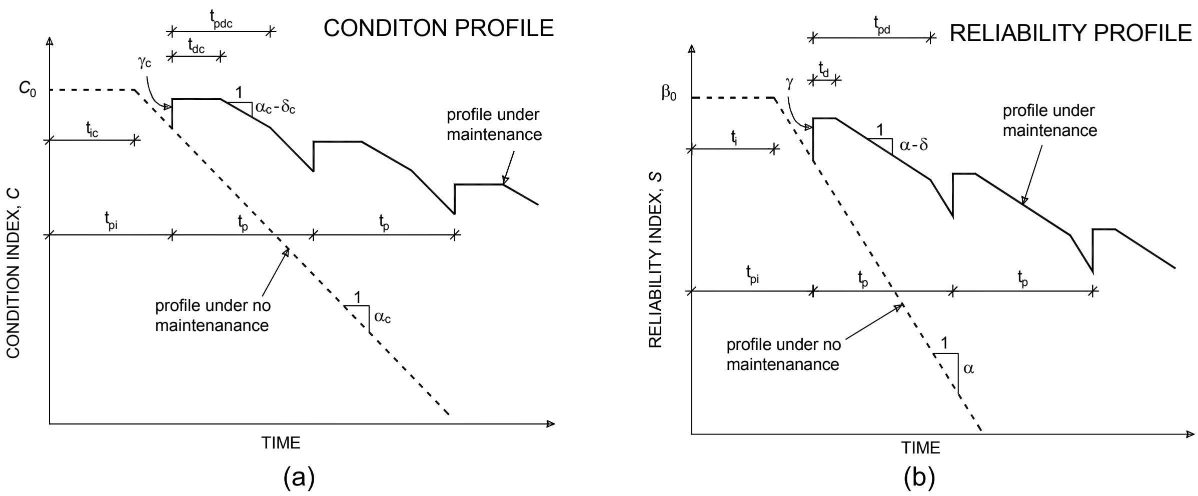

Figure 1 Performance profiles under no maintenance and under maintenance: (a) condition index, and (b) reliability index

Maintenance actions are classified in two groups, considering their times of application. Preventive maintenance actions are applied at regular probabilistic time intervals, irrespective of the performance of the structure at time of application. These maintenance actions are, in general, associated with smaller costs, and small impacts on the performance of the structure. In general, these actions cause no improvement in the condition index and reliability index at time of application, but only a delay in deterioration or a reduction in deterioration rate of condition and reliability.

Essential maintenance actions are, on the other hand, applied when a performance threshold (*i.e.,* condition index or reliability index) reached a predefined threshold. This threshold can be defined as deterministic or probabilistic. These actions cause, in general, a significant improvement in performance at time of application.

If compared with the Markovia Chain approach, described earlier, it becomes clear that in that methodology the effect of preventive maintenance actions can not be included in the analysis. In fact, a delay in deterioration or a reduction in deterioration rate dos not alter current performance and, consequently, does not cause any change in the prediction of future performance.

The cost of each maintenance action can be defined as a deterministic variable, as a probabilistic variable, or a probabilistic function of the effect of the maintenance action.

4 COMPUTATION OF CONDITION, RELIABILITY AND COST PROFILES

Due to the complexity of the condition, reliability, and cost profiles, simulation was used to compute the probabilistic descriptors of the profiles. To reduce the number of samples required to obtain accurate results, Latin Hypercube Sampling was used.

Each deterministic condition, reliability, and cumulative cost profile is computed by superposition of simple profiles. The first profile corresponds to the lifetime performance under no maintenance. The profile associated with each maintenance action are superposed on this profile.

However, if more than one maintenance action is active at any point in time, the superposition of the different profiles would result in unrealistic results. For this reason, if more than one maintenance is active at any point in time, only the action resulting in a larger reduction of the deterioration rate of the condition index and safety index is considered.

To reduce the computational cost of performing this analysis, profiles are computed at one year intervals. However, as random variables are continuous, a weighted average of the deterioration rate during each one year interval must be computed and used to calculate the performance profiles.

This model was implemented in a Windows platform under a software package named Condition and Reliability Analysis under Maintenance (CRAM). In Figure 2 a very general flowchart describing the implementation of CRAM is shown.

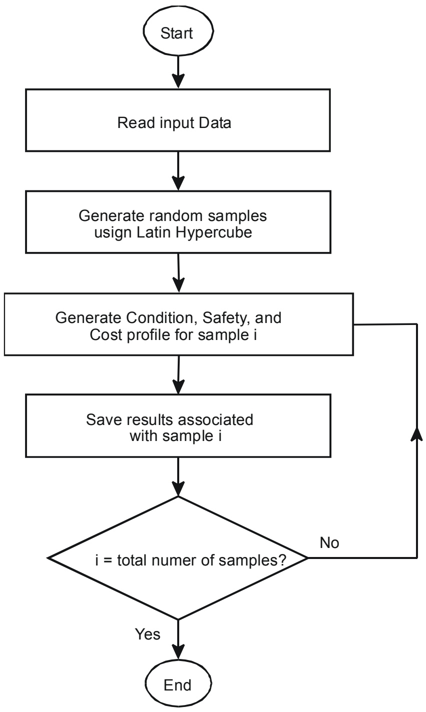

Figure 2 General flowchart of simulation process of condition, reliability, and cost probabilistic indicators.

5 OPTIMIZATION

One of the main objectives of a bridge manager is to find a maintenance strategy that leads to the best possible performance, but also to the lowest possible investment. These are usually conflicting objectives, as improving the lifetime performance is usually associates with higher costs. The best possible balance between these two objectives can only be defined for each specific situation, considering budget constraint, importance of the structure, predicted levels of traffic, among others.

For these reasons, in this work, a multi-objective optimization is employed. This results in a set of optimal solutions, from which the best solution for each specific situation can be chosen. Moreover, the results obtained with this multi-objective optimization show trends common to all optimal solutions, that can be considered valid in most situations.

Since the profiles are discontinuous, and obtained through simulation, the use of conventional optimization methods is extremely difficult. In fact, the numerical errors due to the simulation procedure are often larger than the difference between solutions obtained by finite differences. For this reason, optimization was conducted using Genetic Algorithms.

Genetic algorithms (GAs) loosely emulate the evolution of species according to Darwin theory, simulating the optimization process as a sequence of generations where each new generation is produced based on the properties of the fittest individuals of the previous generation.

A generation is defined, in terms of the best individual of the previous generation, based on two algorithms. The first, *cross-over*, is characterized by a combination of the properties of two individuals, in order to produce two new individuals. The second algorithm, *mutation*, is a perturbation of the properties of an individual, to include characteristics not present in the previous generation.

In order to improve the convergence of the algorithm, an elitism procedure is employed. This procedure consists in generating a population of N individuals. These are joined to the N individuals of the previous generation. The next generation is selected as the more fit among these $2N$ individuals. In this manner, the very best individuals of the two populations are selected.

If multi-objective optimization is to be performed, the choice of more fit individuals is not simple. In this work, a dominance technique is employed. Assuming that all objective functions are to be minimized, an individual A is considered to be dominated by an individual B if (Deb and Goel 2001):

1. Individual B has at least one objective value lower than the corresponding one for individual A;
2. All other values of the objectives associated with individual B are lower or equal to the corresponding ones associated with individual A.

Non-dominated individuals are considered more fit. If more than N non-dominated individuals exist, those better distributed in the objective space are selected. If less than N non-dominated individuals exist, the procedure in repeated in waves.

6 EXAMPLES OF APPLICATION

An existing bridge located in Colorado is presented herein as a case study example using the probabilistic approach described above. Bridge E-17-LE is located over Interstate Highway 25, on 88th Street, between US Highway 36 and State Highway 128. The bridge has two continuous spans with lengths of 110ft and 115ft and a total length of 225ft. The deck consists of a 6.5in layer of reinforced concrete and a 2in surface layer of asphalt. The total width of the bridge is 64.5ft. The slab is supported by eleven steel welded composite plate girders. A comprehensive description of this bridge can be found in Akgül (2002).

A detailed time dependent reliability analysis of this structure, considering the effect of deterioration was carried out by Akgül and Frangopol (2004). This analysis does not include the effect of maintenance actions during the lifetime of the structure. Petcherdchoo and Frangopol (2004) proposed a set of maintenance actions for the girders.

The condition states of the steel girders were defined according to to the recommendation of the Colorado Department of Transportation (CDOT 1998). Five condition states are defined as indicated in Table 1 (CDOT 1998).

Table 1 PONTIS Condition Rating for Steel Painted Girders

Condition Rating	Description
Condition 1	**There is no evidence of active corrosion** and the paint system is sound and functioning as intended to protect the metal surface.
Condition 2	**There is little or no active corrosion**. Surface or freckled rust has formed or is forming. The paint system may be chalking, peeling, curling or showing other early evidence of paint system distress but there is no exposure of metal.
Condition 3	**Surface or freckled rust is prevalent**. The paint system is no longer effective. There may be exposed metal but there is no active corrosion which is causing loss of section.
Condition 4	**The paint system has failed**. Surface pitting may be present but any section loss due to active corrosion does not yet warrant structural analysis of either the element or the bridge.
Condition 5	**Corrosion has caused section loss** and is sufficient to warrant structural analysis to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.

The condition and reliability index profiles of the girders under no maintenance, considering the results presented by Akgül and Frangopol (2004), are defined in Table 2, where the unit of the deterioration rates is year^{-1}.

Table 2 Descriptors of variables describing reliability and condition indices under no maintenance

Random Variable	Distribution Type	Min. Value	Mode	Max. Value
β	Triangular	2.18	2.90	3.62
α	Triangular	0.0037	0.005	0.0063
α_c	Triangular	0.056	0.075	0.094

The initial condition of the bridge is assumed deterministic equal to 1.

Two maintenance actions are considered. The first, minor painting (MP), is considered a preventive maintenance action, being applied at regular time intervals. The second maintenance action, girder repair, is considered an essential maintenance actions applied when the condition index reaches C = 4.0. The effects, times of application and cost of application of these two maintenance actions are shown in Tables 3 and 4. These tables show that the preventive maintenance actions have a much lower impact on condition and reliability indices than the essential maintenance actions, but also a much lower cost.

Table 3 Time of application and effects of maintenance actions on the condition index

Maintenance Action	Time of First Application	Time of Subsequent Application	Condition Improvement	Deterioration Rate During Effect	Duration of Maintenance Effect
	t_{pi} (years)	t_p (years)	γ_c	$\theta_c = \alpha_c - \delta_c$ (year^{-1})	t_{pdc} (years)
Minor Painting	T(0;7.5;15)	T(10;12.5,15)	-	T(0.028; 0.055; 0.082)	T(10;12.5,15)
Girder Repair	When C = 4.0	When C = 4.0	T(2.5;2.75;3.0)	-	-

T(a,b,c) represents a triangular density distribution with minimum = a, mode = b, and maximum = c

Table 4 Effects of maintenance actions on the reliability index and cost of application

Maintenance Action	Reliability Improvement	Deterioration Rate During Effect	Duration of Maintenance Effect	Cost
	γ	$\theta = \alpha - \delta$ (year^{-1})	t_{pd} (years)	
Minor Painting	-	T(0.002;0.004;0.006)	T(7.5;10;12.5)	T(15;30;45)
Girder Repair	T(0.125;0.25;0.375)	-	-	T(750;1500;2250)

T(a,b,c) represents a triangular density distribution with minimum = a, mode = b, and maximum = c

The mean and standard deviation of the condition and reliability indices considering no maintenance, each of the two maintenance actions defined, and both maintenance actions applied during the time horizon considered (i.e., 50 years), was computed using the model proposed. The results obtained, considering a discount rate of money ν = 6%, are shown in Figure 3.

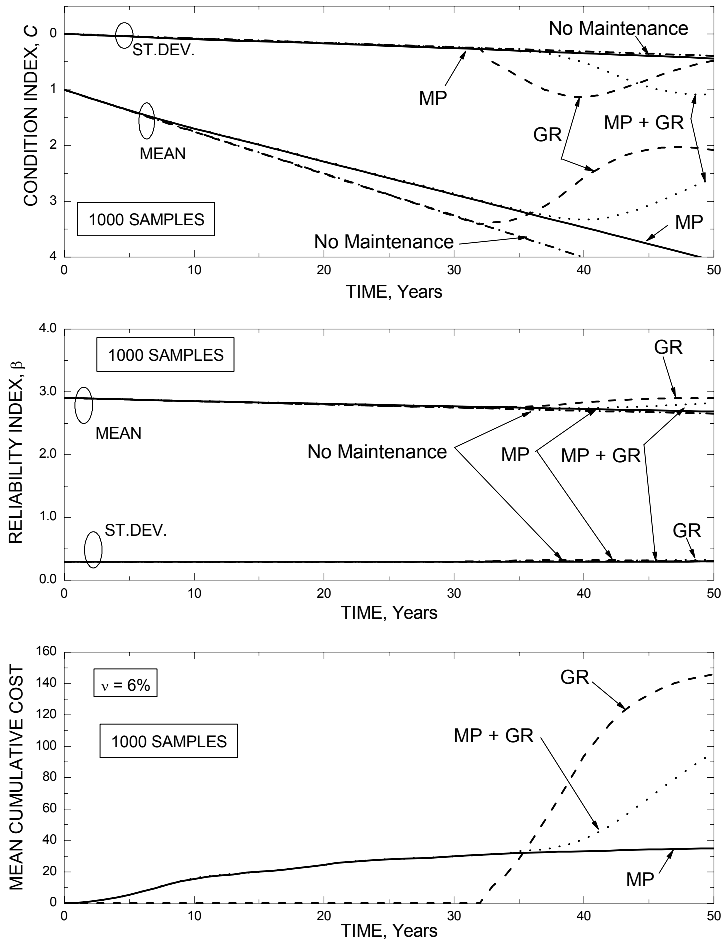

Figure 3 Mean and standard deviation of condition and reliability indices and mean cumulative cost; No Maintenance, Minor Painting (MP), Girder Repair (GR), and Minor Painting + Girder Repair (MP+GR).

These results show that preventive maintenance alone (MP) causes a small improvement in the lifetime condition and reliability indices, insufficient to keep the girders from reaching condition state 4.

Essential maintenance alone leads to a significant improvement in the condition and reliability indices, but also to a very large cumulative cost. The combination of both actions (MP+GR) leads to lower costs than essential maintenance alone, for significant improvement in performance.

GA were used to optimize the time of application of minor painting and the condition threshold at which girder repair is applied. The optimization problem can be defined as:

Goal:

Find the mean time of first application and mean time interval between subsequent applications of minor painting and the condition index threshold at which girder repair is applied

Such that:

Maximum (i.e., worst) mean condition index during entire lifetime is minimized;

Lowest (i.e., worst) mean reliability index during entire lifetime is maximized;
Present value of mean cumulative maintenance cost at time horizon is minimized.

Subject to:

Maximum (i.e., worst) mean condition index during entire lifetime ≤ 4.0; and
Lowest (i.e., worst) mean reliability index during entire lifetime ≥ 3.0.

Genetic algorithms using a population of 100 elements and considering 50 generations were employed. In Figure 4 the worst mean condition during the entire time horizon and mean cumulative cost at time horizon are compared for the optimal and non-optimal solutions obtained.

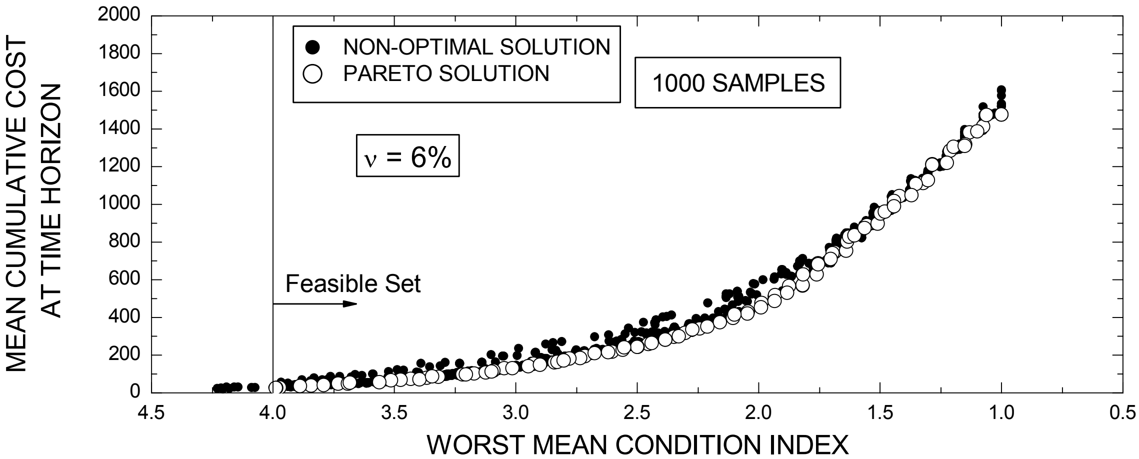

Figure 4 Mean cumulative cost at time horizon vs. worst mean condition index associated with Pareto and non-optimal solutions under minor painting + girder repair.

These results show a fast convergence of GA to the optimal solution. It is also clear from these results that there a non-linear relation between optimal performance and optimal cost. In fact, if the interval between applications of maintenance is reduced significantly, superposition of the effect of several actions occurs, reducing the effectiveness of each action. This results in large increases in cost, for improving performance, for lower values of the condition index.

Analysis of the optimal solutions show that optimal solutions are associated with frequent application of preventive maintenance actions. This leads to a delay in the time of application of essential maintenance actions. Since these are responsible for most of the total cost and due to the discount rate considered, later application of essential maintenance actions leads to reduction of overall maintenance costs.

7 CONCLUSIONS

In this paper, a probabilistic model for the analysis of performance of deteriorating structures, under preventive and essential maintenance actions is presented. Performance is measured by the condition index, resulting from visual inspections, and the reliability index, resulting from detailed structural analysis. The proposed model is combined with a Genetic Algorithms optimization procedure, resulting in optimal maintenance strategies for steel structures. Multi-objective optimization is used to simultaneously consider several objective functions, including reliability, condition, and cumulative cost. A realistic case study is presented, based on a detailed lifetime reliability analysis. The results presented showed the significant differences between the time dependent reliability index and condition index. Moreover, the importance of preventive maintenance actions in keeping structures safe and serviceable, with minimum investment is highlighted.

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