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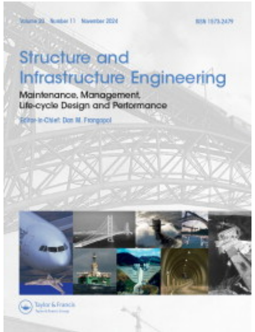
DOI
10.1080/15732479.2024.2403568

Publication date
2024

Document Version
Final published version

Published in
Structure and Infrastructure Engineering



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Structure and Infrastructure Engineering

Maintenance, Management, Life-Cycle Design and Performance

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/nsie20

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To cite this article: Miguel Angel Mendoza-Lugo, Maria Nogal & Oswaldo Morales-Nápoles (23 Sep 2024): Network-level optimisation approach for bridge interventions scheduling, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2024.2403568

To link to this article: https://doi.org/10.1080/15732479.2024.2403568

STRUCTURE AND INFRASTRUCTURE ENGINEERING
https://doi.org/10.1080/15732479.2024.2403568

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Network-level optimisation approach for bridge interventions scheduling

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ABSTRACT

This paper introduces a novel extension of the multi-system optimisation method, known as the 3C concept, tailored for optimising budget allocation for bridge interventions at the network level. This extended methodology accounts for the interdependencies among bridges due to their spatial proximity within the network. It incorporates direct and user costs, bridge performance indicators, and a bridge deterioration model. A real-world case study involving a portfolio of 555 bridges demonstrates the practicality of the methodology, efficiently determining the optimal intervention sequence. Over an 18-year analysis period, the proposed methodology achieved a 23% reduction in total costs by combining repairs for bridges with high to severe damage and maintenance for the others. This represents a significant improvement compared to the traditional approach, used by bridge management agencies, which relies exclusively on maintenance. The optimised procedure outperforms human intuition in managing complex bridge networks, particularly over extended periods. This methodology can assist transportation agencies in implementing and exploring various scenarios by adjusting the time between consecutive interventions and budget constraints, supporting comprehensive analysis and informed decision-making.

ARTICLE HISTORY
Received 6 December 2023
Revised 6 July 2024
Accepted 1 September 2024

KEYWORDS
Bridge network; interventions; maintenance; repair; mixed-integer linear programming; optimisation; multi-system

1. Introduction

Bridge networks are susceptible to degradation caused by factors such as ageing, heavy traffic loads, and natural disasters. Such degradation may result in failures that compromise service quality and create safety hazards (Nili, Taghaddos, & Zahraie, 2021). Coupled with constrained funding for bridge management, this underscores the need for objective assessments to achieve better utilisation of ageing bridges (Melhem & Caprani, 2022). To maintain the functionality of transport infrastructure and related service parameters, bridge managers recognise that effective planning of interventions can significantly enhance infrastructure availability while minimising costs.

For effective intervention programmes, optimal planning should consider both direct and user costs associated with transport disruptions, rather than solely budget availability (Manu Sasidharan & Schooling, 2022). Previous research indicates that when bridges are fully or partially closed, the resulting traveller delays can incur indirect costs several times the actual cost of the bridge (Alipour & Shafei, 2016; Han & Frangopol, 2022b; N. Zhang & Alipour, 2020). These higher costs necessitate the allocation of resources towards optimal strategies for bridge interventions.

A significant number of bridge structures need to be analysed, making it infeasible to re-assess each bridge annually. Consequently, systems that continuously monitor bridge conditions are established to plan interventions based on structural ratings and prioritisation indexes, justifying the funding of conservation actions (de León Escobedo & Torres Acosta, 2010). Integrating performance measures from all individual bridges into optimal budget allocation algorithms can enhance the overall performance of bridge systems (Xia, Lei, Wang, & Sun, 2022).

The literature on optimal bridge management planning can be divided into three main categories: (i) deterioration modelling, (ii) ranking of management alternatives, and (iii) maintenance planning using optimisation techniques (Abarca, Monteiro, & O'Reilly, 2023; Fiorillo & Ghosn, 2022; Yina, Moscoso, Luis, & Matos, 2022). The first category focuses on developing models to predict the deterioration of bridges over time, and the second compares different options based on their effectiveness and other factors for bridge prioritisation. However, these approaches often overlook constraints such as environmental impact, traffic demand, and budget constraints, which are crucial for a bridge intervention programme at the network level. The third category uses optimisation techniques to account for these constraints and find the optimal management scheduling for bridges.

At the bridge level, six intervention approaches[1] are commonly taken: do-nothing, maintenance, repair, rehabilitation, improvement, and total replacement. Do-nothing involves minimal intervention but risks long-term

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/15732479.2024.2403568.

deterioration. Maintenance implies routine activities to preserve the bridge in good condition. Repair fixes defects that affect functionality, safety, or performance. Rehabilitation restores the bridge to a better state to increase its service life. Improvement enhances the bridge beyond its original condition to meet new requirements. Total replacement involves replacing the entire asset with a new one, often incorporating modern technology (Baron, Galvao, Docevska, Matos, & Markovski, 2023; Hong & Hastak, 2007; Patidar, Labi, Sinha, & Thompson, 2007).

Alsharqawi, Dabous, Zayed, and Hamdan (2021) developed a bi-objective optimisation model that minimises total rehabilitation costs and maximises performance resulting from the latest rehabilitation actions applied to bridge decks. In Ehsan Fereshtehnejad and Hur (2022), an optimal budget allocation framework is proposed for maintenance, repair, and total replacement actions for bridge portfolios, aiming to minimise agency costs to maintain bridges in a like-new state.

A multi-objective optimisation model using an exponential chaotic differential evolution algorithm is introduced in Abdelkader, Moselhi, Marzouk, and Zayed (2022). The model includes maximising the performance condition of bridge elements, minimising agency and user costs, minimising traffic disruption duration, and minimising environmental impact. In Han and Frangopol (2022a), optimisation is performed to obtain optimal maintenance strategies with objectives related to connectivity and maintenance cost, considering the conditional failure of network connectivity given the failure of a specific bridge.

Z. Zhang, Labi, Fricker, and Sinha (2017) presented a methodology to establish the optimal timing conditions for each standard maintenance and rehabilitation intervention used by the Indiana Department of Transportation for each highway bridge, thereby developing long-term, condition-based schedules. The effects on the bridge performance trend resulting from differences between post-treatment and pretreatment interventions were also explored. However, no budget constraints were considered in the optimal scheduling process.

At the bridge network level, Casas, Alonso-Farrera, and Nazar (2006) developed a specific bridge stock model to optimise fund allocation for selecting maintenance or rehabilitation policies for the Bridge Management System of Chiapas State in Mexico. This involved utilising joint optimisation of maintenance and rehabilitation policies employing a genetic algorithm to find optimal costs for different policies, considering the deterioration process with Markovian transition matrices.

Patidar et al. (2007) developed a bridge management system to determine the overall optimality of investment decisions based on a desired combination of selected performance measures. This approach enables making investment choices based on optimal forecasted performance. The methodology involves conducting a multi-criteria utility function for the selection of bridge interventions, which includes optimising the identification and evaluation of network-level solution approaches.

These previous examples show how to allocate maintenance resources for a group of bridges or individual bridges in a transportation network. However, few studies consider the impact of executing interventions, such as the interconnected effects of interventions on individual bridges within the network caused by spatial proximity. Bocchini and Frangopol (2011) presented a framework for optimising preventive maintenance scheduling in bridge networks, considering the correlation between bridge states and utilising a probabilistic model. This model accounts for the expected damage levels of two bridges subjected to the same extreme event scenario and their spatial proximity. However, an important aspect of this methodology is its computational efficiency and the absence of real-data-based cost evaluations for the interventions. Kammouh, Nogal, Binnekamp, and Wolfert (2021) presented an integrative multi-system method, known as the 3C concept, to account for infrastructure connectivity by considering the spatial proximity of objects within infrastructure networks. This involves formalising a mathematical method for intervention scheduling at a network level, capable of obtaining the most efficient intervention programme. These examples underscore the importance of developing intervention programmes for spatially close and functionally connected structures simultaneously.

In this study, we introduce a novel extension of the integrative multi-system optimisation 3C concept. This extension, named B-3C, focuses on optimising budget allocation for bridge interventions at the network level, specifically for maintenance and repair activities. B-3C builds upon the core principles of the 3C framework but introduces additional elements and modifications tailored to address optimal budget allocation for bridge intervention programmes. We extend the existing framework by incorporating two types of interventions while maintaining the mathematical linearity of the problem. This mathematical property ensures its applicability to portfolios containing a large number of bridges. Furthermore, it considers factors such as deterioration, budget constraints, and the time between consecutive interventions. The B-3C methodology for optimising bridge intervention scheduling addresses a significant gap by considering the interconnected effects (additional costs) of interventions on individual bridges within the network system caused by the spatial proximity of the bridges. Additionally, the methodology provides practical guidance for estimating both direct and user costs through the analysis of a real-data-based bridge network. It can be applied in conjunction with various bridge ranking systems that rely on performance indicators, including condition state and traffic load effects criticality, making it a valuable tool for efficiently planning interventions within extensive bridge networks.

The remainder of the paper is organised as follows. In Section 2, we present the theoretical introduction of the concepts used in this study, including the framework for optimising intervention activities on bridge networks and the mathematical formulation of the optimisation problem. Section 3 presents a numerical example to illustrate the applicability of the proposed optimisation model. Section 4 discusses the application of the proposed optimisation model to a bridge portfolio of 555 bridges. Finally, conclusions are drawn in Section 5, along with proposed future work.

2. Methodology

In the context of this study, the goal of optimal intervention planning for a bridge network is to schedule interventions for each bridge in a manner that minimises the overall intervention cost. While bridge managers often face other explicit goals, such as minimising vulnerability to damage or maximising the average condition of the bridge network (Patidar et al., 2007), our primary interest is solely to minimise the total cost of interventions. Figure 1 illustrates a simplified version of the proposed framework for optimal intervention planning used in this research.

First, relevant information about the bridges within the network is gathered, cleaned, and analysed to obtain key variables for the analysis. These variables include bridge type, number of spans, construction costs, bridge rating, and average annual daily traffic (AADT). If construction costs are not available, they can be estimated using parametric cost models. Additionally, the direct and user costs associated with bridge interventions at the initial time step of the analysis are calculated.

Next, the rate of bridge deterioration is estimated using a bridge deterioration model. Subsequently, the associated direct and user costs are determined. The 3C concept, extended to bridge portfolios (B-3C concept), is then applied. Finally, the methodology yields an optimal intervention programme aimed at minimising the overall intervention costs. It should be noted that the framework depicted in Figure 1 does not cover all aspects of bridge intervention planning. A practical application of this framework is illustrated in Section 3. The following section introduces the B-3C concept and its mathematical formulation.

2.1. Integrative multi-system optimisation approach: 3C concept

The integrative 3C concept, introduced by Kammouh et al. (2021), is an approach for optimal intervention planning that accounts for the interdependencies between assets across multiple infrastructure systems. It includes three stages: (i) *centralise*, (ii) *cluster*, and (iii) *calculate*. In stage (i), intervention types are classified into central and non-central. Central interventions must occur at pre-established times, with no allowance for delays or advances.

During stage (ii), non-central interventions are clustered with the planned central interventions while respecting predefined individual constraints, such as the time interval between successive interventions of the same type. Each intervention k is assigned two values, $G_{\min,k}$ and $G_{\max,k}$, representing the minimum and maximum time intervals, respectively, between two interventions of the same type. For central interventions, since they occur at fixed intervals, $G_{\min,k}$ and $G_{\max,k}$ are equal.

In the final stage (stage iii), the optimisation of the intervention programme that meets the initial conditions is calculated. The primary objective of the 3C optimisation process is to minimise the overall cost of interventions, divided into direct costs (the interventions themselves) and user costs (service interruptions of affected assets). This optimisation approach is straightforward and easily scalable. Differentiating between central and non-central intervention types enables effective planning in systems with numerous interconnected objects, considering their interdependencies. For a complete overview of the 3C concept, refer to Kammouh et al. (2021).

2.2. Extension of 3C concept to bridge portfolio: B-3C concept

As mentioned in Section 1, this study aims to optimise budget allocation for intervention planning within bridge networks by considering two distinct types of interventions: maintenance and repair. This represents a methodological extension, as the original 3C concept only considers one possible intervention per asset. *Maintenance* refers to proactive actions taken to ensure that a bridge wears and tears as expected, while *repair* refers to actions that correct defects affecting functionality or safety. Maintenance activities are classified as non-central interventions, whereas repair activities are classified as central interventions.

Given the consideration of interactions among various assets, it is important to account for the interdependencies that exist between bridges within the network. Interdependencies can be classified into physical and geographical. Physical interdependency refers to the existence of a physical connection between two objects, such as two bridges in a series. Geographical interdependency arises when an event, such as an intervention, affects the functionality of multiple bridges due to spatial proximity.

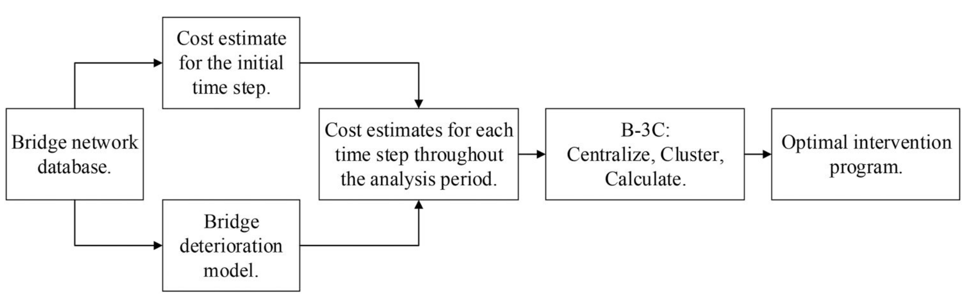


Figure 1. Optimal intervention planning of a bridge network framework.

2.2.1. Bridge total costs

Developing a comprehensive and universally applicable methodology for estimating bridge maintenance and repair costs within the context of bridge service life management is challenging due to the substantial variability in costs arising from diverse circumstances. For the purpose of this research, a global intervention cost function, based on Skokandić and Ivanković (2022) and Kammouh et al. (2021), is utilised and described as follows:

$$C = C_M + C_{U|M} + C_R + C_{U|R} \tag{1}$$

where C represents the total cost of the bridge, C_M stands for bridge maintenance cost, $C_{U|M}$ refers to the bridge user costs due to maintenance interventions, C_R represents the bridge repair cost, and $C_{U|R}$ indicates the bridge user costs resulting from repair interventions.

2.2.2. Bridge maintenance and repair costs

Estimating maintenance work costs often requires adjustments once the work is in progress (Ryall, 2010a). The Organisation for Economic Co-operation and Development proposes that maintenance costs should ideally constitute approximately 3% of the asset value (International Transport Forum, 2023). In contrast, the investment in bridge maintenance in Mexico is around 1% of the bridge value (Quinto & Enrique, 2007). Historical data from UK local authorities indicates that their maintenance budgets have traditionally ranged between 0.3% and 0.5% of the bridge construction cost (Palmer & Cogswell, 1990). Similarly, a study on the maintenance of the Tamar Bridge located in southwest England observed that the mean annual cost of maintenance is around 0.35% of the total bridge value (Harding, Gerard, & Ryall, 1990). Nevertheless, such generalised numbers may lack the necessary specificity for accurately evaluating the maintenance expenses of individual bridge interventions.

Regarding bridge repair costs, the expenses are on average 5% of the initial bridge cost (de Brito, Branco, Thoft-Christensen, & Sørensen, 1997). However, for a more practical application, Skokandić and Ivanković (2022) has developed a more pragmatic approach, building upon the methods introduced by Community Research and Development Information Service (2012) and Mandić Ivanković, Kušter Marić, Skokandić, Njirić, and Šiljeg (2019). This approach offers a straightforward way to estimate repair costs, C_R, by taking into account the bridge reliability levels obtained. It introduces two crucial factors: f_R (see Equation (4)), which represents repair costs as a percentage of the total bridge value, C_{BV}. The total bridge value is a function of f_B, which indicates the bridge importance in the transport network and impacts the construction cost, C_0. Consequently, the following relationships have been established:

$$C_R = f_R C_{BV} \tag{2}$$

$$C_{BV} = f_B C_0 \tag{3}$$

$$f_R = 0.3613\beta^2 - 2.8572\beta + 5.622; \quad \max(f_R) = 2.0 \tag{4}$$

Notice that the maximum value for f_R is 2 (200%), applicable to bridges in critical condition. The reliability indices for various damage levels are presented in Skokandić and Ivanković (2022), Community Research and Development Information Service (2012), and Mandić Ivanković et al. (2019), as shown in Table 1. The bridge importance factor according to Skokandić and Ivanković (2022) can be estimated using:

$$f_B = 1 + \frac{1}{5}[0.25(S_{RC} + S_{AADT} + S_{DD}) + 0.125(S_{LS} + S_{TL})] \tag{5}$$

where S_{RC} denotes the road category grade, S_{AADT} represents the average annual daily traffic grade, S_{DD} indicates the detour distance, S_{LS} stands for the largest span grade, and S_{TL} represents the total length of the bridge grade. Each of these parameters is assigned a grade from 1 to 5 (Mandić Ivanković, Skokandić, Kušter Marić, & Srbic, 2021). As noted, the direct cost of each bridge intervention depends on two factors: the geometric characteristics of the bridge, represented by $C_{BV,}$ and the condition of the bridge at the time of intervention, denoted by f_R. It is important to note that in the context of the work done by Skokandić and Ivanković (2022), this approach assumes full-bridge repair. However, we adopt this method for its practicality in estimating repair costs.

Grades for assessment of the bridge importance factor f_B at the network level are according to five criteria (Mandić Ivanković et al., 2021), adjusted to the size of the MHC network under study.

2.2.3. Bridge user costs

In the context of global cost-benefit analyses of bridge interventions, an increase in bridge user travel time due to congestion resulting from the partial or complete closure of the bridge will result in indirect costs (Bhattacharjee & Baker, 2023). To estimate these costs in terms of daily monetary loss due to prolonged commuting time, the approach of Mandić Ivanković et al. (2019) based on the fundamental concepts of Daniels, Ellis, and Stockton (1999) is used. Hence, the bridge user costs, C_U, are calculated as follows:

$$C_U = AADT \ C_{ve} \ T_U \tag{6}$$

Table 1. Values of reliability index given damage level.

Damage level	Description	Reliability index β
1	Minor damage. No influence on the stability, durability, or traffic safety.	3.8
2	Slight damage. Safety in tolerable range, no impact on traffic.	3.3
3	Medium damage. Safety in tolerable range, medium impact on traffic, traffic obstruction.	3.0
4	High damage. Safety under minimum requirements, durability and traffic are severely affected.	2.3
5	Demolition imminent. Component failure.	$\beta < 2.3$

where $AADT$ is the average annual daily traffic on the bridge, C_{ve} represents the user costs per vehicle based on the estimated prolonged travel time, and T_U is the unavailability period caused by the bridge intervention. As mentioned in Section 2.2.1, two user costs are considered: the bridge user costs due to maintenance intervention $C_{U|M}$, and the bridge user costs due to repair activities $C_{U|R}$.

The estimation of C_{ve} requires numerous parameters, such as intervention urgency, bridge size, and type, to be taken into consideration. Due to the variability involved, the approach presented in Skokandić and Ivanković (2022) to calculate C_{ve} for the unavailability period of one month is employed, as described by the following equation:

$$C_{ve} = (W\ P_{ve}\ w_a + \alpha\ W\ P_{ve}\ w_b)t_p \tag{7}$$

where W is the average daily wage earned by a passenger, P_{ve} represents the average number of passengers per vehicle, w_a and w_b represent the number of weekdays and weekend days considered correspondingly, α is a factor that accounts for the fraction of costs associated with weekend days, and t_p is the estimated prolonged travel time.

2.2.4. Definition of the relationship matrices

Let us assume a bridge portfolio that represents a bridge network $B = \{1, \dots, N\}$. To model the interdependencies among the bridges in the network, an interaction matrix $\mathbf{I}$ is employed. This square matrix, defined in Equation (8), utilises interaction coefficients $I_{i,j}$ to determine whether one bridge affects another. Intervention on one bridge may partially affect other bridges in the network, thus the interdependency between bridges in the network is not necessarily binary (Kammouh et al., 2021). This is mainly due to the existence of alternative routes. In such situations $0 < I_{i,j} < 1$. In this study, to quantify this partial influence, the travel time reliability between bridge i and bridge j according to Equation (9) is employed, where $\min\{tr_{i,j}\}$ is the minimum route travel time of all the routes available between bridge i and bridge j under normal conditions and $\min\{tr_{\text{int},i,j}\}$ is the minimum travel time of all the routes available between bridge i and bridge j under the intervention at bridge i (Arango et al., 2023). It is noted that $tr_{\text{int},i,j}$ is dependent on the estimated prolonged time, t_p, caused by the intervention on bridge i, i.e. $tr_{\text{int},i,j} = tr_{i,j} + t_{p,i}$.

$I_{i,j} = 0$ means that bridge i does not influence bridge j, whereas $I_{i,j} = 1$ signifies the opposite, i.e. bridge i has a full influence on bridge j (for example, due to the absence of alternative routes between the bridges). The interaction matrix can be asymmetric due to non-reciprocal interactions, but its diagonal terms are fixed at $I_{i,i} = 1$ to indicate that a bridge always interacts with itself. Equation (9) implies that as t_p becomes long, the value of $I_{i,j}$ approaches 1. Conversely, for short durations of t_p, $I_{i,j}$ tends to 0:

$$\mathbf{I} = [I_{i,j}] = \begin{bmatrix} I_{1,1} & \cdots & I_{1,N} \\ \vdots & \ddots & \vdots \\ I_{N,1} & \cdots & I_{N,N} \end{bmatrix} \tag{8}$$

$$I_{i,j} = 1 - \frac{\min\{tr_{i,j}\}}{\min\{tr_{\text{int},i,j}\}} = 1 - \frac{\min\{tr_{i,j}\}}{\min\{tr_{i,j} + t_{p,i}\}} \tag{9}$$

To indicate which intervention type k affects each bridge i, a relation matrix $\mathbf{R}$ is established. The components $r_{i,k}$ take binary values, $r_{i,k} = \{0, 1\}$, determining whether bridge i is affected by intervention k, with $k = \{1, 2, \dots, 2N\}$. In the context of bridge interventions, where each bridge can have either maintenance or repair, the range for k is as follows: $k = \{1, \dots, N\}$ corresponds to maintenance interventions, while $k = \{N + 1, \dots, 2N\}$ represents repair interventions. For instance, intervention $k = 1$ is maintenance for bridge 1, and intervention $k = N + 1$ corresponds to the repair of bridge 1. When $r_{i,k} = 0$, it means that bridge i is not affected by intervention k, while $r_{i,k} = 1$ implies the opposite. The relation matrix is:

$$\mathbf{R} = [r_{i,k}] = \begin{bmatrix} r_{1,1} & \cdots & r_{1,N} & r_{1,N+1} & \cdots & r_{1,2N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ r_{N,1} & \cdots & r_{N,N} & r_{N,N+1} & \cdots & r_{N,2N} \end{bmatrix} \tag{10}$$

2.2.5. Objective function

In this study, the optimal intervention plan can be achieved by minimising the total intervention cost over the analysis period. This cost includes both the direct intervention costs and the user costs caused by the unavailability of the bridge, such as partial closure due to the intervention as mentioned in Section 2.2.1. The minimisation process considers both the condition of the bridges and the budget limitations. Within the context of bridge networks, the optimisation problem can be expressed as:

$$\min_{\mathbf{D}}\left[\left(C_M + C_{U|M}\right) + \left(C_R + C_{U|R}\right)\right] \tag{11}$$

where $\mathbf{D} = \{d_{i,t}\}$, with dimensions of $N \times 2T$, is a decision matrix. This matrix indicates when each intervention occurs during the total time of analysis, which is discretised into T time step components representing a $\Delta\tau$ time interval. Thus, the total time of analysis is $T\Delta\tau$. To clarify, two distinct ranges have been defined: $t = \{1, \dots, T\}$ corresponds to maintenance interventions, and $t = \{T + 1, \dots, 2T\}$ represents repair interventions. For example, $t = 1$ indicates maintenance interventions occurring during the first time step, and $t = T + 1$ indicates repair interventions occurring during the first time step of the analysis period.

The total direct cost of bridge maintenance is given by:

$$C_M = \sum_{i=1}^{N}\sum_{t=1}^{T} C_{Mi}\ d_{i,t} \tag{12}$$

where $C_{Mi} \in \mathbb{R}^+$ is the direct cost of performing maintenance on bridge i. $d_{i,t} \in \{0, 1\}$ are the components of the decision matrix indicating at which time step t each maintenance type is conducted.

The total bridge user costs caused by the maintenance given by:

$$C_{U|M} = \sum_{i=1}^{N}\sum_{t=1}^{T} C_{U|Mi}\ \delta\left([I_{i,j}]^{\top}\ r_{i,k}\ d_{i,t}\right), \quad \text{for } k = 1, \dots, N \tag{13}$$

where $C_{U|Mi} \in \mathbb{R}^+$ is the user cost of bridge i caused by performing maintenance. The function $\delta(.)$ represents the Kronecker delta defined as follows:

$$\delta(x) = \begin{cases} 0 & \text{if } x = 0 \\ 1 & \text{if } x \neq 0 \end{cases} \tag{14}$$

The Kronecker delta is applied to every element of the resulting matrix, which has dimensions of $N \times T$. This use of the Kronecker delta enables the assessment of clustering interventions by incorporating the user costs for an affected bridge only once, even if multiple interventions impacting its performance are happening simultaneously.

The total direct cost of bridge reparation is given by:

$$C_R = \sum_{i=1}^{N} \sum_{t=T+1}^{2T} C_{Ri}\ d_{i,t} \tag{15}$$

where $C_{Ri} \in \mathbb{R}^+$ represents the direct cost of performing repair on bridge i.

The total bridge user costs caused by the repair are given by:

$$C_{U|R} = \sum_{i=1}^{N} \sum_{t=T+1}^{2T} C_{R|Ui}\ \delta\left(\left[I_{i,j}\right]^\top\ r_{i,k}\ d_{i,t}\right), \quad \text{for } k = N+1, \ldots, 2N \tag{16}$$

where $C_{U|Ri} \in \mathbb{R}^+$ is the user cost of bridge i caused by performing repair. It is noted that each maintenance or repair intervention is assumed to be entirely performed within a time interval.

2.2.6. Constraints

The first constraint set imposes a minimum time interval between any two successive maintenance interventions of type k per bridge i, denoted by $G_{\min,k,i}$. As repair interventions are assumed to be central, these interventions do not have any minimum time requirements, just the fixed repair time. This first constraint is defined by:

$$0 \leq \sum_{s=t}^{t+G_{\min,k,i}-1} d_{i,s} \leq 1 \quad t = 1 \rightarrow T - G_{\min,k,i} + 1,\ k = 1 \ldots N,\ i = 1 \ldots N \tag{17}$$

The constraints defined restrict any two successive interventions of type k per bridge i to have a time interval not larger than $G_{\max,k,i}$, as shown by Equation (18) for maintenance interventions and by Equation (19) for repair interventions. Equation (19) indicates that the repair intervention should not be carried out after $G_{\max,k,i}$. It is assumed that $G_{\max,k,i}$ for $k = \{N+1, \ldots, 2N\}$ is equal to $G_{\max,k,i}$ for $k = \{1, \ldots, N\}$:

$$\sum_{s=t}^{t+G_{\max,k,i}-1} d_{i,s} \geq 1 \quad t = 1 \rightarrow T - G_{\max,k,i} + 1,\ k = 1 \ldots N,\ i = 1 \ldots N \tag{18}$$

$$\sum_{s=t}^{t+G_{\max,k,i}-1} d_{i,s} \geq 1 \quad t = T+1 \rightarrow 2T - G_{\max,k,i} + 1,\ k = N+1 \ldots 2N,\ i = 1 \ldots N \tag{19}$$

In the context of the analysis, it is important to consider the scenario where repair interventions are required, and maintenance interventions are not needed for the remainder of the time under examination. Let B_m represent a subset of the bridges under study B, containing m elements, which represent the bridges requiring repair, i.e. $B_m = \{b_j\} \subset B$. Consequently, the bridges in B_m do not require any maintenance interventions. This constraint set can be defined as follows:

$$\sum_{t=1}^{T} d_{j,t} = 0 \quad \text{for } j = 1, \ldots, m \tag{20}$$

$$\sum_{t=T+1}^{2T} d_{j,t} = 1 \quad \text{for } j = 1, \ldots, m \tag{21}$$

The maintenance and repair costs for each bridge vary significantly from one time step to another, and there is a limited budget, denoted as E_t, for the bridge owner (Lad, Patel, Chauhan, & Patel, 2022). This budget limitation constraint only impacts the direct costs related to maintenance and repair interventions. The budget limitation constraint is defined as:

$$\sum_{i=1}^{N} \left(C_{Mi}\ d_{i,t} + C_{Ri}\ d_{i,t+T}\right) \leq E_t \quad \text{for } t = 1, \ldots, T \tag{22}$$

It is noted that the mathematical problem defined in Sections 2.2.5 and 2.2.6 is a mixed-integer linear optimisation problem where the variables ($d_{i,t}$) are binary.

3. Illustrative application

3.1. Case study description: Mexican bridge system

The backbone of the Mexican national road network comprises fifteen major highway corridors (MHC), which extend over approximately 20,000 km. These corridors represent over 55% of the highway traffic volume in the country (Secretaría de Comunicaciones y Transportes, 2017). To effectively manage, preserve, and maintain the numerous bridges within this network, Mexico employs the Mexican Bridge System, known as SIPUMEX (for its acronym in Spanish) (Dirección General de Conservación de Carreteras, 2021). Managed by the Mexican agency Ministry of Communications and Transport (SCT, for its acronym in Spanish), SIPUMEX plays a pivotal role by documenting the structural condition of individual assets and allowing the scheduling of necessary maintenance activities. As of 2009, SIPUMEX data indicates that there are a total of 576 bridges strategically positioned within the MHC network.

SIPUMEX employs a rating index (B_R) system to determine the condition of bridges and to carry out the necessary actions for their maintenance or repair. This scale ranges from 0 for bridges that are in excellent condition to 5 for bridges with significant damage that requires immediate attention. The bridge scale, description, and corresponding time intervals between two consecutive interventions, G_{min} and G_{max}, are presented in Table 2. It is noted that the time intervals in the description are only established for rating indices $B_R = \{3, 4, 5\}$. However, to offer a comprehensive illustration in this study, uniform increases of two years for the remaining rating indices are assumed. For $B_R = 2$, the time interval ranges from $G_{min} = 5$ to $G_{max} = 7$ years, and for $B_R = 1$, the time interval ranges from $G_{min} = 7$ to $G_{max} = 9$ years (as presented in italics in Table 2).

3.2. Intervention cost estimation

To quantify the financial aspects of the intervention planning, construction costs are estimated. The estimation of intervention costs related to bridge maintenance and repair is conducted following the methodology presented in Sections 2.2.2 and 2.2.3. To illustrate this process, a specific example is provided. The MHC number 3, known as *Querétaro-Ciudad Juárez*, includes a total of twelve bridges, as shown in Figure 2. The general information related to these bridges is summarised in Figure 2. This information is derived from the SIPUMEX database and provides a concise overview of the key characteristics of these bridges. The construction costs, C_0, are estimated using the parametric cost approach specified by the SCT for the year 2023 (Secretaría de Comunicaciones y Transportes, 2022) as shown in Supplementary Appendix A.1.

The specific cost breakdown for each bridge type is presented in Supplementary Tables A.1 to A.3. These costs are direct costs associated with the construction of the bridges, which depend on geometric characteristics such as the number of lanes, maximum span length, and maximum bridge height. An analysis period of 18 years is selected to encapsulate the maximal temporal extent of the interventions at least twice, in accordance with Table 3. The time interval $\Delta\tau$ is set to one year, thus $T = 18$. Nevertheless, the methodology allows for a wider (or narrower) range of years to be used for different analyses.

To calculate the total intervention cost C_{BV}, Equations (3) and (5) are employed, utilising the relevant data sourced from the SCT. The bridge repair costs C_R are determined using Equations (4) and (2). The grades for the computation of f_B adjusted to the size of the MHC network under study are shown in Supplementary Table A.4. A direct association with the values of B_R shown in Table 2 and the damage levels shown in Table 1 is made according to the corresponding descriptions. Hence, the values of the reliability index β are directly inferred from the rating values. For example, a bridge with $B_R = 4$ corresponds to $\beta = 2.3$. It is noted that while the inferred β values serve the purpose of exemplification, they may not precisely correspond with reality. For the sake of simplicity, it is assumed that the maintenance costs, C_M, are equivalent to 15% of the repair costs, i.e. $C_M = 0.15C_R$. This is roughly equivalent to 3% of the bridge construction costs suggested by International Transport Forum (2023), particularly for bridges with a

Table 2. SIPUMEX rating scale.

B_R	Description	G_{min}	G_{max}
0	Recently built or repaired structures, no problems.	–	–
1	Bridges in good condition. No attention is required.	*7*	*9*
2	Structures with minor problems, indefinite time frame for attention.	*5*	*7*
3	Significant or medium damage, repair required within three to five years.	3	5
4	High to severe damage, repair required within one to two years.	1	2
5	Extreme damage or risk of total failure. Repair required immediately or within one year	0	1

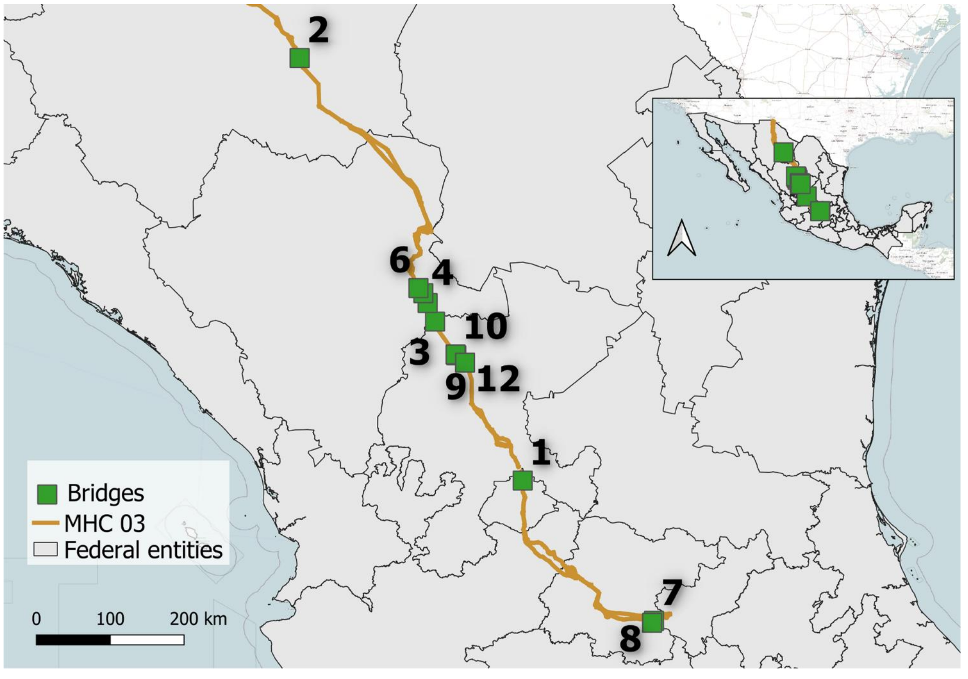


Figure 2. Bridges with a $B_R > 0$ located at MHC 3. Labels located next to each bridge represent its corresponding ID number.

Table 3. General information about bridges with a $B_R > 0$ located at the MHC 3 Bridge construction cost, C_0, in millions of Mexican pesos (MMP, 1 MP ≈ 0.05 EUR.).

Bridge (i)	Name	Lanes	Spans	Max span [m]	Total length [m]	AADT	B_R	C_0 [MMP]	β	G_{min} [years]	G_{max} [years]
1	San Pedro	4	1	9.8	9.8	6997	1	19.03	3.82	7	9
2	Maravillas	2	2	6	11.9	8009	2	3.28	3.30	5	7
3	San Antonio	2	1	18.7	18.7	5114	2	11.28	3.30	5	7
4	La Sed	2	1	10.5	10.5	4919	2	10.35	3.30	5	7
5	Sombreretillos	2	1	11.6	11.6	4378	2	10.35	3.30	5	7
6	Cerro Gordo	2	1	15.7	15.7	4748	1	11.28	3.82	7	9
7	El Sabino	2	2	7.3	14.6	9703	3	3.67	3.00	3	5
8	Apaseo el Alto II	2	2	6.4	12.7	12,619	2	3.40	3.30	5	7
9	Las Nieves	2	2	6.3	11.7	5033	1	3.25	3.82	7	9
10	Los Gemelos I	2	1	6.1	6.1	5033	2	7.25	3.30	5	7
11	Los Gemelos II	2	1	6.1	6.1	5033	1	7.25	3.82	7	9
12	Nuevo Rio Grande	2	3	20.7	61.7	2850	2	11.54	3.30	5	7

rating index of 2, a characteristic shared by the majority of bridges under study. It is noted that this assumption is made to illustrate and facilitate the use of the methodology presented herein. However, it is acknowledged that the assumption needs to be validated for all bridges, especially those with rating indices different from 2.

The user costs arising from the unavailability of bridges due to intervention actions are obtained using Equation (6). When bridge maintenance is executed, assuming that intervention works are conducted separately for each lane, a prolonged travel time (t_p) of approximately 1.5 min is considered. Furthermore, the unavailability period, T_U, due to maintenance is approximated at two months. The repair work duration spans 11 months, with a corresponding t_p of approximately 5 min, taking into account available alternate routes and considering that repair works are performed independently for each lane. This means that under neither of the two interventions under study will the bridge ever be fully closed. It is noted that, in practice, t_p could exceed the assumed values. This could depend on numerous factors such as the location and area of the bridges. However, for simplification purposes, the assumed unavailability periods and prolonged travel times are derived following the recommendations of Community Research and Development Information Service (2012) and Skokandić and Ivanković (2022).

For calculations involving the user costs, C_U and C_{ve} (see Equation (7)), an average hourly wage (W) of 36.62 MP (Mexican pesos) and an average of 1.8 passengers per vehicle (P_{ve}) are considered, both obtained from data gathered by the National Institute of Statistics and Geography (INEGI, for its acronym in Spanish) (Instituto Nacional de Estadística y Geografía, 2023b) and the Mexican Institute of Transport (IMT, for its acronym in Spanish) (Instituto Mexicano del Transporte, 2020). Additionally, 20 weekdays (w_a) and 10 weekend days (w_b) are considered. To derive an estimate for weekend days, it is considered a cost equivalent to 50% ($\alpha = 0.5$) of the workday cost. The obtained intervention costs for the bridges located at MHC 3 are shown in Table 4. In Supplementary Appendix A.2, a numerical example of the estimation of the intervention cost for one bridge is presented.

Table 4. Intervention costs in millions of Mexican pesos (MMP, 1 MP ≈ 0.05 EUR).

Bridge (i)	C_{BV} [MMP]	C_M [MMP]	$C_{U\|M}$ [MMP]	C_R [MMP]	$C_{U\|R}$ [MMP]
1	31.40	0.05	0.29	0.31	5.77
2	5.25	0.10	0.33	0.67	9.90
3	18.61	0.36	0.21	2.38	6.32
4	17.08	0.33	0.20	2.19	4.05
5	17.08	0.33	0.18	2.19	5.41
6	18.61	0.03	0.20	0.19	5.87
7	6.05	0.27	0.40	1.83	11.99
8	5.60	0.11	0.52	0.72	15.60
9	5.36	0.01	0.21	0.05	6.22
10	11.96	0.23	0.21	1.53	4.15
11	11.96	0.02	0.21	0.12	4.15
12	19.32	0.37	0.35	2.47	4.31

3.3. Bridge deterioration modelling

Bridge deterioration modelling plays a crucial role in formulating effective bridge maintenance programmes. An accurate estimation of the rate of deterioration for a bridge enables bridge owners to plan their budgets efficiently for necessary interventions. In this context, the use of a deterioration model based on the Simplified Kaplan–Meier probabilistic deterioration model, specifically designed for prestressed concrete superstructures in the United States (Cavalline, Whelan, Tempest, Goyal, & Ramsey, 2015), is illustrated. This simplified deterioration model adopts the characteristics of a stationary Markov-chain model.

In the United States, bridge ratings range from 0 to 9, with 9 representing excellent condition. On the other hand, Mexican bridges follow a scale from 5 to 0, where 0 represents excellent condition or recently built or repaired structures. To align these differing rating systems, a straightforward correspondence is established based on the interpretation of each rating. For instance, a United States bridge rated at 7, categorised as being in Good Condition, corresponds to a Mexican bridge with a rating of 1. It is noted that this example might not represent the actual relationship between the bridge rating systems of the United States and Mexico. Bridge rating systems are considerably intricate and encompass various other influential factors. For comprehensive and bridge-specific models, sophisticated methodologies such as Time In Condition Rating or Markov Transition

Probability should be employed (Cavalline et al., 2015). The transition probability matrix used for making predictions about condition ratings based on the Simplified Kaplan–Meier probabilistic deterioration model is given by:

$$P = \begin{bmatrix} 0.96 & 0.04 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.94 & 0.06 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.97 & 0.03 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.91 & 0.09 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.96 & 0.04 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.99 & 0.01 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (23)$$

For illustrative purposes, the costs associated with the bridge *El Sabino* (bridge $i = 7$, according to Table 3) for deterioration over the first 11 years are shown in Table 5. It is noted that the parameters $G_{\min,k}$ and $G_{\max,k}$ maintain a consistent value over the entire duration of the analysis, regardless of the extent of degradation encountered by the bridge at each time step. This consistency arises from the underlying applied degradation model. Specifically, the bridge rating remains unchanged during intervals between two successive maintenance interventions that occur within intervals of less than 15 years, particularly in cases where the initial rating of the bridge is below 4. As can be seen in Table 5, the rating of the bridge *El Sabino* (initial rating of 3) changes to 3.25 after 11 years. However, due to rounding, the rating value remains classified as 3. In the case of bridges with an initial rating of 4, progression to level 5 occurs within a mere three-year time frame. As a result, repairing these bridges within the initial two years presumably would be a more cost-effective strategy than their continuous maintenance.

Notice that the costs shown in Table 5 must be adjusted according to a simple investment principle. A capital, denoted as CAP, when invested over $T\Delta\tau$ years at an interest rate of ir, leads to an outcome denoted as $C = \text{CAP}(1 + ir)^{T\Delta\tau}$ (Ryall, 2010b). Employing an interest rate of 4.5%, which corresponds to the average inflation rate of Mexico during the interval 2012–2022 (Instituto Nacional de Estadística y Geografía, 2023b), the total cost of bridge maintenance interventions $C_M + C_{U|M}$ per bridge and the total cost of bridge repair interventions $C_R + C_{U|R}$ for the first five years are shown in Table 6.

Once the direct costs given the deterioration model and the user costs are estimated for all the bridges under study, the following section presents the application of the B-3C concept optimisation model.

3.4. Relationship matrices

In the MCH 3, there are three clusters of bridges closely located to each other. A bridge is assumed to belong to a cluster when the distance to other bridges is less than or equal to 10 km, as illustrated in Figure 2. These clusters are: (1) bridges $i = \{5, 6\}$, (2) bridges $i = \{7, 8\}$, and (3) bridges $i = \{7, 8, 9\}$. Any intervention on one bridge within a cluster will impact the performance of other bridges in the same cluster. Performing interventions on bridges $i = \{1, 2, 3, 4, 12\}$ will not affect any of the other bridges.

For example, Table 7 presents the information necessary to compute the interaction matrix for cluster 3 (see Figure 3) assuming a $t_p = 5$ min for all bridges. The first two columns display the bridge indices, indicating the direction of travel flow from bridge i to j. The third column represents the route travel time between bridge i and bridge j, assuming free flow and a constant travel speed of 60 km/hr. The fourth

Table 5. Bridge *El Sabino* intervention costs associated with bridge deterioration rating using the simplified Kaplan–Meier probabilistic deterioration model.

Year	0	1	2	3	4	5	6	7	8	9	10
B_R	3.00	3.01	3.03	3.05	3.07	3.10	3.12	3.15	3.18	3.22	3.25
β	3.00	2.99	2.98	2.97	2.95	2.93	2.91	2.89	2.87	2.85	2.83
f_R	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.38	0.40	0.41	0.43
C_R[MMP]	1.83	1.87	1.92	1.98	2.05	2.12	2.21	2.30	2.40	2.51	2.62
C_M[MMP]	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.35	0.36	0.38	0.39

Table 6. Annual total costs of bridge maintenance, $C_M + C_{U|M}$, and repair, $C_R + C_{U|R}$, interventions.

	$C_M + C_{U\|M}$ [MMP]					$C_R + C_{U\|R}$				
	Year									
Bridge (i)	0	1	2	3	4	0	1	2	3	4
1	0.34	0.35	0.38	0.40	0.42	6.08	6.38	6.70	7.03	7.39
2	0.43	0.45	0.48	0.51	0.53	10.57	11.08	11.60	12.15	12.73
3	0.57	0.61	0.65	0.70	0.74	8.70	9.19	9.71	10.25	10.82
4	0.53	0.57	0.61	0.65	0.69	6.24	6.61	7.00	7.41	7.84
5	0.51	0.55	0.58	0.62	0.67	7.60	8.03	8.48	8.96	9.46
6	0.22	0.24	0.25	0.26	0.28	6.06	6.34	6.65	6.97	7.30
7	0.67	0.71	0.75	0.80	0.84	13.82	14.48	15.19	15.94	16.75
8	0.63	0.66	0.69	0.73	0.77	16.31	17.08	17.88	18.71	19.59
9	0.22	0.23	0.24	0.25	0.26	6.28	6.56	6.86	7.18	7.51
10	0.44	0.47	0.50	0.53	0.56	5.68	6.00	6.33	6.68	7.05
11	0.23	0.24	0.25	0.26	0.28	4.27	4.47	4.68	4.91	5.14
12	0.72	0.77	0.82	0.87	0.93	6.78	7.19	7.61	8.06	8.54

Note: Costs in [MMP].

Table 7. Travel times (in minutes), and partial effects caused by intervention in bridges $i = \{9, 10, 11\}$.

B_i	B_j	$tr_{i,j}$	$t_{p,i}$	$tr_{\text{int},9,j}$	$tr_{\text{int},10,j}$	$tr_{\text{int},11,j}$	$I_{9,j}$	$I_{10,j}$	$I_{11,j}$	Max $I_{i,j}$
9	10	1.44	5.00	6.44	1.44	1.44	0.78	0.00	0.00	0.78
9	11	1.45	5.00	6.45	6.45	1.45	0.78	0.78	0.00	0.78
10	11	0.04	5.00	0.04	5.04	0.04	0.00	0.99	0.00	0.99
10	9	1.44	5.00	1.44	6.44	1.44	0.00	0.78	0.00	0.78
11	9	1.45	5.00	1.45	6.45	6.45	0.00	0.78	0.78	0.78
11	10	0.04	5.00	0.04	0.04	5.04	0.00	0.00	0.99	0.99

column denotes the prolonged travel time caused by the intervention. Columns five to seven display the route travel time between bridge i and bridge j caused by intervention on bridge i. Columns eight to ten correspond to the computed elements of the interaction matrix, I, resulting from intervention on bridge i using Equation (9). Finally, column eleven shows the selected element for the interaction matrix, which corresponds to the maximum value obtained from interventions on individual bridges, i.e. the maximum value of columns eight to ten.

It is noted that $I_{10,j}$ shows higher values when compared to $I_{9,j}$ and $I_{11,j}$. This suggests that intervention in bridge $i=10$ has a more significant influence on other bridges, implying a potentially more disruptive scenario compared to interventions on bridges $i=9$ and $i=11$. However, to capture the biggest influence, the maximum values of the computed interactions are selected. The result can be read as follows: executing an intervention in bridge $i=9$ will affect 78% partially bridge $i=10$ and $i=11$. Performing and intervention in bridge $i=10$ will affect 99% partially bridge $i=11$.[2]

Using the same procedure for the other clusters, results show that an intervention in bridge $i=5$ will affect 34% partially bridge $i=6$ and an intervention in bridge $i=7$ will affect 56% partially bridge $i=8$. Therefore, the interactions between the bridges in MHC 3 can be mathematically represented using:

$$I = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0.34 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.34 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.56 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.56 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.78 & 0.78 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.78 & 1 & 0.99 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.78 & 0.99 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

Each intervention is associated with a specific bridge. As a result, a total of $K=24$ intervention types are established, since there are 12 bridges and 2 possible interventions (i.e. maintenance or repair) for each bridge. This breaks down into 12 maintenance intervention types $k = \{1, \ldots, 12\}$ and 12 repair intervention types $k = \{13, \ldots, 24\}$ according to the notation presented in Section 2.2.4. In Equation (25), the relation matrix between these intervention types and the bridges is shown:

$$R = [I_{12} | I_{12}] \quad (25)$$

where I_{12} represents the identity matrix of size 12×12.

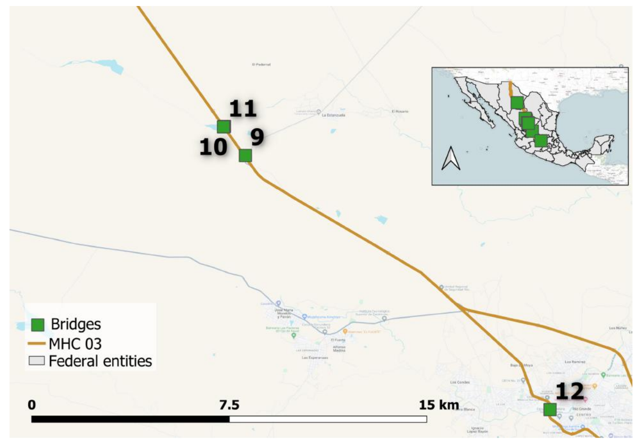


Figure 3. Bridges $i = \{9, 10, 11, 12\}$, according to the notation presented in Table 3 and shown in Figure 2.

3.5. MHC 3 results

The optimal intervention programme is obtained through the optimisation problem Equation (11) to Equation (22). In the given example, the most critical state is defined as those exhibiting substantial damage, necessitating interventions within a timeframe of three to five years for bridge $i=7$ (see Table 3). Consequently, no immediate bridge repairs are necessary. However, to delve into the application of the B-3C method, two scenarios are presented: (1) a case where no repair is needed and (2) a case where bridges $i = \{7, 8, 9\}$ must be repaired. For Scenario (1), an annual budget constraint of 0.61 MMP ($E_t = 0.61$ for $t = \{1, \ldots, T\}$) is assumed, roughly equivalent to 0.6% of the MHC 3 bridge network total value. Additionally, an interest rate of 4.5% is applied. On the other hand, for Scenario (2), where repairs are indeed necessary, and prompt action is preferred within the initial two years due to cost escalation, an extra annual budget of 1.2 MMP, i.e. $E_t = 1.2$ for $t = \{1, 2\}$ and $E_t = 0.61$ for $t = \{3, \ldots, T\}$ is allocated. The budget allocated, 1.2 MMP, represents around 1.2% of the value of the MHC 3 bridges, specifically designated for facilitating the necessary repairs.

Given the escalating costs resulting from bridge degradation, an initial inference might be that initiating interventions during the initial years of analysis would lead to cost benefits. However, adopting this approach would require a more frequent intervention schedule over the study period. The advantage of the methodology presented herein is the ability to determine the optimal sequence that minimises the total number of interventions while ensuring early implementation to reduce overall expenses.

The number of decision variables in the demonstrative example is $T \times K = 18 \times 24 = 432$ ($K=16$ is the number of intervention types). The optimisation problem was solved using the Python `scipy` (Virtanen et al., 2020) Mixed-Integer Linear Programming algorithm `scipy.optimize.milp`. Tables 8 and 9 show the optimal intervention programme of the intervention types for a period of 18 time steps for Scenario (1) described in Section 3.4.

In the figure depicted in Table 8, every row on the graph represents the intervention programme of one intervention type, where blue squares represent maintenance interventions and red triangles represent repair interventions (see Scenario (2) Supplementary Table A.5). As can be seen, the optimisation algorithm assigns the year of intervention according to the decision matrix **D** to minimise the total cost at the end of the study period, given the minimum and maximum time between interventions and the annual budget constraints. The table in Table 8 shows, in net present value, both the annual budget constraint and the direct cost. Additionally, the ratio between direct cost and the annual budget is presented, which shows that the total direct cost is always below the available annual budget.

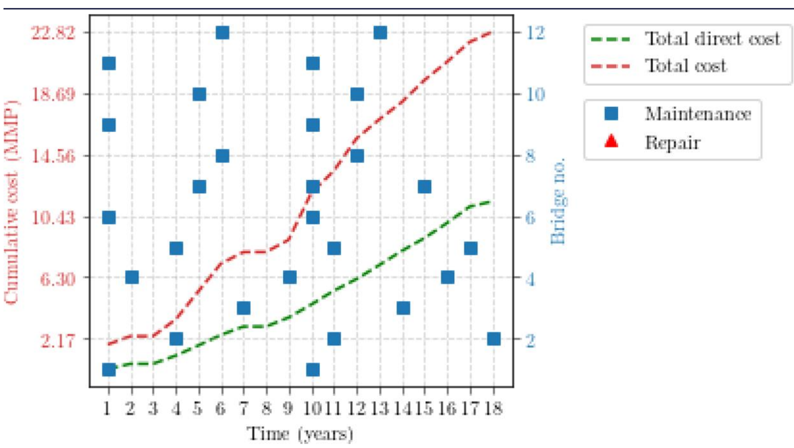
Table 9 shows an overview of the optimal intervention programme. The first column identifies the bridges in the provided example. The second column indicates the recommended year for conducting repair interventions. Columns 3, 4, and 5 display the years assigned for three maintenance interventions. The remaining columns, 6 to 10, present the corresponding total costs for the interventions. Similarly, the results of Scenario (2) are depicted in Supplementary Table A.6. The total cost for Scenario (1) corresponds to $C_{S_1} = 22.82$ MMP, while for Scenario (2), the total cost is $C_{S_2} = 76.65$ MMP. C_{S_1} amounts to approximately 30% of the total cost C_{S_2}. However, when considering only the total direct cost for both scenarios, $C_{D_{S_1}}$ and $C_{D_{S_2}}$ respectively, the direct cost in Scenario (1), $C_{D_{S_1}} = 11.42$ MMP, represents roughly 2% more than the total direct cost in Scenario (2) ($C_{D_{S_2}} = 11.15$ MMP).

The previous comparison suggests that when looking solely at the direct cost, Scenario (1) could be a more effective strategy due to its higher investment compared to Scenario (2). However, the lower direct cost of Scenario (2) is attributed to the state of bridges $i = 8$ and $i = 9$ with $B_R = 2$ and $B_R = 1$, respectively, leading to cheaper intervention costs. In real-life bridge scenarios, these bridges would not need repair, as shown in Table 1.

In a practical scenario where bridges requiring repair have $B_R \geq 3$, Scenario (2) may be a better strategy. By allocating an additional budget for repair, some bridges will be

Table 8. Optimal intervention programme Scenario (1).

Intervention programme



Year	Et [MMP]	CD [MPP]	$\frac{C_D}{E_t}$
1	0.61	0.10	16%
2	0.61	0.33	54%
4	0.61	0.46	75%
5	0.61	0.55	89%
6	0.61	0.55	89%
7	0.61	0.42	68%
9	0.61	0.41	67%
10	0.61	0.56	92%
11	0.61	0.57	94%
12	0.61	0.47	76%
13	0.61	0.52	86%
14	0.61	0.52	85%
15	0.61	0.44	73%
16	0.61	0.50	82%
17	0.61	0.52	85%
18	0.61	0.16	27%

(Annual cost (NPV))

Notes: Annual cost expressed in net present value (NPV). E_t: annual budget constrain; C_D: total direct cost ($C_M + C_R$).

Table 9. Overview of Scenario (1) results.

Bridge (i)	Repair int$_1$	Maintenance int$_1$	int$_2$	int$_3$	C_R	C_M	$C_{M\|U}$	$C_{R\|U}$	C
1	–	1	10	–	0.0	0.19	0.58	0.0	0.77
2	–	4	11	18	0.0	0.71	0.99	0.0	1.70
3	–	7	14	–	0.0	1.54	0.42	0.0	1.96
4	–	2	9	16	0.0	1.99	0.61	0.0	2.60
5	–	4	11	17	0.0	2.22	0.73	0.0	2.95
6	–	1	10	–	0.0	0.11	0.53	0.0	0.64
7	–	5	10	15	0.0	1.78	1.88	0.0	3.66
8	–	6	12	–	0.0	0.41	1.62	0.0	2.04
9	–	1	10	–	0.0	0.03	1.06	0.0	1.09
10	–	5	12	–	0.0	0.85	1.15	0.0	2.00
11	–	1	10	–	0.0	0.07	1.15	0.0	1.22
12	–	6	13	–	0.0	1.48	0.70	0.0	2.19
Total					0.00	11.38	11.42	0.00	22.82

Note: Total cumulative cost, $C = 22.82$ MMP, total direct cost, $C_D = C_M + C_R = 11.38$ MMP. int$_n$: intervention number in year $t\Delta\tau$.

completely repaired, resulting in a healthier infrastructure network. It is crucial to highlight the importance of considering the interconnected effects of interventions on individual bridges within the network system. If these effects are not taken into account, i.e. $I = [I_{12}]$, the total cost could be significantly underestimated. For example, without considering the spatial proximity of the bridges for Scenario (1), the total cost corresponds to $C_{S_1|I=[I_{12}]} = 19.12$ MMP. However, this estimation would be erroneous, representing a deviation of 3.6 MMP from the actual value. This discrepancy translates to approximately 3.6% of the total value of the bridge network.

3.6. Agency intervention programme comparison

To evaluate the cost-effectiveness of the solutions, a comparison is made between the optimal intervention scheduling and the existing SIPUMEX intervention programme adopted by the SCT, which operates in two stages. (I) Preliminary prioritisation: this phase relies on the automated ranking system based on key factors such as bridge rating, average annual daily truck traffic (*AADTT*), and average annual daily traffic (*AADT*). (II) Final prioritisation: a manual ranking process prioritises bridges initially identified as high-ranking (urgent interventions) in the preliminary phase, while the rest are assessed by performing an individual review of the bridges and looking for the most damaged according to the condition of the individual components and photographic reports until the estimated budget has been reached (Road Directorate, 1994; Sánchez Jacobo, 2017). Usually, it is assumed that the minimum number of interventions implies the minimum cost (Adey, Burkhalter, & Martani, 2020). This implies that the time within two consecutive interventions is $G_{min} = G_{max}$.

In Table 10, the comparison of intervention programmes for Scenario (1) is shown. The table presents data regarding the bridges, including their ranking based on the SIPUMEX preliminary prioritisation, the corresponding maintenance years, the total cost of these interventions (C^*), the total cost using the B-3C approach (C), and the percentage of savings obtained. The B-3C programme achieves savings for most bridges. However, when considering the total cost, the results reveal that the optimal plan leads to a 14% reduction in costs compared to the SIPUMEX approach. Notice that, using the SIPUMEX approach for this particular example, there are $3^{12} = 531\ 441$ (3 time-steps between $G_{\min,k}$, $G_{\max,k}$ and 12 bridges) possible combinations of time between intervals.

The minimum total cost is obtained with $G_{\max} = \{5, 7, 7, 7, 7, 7, 7, 7, 9, 9, 9, 9\}$ resulting in a total $C^* = 26.54$ MMP. Additionally, taking into account the budget constraint of Scenario (1), it is notable that the allocated budget will be fully utilised by year 11, i.e. SIPUMEX costs are over the budget. Consequently, there will be no remaining budget for years 15 and 16, resulting in seven bridges lacking maintenance intervention. The primary drawback of the SIPUMEX approach becomes evident in the large number of combinations that need evaluation to obtain the minimum total cost. For example, if applied to the entire network under study, it would necessitate assessing 3^{555} possible combinations, which is impractical.

3.7. Additional travel time sensibility analysis

The additional travel time, t_p, depends on the type of intervention and the size of the bridge, which varies for each bridge in the network. Unfortunately, detailed data on the prolonged time required for each bridge is not available. As such, the precise quantification of time per bridge falls beyond the scope of this investigation.

It is expected that if there is greater travel time, the total intervention cost will increase. Conversely, reducing the travel time will decrease the total cost. This is directly reflected in the interaction matrix, I (see Equation (9)). However, this also affects the scheduling using the current bridge agency approach. For comparison purposes, Scenario (1) is selected to model three cases of delay caused by maintenance: a 2-min delay, a 30-min delay, and a linear function that depends on the bridge area (B_A), i.e. $t_p = 0.01B_A + 1.45$. The linear relationship is established such that the minimum prolonged time (the prolonged time for the smallest bridge) is 2 min, and the maximum prolonged time is 62 min.

It is noted that these cases are for exemplification purposes only and do not represent the reality of individual bridges or any bridge network. The results are presented in

Table 10. Comparison of the total cost between the bridge agency (C^*) and the B-3C (C) intervention programmes for $T = 18$ years.

Bridge(i)	B_R	AADTT	AADT	G_{max} [Years]	int_1^*	Maintenance int^*_2	int_3^*	C^* [MMP]	C [MMP]	Saving [%]
7	3	2367	9703	5	6	11	16	3.83	3.66	4
10	2	3133	5033	7	8	15	–	1.73	2.00	−16
8	2	2778	12,619	7	8	15	–	2.17	2.04	6
5	2	2211	4378	7	8	15	–	2.1	2.95	−40
3	2	2163	5114	7	8	15	–	3.08	1.96	36
4	2	2128	4919	7	8	15	–	2.97	2.60	12
12	2	1956	2850	7	8	15	–	3.71	2.19	41
2	2	893	8009	7	8	15	–	3.13	1.70	46
9	1	3133	5033	9	10	–	–	1.06	1.09	−3
11	1	3133	5033	9	10	–	–	1.19	1.22	−3
1	1	2348	6997	9	10	–	–	1.19	0.77	35
6	1	2211	4748	9	10	–	–	0.38	0.64	−68
Total								26.54	22.82	14

Note: int_n^* : intervention number in year $t\Delta\tau$ according agency approach.

Table 11. As observed, the table illustrates the sensitivity of total costs to the choice of prolonged travel time. Additionally, the table shows the savings percentage associated with the comparison between the two approaches. These percentages indicate the potential cost savings achieved by opting for the B-3C programme over the agency programme. For instance, at a prolonged time of 2 min, B-3C achieves approximately 11.4% savings in terms of total intervention costs. Overall, the B-3C methodology consistently reduces the total cost compared to the agency approach under identical assumptions.

4. Application to the entire bridge portfolio

After explaining the proposed methodology and presenting results for the bridges at MHC 3, the optimal intervention plans for the entire bridge portfolio are discussed. For this investigation, bridges with a rating greater than 0 are used as a case study, i.e. 555 bridges in total. The geographical distribution of these bridges can be visualised in Figure 4.

According to the information in Table 2, bridges with a rating of 5 are marked for repair. It is noted that, as reported in the SIPUMEX database, no bridges fall into this category. Consequently, there is no immediate need for bridge repairs based on the available data. Nonetheless, for cost comparison, similar to the case illustrated in Section 3.4, two scenarios are presented. The first one, Scenario (3), assumes that no repairs are necessary. The second, Scenario (4), assumes a case where bridges with a rating above 3 require repair (17 bridges). Furthermore, since one of the advantages of the proposed methodology is that central interventions can be chosen based on any bridge performance indicator, a Scenario (5) is also considered. For this scenario, the load effect performance indicator, which refers to the ratio between the extreme traffic load effect selected and the characteristic load effect induced by the design live load model (Mendoza-Lugo, Nogal, & Morales-Nápoles, 2024), is used. Specifically, the bending moment with a 50-year return period performance indicator M_{50r}. Scenario (5) assumes that bridges with $B_R > 3$ or $M_{50r} > 1.56$ require repair intervention (38 bridges). For complete details regarding the M_{50r} bridge performance indicator, the reader is referred to Mendoza-Lugo et al. (2024).

Similar to the approach detailed in Section 3.2, the Simplified Kaplan–Meier probabilistic deterioration model is used, along with the percentage of interaction, the analysis period, and the interest rate. Intervention costs were estimated as outlined in Section 2.2.1. In terms of budget limitations, for Scenario (3) an annual budget of 1.35% of the total bridge network value (98.44 MMP) is assumed. For Scenarios (4) and (5), approximately 1.5% of the total bridge network value (around 109.3 MMP) was allocated for the first two years to cover repairs for the selected bridges. For subsequent years, the budget constraint was set to about 1% of the total bridge network value (69.3 MMP). It is noted that the budget limitations presented represent the minimum required funds to apply interventions to all the bridges under study.

The optimisation problem involved a total of 19,980 variables, including 1110 intervention types. The optimisation procedure was executed using the Python algorithm `scipy.optimize.milp` on a laptop running Windows 10,

Table 11. Comparison of the total costs for Scenario (1) between the agency approach (C^*) and B-3C (C).

t_p [min.]	C^* [MMP]	C [MMP]	Saving [%]
2	28.51	25.26	11.40
30	297.92	265.51	10.88
Linear	45.99	37.32	18.85

Note: Intervention programmes for $T = 18$ years assuming different prolonged times.

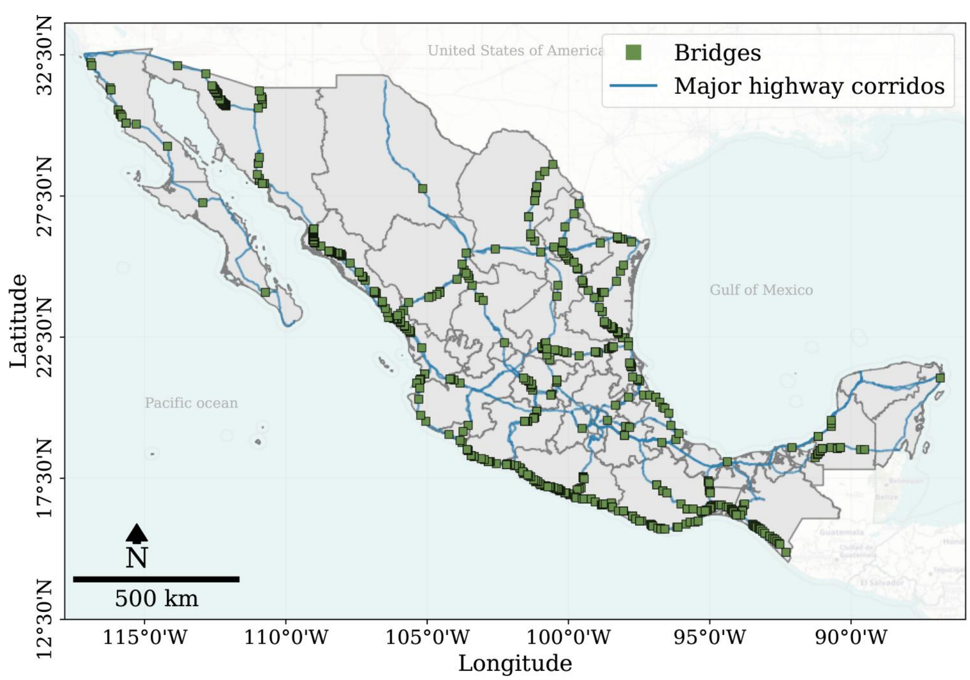


Figure 4. Location of the bridges under study.

equipped with an Intel Core i7–8665U CPU @ 1.90 GHz, and 32 GB of RAM. The entire simulation process took approximately 28 min. The budget constraints, total direct costs, and total costs of the optimal intervention plan for the 555 bridges studied are presented in Table 12. A graphical representation of the optimal intervention plan for Scenario (4) is shown in Figure 5, while the corresponding plans for Scenarios (3) and (5) are shown in Supplementary Figures A.1 and A.2. The estimated intervention costs and the optimal programme overview can be found in the supplementary material.

The analysis reveals three distinct cost scenarios for managing the bridge portfolio under study. First, the total cost for performing maintenance exclusively (C_{S_3}) amounts to approximately 2828.98 MMP. Second, the alternative strategy involves repairing bridges with a condition index $B_R >$ 3 and maintaining the others (C_{S_4}). This approach leads to a cost of approximately *2359*.95 MMP. Finally, the total cost obtained for Scenario (5), C_{S_5}, amounts to approximately *2560*.29 MMP. Opting for the C_{S_4} approach results in a cost reduction of 16.5% compared to the C_{S_3} strategy.

The cost ratio between the Scenarios (3) and (4) approaches shows the economic advantage of the C_{S_4} strategy. Specifically, C_{S_4} corresponds to 83.5% of the cost of C_{S_3}. This indicates that the C_{S_4} approach is more cost-effective, saving nearly 17% of the expenses associated with maintenance. Additionally, the analysis considers the direct costs associated with both strategies. For the C_{S_3} approach, the direct cost ($C_{D_{S_3}}$) amounts to *2060*.49 MMP. In contrast, the C_{S_4} approach provides lower direct costs, with $C_{D_{S_4}}$ of *1523*.69 MMP. This difference results in a 26% reduction in direct costs when opting for the C_{S_4} approach. The direct costs of Scenarios (4) and (5) are virtually identical, with the cost ratio C_{S_4}/C_{S_5} corresponding to 92.1%. The marginal difference suggests that opting for Strategy (5) might be a better choice, as it benefits more bridges while guaranteeing the adaptability of the bridge network to the actual traffic load demands.

Table 12. Overview of optimal intervention results for Scenarios (3), (4) and (5).

Scenario	E_M [MMP]	E_R [MMP]	C_D [MMP]	C [MMP]
(3)	98.44	–	2060.49	2829.02
(4)	69.30	109.3	1523.69	2360.10
(5)	69.30	109.3	1543.42	2560.29

Furthermore, when comparing the total cost of Scenario (3) with the total cost obtained with the agency approach ($C^* = 3075.9$ MMP, assuming the time between two consecutive interventions $G_{min} = G_{max}$) described in Section 3.6, an 8% reduction in total costs is observed when applying the B-3C approach. It is noted that when the interaction effects within the bridges are not taken into account, i.e. $I = [I_{555}]$, the total costs for Scenario (3) correspond to $C_{S_3|I=[I_{555}]} = 2621.93$ MMP, representing a deviation of 266.6 MMP from the actual value (2.8% of the bridge network total value). When compared with the optimal result of Scenario (4) using the agency approach, a reduction of around 23% was found. It is pointed out that given the budget constraints, opting for the agency approach will be sufficient to fund interventions up to year 15.

5. Conclusions

This paper presents a novel methodology for optimising bridge intervention planning, named B-3C approach, based on the multi-system optimisation technique known as the integrative 3C concept. The proposed methodology takes into consideration the interactions between various assets within a bridge network, including different types of interventions. To model these interactions, the employed approach utilises an interaction matrix capable of representing diverse interdependencies caused by the spatial proximity of the bridges. Additionally, a relation matrix is established to specify which intervention type affects each asset. In the specific context under study, the focus is on two intervention types: maintenance and repair. Furthermore, the methodology enables the distinction between central and non-central intervention types by considering the time intervals between successive interventions. This allows the incorporation of various bridge

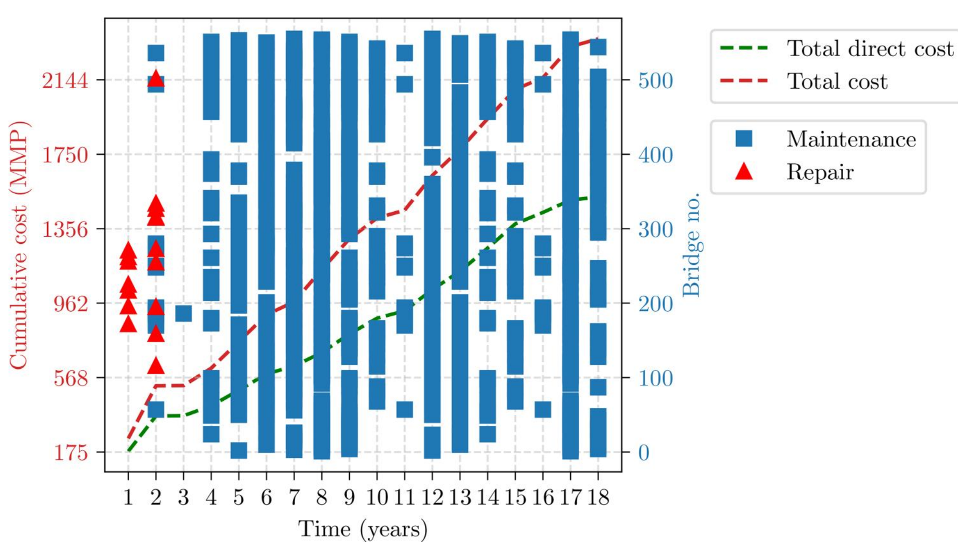


Figure 5. Optimal intervention programme for the 555 bridges under Scenario (4).

performance metrics into the analysis, facilitating the prioritisation of central interventions. The intervention scheduling approach is formalised by developing an optimisation mathematical model that incorporates pre-established constraints.

The main goal of the optimisation process in this study is to minimise the total cost associated with implementing interventions. This objective is achieved through the utilisation of a global intervention cost function that accounts for the direct costs of the interventions, the user costs resulting from the interventions, and the bridge deterioration model. It is acknowledged that bridge managers often encounter additional optimisation goals, or agencies may have varying performance criteria for different bridges or groups of bridges. However, in most cases, during a given planning exercise, minimising costs would support the manager in economically prioritising bridges to address specific optimisation goals.

To demonstrate the practicality of the presented methodology, a numerical example involving a network of 555 bridges and four scenarios is provided. This methodology offers a clear benefit by helping to determine the most efficient sequence for interventions that minimise the overall number of required interventions while ensuring early implementation to lower costs. The results of the numerical example emphasise the clear cost-saving advantages and the importance of including the interaction matrix. Specifically, by combining bridge repairs for those with a condition rating index exceeding 3 and maintenance for the rest, a reduction of 23% in the total cost is achieved when compared to the bridge management agency approach based on exclusive maintenance. Notably, when the interaction matrix is not considered, deviations in total costs of up to 3.6% of the total bridge network value have been observed. Furthermore, a step-by-step description of how to incorporate the bridge state into the cost estimation is offered. This estimation, which is a function of the bridge reliability index, is dynamically considered in the optimisation process.

The principal sources of uncertainty in this study are the deterioration model, the average annual inflation rate, and the extent of the impact induced by interventions on other bridges, as indicated by the interaction matrix. The interaction matrix analysis focuses solely on bridges i to j (or vice versa). In cases where additional interventions on other bridges are simultaneous with bridges i and j, the interaction matrix cannot account for this scenario. This limitation arises from the simplified network analysis used to estimate travel time calculations, which do not allow for straightforward addition of various elements in the interaction matrix. However, the variables have been quantified in a simplified manner solely for illustrative purposes. Properly quantifying these variables for each bridge within the network will lead to a more precise estimation of the optimal intervention plan. The limitations of this study underscore the necessity for future research to (1) explore more advanced methodologies for computing the interaction matrix and (2) investigate the effects of different intervention activities, such as rehabilitation and replacement, and their integration into the framework. This in-depth exploration will refine our approach and improve our understanding of how repair strategies impact optimisation outcomes.

Although the optimal intervention programme derived from the analysis may seem arbitrary initially, these results stem from a rigorous optimisation process. They demonstrate superior performance compared to what human intuition alone could achieve, particularly when dealing with extended analysis periods and complex bridge networks with numerous assets. Therefore, the methodology presented here underscores its practical value as a bridge management optimisation tool. It can help transportation agencies implement and explore various scenarios by adjusting the time between consecutive interventions and budget constraints. This methodology facilitates the assessment and comparison of associated costs, supporting a more comprehensive analysis and informed decision-making.

Notes

1. It is noted that previous literature often categorizes these actions into two main groups: preventive maintenance (including maintenance and minor repairs) and corrective maintenance (including major repairs, rehabilitation, improvements, and replacements).
2. It is noted that bridges $i = 10$ and $i = 11$ are in close proximity. By reviewing the bridge database and satellite images, these bridges span two adjacent branches of a river.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the Mexican National Council for Science and Technology (CONACYT) under project number 2019-000021-01EXTF-00564 CVU 784544. The authors would like to thank Dr. Andrés Antonio Torres Acosta, Research Professor at the Department of Sustainable and Civil Technologies, School of Engineering and Sciences, Tecnológico de Monterrey for his contributions to this research. The opinions and conclusions presented in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organisation.

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