Optimization-based maintenance scheduling for prestressed concrete bridges using Markov chains models. The state of Indiana, U.S.

Luis Rincon[1,2], Erica Arango[1], Maria Nogal[3], Emilio Bastidas-Arteaga[2], Hélder S. Sousa[1], Yina F. Muñoz[1], José C. Matos[1]

[1] *Universidade do Minho, Guimarães, Portugal, id9635@alunos.uminho.pt*

[2] *LaSIE UMR CNRS 7356, La Rochelle Université, La Rochelle, France, luis.rincon_prada@univ-lr.f*

[3] *Technical University of Delft, Delft, The Netherlands.*

ABSTRACT Road transport infrastructures have high strategic importance for nations' economic and social development. Bridges are considered as critical assets for road network functionality i.e., any damage can have disastrous social repercussions. However, bridges are one of the most exposed assets; their deterioration can be attributed to material properties, load, and climatic factors, or catastrophic events. As a result, maintenance, rehabilitation, and repairs of existing structures account for about 50% of construction sector spending in most developed nations, and this percentage is projected to rise. Establishing a network-level budget and maintenance schedule is particularly complex due to the heterogeneity of bridge configurations and functions. Deterioration models are established in this sense to determine asset performance and cost-effective and efficient planned maintenance solutions to ensure continuous and correct operation. Markov chains are one of the most used models in this sense, i.e., to assess structure deterioration. The stochastic nature of Markov chains allows for taking into account the uncertainty of complex phenomena as well as their ease of application and compatibility. This study analyzed box beam and girder prestressed concrete bridges in the state of Indiana, U.S. Markov chains degradation models were implemented using National Bridge Inventory data of the last thirty-one years. Annual maintenance costs and budgets were established, and a genetic optimization algorithm was applied to determine the minimum annual maintenance cost for a period of eleven years. The results of the study demonstrate the contribution of the proposed methodology to ensure proper infrastructure maintenance and reduce costs.

Keywords Bridge management systems; Degradation models; Markov chains models; Optimization, Maintenance

I. INTRODUCTION

The road system has become heavily reliant on society, thus any disruptions to the infrastructure could have serious negative effects on people's well-being and economic growth (Arango, Sousa and Matos, 2021). Thus, the aging of bridges and their degradation over time is a major concern for transportation departments around the world. According to the most recent Infrastructure Report Card, 42% of all bridges in the United States (U.S.) are at least 50 years old, and more than 40,000 bridges are classified as structurally deficient (ASCE, 2021). To maintain the nation's bridges at reasonable health, the report estimated that an amount of $125 billion is required.

Adequate, and timely maintenance of bridges is critical to ensure the safety and reliability of the infrastructure. According to the current rate of investment for bridges in the U.S, it would take until 2071 to complete all repairs without considering future deterioration and it is estimated that the additional deterioration over the next 50 years will become overwhelming (ASCE, 2021).

Establish maintenance schedules that allow for optimal management of resources and ensure adequate service is vital. Supporting transportation departments in making more informed bridge maintenance decisions requires an understanding of the bridge degradation process. Bridge degradation is a complex process that is influenced by multiple factors, such as exposure to extreme weather conditions, traffic loading, quality of construction and maintenance, among others (Rincon *et al.*, 2022). Moreover, degradation is not a linear and predictable process, which increases the complexity of the phenomenon and makes it difficult decision-making process. In this context, degradation models are valuable tools to represent the degradation process of bridges. The main degradation models are based on the idea that bridge degradation can be described as a stochastic process, with Markov chains being the most used models in bridge management systems (Li, Sun and Ning, 2014; Moscoso *et al.*, 2022). However, entities such as nations or departments must establish maintenance budgets for regions considering all existing structures and the available resources. Therefore, the individual analysis of a bridge provides insufficient information for decision-making and maintenance planning must consider the portfolio of the bridges in the network analyzed.

This paper presents a maintenance scheduling based on optimization as an essential tool to plan the investment needed to maintain the required performance of a portfolio of bridges. Considering, degradation models based on Markov chains, developed and applied to determine the need for future maintenance of the state's high traffic prestressed concrete bridges. Optimization model is used to minimize the maintenance cost in a given an analyzed period – e.g, 11 years. The methodology is applied for a portfolio of bridges in the state of Indiana, using the National Bridges Inventory (NBI) database. It demonstrates that the methodology can be of great value to transportation departments in improving the safety and reliability of transportation infrastructure.

The paper is structured as follows: Section 2 presents the methodology implemented. Section 3 presents the application's information. Section 4 describes the results and discussion of the procedure. Finally, the conclusions of the research are presented.

II. METHODOLOGY

The methodology has two main steps: (I) the development of Markov models and (II) optimization-based maintenance scheduling.

A. Stochastic models

Bridge degradation can be described by Markov chain models, which define condition states and set probabilities of passing a next state or remaining in the same state (Yi Jiang, 2010). This model describes systems that change over time in a finite set of states, where the probability of changing from one state to a state with higher damage depends only on the current state. In a Markov chain model, the transition probability matrix is determined by the term $P_{i,j}$ defined as the probability of transitioning from state i to state j during a set period. This probability is computed using the CR database using equation 1.

$$P_{i,j} = \frac{n_{i,j}}{n_i} \quad (1)$$

Where, $n_{i,j}$ is the number of bridges with state i that change to state j in the following year, and n_i is the number of bridges with state i in the analyzed period. From equation 1, the transition probability matrix is established and used in equation 2 to describe the condition of an analyzed bridge.

$$C(t) = C_o * P^t \quad (2)$$

Where, C_o is the initial condition of the bridge, t is the time analyzed in years and P is the matrix of the transition probability matrix. The present research used the historic data of the bridges in the state of Indiana to establish a Markov chain model that describes the degradation of the bridges analyzed throw time from the initial condition and after every maintenance intervention.

B. Metaheuristic optimization models

Metaheuristic optimization models are a strategy of solving a problem using higher levels of abstractions (Kaveh, 2017). These models aim at finding a minimum or maximum of a system and are particularly more efficient and faster than traditional models when there are complex variables and configurations. Genetic Algorithms (GA) are based on the concept of generations and population, where the population is a set of solutions of the problem to be optimized (Ghodoosi *et al.*, 2018). These solutions are combined with each other considering criteria such as mutation, copying, swapping, and surviving, to create a second generation set of solutions. In this way, optimal solutions to the problem can be obtained. GA has proven to be one of the most effective and robust optimization techniques for single-objective optimization problems (Liu, Hammad and Itoh, 1997).

III. APPLICATION

A. Database availability

The Federal Highway Administration established the National Bridge Inventory (NBI), a system for the annual inspection of bridges based on the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges" (U.S. Deparment of Transportation, 1995). The NBI is a database that since 1992 has annually recorded more than 617,000 bridges across the United States and provides information about construction materials, geometry, location, design loads, connecting roadway information, average daily traffic, among others. In addition, the NBI establish a Condition Rating (CR) used to describe the existing, in-place bridge as compared to the as-built condition. These condition ratings describe the condition of the Deck, Superstructure and Substructure according to visual criteria such as cracking, deterioration, damage, sections loss, malfunction, among others. As a result of these inspections, the load-carrying capacity is not considered in the criteria (U.S. Deparment of Transportation, 1995). Table 1 shows the CR scale, ranging from 9 associated with a new structure to 0, which corresponds to the total loss of the structure.

Due to the differences in degradation related to roadway characteristics evidenced by Rincon et al. (2022), and the differences due to the intrinsic characteristics of the structures evidenced by Moscoso et al. (2022), the present study analyzed bridges in the state of Indiana (U.S.) that have an average daily traffic of more than 10,000 vehicles, built in prestressed concrete and of beam-slab, slab or box-beam type structures. The research considers CRs as states in Markov chain models. Thus, the CRs of 117 existing, reconstructed and destroyed bridges were considered, and the characteristics of Deck, Superstructure and Substructure were analyzed separately.

TABLE 1. Condition rating scale. Adapted from U.S. Deparment of Transportation, (1995)

Code	State	Description
9	Excellent	New condition, no noteworthy deficiencies
8	Very good	No repair needed
7	Good	Some minor problems, minor maintenance needed
6	Satisfactory	Some minor deterioration, major maintenance needed
5	Fair	Minor section loss, cracking, spalling or scouring for minor rehabilitation; minor rehabilitation needed
4	Poor	Advanced section loss, deterioration, spalling or scouring; major rehabilitation needed
3	Serious	Section loss, deterioration, spalling or scouring that have seriously affected the primary structural components
2	Critical	Advanced deterioration of primary structural elements for urgent rehabilitation; bridge may be closed until corrective action is taken
1	Imminent failure	Major deterioration or loss of section; bridge may be closed to traffic, but corrective action can put it back to light service
0	Failed	Out of service and beyond corrective action

IV. RESULTS AND DISCUSSION

The database of 117 existing, destroyed, and reconstructed bridges was used to establish the damage state transition probabilities. Equation 3 presents the transition probability matrix for substructure, where a bridge with substructure rating of 9 has a 68% probability of remaining in that state and a 32% probability of deteriorating to the next state.

$$P = \begin{bmatrix} 0.68 & 0.32 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.92 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.95 & 0.05 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.96 & 0.03 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.93 & 0.07 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.99 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.84 & 0.16 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

The damage state transition probabilities matrix obtain from the Markov chain models was used to stablish the degradation of the 58 state's high traffic prestressed concrete bridges in currently in use in the state of Indiana. Figure 1 shows the degradation of the superstructure of one bridge with an initial CR of 9 can have over a 200-year lifespan. Without any maintenance, this bridge will start to show a poor condition where a major rehabilitation is needed from year 69 onwards.

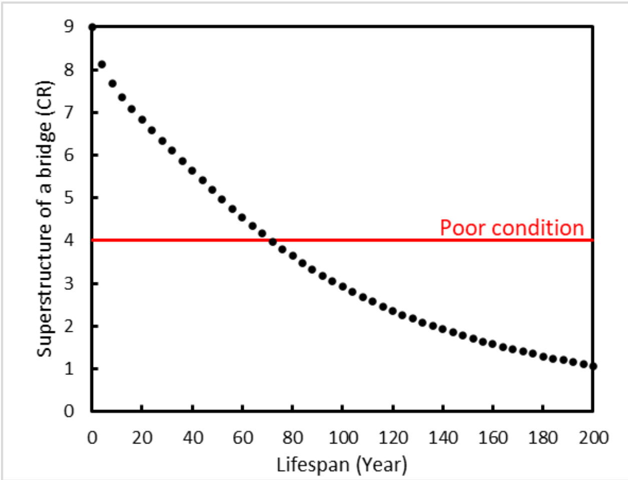

FIGURE 1. Degradation of the superstructure of a bridge with initial CR of 9

A. Maintenance optimization

The objective of the optimization is to minimize the maintenance intervention costs of the portfolio bridges, X, during a window of time. These costs are calculated as

$$\min_{X} \sum_{j=1}^{J} \sum_{i=1}^{I} c_i^j x_i^j \tag{2}$$

where c_i^j is the cost of intervention to raise the condition rate one level for the element (i) of the bridge (j) and x_i^j is the number of condition rate levels increase for the element (i) in the bridge (j) to guarantee an acceptable level of service to the bridge under analysis. J is the total number of bridges, and I represent the elements of the bridge, in this case the deck, superstructure, and substructure. In order to give greater importance to the maintenance of bridges in worse condition c_i^j is penalized for the higher CR as, $c_i^j = c_i^j + 0.2c_i^j \, {CR}/{CR_0}$. Where CR_0 is the optimum CR value, i.e., 9 in this case.

Eq. (1) is subjected to four constraints; first, there is a maximum budget per element that must not be exceeded during the period analyzed, this maximum budget is calculated on the basis of the number of CR levels that element (i) is short of to reach CR_0. Second, it is desired that at least 50% of the total annual budget must be invested. The third restriction is used to establish that the total maintenance actions should not exceed the total annual budget with the objective of avoiding years with large maintenance budgets and others without maintenance, which can bring consequences to the municipalities and users. Finally, the fourth restriction establishes that the CR of bridges must be higher than the acceptable level of service. In this case bridge elements should not be less than

4, thus guaranteeing that despite the need for major rehabilitation, the structure is still in a usable condition, does not represent a risk or seriously affect the road network.

The 2021 Infrastructure Report Card reports that the current maintenance budget in the United States is $14.4 billion, which equates to approximately $23,000 per bridge. The report specifies that with the annual maintenance budget, it would take until 2071 to make all the necessary repairs today (ASCE, 2021). The mentioned report states that with the annual budget, it would take 50 years to repair the current damage without considering future deterioration and suggests a minimum increase of 58% to the budget to improve the condition of the current bridges. In the preliminary analysis of this research, it became evident that under the assumptions imposed, a 100% increase in the budget would only be enough to prevent the deterioration of the bridges analyzed for 3 years.

Therefore, a budget per bridge was establish at 3,715,116 €, assumed as three times the equal distribution of the current U.S. bridge maintenance budget from the 2021 Infrastructure Report Card projections, in the aim of having a budget that is capable of repairing future deterioration. On the other hand, consider CR definition in Table 1, maintenances activities are classified as a (i) proactive actions if the $CR \geq 7$, and (ii) reactive actions for lower CR values.

Maintenance activities cost are considered from the information available in the Bridge Inspection and Diagnosis Manual are taken into account (Japan International Cooperation Agency, 2017). It establishes a price list for the repair of the different components of a bridge depending on the health index (See Table 2) and establishes a linear relationship between the percentage of damage and the repair cost. The present study assumes a linear relationship between condition ratings and maintenance activities cost.

TABLE 2. Costs of repair of the different elements of a bridge. Adapted from Japan International Cooperation Agency (2017)

Deck	**Cost**	**Unit**
Pavement	4.4	$€/m^2$
Expansion Joint	71.5	$€/m$
Accessories	38.5	$€/m$
Approaches	68.2	$€/m$
Superstructure	**Cost**	**Unit**
Beams	267.3	$€/m^2$
Deck slab	319	$€/m^2$
Diaphragm	144.1	$€/m^2$
Substructure	**Cost**	**Unit**
Bearing	1459.7	$€/m$
Substructure	391.6	$€/m^2$

The adjusted prices of the Japan International Cooperation Agency (2017), contemplated a linear relationship between damage and maintenance, therefore the algorithm did not contemplate a difference between the maintenance of a structure with good condition (CR of 8) and another with poor condition (CR of 4). To give greater importance to the maintenance of bridges in worse condition, a difference of 20% was established, thus it is better to maintain a structure in worse condition than one in better condition. Therefore, the accuracy of the results depends on the availability of costs for the case under study. Also, the consideration of non-linear functions to indicate the maintenance cost for each CR could improve the accuracy of the results if the cost per element required it.

Figure 2 shows the annual maintenance cost for the window analyzed and the number of bridges intervened for each year. From year 10 onwards, there is an annual increase in expenditure and the number of bridges intervened decreases. From year 12 onwards the number of bridges under poor condition in need of repair exceeds the available budget.

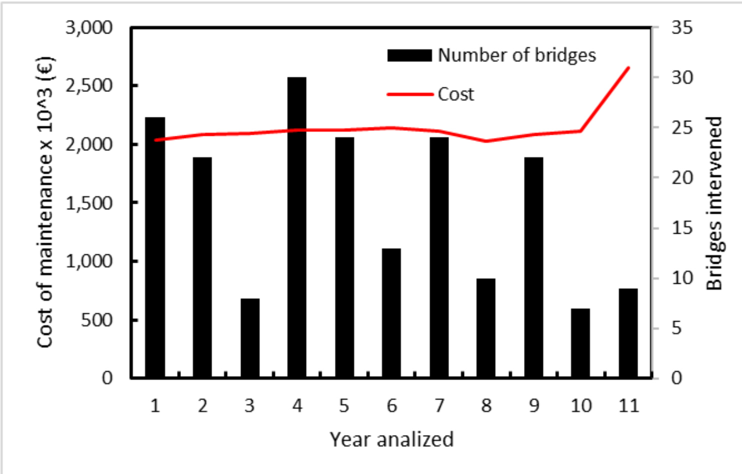

FIGURE 2. **Bridges intervened and maintenance cost.**

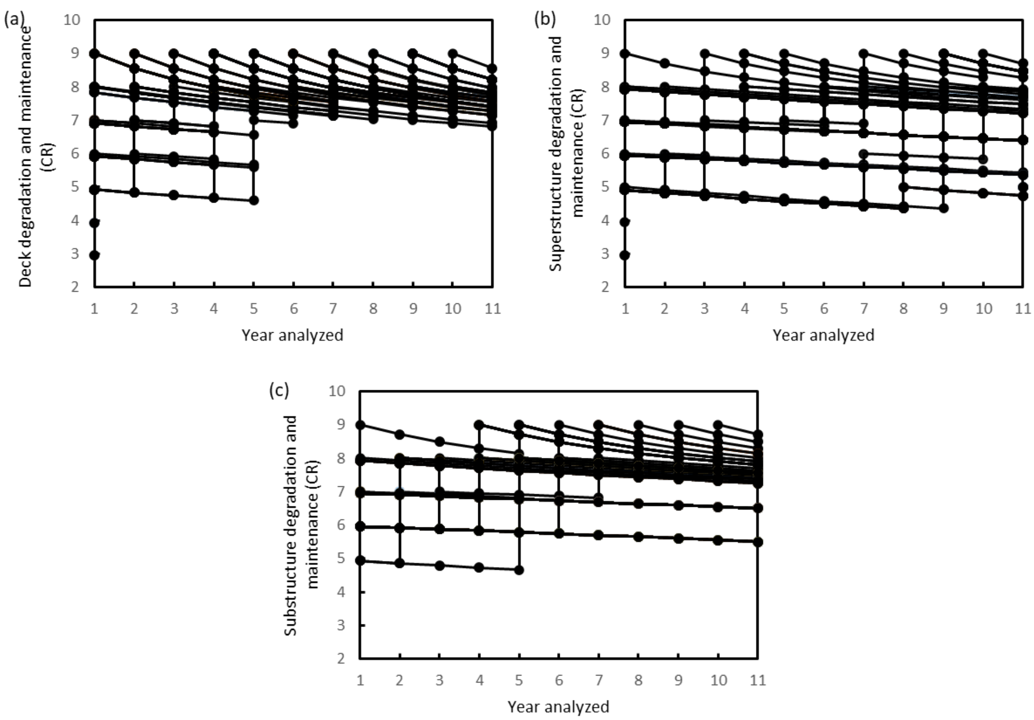

FIGURE 3. **Degradation and maintenance of the elements of the bridges analyzed: (a) deck, (b) superstructure, and (c) substructure**

Figure 3 depicts the CR when simulating degradation and maintenance of the 58 bridges analyzed for its three components deck, superstructure, and substructure. Since decks have the lowest maintenance costs (Table 2), the model tends to give them maintenance priority by maintaining an average degradation of 7.69 at the end of the 11 years analyzed. Meanwhile maintenance actions for the substructures are less regular, thus they present the worst CR average with 6.65. At the year 12, four bridges reach a poor state in the superstructure, and thus the system exceeds the annual budget consequently the algorithm cannot continue (See Figure 4).

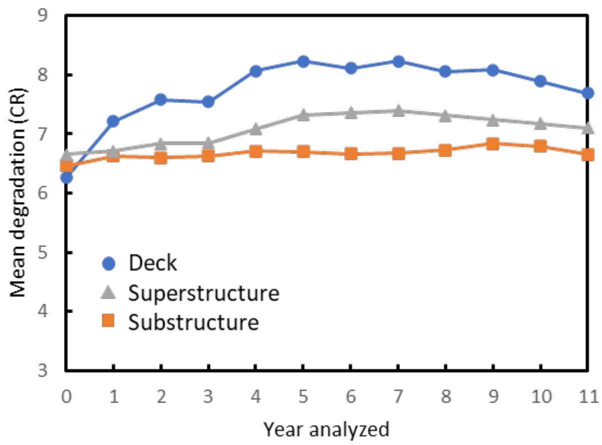

FIGURE 4. **Mean degradation of bridge elements.**

V. CONCLUSIONS

According to the 2021 Infrastructure Report Card, $22.7 billion is needed to maintain the current state of bridges in the U.S., which equates to €1,951,424 per bridge per year (ASCE , 2021). However, the results showed that a budget of €3'715,116 per bridge per year is not enough to compensate for the expected degradation.

The assumption of maintenance cost reduction depending on the damage presents adequate results. However, a multi-objective optimization that considers bridges near poor conditions without the cost reduction may present a better solution. Other factors such as the connectivity and road importance may help in the design of better maintenance strategies. That aspect will be addressed in future works.

The optimization model showed that from year 12 onwards, the elements that reach a poor condition exceed the annual maintenance budget. However, the results are very sensitive to maintenance costs, which can vary depending on the area and the maintenance required.

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