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ARTICLE

Adaptive Maintenance Management Framework for Steel Truss Bridges Subjected to Climate Change-Induced Corrosion

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ABSTRACT: Climate change modifies environmental exposure conditions and affects the corrosion-driven deterioration of steel bridges, thereby challenging conventional maintenance planning approaches. Thus, more advanced maintenance management strategies are required to address the challenges associated with varying corrosion rate projections. In this study, a novel adaptive maintenance management framework is proposed for steel truss bridges to address climate change-induced corrosion under evolving deterioration conditions. Adaptivity is achieved by updating corrosion rates to consider time-varying deterioration conditions associated with climate change. This enables time-dependent representation of corrosion progression under changing environmental conditions. The framework is demonstrated on a benchmark steel truss bridge and applied to two cities with distinct climate-induced corrosion scenarios to capture spatial variability in environmental exposure conditions. Structural performance objectives are defined in terms of preserving load-carrying capacity and limiting joint displacements to maintain the original design throughout the service life. To achieve an economical maintenance strategy, life cycle cost analyses are conducted for different maintenance alternatives under varying corrosion scenarios, incorporating preventive and essential maintenance actions. In addition, the impact of changes in economic and social indicators, specifically the discount rate and the average daily traffic, on the total cost is evaluated within the proposed adaptive framework. Analysis results reveal that lower discount rates and higher average daily traffic rates significantly increase total costs and amplify the economic consequences of climate change-induced corrosion. The results highlight the importance of integrating scenario-based corrosion evolution into adaptive maintenance frameworks for long-term infrastructure management under climate-driven deterioration conditions.

KEYWORDS: Climate change; corrosion deterioration; steel truss bridges; adaptive maintenance; life cycle cost; preventive maintenance

1 Introduction

Corrosion poses a significant threat to infrastructure worldwide and causes substantial economic losses. The annual cost of corrosion in terms of GDP was reported as 3.4% for the USA [1], and 3% to 4% for other industrialized countries [2]. Thus, extensive research has been conducted to identify and assess the undesired effects of atmospheric corrosion on steel structures [3–5]. In particular, steel bridges, which are part of transportation infrastructure, are susceptible to corrosion as they are often exposed to harsh atmospheric conditions. Deterioration due to corrosion leads to the breakdown of the structural integrity of steel bridges, resulting in costly repairs, extended service interruptions, and, in extreme cases, catastrophic failures [6,7].

Effective corrosion protection of steel bridges is essential not only for preserving transportation infrastructure but also for ensuring public safety. The majority of steel bridges mostly have initial coatings applied to provide adequate safety and full functionality [8]. Since coatings have a limited lifespan compared to the steel bridge, coatings degrade over time and eventually necessitate repainting [9]. Thus, the demand for renewal of coating systems and maintenance of steel bridges became a priority to ensure adequate corrosion protection [10,11]. Maintenance of steel bridges is mostly performed using preventive maintenance (PM) actions that aim to delay and mitigate the detrimental effects of corrosion by applying repetitive full repainting with predefined repainting time intervals. Leiva-Maldonado et al. [12] stated that INDOT's current practice considers only full repainting of the bridge members as a general maintenance procedure. However, in some cases, PM may not be able to keep the structural safety over the desired safety level, and essential maintenance (EM) becomes necessary. The process of selecting deteriorated steel members and replacing them with new ones to strengthen the steel bridge is generally called EM. Accordingly, the management of PM and EM for the maintenance of steel bridges becomes a fiscal problem while ensuring structural safety and serviceability. For the USA, corrosion-related maintenance expenses are a significant expenditure item [13]. In particular, the corrosion of highway steel bridges in the USA is estimated to result in a direct cost of $500 million annually [14]. In order to determine the financial plan and the total cost, life cycle cost (LCC) analyses, which provide an opportunity to compare different maintenance alternatives and determine the optimal solution, are generally performed [15,16]. In this perspective, Okasha et al. [17] presented an approach for calculating the LCC of steel girder bridges deterministically and probabilistically for maintenance alternatives. Different repainting intervals for PM were used, such as 15-year, 20-year, and 25-year by Okasha et al. [17] and 15-year and 25-year by Han et al. [8] for single-span steel bridges. In addition, Soliman and Frangopol [16] accounted for traffic delays and environmental effects associated with indirect costs, which can significantly increase the LCC of the bridge under the impacts of corrosion.

Corrosion processes can be influenced by rising temperatures, changes in acidity and precipitation, increasing relative humidity, more frequent extreme weather events, and atmospheric pollution levels. Hence, changes in the exposure conditions are likely to be responsible for changes in the deterioration process, including the rate of corrosion. Tidblad [18] reported that climate change could increase corrosion by one category in extreme cases and concluded that corrosion in Southern Europe could be higher than the highest values experienced in Europe today. Although climate change generally tends to increase corrosion rates, in some specific cases and geographical conditions, decreasing corrosion rates can also be observed. The local environment of the structure has a substantial influence on the rate of corrosion of the exposed steel and the deterioration of the protective coating [19]. Kumar and Imam [20] investigated air pollution and the changing environment of built infrastructure in London and determined the thickness loss of carbon steel. Similarly, Nguyen et al. [21] examined the potential impacts of climate change on the atmospheric corrosion rates of exposed steel structures by accounting for the emission scenario defined by the Intergovernmental Panel on Climate Change (IPCC) and calculated the projected changes in corrosion rates for Brisbane and Melbourne, two cities in Australia. Orcesi et al. [22] focused on the effects of expected changes to local climatic conditions and evaluated the potential degradation processes of materials, affecting the durability and service life of infrastructures. Stewart et al. [23] stated that corrosion imposes significant direct and indirect costs, and even a small increase due to climate change could amplify annual maintenance and repair expenses into the hundreds of billions of dollars. In addition, Han and Frangopol [24] emphasized that climate change can significantly influence infrastructure risk and alter the optimal maintenance scheduling of bridge networks subjected to corrosion deterioration. Given these assessments and the increasing need for adaptation strategies, recent studies have expanded climate-adaptive infrastructure management by considering changing environmental conditions, structural robustness, and decision-making in long-term infrastructure maintenance and performance evaluation [25,26]. As conducted in the literature, while the potential impacts of climate change on atmospheric corrosion rates have been studied, the maintenance management of steel bridges under climate change-induced corrosion has not been thoroughly explored. Conventional maintenance strategies may be insufficient for steel bridges exposed to climate change-induced corrosion; therefore, adaptive maintenance management strategies are required.

In the current study, a novel adaptive maintenance management framework was proposed for steel truss bridges exposed to climate change-induced corrosion. An optimized and economically advantageous Petit type of steel truss bridge was selected from the literature, and the proposed maintenance management method was applied considering varying corrosion rate projections due to climate change. The structural performance objectives were set as preserving load-carrying capacity and limiting joint displacements. In order to achieve these objectives, PM by full repainting at predefined time intervals and EM by replacing selected steel members with new steel members were employed to sustain the original structural safety through the service life. LCC was calculated to evaluate the maintenance alternatives from an economic perspective. The total cost of the steel bridge was assessed by considering two climate-dependent scenarios, corresponding to increasing and decreasing corrosion rates. Moreover, the most economical maintenance alternative for each environment was obtained based on the adaptive maintenance management framework. Finally, economic and social indicators, which are the discount rate and the increase rate in average daily traffic (ADT), were examined to determine their effects on the total cost considering climate change-induced corrosion.

2 Deterioration of Steel Bridges Considering Climate Change-Induced Corrosion

Coatings provide the primary corrosion protection system for steel bridges by isolating the base material from the environment [19]. ISO 9224 [27] offers a degradation model to calculate the penetration depth due to atmospheric corrosion. Since the behaviors of coated steel members are different than the steel members without any coating, a limited number of degradation models have been suggested in the literature for steel structures [28]. Kee Paik et al. [29] proposed a model that considers the duration of coating protection, delaying the initiation of corrosion on steel members until the coating has completely lost its effectiveness. However, in practice, the deterioration of both the steel and the coating occurs concurrently. Accordingly, Kere and Huang [30] proposed a model that accounts for the coating protection and steel member deterioration along with each other. In addition, Seçer and Saylan [31] modified the Kere and Huang [30] model using the equation of ISO 9224 [27] about corrosion depth instead of the NCHRP formula [32]. However, the potential impacts of climate change on the atmospheric corrosion rates of exposed steel members were not considered in these models. Thus, an improved thickness loss formula for steel members that considers time-dependent corrosion rate was proposed with Eq. (1):

$$d(t) = \begin{cases} r_{corr}(t) \cdot (T_U - T_{50\%})^B \cdot \left(0.6\left(\frac{t}{T_{50\%}}\right)^2 - 0.1\left(\frac{t}{T_{50\%}}\right)\right), & t < T_U \\ r_{corr}(t) \cdot (t - T_{50\%})^B, & T_U \leq t < T_{50\%} + 20 \\ r_{corr}(t) \cdot (20^B + B\left(20^{B-1}\right) \cdot (t - (T_{50\%} + 20)), & t \geq T_{50\%} + 20 \end{cases} \tag{1}$$

where $r_{corr}(t)$ is the climate change-induced corrosion rate in mm/year, t is the exposure time in years, B is the metal-environment-specific time exponent and referred to as 0.549 for steel [27,30], $T_{50\%}$ represents the half-life of the coating, T_U is the time when the coating is fully degraded from the steel surface as $T_U = 1.38T_{50\%}$ [30]. Beside the robust empirical approach of ISO 9224, deep learning frameworks [33] can also be used to predict corrosion behavior under complex nonlinear environmental conditions.

Efficient corrosion protection of steel bridges can be achieved by appropriate maintenance strategies, since coatings deteriorate over time [10,11]. Maintenance of steel bridges is generally carried out with PM to ensure the service life of a bridge by delaying the deterioration due to corrosion. In PM, full repainting with predefined repainting time intervals is applied. However, in some cases, PM actions may become inadequate to maintain the structural performance above a predefined threshold value, and the application of EM becomes necessary. For determining the appropriate time of EM, more than one structural performance indicator can be used. Load-carrying capacity and mid-point joint displacements can serve as multiple structural performance indicators for steel truss bridges. Therefore, minimum acceptable performance thresholds can be defined for each indicator independently and assessed simultaneously to ensure structural integrity.

On the other hand, climate change may affect the structural performance of steel bridges, as they are exposed to open-air environments for extended periods. Therefore, assuming a constant climate condition throughout the service life of the bridges may lead to inaccurate predictions. To illustrate the effect of climate change on the maintenance of steel bridges, the relationship between structural performance and time is presented in Fig. 1. The effects of increasing corrosion rate due to climate change cause a rapid reduction in structural performance when compared with the case that omits the effect of climate change. Moreover, increasing corrosion rate due to the effect of climate change necessitates earlier EM to keep the structural performance above the threshold value. On the contrary, decreasing the corrosion rate postpones the requirement of EM.

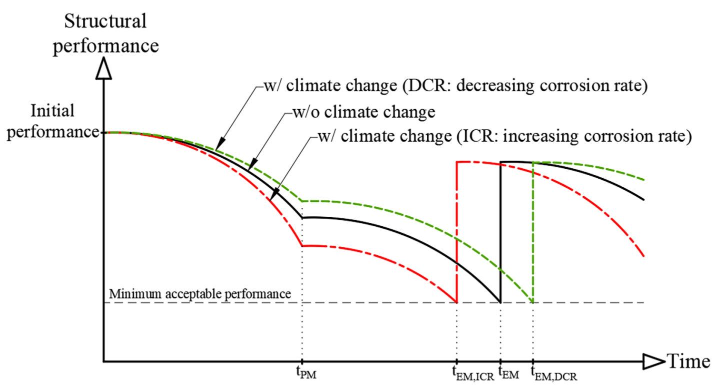

Figure 1: Structural performance and time relationship.

3 Life Cycle Cost Calculations

LCC of a steel truss bridge represents the cumulative expenses required to construct and maintain the structure over its service life. Initial cost consists of material acquisition, fabrication, transportation, and painting costs [17], and maintenance costs cover the cost of full repainting as PM and the cost of member replacement as EM [16]. Additionally, costs related to maintenance can be evaluated under two different cost groups, namely direct and indirect costs, to provide a comprehensive assessment of the economic impact.

Direct costs (C_{Dir}) include the expenses related to labor, materials, and equipment required for maintenance actions of full repainting and member replacement [17]. The direct cost of repainting involves surface preparation as SP10-near-white metal blast cleaning [34], the application of new coating, and direct member replacement costs cover the material costs for steel components. On the other hand, indirect costs include time loss cost (C_{TL}) due to traffic congestion and delays for the goods and users [16], additional vehicle operating costs (C_{Run}) from detours [35], and environmental costs (C_{Env}) associated with increased carbon emissions [36]. The maintenance cost and its components are presented in Eqs. (2)–(5):

$$C_m = C_{Dir} + C_{TL} + C_{Run} + C_{Env} \tag{2}$$

$$C_{TL} = ADT \times d\left(\frac{l}{S_D} - \frac{l}{S_0}\right)\left[c_w O_c (1 - T) + \left(c_c O_t + c_g\right) T\right] \tag{3}$$

$$C_{Run} = l \times ADT \times d\left[c_{Run,car}(1 - T) + c_{Run,truck} T\right] \tag{4}$$

$$C_{Env} = c_{Env} \times l \times ADT \times d\left[E_{d,c}(1 - T) + E_{d,t} \times T\right]\frac{E_{S_D} - E_{S_0}}{E_{S_0}} \tag{5}$$

where; ADT is the average daily traffic for the bridge, l is the net detour length, and d is the duration of the maintenance. For the numerical case study of this paper, the maintenance cost parameters in Eqs. (2)–(5) were defined in Table 1.

Table 1: Life cycle cost parameters.

Description	Notation	Value	Unit
Unit cost of unpainted carbon steel member [17,37]	–	2897.5	USD/t
Unit cost of coating, Single Coat Inorganic Zinc (SIOZ) [38]: Surface preparation: 7.53 USD/m^2 Application (spray): 8.07 USD/m^2 Job multiplier: 1.2 Material cost: 4.16 USD/m^2	-	22.89	USD/m^2
Average wage per hour [39]	c_w	23.36	USD/h
Average compensation for the trucks per hour [39]	c_c	29.28	USD/h
Monetary value of the goods transported with trucks per hour [40]	c_g	3.81	USD/h
Average costs to run cars [41]	$c_{Run,car}$	0.08	USD/km
Average costs to run trucks [41]	$c_{Run,truck}$	0.375	USD/km
Cost of CO_2 per unit weight [42]	c_{Env}	26	USD/t
Restricted traffic speed [30]	S_D	32.19	km/h
Unrestricted traffic speed [30]	S_0	88.51	km/h
Average occupancies for cars [43]	O_c	1.5	–
Average occupancies for trucks [43]	O_t	1.05	–
Ratio of the average daily traffic to the total average daily traffic [44]	T	0.04	–
CO_2 emissions for coating (SIOZ) application [45]	-	0.50	kg/m^2
CO_2 emissions of carbon steel from production and acquisition [46]	-	2100	kg/t
CO_2 emissions per extra distance due to detours for cars [39]	$_{d,c}$	0.22	kg/km
CO_2 emissions per extra distance due to detours for truck [38]	$E_{d,t}$	0.56	kg/km
CO_2 emissions at restricted traffic speeds [16]	E_{SD}	0.416	kg/km
CO_2 emissions at unrestricted traffic speeds [16]	E_{S0}	0.298	kg/km

Indirect cost mainly depends on *ADT* as presented in Eqs. (3)–(5). The *ADT* can vary from 2000 vehicles/day to more than 100,000 vehicles/day [30]. Since *ADT* can rise annually, the maintenance cost will inherently vary over time [16] and can be accounted for as in Eq. (6):

$$ADT(t) = ADT \times (1 + v)^t \tag{6}$$

where v is the annual increase rate in the ADT. For the traffic delays, the annual increase rate in the ADT, which is an indirect measure of increasing population and a social indicator, Soliman and Frangopol [16] considered this value as 0.5% to 1.5%. Likewise, Kere and Huang [30] used a constant value of 1% for the annual increase rate in ADT.

In order to assess maintenance costs over time, net present value (NPV), which uses discount rates to project future expenses in current monetary terms, is applied to maintenance costs. Next, by integrating initial and maintenance costs, LCC provides a comprehensive overview of the bridge's economic demands, supporting more informed decision-making for maintenance planning. The maintenance cost can be calculated by Eq. (7) in terms of net present value [16]:

$$C_m = \sum_{i=1}^{n} \frac{C_{m,i}}{(1+r)^{t_i}} \tag{7}$$

where $C_{m,i}$ is the total cost of ith maintenance action, including direct and indirect costs, r is the discount rate of the money, and n is the total number of maintenance actions. Recently, Dong and Frangopol [43], Han et al. [41] and Seçer and Saylan [31] used a discount rate of 2% for maintenance or repair actions to meet the safety requirements for bridges subjected to corrosion. Okasha et al. [17] examined maintenance considering discount rates of 0% and 3%. In addition, Han et al. [41] stated that different conclusions can be drawn when the monetary discount rate is higher.

4 Adaptive Maintenance Management Framework

An adaptive maintenance management framework was proposed for deteriorating steel truss bridges under the effects of climate change-induced corrosion. The novelty of the proposed framework lies in the integration of climate change-induced time-dependent corrosion projections into structural performance evaluation, adaptive maintenance scheduling, and life cycle cost assessment for steel truss bridges. Unlike conventional maintenance approaches assuming stationary environmental conditions, the proposed framework accounts for evolving corrosion deterioration trends associated with climate change throughout the service life. To apply the adaptive maintenance management framework, a new programming code was developed in Python, and the flowchart summarizing the proposed method is presented in Fig. 2.

A dedicated Python-based computational framework was developed specifically for this study. Existing finite element method libraries were not employed, since they do not directly support the implementation of time-dependent corrosion-induced deterioration together with adaptive maintenance scheduling for steel truss bridge members. Within the developed framework, corrosion depth and corresponding sectional property reductions of structural members were updated iteratively on a yearly basis throughout the 100-year service life. At each yearly time step, the deterioration state was updated first, followed by nonlinear structural analysis to re-establish equilibrium and evaluate the updated structural performance in terms of load-carrying capacity and displacement. Geometric nonlinear behavior was considered using the Newton–Raphson iterative method with load incremental steps. For the iterative solution procedure, a force-based convergence criterion, defined as the ratio of unbalanced force to internal force, was adopted with a convergence tolerance of 10^{-10}. In addition, member capacities were calculated according to AISC 360-22 provisions [47], and plastic hinges were used to model elastic-perfectly plastic behavior of structural members. The proposed framework builds upon previously developed methodologies for time-dependent structural analysis and maintenance management of steel truss bridges subjected to atmospheric corrosion [31,48–50]. In the current study, these previously developed methodologies were extended by incorporating climate change-induced corrosion-rate projections into the deterioration and maintenance assessment procedure.

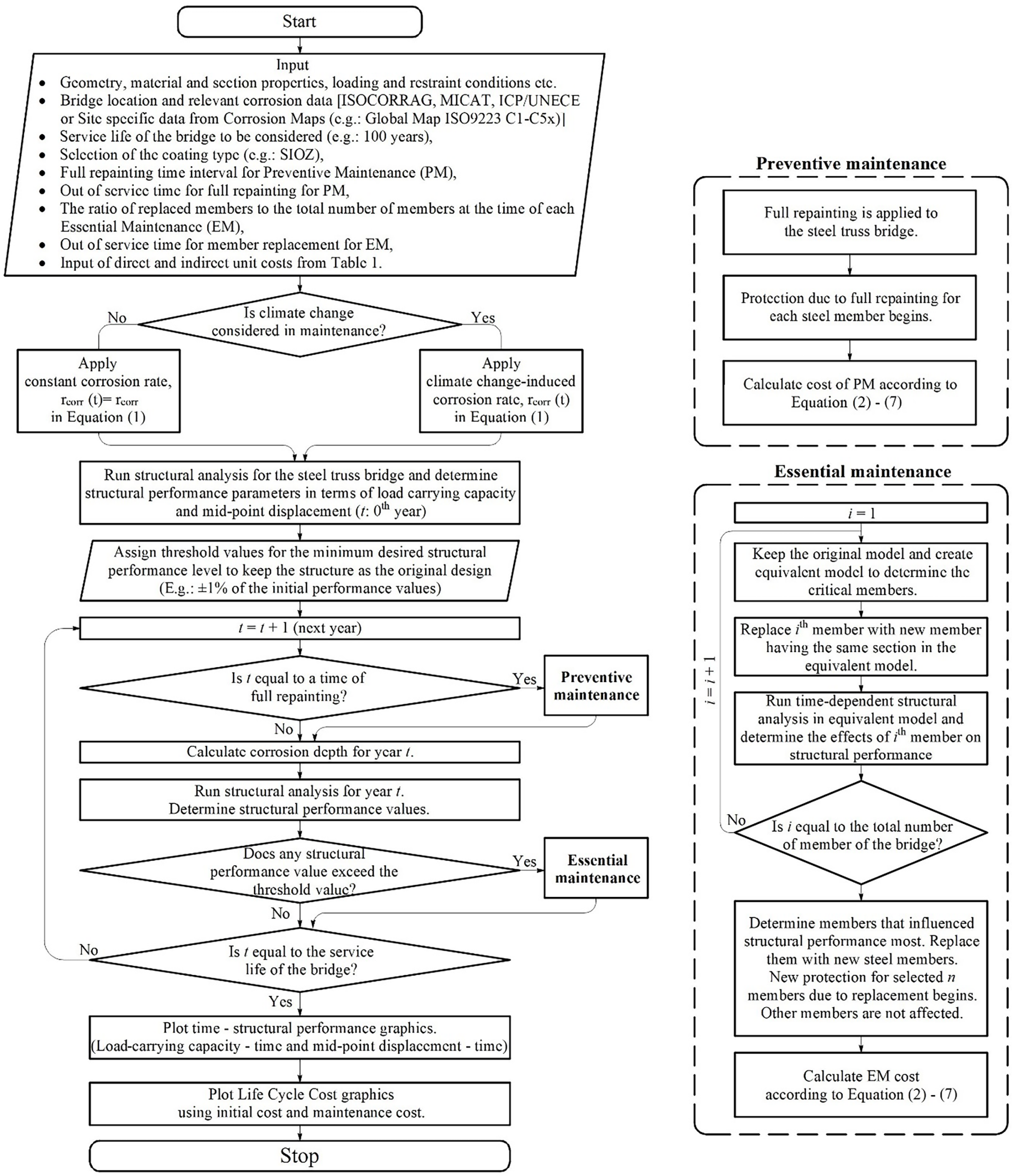

Figure 2: Flowchart of the adaptive maintenance management framework for steel truss bridges.

In order to consider the effects of climate change, increasing or decreasing corrosion rates were accounted for by the new thickness loss formula as in Eq. (1), which considers time-dependent corrosion rate for coated steel members. Load-carrying capacity and mid-point displacement of the steel truss bridge were targeted as structural performance objectives, and maintenance was applied with the combination of PM and EM actions. At first, the PM was examined to achieve a delay in the decrease of structural performance for different repetitive full repainting intervals. However, in some cases, PM was not adequate to keep the structural performance above the threshold value, and EM became necessary.

From the financial perspective, LCC was determined for different maintenance alternatives that consist of direct and indirect costs for the evaluation of PM and EM actions. Material cost, fabrication cost, initial painting cost, shop inspection cost, and transportation costs were calculated for the direct cost. Time loss cost, environmental cost, and running cost were added to determine the indirect cost. Since PM and EM actions were applied at different times throughout the service life, NPVs were calculated to compare the total cost. Consequently, the effect of climate change-induced corrosion was incorporated into an adaptive maintenance management method, and the most economical maintenance choice was determined based on LCC results.

The adaptive characteristic of the proposed framework originates from its ability to incorporate updated corrosion-rate projections into the deterioration analysis rather than assuming a fixed corrosion scenario throughout the service life. For a given climate change scenario, the climate change-induced atmospheric corrosion model is used to determine the corresponding time-dependent thickness loss of structural members. Subsequently, the developed computational framework evaluates the structural performance of the bridge and determines the required timing of preventive and essential maintenance actions together with the associated life cycle costs. Therefore, the proposed framework can also be applied to alternative climate projections provided that the corresponding time-dependent corrosion rate functions are available. Uncertainties associated with different emission scenarios, General Circulation Models (GCMs), and climate projections may be explicitly quantified. Future studies may incorporate probabilistic approaches and uncertainty evaluation techniques to further enhance the framework.

5 Numerical Case Study

A Petit type of steel truss bridge was selected from the literature [51] to implement and evaluate the proposed maintenance management framework under climate change-induced atmospheric corrosion. Hasançebi and Doğan [51] determined that the Petit type of steel truss bridge had the lowest design weight among nine different topological truss forms based on an optimization with the Simulated Annealing algorithm. The Petit type of steel truss bridge, having a 182.88 m (600 ft) span, is presented in Fig. 3, and the cross-sections of the bridge members made of carbon steel were given in detail in the reference study. Hasançebi and Doğan [51] modeled equivalent vertical joint loads to the lower chord in the direction of gravity at each joint as the combinations of live loads of the traffic and dead loads of the deck and the floor system. In the current paper, the steel truss bridge was assumed to be protected with SIOZ coating since it is a cost-effective and high-quality corrosion protection system that provides barrier protection to the underlying steel [52]. The predicted service life of SIOZ was considered as 15 years [38,52], and the unit cost of the coating is presented in Table 1.

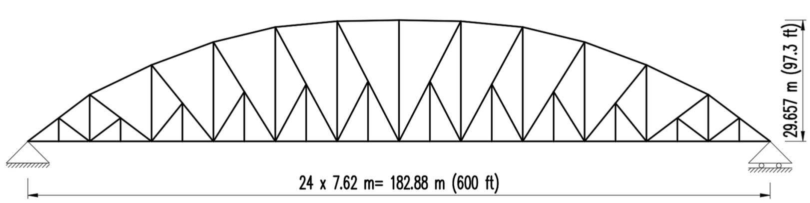

Figure 3: Petit type of steel truss bridge.

The effect of climate change on the maintenance of the Petit steel truss bridge was examined by considering two urban environments with different climate change projections. Accordingly, Brisbane and Melbourne were selected to demonstrate the impact of climate change on increasing and decreasing corrosion rates, respectively. The initial corrosion rate was accounted as 65 μm/year, considering these cities by using ISO 9223 C1-C5x Environmental Classification Tool [53]. Accordingly, these corrosion rates correspond to the C4 corrosivity category based on ISO 12944-2 [54].

For these Australian cities, Nguyen et al. [21] conducted comprehensive research on the potential impacts of climate change on atmospheric corrosion rates. The assessments of climate change were made by Nguyen et al. [21] using the A1FI emission scenario, the highest emission scenario defined by the IPCC, applied to the nine General Circulation Models (GCMs) to take into account the uncertainties in impact assessments. Hence, increasing and decreasing normalized corrosion rates due to climate change were adopted from the study of Nguyen et al. [21] for Brisbane and Melbourne and are plotted in Fig. 4.

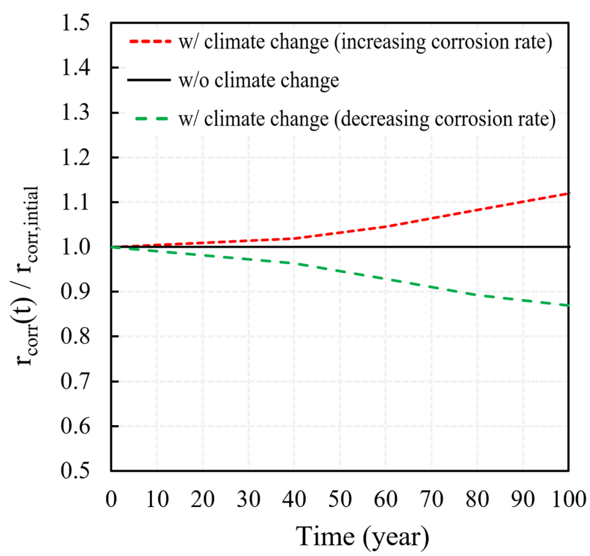

Figure 4: Normalized corrosion rates due to the potential impacts of climate change.

In order to examine the potential impacts of climate change-induced corrosion on the maintenance of the Petit steel truss bridge, time-dependent structural performance was evaluated. The 100-year service life was accounted for in the current study since it was a reasonable period for the Australia-New Zealand region [55]. For maintenance actions, 15-year, 20-year, and 25-year full repetitive repainting intervals were applied separately for PM. Accordingly, the required number and sequence of EM actions to keep the structural performance above the threshold value were determined for each PM. Change in the load-carrying capacity and the mid-point vertical displacement values were limited by 1% threshold to keep the structure's performance as the original design throughout the service life. In addition, corrosion-induced deterioration can significantly influence the dynamic characteristics of steel truss bridges, including structural frequencies and modal behavior [48]. However, the proposed adaptive framework is not restricted to this threshold and can accommodate alternative performance criteria depending on agency requirements and acceptable risk levels. Higher thresholds such as 5% or 10% would delay the initiation of essential maintenance actions and likely reduce the total life cycle cost, although at the expense of permitting greater structural deterioration before intervention. On the other hand, the ratio of replaced members to the total number of members was considered as 5% since it was determined as a cost-effective ratio [48]. Structural performance indicators of load-carrying capacity—time and the mid-point displacement—time relationships for the Petit truss bridge are plotted considering the increasing corrosion rate due to climate change in Fig. 5 and considering the decreasing corrosion rate due to climate change in Fig. 6.

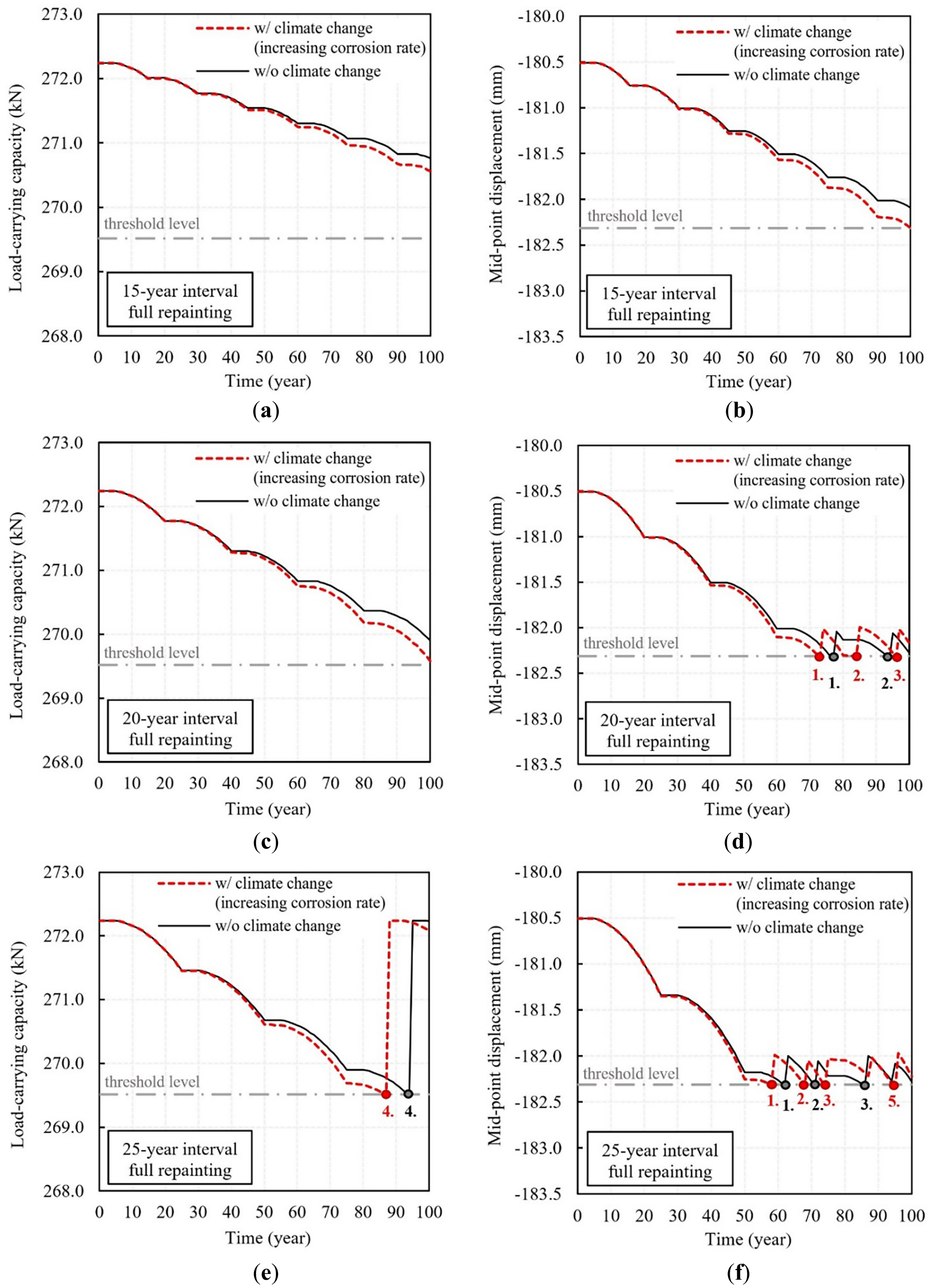

Figure 5: Load-carrying capacity—time and mid-point displacement—time relationships considering the increasing corrosion rate due to climate change: (**a**,**b**) 15-year; (**c**,**d**) 20-year; (**e**,**f**) 25-year PM intervals.

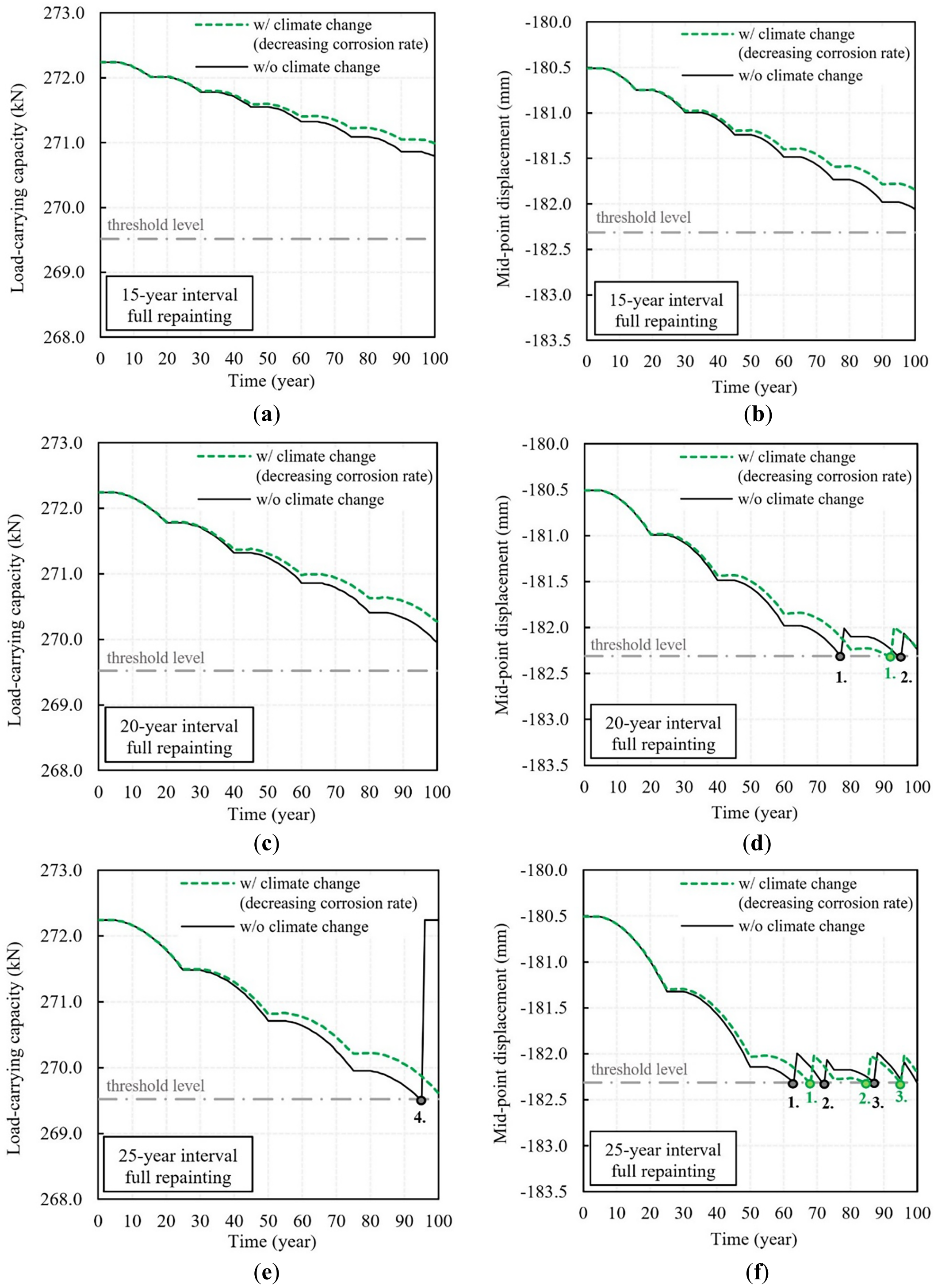

Figure 6: Load-carrying capacity—time and mid-point displacement—time relationships considering the decreasing corrosion rate due to climate change: (**a**,**b**) 15-year; (**c**,**d**) 20-year; (**e**,**f**) 25-year PM intervals.

Load-carrying capacity—time and mid-point displacement—time relationships considering the climate change-induced corrosion in maintenance showed that frequent full repainting of the bridge with 15-year intervals was able to protect the steel members effectively, and EM was not required throughout the service life. However, full repainting of the bridge with 20-year intervals and 25-year intervals necessitated EM actions. The required number of EM was determined as 2 and 4 for PM with 20-year and 25-year intervals, respectively, when the effect of climate change on corrosion was neglected. Infrequent full repainting of the bridge caused inadequate structural performance, and high numbers of EM were required to be applied to the bridge for maintenance. In addition, the required number of EMs was determined to be 3 and 5 when increasing corrosion rate due to climate change was considered in the time-dependent analysis. Increasing corrosion rate due to climate change necessitated the application of additional EM for both 20-year and 25-year PM interval cases as given in Fig. 5. The influence of climate change-induced corrosion changed the application time of EM. Increasing corrosion rate due to climate change required relatively earlier application of EM to keep the structural performance above the threshold. On the other hand, considering the decreasing corrosion rate due to climate change necessitated a smaller number of EMs as presented in Fig. 6. For the case of decreasing corrosion rate, the required number of EM was determined as 1 and 3 for PM with 20-year and 25-year intervals, respectively. In addition, decreasing corrosion rate due to climate change caused a delay in the application time for EM. The change in the number and time of EM due to climate change-induced corrosion affected the total cost, which is a key factor for decision-makers.

In order to allocate limited resources and form consistent fiscal plans, LCC was determined for the maintenance of the steel truss bridge considering the climate change-induced corrosion. Since each city has a different population, 10,000 and 20,000 vehicles per day were assumed as initial ADT. In the LCC calculations, the increase in ADT was accounted as 1%, and the discount rate was accounted as 2% since these values have been commonly used in the literature [16,17,30,41]. Results of LCC are given for the increasing and decreasing corrosion rates due to climate change in Figs. 7 and 8, respectively. Besides, 15-year, 20-year, and 25-year repainting time intervals were examined separately, considering the required numbers of EM for each case, and total costs were determined. The maximum difference between the total costs with and without climate change-induced corrosion was observed when 25-year intervals were used for the PM. On the other hand, analysis results revealed that 20-year repainting intervals were the most economical alternative for both cases with and without climate change.

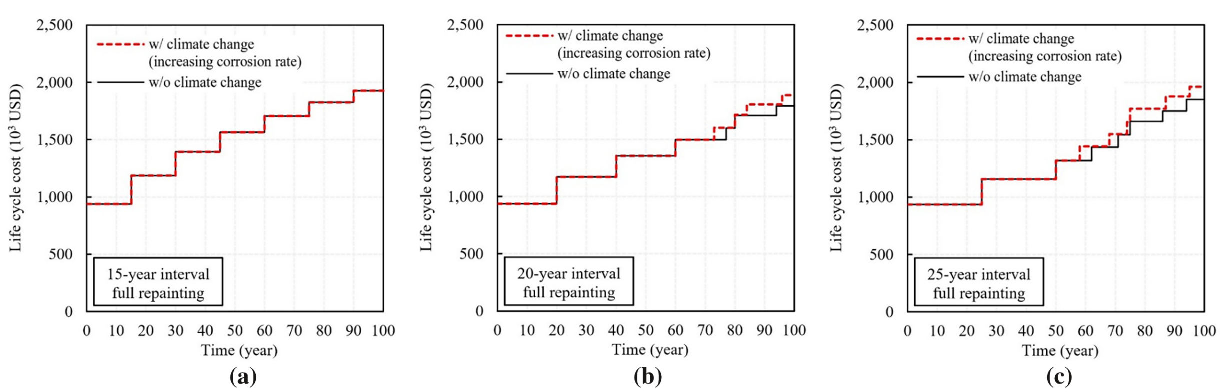

Figure 7: Life cycle cost—time relationships for different full repainting time intervals considering the increasing corrosion rate due to climate change: (**a**) 15-year; (**b**) 20-year; (**c**) 25-year.

The LCC results indicated that accounting for climate change–induced corrosion in maintenance had no significant effect on the total cost of the steel truss bridge, assuming frequent full repainting at 15-year intervals. This is due to the fact that structural performance was affected slightly, and frequent full repainting of the bridge did not necessitate any EM action. However, LCC results revealed that full repainting actions of the bridge with 20-year and 25-year intervals decreased the number of PMs and necessitated EM, and thus, total costs were affected.

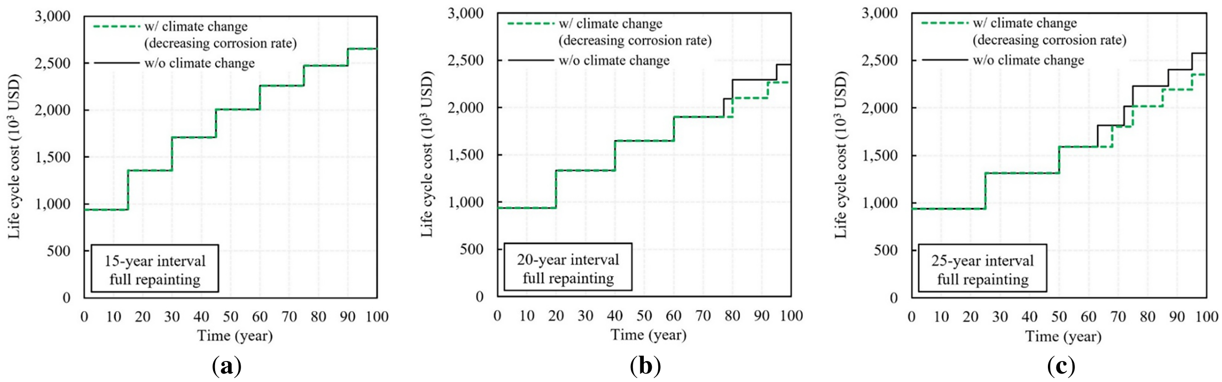

Figure 8: Life cycle cost—time relationships for different full repainting time intervals considering the decreasing corrosion rate due to climate change: (**a**) 15-year; (**b**) 20-year; (**c**) 25-year.

Increasing corrosion rate due to climate change caused an increase in the total cost by 5% and 6% for 20-year and 25-year full repainting interval cases, as presented in Fig. 7. In addition, increasing corrosion rate due to climate change required earlier application of EM, and therefore costs increased earlier than in the case of neglecting climate change. On the contrary, considering the decreasing corrosion rate due to climate change resulted in a lower number of EM and total cost, as presented in Fig. 8. Decreasing corrosion rate due to climate change decreased the total cost by 8% and 9% for 20-year and 25-year full repainting interval cases. In addition, decreasing corrosion rate due to climate change caused a delay in the application time for EM, and costs decreased relatively later than in the case of neglecting climate change. LCC results revealed that climate change-induced corrosion significantly affected the total cost.

In order to provide a comprehensive perspective, the effects of changes in the discount rate and increase rate of ADT were accounted for in the total cost calculations. Since LCC results revealed that 20-year repainting intervals were the most economical alternative for both cases with and without climate change, the PM interval of 20 years was selected for further total cost evaluations. The total costs were calculated considering various discount rates and ADTs for the cases of the increasing and the decreasing corrosion rate projections for Brisbane and Melbourne, as in Figs. 9 and 10, respectively. In addition, the case that neglected the climate change-induced corrosion was also presented in these figures on a comparable basis.

LCC analyses revealed that both the discount rate and the increasing rate of the ADT, which are economic and social indicators, had a significant impact on the total cost. An increase in the discount rate for the constant rate of ADT decreased the total cost since future costs were discounted to a lower present value. On the other hand, an increase in the rate of ADT for a constant discount rate increased the total cost due to higher traffic volume leading to higher indirect costs. Besides, the total cost increased when the increasing corrosion rate projection due to climate change was considered. This is due to the fact that the increasing corrosion rate accelerated deterioration, causing substantial maintenance requirements. On the contrary, decreasing the corrosion rate projection caused a decrease in the total cost. Consequently, lower discount rates and higher ADT rates influenced the total cost and amplified the economic consequences of climate change-induced corrosion.

The maintenance cost distributions were investigated under both decreasing and increasing corrosion rate scenarios. The corresponding direct and indirect costs for the with and without climate change scenarios are separately presented in Fig. 11.

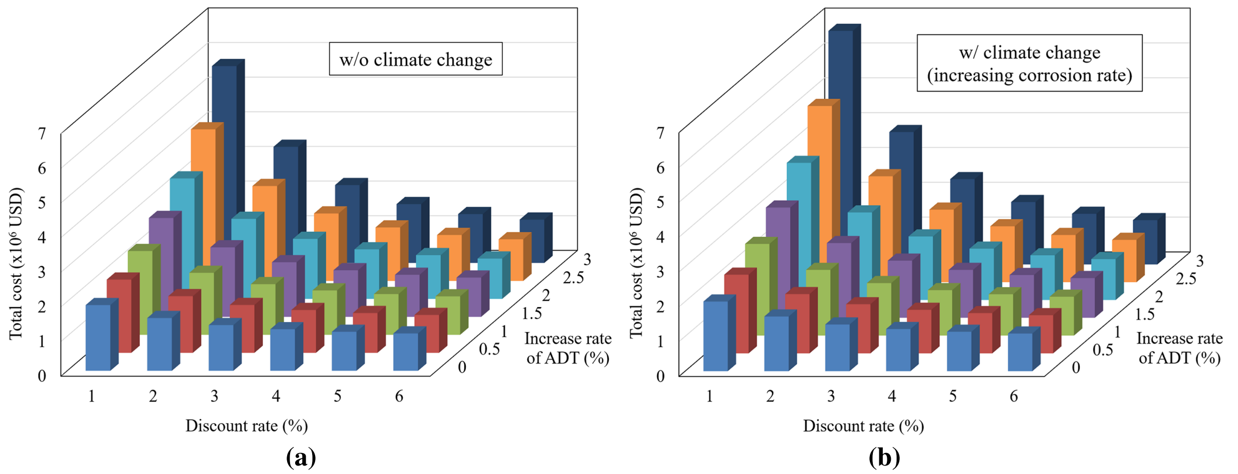

Figure 9: Total cost under different discount rates and ADT increase rates: (**a**) without climate change; (**b**) with climate change, considering the increasing corrosion rate.

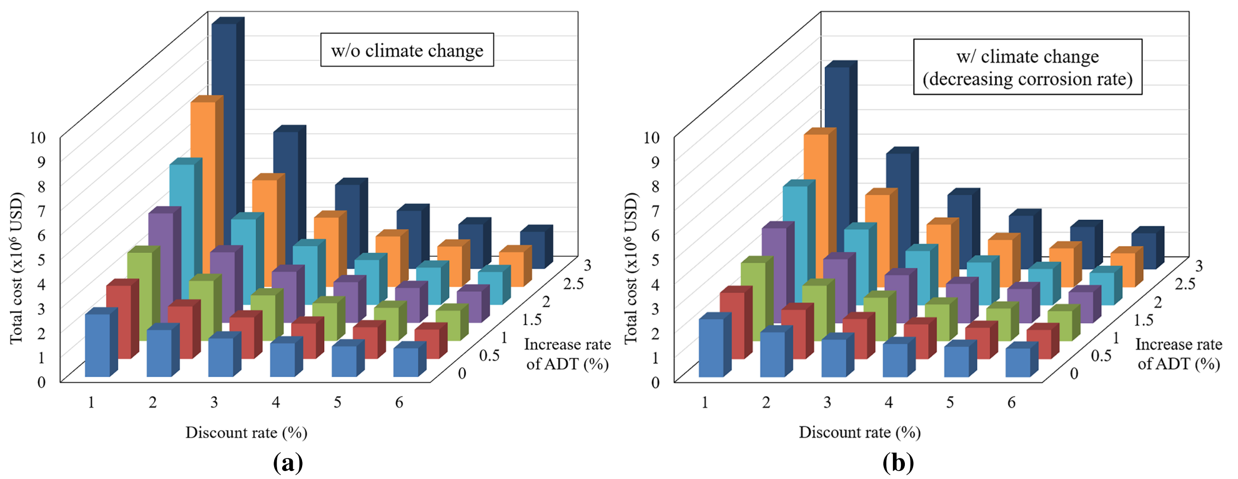

Figure 10: Total cost under different discount rates and ADT increase rates: (**a**) without climate change; (**b**) with climate change, considering the decreasing corrosion rate.

Fig. 11 presents the total cost distributions for the decreasing and increasing corrosion rate scenarios, with direct and indirect costs shown separately. Each box represents the interquartile range of total costs, with the red line indicating the median and the green triangle denoting the mean. The y-axis is displayed on a logarithmic scale to accommodate the wide range of values. Indirect costs exhibit a highly right-skewed distribution across all scenarios, with extreme upward outliers pulling the mean considerably above the median. This wide spread primarily reflects the sensitivity of indirect costs to the ADT growth rate, as higher traffic volumes directly amplify associated user costs. In contrast, direct costs remain narrow and nearly identical across all scenarios, since they are governed by costs of repainting and replaced members rather than traffic volume and maintenance duration. Therefore, ADT fluctuations did not influence direct costs and the only source of variability in direct costs is the change in the discount rate. Across all scenarios, the mean indirect cost exceeds the mean direct cost, confirming that indirect costs constitute the dominant cost component.

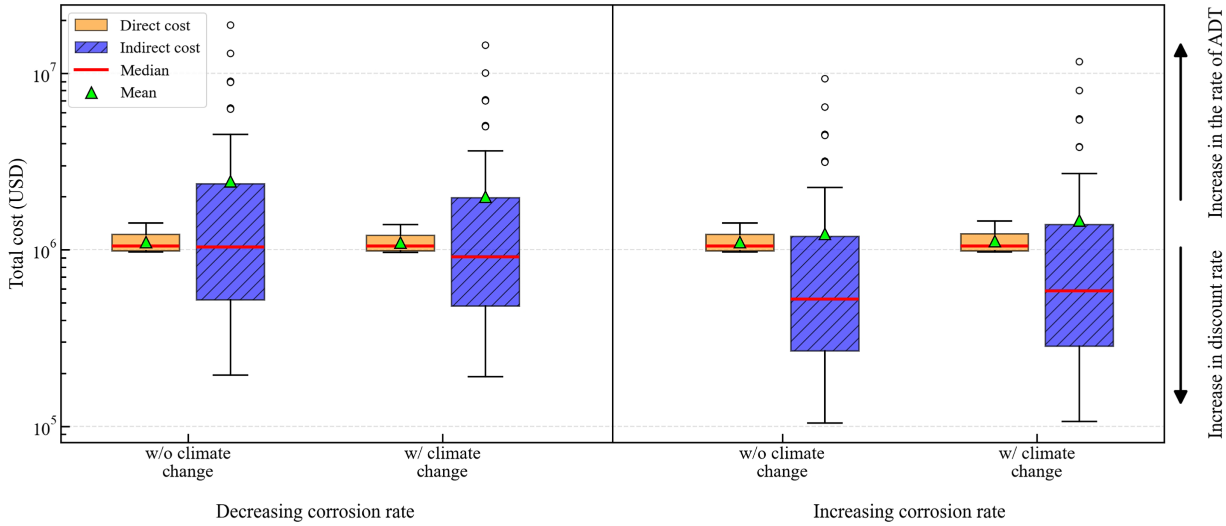

Figure 11: Direct and indirect cost distributions for the decreasing and increasing corrosion rate scenarios, with and without climate change.

Regarding the effect of climate change, the two scenarios exhibit opposing trends. In the decreasing corrosion rate scenario, the inclusion of climate change reduces the mean indirect cost compared to the without climate change scenario, consistent with lower long-term maintenance demands. In the increasing corrosion rate scenario, climate change increases the mean indirect cost, reflecting the compounding effect of an accelerating corrosion rate on maintenance expenditures.

6 Conclusions

This study proposed an adaptive maintenance management framework to address the effects of climate change–induced corrosion on steel truss bridges. In order to determine the efficacy of the proposed method, a steel truss bridge was examined for two different environments, considering varying corrosion rate projections due to climate change. Different maintenance alternatives were evaluated based on LCC, and the following conclusions were reached:

- The proposed framework successfully incorporated the impact of climate change-induced corrosion into the maintenance management of the steel truss bridge, enabling the identification of the most cost-effective maintenance strategy among the considered alternatives. Since the presented maintenance management framework is formulated in a general manner, it can be utilized for different corrosion rate projections under various climate change scenarios. As a limitation, the corrosion deterioration was modeled using a modified ISO 9224-based empirical formulation. While the adopted model provides a robust engineering-oriented approach, data-driven corrosion prediction techniques, including machine learning and explainable artificial intelligence frameworks, may further improve prediction capability under varying environmental conditions.
- LCC results of the numerical case study revealed that the increasing corrosion rate due to climate change necessitated additional EM, leading to higher total costs when 20-year and 25-year PM intervals were used. On the contrary, the decreasing corrosion rate due to climate change reduced the number of EM and total cost for 20-year and 25-year PM intervals. Besides, climate change-induced corrosion did not significantly affect the total maintenance cost of the steel truss bridge when frequent repainting with 15-year intervals was used. However, this maintenance alternative required a high number of PMs, resulting

in relatively high total cost. Consequently, 20-year full repainting intervals were determined to be the most cost-effective maintenance alternative for both climate change-induced corrosion scenarios and for the case of neglecting climate change.
- The effects of climate change-induced corrosion on steel bridge maintenance were assessed by incorporating economic and social indicators as varying discount rates and the increase rate in ADT. Lower discount rates combined with a higher increase rate in ADT significantly amplified the impact of climate change-induced corrosion. Consequently, the discount rate, the increase rate in ADT, and climate change effects collectively play a crucial role in determining the total cost.
- The proposed framework was implemented using representative climate change-induced corrosion projections to provide a practical engineering-oriented approach for maintenance decision-making. Future studies may incorporate uncertainty quantification methods and reliability-based approaches to evaluate the influence of climate projection variability on maintenance strategies.

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Availability of Data and Materials: The data that support the findings of this study are available from the Corresponding Author, [Mutlu Seçer], upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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