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Toward sustainable steel bridge maintenance: anti-corrosion coating systems

Nafiseh Ebrahimi, Misagh Khanlarian, Mojtaba Momeni, Leila Ahmadi, Danick Gallant

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Abstract The paper examines the significance of anti-corrosion coating systems for steel bridges within transportation networks, with a particular focus on their long-term sustainability. The study assesses the long-term sustainability of four coating systems, analyzing their performance, cost, and environmental impact over a hypothetical 75-year bridge lifespan. Key considerations include the service life of each coating system, the frequency and extent of maintenance required, the emission of volatile organic compounds (VOCs), and the broader social costs, such as public inconvenience due to maintenance activities. The research presents detailed data, equations for estimating costs, and methodologies for sustainability analysis in varying corrosive environments (C2, C3, and C5). The findings underscore the necessity of selecting low-VOC materials to minimize environmental impact, while also considering the efficacy of corrosion protection and the associated social impacts. This comprehensive approach aims to guide stakeholders in selecting the most sustainable corrosion protection strategies, ensuring relevance in diverse and evolving environmental and societal contexts.

Keywords Sustainability, Corrosion protection, Coating, VOC emission, Cost, Steel bridge

Abbreviations

VOC	Volatile organic compound
OZ	Organic zinc
MC	Moisture-cured
WB	Waterborne
DFT	Dry film thickness
SPC	Surface preparation cost
CMC	Coating material cost
A	Area
HSE	Health, safety, and environment
ADT	Average daily traffic
$C_{\mathrm{r,\ car}}$	Car operation cost
$\mathrm{TT_P}$	Percentage of trucks in ADT
$C_{\mathrm{r,\ truck}}$	Truck operation cost
D_{l}	Detour extra mileage
P_{t}	Percentage of the time for total closure
d_{t}	Duration of maintenance activities
C_{gas}	Gas unit cost
FC	Fuel consumption
C_{diesel}	Diesel unit cost
FCI	Fuel consumption increase
PPT	Persons per trip
C_{w}	Average hourly income
t_{w}	Daily working hours
PPA	Persons per accident
ANA	Average number of accidents
r_{injury}	Rate of injuries
RAI	Rate of accident increase

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r_d	Average recovery time
r_{damage}	Rate of property damage in road accidents
C_d	Average compensation value for property damage

Introduction

Bridge construction has been a cornerstone of human engineering for thousands of years. These structures are essential components of transportation networks, with their enduring performance and integrity vital for supporting residential, commercial, and economic activities over time. Following the invention of the Bessemer process in 1850, which revolutionized steel production by making it economically viable, steel started to establish itself as a primary material in bridge construction.[1,2] Now, steel bridges constitute 31% of highway bridges in the USA.[3]

Since the construction of the first steel bridge in Austria in 1828,[1] corrosion protection has been a critical consideration. While corrosion itself does not necessarily lead to structural failure, it remains a primary factor contributing to the deterioration of a steel infrastructure. This deterioration can significantly compromise structural integrity, making the infrastructure more susceptible to natural or human-made hazards.[4–6]

According to the National Association of Corrosion Engineers (NACE), corrosion inflicts approximately $2.5 trillion in economic damage annually, equivalent to 3.4% of the global GDP in 2013.[7] Each year, corrosion results in the loss of more than 10% of the world's annual production of metals used across various industries and services.[8] Moreover, corrosion not only affects the economy but also harms the environment by releasing contaminants and pollutants. It poses significant threats to society, impacting safety and causing widespread inconvenience, such as heavy traffic due to maintenance activities on transportation infrastructures.[9,10]

The corrosion resistance of steel bridges depends significantly on two main factors: macro-environment and micro-environment. The macro-environment consists of local weather conditions such as precipitation, sunlight, temperature, humidity, and levels of contaminants like chloride. On the other hand, the micro-environment includes metallurgical and structural considerations such as the type of material used, its mechanical and chemical properties, the bridge's orientation relative to roadway runoff or splash, stress conditions, and other relevant factors.[2,5,11] As a result, while each bridge is exposed to a single macro-environment, it may encounter multiple micro-environments based on its design and surrounding conditions.

While the micro-environment does affect the corrosion of steel bridges, these factors are primarily addressed during the bridge's design and manufacturing stages. Conversely, for protective coatings, it is the local environment or macro-environment surrounding the structure that significantly influences the corrosion rate of exposed steel and the degradation of the coatings. Therefore, when selecting coatings, it is crucial to prioritize considerations of the local environmental conditions.[2,11,12]

According to ISO 9223:2012, macro-environments are classified based on their corrosivity rate ranging from C1 (mild) to C5 (severe), with an additional category, C5M (severe marine) (Table 1).[11,13,14]

The service life of protective coatings is directly related to their exposure environment. Therefore, in some locations with less corrosivity, there might be several corrosion protection systems suitable, while in more corrosive locations, there may only be a few options.

Before 1970, the initial approach to corrosion protection for steel bridges involved the use of oil or alkyd-based paints containing lead or chromium pigments. One key benefit of these coatings is their cost-effectiveness and ease of application. However, the service life of lead-based paints in the marine environment is as few as 5 years.[1,15]

In the 1970s, a new generation of paints for steel bridges emerged in response to growing awareness of environmental and health risks associated with lead and chromium pigments. Despite their higher cost, zinc-rich primer three-coat systems were introduced to provide improved protection while minimizing environmental impact. Zinc-based primers provide longer-lasting corrosion resistance by sacrificially corroding the Zn component before the steel when exposed to moisture and air. These primers can be either organic or inorganic in origin. The typical expected service life, including total removal and replacement using a three-coat paint system, ranges from 15 to 30 years depending on environmental conditions, topcoat materials, and surface preparation.[15–17]

The primary concern with three-coat systems is the significant presence of volatile organic compounds (VOCs) found in the solvents used within these

Table 1: Carbon steel corrosion rates for macro-environment classifications based on ISO 9223:2012[14]

Environment	Carbon steel corrosion rate (mils/year)
C1	≤ 0.05
C2	< 1
C3	1–2
C4	2–3
C5	3–8
C5M	8–28

coatings. VOCs are known for their carcinogenic properties and high vapor pressures, leading to atmospheric vaporization and the formation of low-level ozone. The 1990 Clean Air Act Amendment in the US aimed to restrict ozone generation.[18] Globally, various regulations have been established to limit VOC concentrations in infrastructure coatings, including those used for steel bridges. In the US, architectural coatings are subject to a nationwide limit of 450 g/L, while the OZONE Transport Commission has set a stricter limit of 340 g/L for VOC content in coatings.[19] In Canada, under the Canadian Environmental Protection Act, the VOC concentration limit for industrial maintenance coatings is also set at 340 g/L.[20] These regulations marked the onset of a new era in steel bridge coating systems, prompting the introduction of low-VOC and zero-VOC coating alternatives. There is no universally accepted definition for "low-VOC" and "zero-VOC" terms, but paint manufacturers generally classify low-VOC products as containing between 50 g/L and 250 g/L, and zero-VOC products as containing less than 5 g/L VOC.[21] The evolution of low-VOC three-coat systems began in the 1990s. This shift toward low-VOC formulations prompted the development of waterborne coatings, initially introduced in the 1950s.[22] More recently, there has been a growing demand for advanced and cost-effective paint systems, leading to the development of two-coat and one-coat systems.[23,24]

While VOC concentration is crucial in coating systems, sustainability encompasses more than just this parameter. Society, economy, and environment form the three pillars of sustainability.[25] The United Nations (UN) Commission on Environment and Development defined sustainable development as meeting present needs without compromising future generations' ability to meet their own needs.[26] Sustainability has permeated every aspect of our lives, with the construction industry, contributing 13% to global GDP, receiving significant governmental attention. Sustainable construction must address not only ecological concerns but also economic factors like costs and construction timelines, as well as social aspects such as health and safety and local community needs.[27,28]

In bridge coatings, as in other areas of construction, sustainability is critical. While adhering to current VOC limit regulations offers an advantage in coating systems, lower VOC concentration alone does not ensure greater sustainability. Factors beyond VOC levels, such as the service life of the coating system, maintenance needs, and cost considerations, play significant roles in determining sustainability when selecting a coating.

This study aims to evaluate the long-term sustainability of four commonly used steel bridge liquid coating systems. These systems include three three-coat systems and one two-coat system, all of which are field-applicable for the maintenance of existing steel bridges. Metallic coatings and shop-based coatings such as inorganic zinc-rich primer coatings are excluded from consideration in this study.

Coating systems

In this analysis, we will refer to a coating system as a combination of surface preparation method, coating layer structure, and coating chemical composition.

Various factors, such as environmental conditions, surface preparation, and the type of coating, significantly influence the service life of the coating systems. It is crucial to choose a coating system based on the corrosive nature of the bridge's environment. In a less corrosive environment, a coating system with moderate corrosion protection and simpler surface preparation could last for decades at a lower cost. Conversely, employing the same system in a highly corrosive environment might necessitate coating removal and replacement every 5 years.[29]

Surface preparation

The initial preparation of the substrate's surface before coating application is the primary determinant of coating system quality. This process not only cleans the steel but also improves the adhesion of the coating. The leading guidelines for surface preparation are set by the society for protective coatings (SSPC), commonly referenced as Table 2 in industry standards.[30]

Various studies have demonstrated that improved surface preparation significantly extends the service life of coating systems. However, there exists a trade-off between the cost of surface preparation and the durability of the coating system.[23,29]

Coating materials and structure

Coating materials are classified into organic, inorganic, and metallic categories. These coatings may consist of single layers of any of these materials or multilayer combinations, all designed to enhance overall coating

Table 2: Standard methods for surface preparation as defined by the Society for Protective Coatings (SSPC)[30]

Surface preparation method	SSPC number
Solvent cleaning	SSPC-SP1
Hand tool cleaning	SSPC-SP2
Power tool cleaning	SSPC-SP3
White metal blast cleaning	SSPC-SP5
Commercial blast cleaning	SSPC-SP6
Brush off blast cleaning	SSPC-SP7
Near white metal blast cleaning	SSPC-SP10

protection.[31] These coating layers typically include multiple layers—primers and topcoats—that may originate from either organic or inorganic sources. Organic liquid coatings, comprising resins, binders, pigments, and additives, are widely utilized for corrosion protection. While inorganic zinc-rich primer liquid coatings and metallic coating systems offer superior corrosion resistance, organic liquid coatings have the advantage of being field-applicable, making them preferable over shop-based inorganic and metallic coatings for steel bridge maintenance projects. Additionally, liquid coatings are more cost-effective compared to metallic coatings. Waterborne coatings are a type of liquid coatings that utilize water as the main solvent, offering a low-VOC alternative to organic solvent-borne liquid coatings.[29,32] The selection between these coating types depends on factors such as the service environment of the steel bridge, the availability and cost of the coating materials, and the feasibility of renewal and repair during operation.

In this context, four commonly used coating systems were evaluated. However, it is important to note that the methodology was designed for compatibility with any 1-, 2-, or 3-coat system. One of these is a traditional three-coat system featuring an organic zinc-rich primer, an epoxy mid-coat, and a polyurethane topcoat, widely utilized in bridge coatings and extensively studied as a benchmark for evaluating other coating systems.[33] A moisture-cured three-coat system was chosen as an alternative to traditional zinc-rich primer three-coat systems, demonstrating particular effectiveness in high-moisture environments. These coatings offer extended protection and are less demanding in terms of surface preparation and application. However, their optimal performance relies on environments with abundant moisture content due to the curing process requirements.[34,35] The third option selected is a three-coat waterborne acrylic system that primarily utilizes water as solvent or dispersant. Waterborne systems significantly reduce VOC emissions compared to traditional solvent-borne coatings.[18,29,36] Finally, the two-coat system chosen mirrors conventional three-coat systems but with the removal of the mid-coat, aimed at achieving potential cost savings.[23,24]

The four coating systems selected for evaluation are as follows:

- Organic zinc (OZ)/epoxy/polyurethane (PU) three-coat system;
- Moisture-cured zinc-rich polyurethane (MC-Zn-PU)/moisture-cured urethane (MCU)/MCU three-coat system;
- Waterborne (WB) acrylic/WB acrylic/WB acrylic three-coat system;
- Organic zinc (OZ)/polyurethane (PU) two-coat system.

Table 3 displays the estimated service life of the coating systems for two different surface preparations—SP6 and SP10—along with their corresponding VOC concentrations.

Service life and VOC levels

Determining the service life of coating systems relies heavily on comprehensive databases documenting their real-world application over extended periods. A critical assessment of coating service life was undertaken by Brevoort et al. (1979), covering 89 different coating systems.[11] The study underwent subsequent updates in 1982, 1984, 1986, 1988, 1990, and 1996, drawing on input from coatings manufacturers, painting contractors, NACE, and the Society for Protective Coatings (SSPC).[38] The paper was subject to multiple revisions by various authors from 2006 to 2022, yet the service life estimates for conventional liquid coatings largely remained unchanged.[37,39,40]

While the service lives of conventional liquid coatings have remained relatively stable over the past 40 years, advancements such as lower VOC levels and innovative materials have improved coating formulations. The service lives provided in Table 3 are based on these consensus reports. However, the actual service life of a coating system depends on multiple factors, including application methods, manufacturing quality, surface preparation, and maintenance frequency. Therefore, the values in Table 3 should be considered general assumptions derived from industry surveys, with variations expected across different products.

Similarly, the VOC concentrations reported in Table 3 are estimated values derived from literature on similar coating systems, specifically aligned with those from Kogler's study (1997), which examined real-world coating applications. Table 4 presents the VOC concentration ranges for industrial liquid coatings available on the market, and the values used in Table 3 are also consistent with these ranges. It should be noted that these values are derived from various commercial products, but there may be specific products with VOC concentrations outside these ranges. Finally, the reported solid contents represent average values derived from the ranges of commercial products listed in Table 4.

It is important to note that coatings like WB acrylics, which have lower VOC concentrations and solid content, will result in a lower DFT than solid-rich paints when the same WFT is applied. If the volume solids content remains unchanged—ensuring the same DFT is achieved with a similar WFT—then using a lower VOC coating can reduce total VOC emissions for a given system. While many commercial products may have VOC levels other than the estimated VOC values presented in Tables 3 and 4, the focus of this study is to evaluate the impact of coating system selection—including its VOC level and service life—on cost and sustainability. The methodology used in this

Table 3: Estimated service life of coating systems in atmospheric exposure[29,32,37]

Coating system	Surface preparation	DFT (mils)	VOC (g/L)*	Volume of solids (%)	Environment	Practical service life (yrs)	Maintenance (yrs)	Remove & repaint (yrs)
OZ/Epoxy/PU	SP6	9	240/210/270	65/75/65	C2	19.50	29.25	39
					C3	15	22.50	30
					C5	12	18	24
	SP10				C2	28.50	42.75	57
					C3	19.50	29.25	39
					C5	13.50	20.25	27
MC-Zn-PU/MCU/MCU	SP6	9	335/335/340	65/65/65	C2	28.5	42.75	57
					C3	19.5	29.25	39
					C5	13.5	20.25	27
	SP10				C2	29	43.5	58
					C3	21	31.5	42
					C5	14	21	28
WB acrylic/WB acrylic/WB acrylic	SP6	6	75/75/75	45/45/45	C2	15	22.5	30
					C3	10.5	15.75	21
					C5	7.5	11.25	15
	SP10				C2	16.5	24.75	33
					C3	12	18	24
					C5	9	13.5	18
OZ/PU	SP6	7	240/270	65/65	C2	22.5	33.75	45
					C3	15	22.5	30
					C5	12	18	24
	SP10				C2	24	36	48
					C3	16.5	24.75	33
					C5	12	18	24

*The VOC contents are derived from cross-comparisons of values reported in Table 4 and References 29, 32, and 37

Table 4: VOC concentration and volume of solids ranges for commercially available liquid coatings

Liquid painting	VOC concentration range (g/L)	Volume of solids (%)
OZ primer	70–360	55–70
Epoxy	145–285	65–90
PU	230–340	60–70
MC-Zn-PU	330–340	60–70
MCU	330–340	60–70
WB acrylic	50–100	35–55

analysis, which forms the foundation of this paper, can also be applied to newer coating systems.

Coating maintenance schedule

While there are various protocols for maintaining steel bridges, they generally fall into three categories beyond the initial painting: spot painting, maintenance repainting (overcoating), and complete removal and repainting.

The data in Table 3 are based on the assumption that each coating system undergoes one cycle of spot painting and one cycle of overcoating before a complete removal and repainting. The practical service life is defined as the point at which 5 to 10% of the coating shows breakdown (according to SSPC-Vis 2 Rust Grade 4), signaling when spot painting should be performed.[40] Maintenance time is the period until the coating system requires overcoating (15–20% breakdown), estimated to be 1.5 times the practical service life. The cycle for removal and repainting is expected to occur approximately twice the practical service life of the coating system.[37,38]

Sustainability analysis

In the current study, the sustainability analysis of the coating systems focuses on the triple bottom line (TBL) of sustainability: cost, environmental impact, and social impact. To compare the sustainability of the four selected coating systems, a steel bridge with a total steel area of 100,000 ft^2 and a service life of 75 years was assumed. Calculations for each coating system were performed using both SP6 and SP10 surface preparation standards. In the presented scenarios, the coating materials used for spot painting, overcoating, and replacement are assumed to be the same as the original coatings. However, it is important to note that maintenance coatings do not necessarily have to match the original materials. The selection of maintenance coatings depends on various factors, including surface preparation requirements, compatibility with existing coatings, environmental conditions, and the concentration of soluble salts. The cost and environmental impact of applying each coating system to this bridge were evaluated based on the data presented in Table 3.

Cost considerations

Cost considerations play a crucial role in developing sustainable steel bridge coating systems. Conducting life cycle cost analyses for coating projects necessitate a comprehensive grasp of surface preparation and application expenses, coating material costs, local environmental conditions, available generic coating systems suitable for those conditions, and the anticipated service life of both the bridge and coating systems. These factors are essential for optimizing the return on the significant investment required for maintaining steel bridges[37,38] and are out of the scope of this analysis. The life cycle cost of coating maintenance for a structure refers to the total expenditure, calculated in present-day dollars, needed to sustain a bridge paint system for the entirety of its remaining useful life.[29]

The typical process of painting a bridge involves several key activities, such as surface preparation, paint application and material costs, waste cleanup and disposal, containment, workers health and safety programs, quality assurance, and access costs (including equipment mobilization, rigging, traffic control, and any impact on public access costs).[41] Each of these activities includes equipment, materials, and labor costs that must be carefully analyzed for cost assessment. Surface preparation and coating costs constitute only about 25% of the total maintenance expenses, highlighting the minimal savings that might result from opting for cheaper, yet less durable coatings compared to the overall cost incurred by earlier paint replacement.[29] Therefore, a critical question that must be

Table 5: Coating materials cost per 1 mil DFT[37]

Coating material	Coating cost ($/ft^2)	Spray cost ($/ft^2)*
WB acrylic, primer	0.099	0.141
WB acrylic, topcoat	0.105	0.150
Polyurethane, topcoat	0.106	0.152
OZ rich, primer	0.140	0.200
Zinc rich MC polyurethane, primer	0.133	0.189
MC urethane	0.100	0.143
Epoxy, intermediate	0.065	0.093

*The Coating cost is included in the Spray cost

Table 6: Surface preparation cost including equipment and labor costs[37]

Surface preparation	Cost ($/ft^2)
SP6	1.80
SP10	2.47

Table 7: Field application cost of coating materials including labor and equipment[37]

Method	Cost ($/ft^2)
One-pack by spray	0.55
Two-pack epoxies by spray	0.67
Two-pack urethanes by spray	0.72
Zinc rich primers by spray	0.79

addressed before conducting a life cycle analysis is the expected service life of the coating system in specific environmental conditions. Tables 5, 6, 7 show the cost of coating materials, surface preparations, and field applications, respectively. The spray cost reflects the material cost, incorporating a ca. 40% loss due to the spray process.

It has been proven that maintenance painting can extend the service life of steel bridge coatings. However, the expenses associated with maintenance painting have escalated due to factors such as labor costs, training requirements, and stricter regulations governing the removal and application of coatings. As a result, maintenance painting is often excluded from many transportations department work plans, leading to postponements until the entire bridge requires recoating.[41,42]

The coating costs include surface preparation, materials, application, and labor. It is assumed that the coating cost for spot painting, overcoating, and removal and replacement are 40%, 70%, and 135% of the original coating cost, respectively.[37,38]

The original coating cost for each coating system is the price of the coating cost for the new bridge which includes the surface preparation cost, coating material cost, and field application cost:

$$\text{Original cost} = (\text{SPC} + \text{CMC} + \text{FAC}) \cdot \text{A} \quad (1)$$

where SPC is surface preparation cost ($/ft^2), CMC is coating material cost ($/ft^2), FAC is field application cost ($/ft^2), and A is the total area needed to be coated (ft^2).

The coating cost during the 75-year service life of the bridge is the summation of the original cost, and the maintenance coatings which consist of spot painting, over coating, and removal and replacement:

$$\text{Coating cost} = (1 + 0.4n_1 + 0.7n_2 + 1.35n_3) \cdot \text{Original cost} \quad (2)$$

The number of times spot painting (n_1), overcoating (n_2), and paint removal and recoating (n_3) have to be repeated during the service life of the bridge is considered through variables n_1, n_2, and n_3, respectively.

The project cost for each coating system over the 75-year service life of the bridge includes the coating cost as well as access and HSE (health, safety, and environment) costs. Access costs cover equipment mobilization, rigging, traffic control, and any impacts on public access and commerce. HSE costs encompass worker health, environmental monitoring, waste disposal, and containment expenses. Always throughout the 75-year service life, Kogler et al.[29] estimated HSE costs to be 3 times the coating cost for a three-coat OZ-epoxy-polyurethane system in a SP10 environment (equation 3); this specific HSE cost estimate serves as the baseline for all coating systems.

$$\text{Access \& HSE cost} = 3(1 + 0.4n_1 + 0.7n_2 + 1.35n_3) \cdot \text{Original cost OZ/Epoxy/PU in SP10} \quad (3)$$

In this context, as expressed in Eq. 4, the project cost for the OZ/Epoxy/PU system with SP10 surface preparation in a C2 environment is the coating cost plus three times the coating cost (to cover access and

HSE expenses). If the waterborne (WB) acrylic/WB acrylic/WB acrylic three-coat system is considered, the project cost would encompass the coating cost of this system along with the access and HSE costs calculated for the OZ-epoxy-polyurethane system, assuming SP10 surface preparation in the same environment.

$$\begin{aligned}\text{Project cost} &= \text{Coating cost} + \text{Access \& HSE cost}\\ &= (1+0.4n_1+0.7n_2+1.35n_3)\\ &\quad\cdot \text{Original cost}\\ &\quad+3(1+0.4n_1+0.7n_2+1.35n_3)\\ &\quad\cdot \text{Original cost of OZ/Epoxy/PU in SP10}\end{aligned} \tag{4}$$

Environmental analysis

The bridge maintenance process involves several processes that each has its own environmental footprint, and a comprehensive understanding of those effects demands a thorough life cycle analysis (LCA) which is out of scope of this work. Nonetheless, the majority of coating application processes are comparable across different types of coatings. In this study, one of the variables is the chemistry of the coating. The examined coatings contain volatile compounds, with levels varying between the different coatings analyzed. Therefore, in this study, our analysis focuses solely on the VOC emissions generated during the coating application process.

For VOC emissions calculations, it is assumed that for all systems, except the two-coat OZ/polyurethane system, both the mid-coat and topcoat are replaced during the overcoating process. For the two-coat system, only the topcoat is replaced. VOC emissions from spot painting are excluded from calculations, as their contribution to the total VOC emissions is expected to be negligible.

The VOC emissions (in kg) for a coating layer—primer, mid-coat, or topcoat—in each coating system are given as follows:

$$\text{VOC emissions}_{\text{layer}} = \frac{\text{DFT}}{\text{Volume of solids}/100}\cdot \text{A}\cdot \text{VOC} \tag{5}$$

where DFT is the dry film thickness of the layer (m), volume of solids is the percentage of solids in the total wet volume of the coating layer (%), A is total area to be coated (m^2), and VOC is the volatile organic concentration of the material (kg/m^3).

The VOC emissions of the coating system is the summation of the VOC emissions of all coating layers including primer, mid-coat, and topcoat:

$$\text{VOC emissions}_{\text{coating}} = \sum\nolimits_1^m \text{VOC emissions}_{\text{layer}_\text{m}} \tag{6}$$

where m is the number of layers.

The total VOC emission of the three-coat system during the 75-year service life of the bridge is given by equation (7) based on the number of overcoating sequences (n_2), and total removals and replacements (n_3) required in that period:

$$\begin{aligned}\text{Total VOC emissions} = {} & (1+n_3)\text{VOC emission}_{\text{coating}}\\ & +(n_2)(\text{VOC emission}_{\text{mid-coat}}\\ & +\text{VOC emission}_{\text{topcoat}})\end{aligned} \tag{7}$$

The factor $1 + n_3$ accounts for both the initial coating process and the subsequent removal and replacement cycles. The formulation derived above is helpful to understand the total VOC emissions resulting from coating maintenance throughout the bridge lifetime.

Social analysis

Bridge coating maintenance services have several social impacts. On the positive side, they enhance public safety by ensuring bridges remain structurally sound, reducing the risk of accidents. These projects also create job opportunities, contributing to local economic growth. Additionally, proper maintenance extends the lifespan of bridges, ensuring they remain functional and safe for longer periods, while also improving the esthetic appeal of the area, which can boost community pride and attract tourism. Despite these positive points, the coating maintenance services for the bridge also have negative societal impacts. These impacts, resulting from policies, incidents, or other social changes, can be quantified as social costs, which represent the external costs borne by the public rather than the project stakeholders. Social costs are often overlooked in sustainability analyses. They can be categorized into two main groups: direct social impacts and indirect social impacts. Direct social impacts are factors that affect each individual personally, while indirect social impacts are factors that influence society as a whole, with individuals experiencing these effects indirectly. These include various parameters such as the physical, psychological, and economic conditions of affected individuals (e.g., builders and infrastructure users), as well as changes to human settlements, socioeconomic conditions, and social resources.[43–45]

In the context of coating maintenance services for steel bridges, the social impacts are primarily assessed through the personal economic conditions of bridge users. However, direct social impacts extend beyond these costs. Other effects include physical and psychological impacts from road closures and traffic control. In order to consider these social costs, the number of disabilities caused by the accidents during the construction and the value of statistical life in the target society should be considered. Additionally, indirect impacts—such as the influence of construction noise on property values, the coating project's effects on socioeconomic conditions, or social resources—are either not applicable or deemed negligible in the context of a coating project. This study evaluates the social costs of bridge coating projects in terms of: (i) extra fuel and vehicle operation costs, (ii) travel delay cost, (iii) income loss cost, and (iv) property damage cost, assuming no fatality happens due to the accidents during the coating projects. Including additional social impacts would obviously increase the overall social cost of the project.[46]

The following scenario was designed to illustrate the social costs associated with a typical maintenance project. In this scenario, the social cost values are calculated for a bridge maintenance project impacting a 4.57 km stretch of a four-lane road. It is assumed that during 90% of the maintenance period, the bridge is partially closed, allowing only two lanes to remain in service. During the remaining 10% of the maintenance period, the bridge is completely closed, requiring traffic to use a 5 km detour.

The additional vehicle operation costs due to the detour, for the duration of the maintenance, can be calculated as follows: [43,46]

$$\text{Extra vehicle operation cost} = \left[C_{\text{r.car}}\left(1-\frac{\text{TT}_{\text{P}}}{100}\right) + C_{\text{r,truck}}\left(\frac{\text{TT}_{\text{P}}}{100}\right)\right]D_{1} \cdot \left(\frac{P_{\text{t}}}{100}\right) \cdot \text{ADT} \cdot d_{\text{t}} \tag{8}$$

where $C_{\text{r,car}}$ and $C_{\text{r,truck}}$ are the operation cost of cars and trucks ($/km/vehicle), TT_{P} is the percentage of trucks in daily average traffic (%), D_1 is the extra mileage caused because of detour (km), P_{t} is the percentage of the time that the road is totally closed (%), ADT is the average daily traffic (vehicle/day), and d_{t} is the duration of maintenance activities (day).

The extra fuel cost resulting from frequent speed changes caused by the maintenance activities is given as follows:

$$\text{Extra fuel cost} = \left[\left(1-\frac{\text{TT}_{\text{P}}}{100}\right)\left(\frac{\text{FC}_{\text{car}}}{100}\right)C_{\text{gas}} + \left(\frac{\text{TT}_{\text{P}}}{100}\right)\left(\frac{\text{FC}_{\text{truck}}}{100}\right)C_{\text{diesel}}\right]L \cdot \text{ADT} \cdot d_{\text{t}} \cdot (1-\frac{P_{\text{t}}}{100}) \cdot (\frac{\text{FCI}}{100}) \tag{9}$$

where FC_{car} and FC_{truck} are the fuel consumption for cars and trucks, respectively (L/100 km/vehicle), L is the length of the bridge (km), FCI is the fuel consumption increase resulting from sudden braking and frequent changes in speed (%), and C_{gas} and C_{diesel} is the unit cost of gas and diesel ($/L).

The extra vehicle cost is given in equation (10) as the summation of extra vehicle operation and fuel costs:

$$\begin{aligned}\text{Extra vehicle cost} = {} & \text{Extra vehicle operation cost} \\ & + \text{Extra fuel cost}\end{aligned} \tag{10}$$

Bridge maintenance and lane closures result in travel delays for commuters, leading to extended travel times and, consequently, a loss of productive working hours. The travel delay cost is calculated as follows:

$$\text{Travel delay cost} = \left[\text{PPT}_{\text{car}}\left(1-\frac{\text{TT}_{\text{P}}}{100}\right) + \text{PPT}_{\text{truck}}\left(\frac{\text{TT}_{\text{P}}}{100}\right)\right] \cdot \text{ADT} \cdot d_{\text{t}} \cdot C_{\text{w}}\left(t_{\text{loss,detour}} \cdot \left(\frac{P_{\text{t}}}{100}\right) + t_{\text{loss,lane reduction}} \cdot \left(1-\left(\frac{P_{\text{t}}}{100}\right)\right)\right) \tag{11}$$

where PPT_{car} and $\text{PPT}_{\text{truck}}$ represent the number of persons per trip for cars and trucks (person), respectively, C_{w} is the average hourly income ($/h), and $t_{\text{loss,detour}}$ (see equation 12) and $t_{\text{loss, lane reduction}}$ (see equation 13) (in hour/person) are the time losses caused by the detour and lane reduction, respectively.

$$t_{\text{loss,detour}} = \left(\frac{L + D_1}{\text{speedlimit}_{\text{detour}}}\right) - \left(\frac{L}{\text{speedlimit}_{\text{regular}}}\right) \tag{12}$$

$$t_{\text{loss,lane reduction}} = \left(\frac{n_{\text{lane,regular}}}{n_{\text{lane,construction}}}\right)\left(\frac{L}{\text{speed limit}_{\text{construction}}}\right) - \left(\frac{L}{\text{speed limit}_{\text{regular}}}\right) \tag{13}$$

Another social cost associated with the maintenance is income loss. This cost originates from lost work hours due to increased accidents and resulting injuries in the maintenance zone.[45,47,48] The income loss cost can be calculated as follows:

$$\text{Income loss cost} = \text{PPA} \cdot (\text{ADT} \cdot d_{\text{t}}) \cdot (\left(\frac{\text{ANA}}{365}\right) \cdot d_{\text{t}}) \cdot r_{\text{injury}} \cdot \text{RAI} \cdot d_{\text{r}} \cdot C_{\text{w}} \cdot t_{\text{w}} \tag{14}$$

where PPA is the number of persons per accident (person/accident), ANA is the average number of accidents in road trips (accidents/vehicle/year), r_{injury} is the rate of injury in the accidents, RAI is the rate of increase in accidents during construction, t_{w} is the number of daily working hours (h/day), and d_{r} is the average recovery time (day/person).

The last social cost associated with bridge maintenance is the property damage cost, specifically damage to vehicles. The increased number of accidents on the road due to maintenance leads to vehicle damage, adding an additional expense for travelers.[49] This increase in the number of accidents causes an additional cost that can be calculated as follows:

$$\text{Property damage cost} = (\text{ADT} \cdot d_t) \cdot \left(\frac{\text{ANA}}{365} \cdot d_t\right) \cdot r_{\text{damage}} \cdot \text{RAI} \cdot C_d \tag{15}$$

where r_{damage} represents the rate of property damage specific to collisions in road accidents and C_d denotes the average compensation value for property damage ($).

The total social cost (equation 16) is the sum of extra vehicle (equation 10), travel delay (equation 11), income loss (equation 14), and property damage (equation 15) costs.

$$\begin{aligned}\text{Social cost} &= \text{Extra vehicle cost} + \text{Travel delay cost} \\ &\quad + \text{Income loss cost} \\ &\quad + \text{Property damage cost}\end{aligned} \tag{16}$$

In the scenario outlined in this paper, the social costs were calculated using the values provided in Tables 8 and 9, which detail the maintenance duration and other social cost parameters.

The values reported in Tables 8 and 9 are case sensitive and can be determined based on the project size, and government surveys and reports. The maintenance duration values in Table 8 are part of the scenario assumed for this study. However, except for the arbitrary values assumed for the purpose of this study, the other parameters in Table 9 such as car and truck operation costs, average number of accidents, rate of injuries, and average hourly income are derived from reports, surveys, and statistics for North America.

Analysis results

The project cost (see equation 4), VOC emissions (equation 7), and social costs (equation 16) for each coating system are determined based on the required number of spot paintings, overcoating, and total removals and replacements during the bridge's 75-year service life. The maintenance schedules are detailed in Tables 11, and 12. It is important to note that maintenance timing depends on the estimated service intervals. Additionally, the decision to perform maintenance is influenced by the remaining service life of the bridge. For instance, for the OZ/epoxy/polyurethane system in a C2 environment with surface preparation SP6, the schedule presented in Table 10 includes two spot paintings, one overcoating, and one total removal and replacement. According to Table 3, this means one spot painting is planned after 19.5 years, one overcoating after 29.25 years, one total removal and replacement after 39 years, and another spot painting after 19.5 years. Although theoretically another overcoating is due 29.5 years after the 1st removal and replacement (at this point, the bridge age would be 68.5 years), it is not carried out because the bridge's remaining estimated service life is less than 7 years at that point.

Before presenting the discussion of the results, it is beneficial to present a graphical summary of the data provided in Tables 10, 11, and 12. To ensure clarity and provide a concise overview, only the results for the surface preparation methods that offer the most sustainable option for each of the C2, C3, and C5 environments are shown in Figs. 1, 2 and 3, which are the SP6 surface pretreatment for the C2 environment, and the SP10 approach for the C3 and C5 environments. Readers are encouraged to refer to Tables 10, 11, 12 for information on other conditions.

In each of Figs. 1, 2 and 3, all four coating systems are depicted. In the a) panels, the maintenance timeline is visually represented. An arrow indicates the 75-year lifespan of the hypothetical steel bridge, while markers show the maintenance activities required for each coating system during this period. The colors denote the type of maintenance: green for spot painting, blue for overcoating, and red for remove-and-replace maintenance. At the bottom of each figure, the total VOC emissions, project cost, and social cost are summarized (please note that the y-axis on the left is presented on a logarithmic scale). This graphical illustration aids readers in comprehending the discussion that follows.

Discussion

This study investigated the sustainability of anti-corrosion systems for steel bridge infrastructures. Various coating systems were evaluated, with a focus on the cost of maintenance over the hypothetical 75-year lifespan of a bridge, total VOC emissions, and social costs. The primary parameters considered in the coating systems included surface preparation methods, coating structure, and composition. These systems were further examined across three different corrosive environments: C2 (benign), C3 (moderate), and C5 (highly corrosive).

Table 8: Duration of the maintenance stages

Maintenance	Duration (days)
Spot painting	30
Over coating	90
Remove and replace	180

Table 9: Social cost parameters

Parameter	Value	Reference
Average daily traffic (ADT)	30,000 (vehicle/day)	Assumption
Car operation cost ($C_{r,\ car}$)	0.45 ($/km/vehicle)	50
Truck operation cost ($C_{r,\ truck}$)	1.50 ($/km/vehicle)	51
Detour extra mileage (D_l)	5 (km)	Assumption
Percentage of trucks in ADT (TT_P)	5 (%)	Assumption
Fuel consumption for cars (FC_{car})	13 (L/100 km/vehicle)	Assumption
Fuel consumption for trucks (FC_{truck})	40 (L/100 km/vehicle)	Assumption
Gas unit cost (C_{gas})	0.90 ($/l)	Assumption
Diesel unit cost (C_{diesel})	1.00 ($/l)	Assumption
Fuel consumption increase (FCI)	25 (%)	52
Percentage of the time for total closure (P_t)	10 (%)	Assumption
Average recovery time for one person injured (d_r)	7 (day/person)	Assumption
Average hourly income (C_w)	19.30 ($/hr)	Assumption
Daily working hours (t_w)	7.5 (h/day)	Assumption
Persons per trip for cars (PPT_{car})	1.5 (person/vehicle)	52
Persons per trip for trucks (PPT_{truck})	1.0 (person/vehicle)	Assumption
Persons per accident (PPA)	1.0 (person/accident)	Assumption
Speed $limit_{regular}$	80 (km/h)	Assumption
Speed $limit_{construction}$	50 (km/h)	Assumption
Speed $limit_{detour}$	80 (km/h)	Assumption
$n_{lane,\ regular}$	4	Assumption
$n_{lane,\ construction}$	2	Assumption
Average number of accidents (ANA)	0.021 (accident/vehicle/year)	53
Rate of injuries (r_{injury})	0.28	53
Rate of accident increase (RAI)	0.25	52
Rate of property damage in road accidents (r_{damage})	0.71	53
Average compensation value for property damage (C_d)	4711 ($/accident)	54

Table 11: Estimated VOC emissions, and coating, project and social costs of the coating systems in a C3 environment

Coating system	Surface prep	DFT (mils)	# of spot painting/ overcoating/remove and replace	Total VOC emissions (kg)	Coating cost (M$)	Project cost (M$)	Social cost (M$)
OZ/epoxy/polyurethane	SP6	3/3/3	2/2/2	3245	3.1	13.7	192
	SP10		2/1/1	2000	2.3	9.2	101
MC Zn-rich polyurethane/ MC urethane/MC urethane	SP6	3/3/3	2/1/1	2935	2.1	9.0	101
	SP10		2/1/1	2935	2.4	9.3	101
WB acrylic/WB acrylic/WB acrylic	SP6	2/2/2	3/3/3	1416	3.6	18.6	287
	SP10		3/3/2	1180	3.5	16.1	219
OZ/polyurethane	SP6	3/4	2/2/2	2745	2.7	13.3	192
	SP10		2/2/2	2745	3.1	13.7	192

In this section, we will discuss the results obtained from the development of the selected scenarios. It is important to clarify that the primary objective of this study is not to endorse or reject any specific type of coating for application. Instead, the aim is to provide a methodological analysis that assists decision-makers in selecting protective coatings based on their objectives and policies. Consequently, the results presented in this analysis—and those discussed in this section—are categorized according to the three pillars of sustainability: cost, society, and environment. Ultimately, it is the responsibility of bridge designers and owners to assign appropriate weight to each of these pillars when selecting a coating system. However, for the purpose of

Table 12: Estimated VOC emissions, and coating, project and social costs of the coating systems in a C5 environment

Coating system	Surface prep	DFT (mils)	# of spot painting/ overcoating/remove and replace	Total VOC emissions (kg)	Coating cost (M$)	Project cost (M$)	Social cost (M$)
OZ/epoxy/polyurethane	SP6	3/3/3	3/3/2	3738	3.7	16.3	219
	SP10		3/2/2	3245	3.8	15.1	196
MC Zn-rich polyurethane/ MC urethane/MC urethane	SP6	3/3/3	3/2/2	4770	3.4	14.8	196
	SP10		3/2/2	4770	3.9	15.2	196
WB acrylic/WB acrylic/WB acrylic	SP6	2/2/2	5/5/4	1966	5.2	26.5	410
	SP10		4/4/3	1573	4.7	21.7	314
OZ/polyurethane	SP6	3/4	3/3/2	3137	3.2	15.7	219
	SP10		3/3/2	3137	3.6	16.2	219

Table 10: Estimated VOC emissions, and coating, project and social costs of the coating systems in a C2 environment

Coating system	Surface prep	DFT (mils)	# of spot painting/ overcoating/ remove and replace	Total VOC emissions (kg)	Coating cost (M$)	Project cost (M$)	Social cost (M$)
OZ/epoxy/polyurethane	SP6	3/3/3	2/1/1	2000	2.1	9.0	101
	SP10		1/1/1	2000	2.1	8.3	96
MC Zn-rich polyurethane/ MC urethane/MC urethane	SP6	3/3/3	1/1/1	2935	1.9	8.1	96
	SP10		1/1/1	2935	2.1	8.3	96
WB acrylic/WB acrylic/WB acrylic	SP6	2/2/2	2/2/2	1023	2.6	13.2	192
	SP10		2/2/2	1023	3.0	13.5	192
OZ/polyurethane	SP6	3/4	1/1/1	1699	1.6	7.8	96
	SP10		1/1/1	1699	1.8	8.0	96

this study, the option that emits the least VOCs, incurs the lowest cost for corrosion protection, and imposes the smallest social cost will be identified as the most sustainable.

VOC emissions

It is important to note that this analysis of environmental impact focuses solely on the VOC emissions from coating systems. Other factors, such as increased CO_2 emissions due to idling vehicles in traffic congestion or emissions from maintenance vehicles, were not included. To fully understand the environmental effects of the maintenance process, conducting a life cycle assessment (LCA) is necessary. Nevertheless, LCA is the subject of another investigation and in this work, we solely focused on VOC emissions calculations presented above from the painting process and infrastructure maintenance.

The primary source of VOC emissions are the materials used in the primer, intermediate, and topcoats. Therefore, the type of material and the number of applications directly influence the overall VOC emissions over the lifetime of the bridge. All coatings investigated in this analysis met the VOC emissions requirements for coating materials [20]. However, they included a range of materials with varying levels of VOC emissions, from waterborne acrylics, which have low VOC contents, to moisture-cured zinc-rich polyurethane, which has comparatively high VOC emissions.

The first key observation is that, regardless of environmental corrosivity (C2, C3, C5), following the maintenance schedule for the coating system reveals that the moisture-cured zinc-rich polyurethane system is the highest emitter of VOCs (see Figs. 1, 2 and 3). In contrast, waterborne coatings emitted the least VOCs over the 75-year lifespan of the bridge in all C2, C3, and C5 environments. This finding reinforces the idea

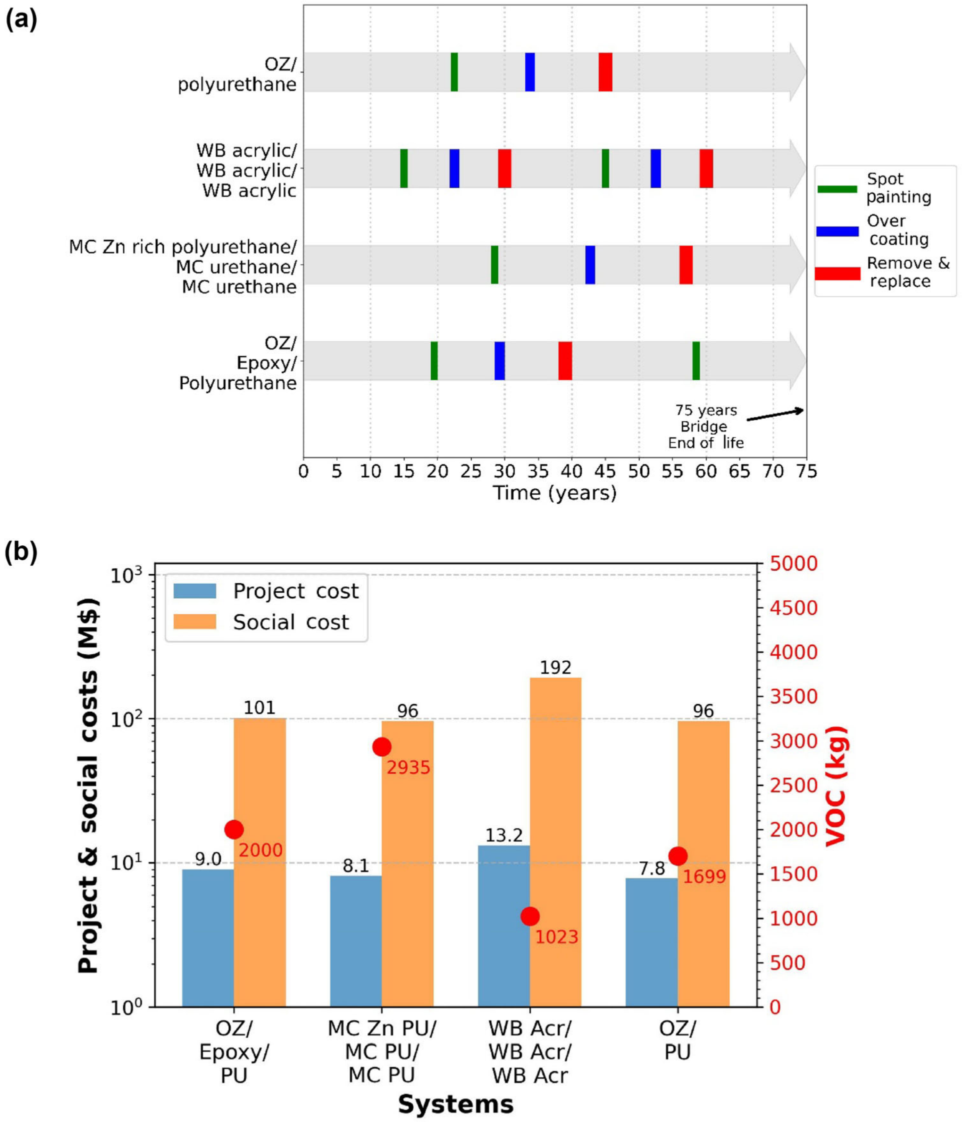

Fig. 1: Sustainability analysis of coatings in a C2 environment with SP6 surface preparation: (a) the timeline for the maintenance services and (b) cost and VOC emissions

that low-VOC coatings can provide a low-VOC anticorrosion solution, while also considering the varying maintenance requirements of different coating chemistries. The frequency of maintenance events emerges as a critical factor in selecting a coating system with low VOC emissions, particularly for overcoating and remove-and-replace maintenance processes. In the most aggressive environment, C5, waterborne coatings provide a significant advantage, emitting 50% less VOCs than the second lowest emitter. In C2 and C3 environments, waterborne products also demonstrate a clear benefit, reducing VOC emissions by 40% and 41%, respectively, compared to the second lowest emitter. Although waterborne coatings offer superior VOC reduction compared to other options, they come with significantly higher lifecycle costs (see Section "Cost considerations").

This analysis demonstrates the importance of considering the environmental context of the bridge when choosing a coating system. The results determine that while the VOC content of the coating materials plays a significant role in the total VOC emissions of the protective system, the level of corrosion protection provided by the coating, and consequently the required maintenance, are also critical factors that require the attention of designers.

Cost considerations

The analysis conducted in this work aimed to identify the main factors contributing to the overall cost of a bridge coating system. The costs associated with maintaining a bridge's coating system extend beyond

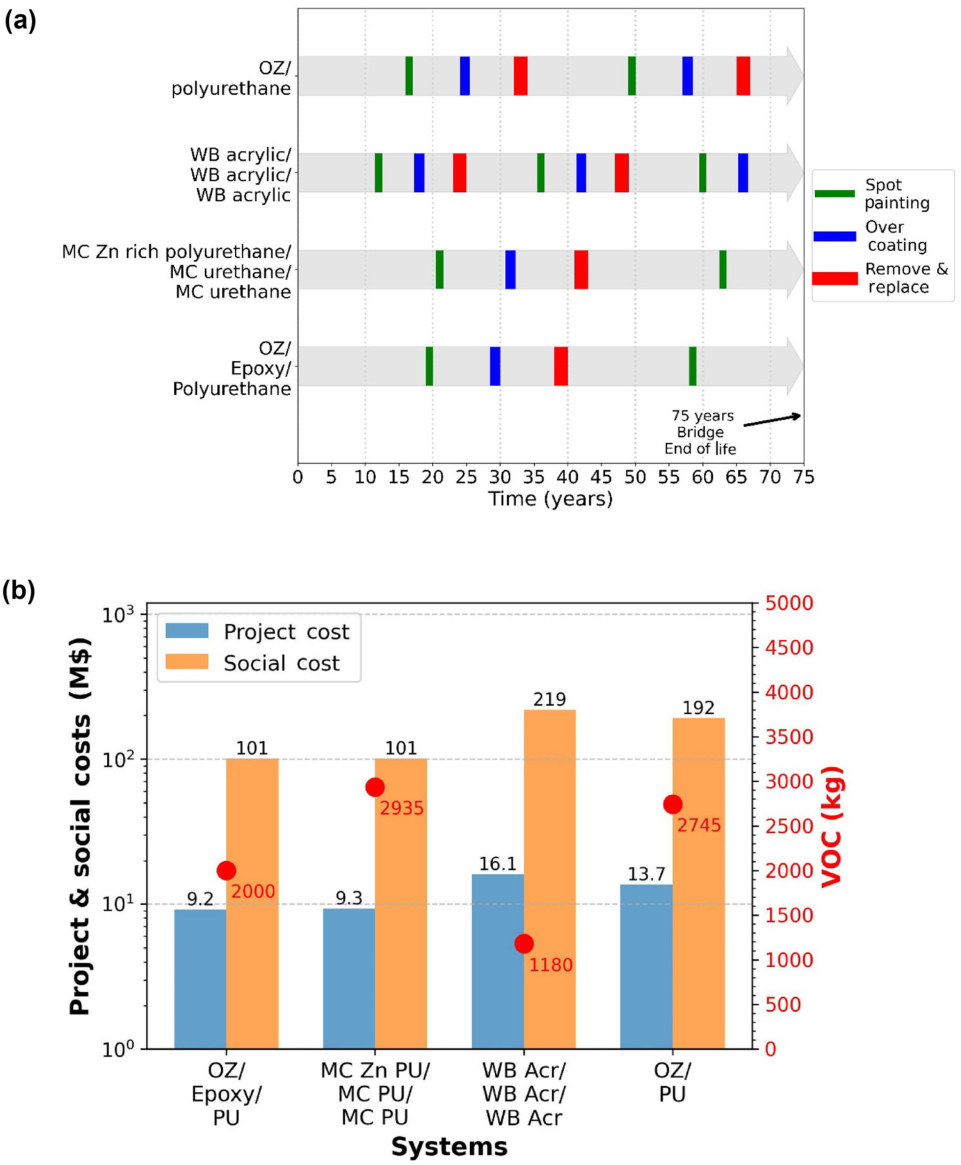

Fig. 2: Sustainability analysis of coatings in a C3 environment with SP10 surface preparation: (a) the timeline for the maintenance services and (b) cost and VOC emissions

just the materials and application. They include expenses related to surface preparation, waste disposal, containment, and worker safety.[37,38]

The cost analysis presented here is based on factors examined in this study. Although one might argue that other parameters, such as coating thickness, could influence the cost analysis, these were not included due to insufficient literature or field studies. Including such parameters would have introduced additional complexity, making the analysis of the results more confusing. Nevertheless, further research is encouraged to generate more reliable data for similar analyses that could include additional parameters. Lastly, this section will discuss the results in a manner that helps readers understand how the omitted parameters might influence the cost of corrosion protection. It is important to remember that the cost considerations presented here are solely based on the project costs detailed in Tables 10, 11, 12, and Figs. 1, 2, 3. Social costs will be discussed in the next section.

The results, derived from three different corrosive environments, reveal that the coating system—encompassing surface preparation, layered structure, and chemistry—significantly influences the total project cost. One of the main factors contributing to cost analysis is the price of the coating materials. As shown in Table 5, the coating materials investigated in this analysis are mostly comparable in terms of pricing. This initial high material cost can translate into an overall high maintenance cost if all other factors, such as the mid-coat, topcoat, and maintenance schedule, remain the same. However, as shown in Figs. 1, 2 and 3,

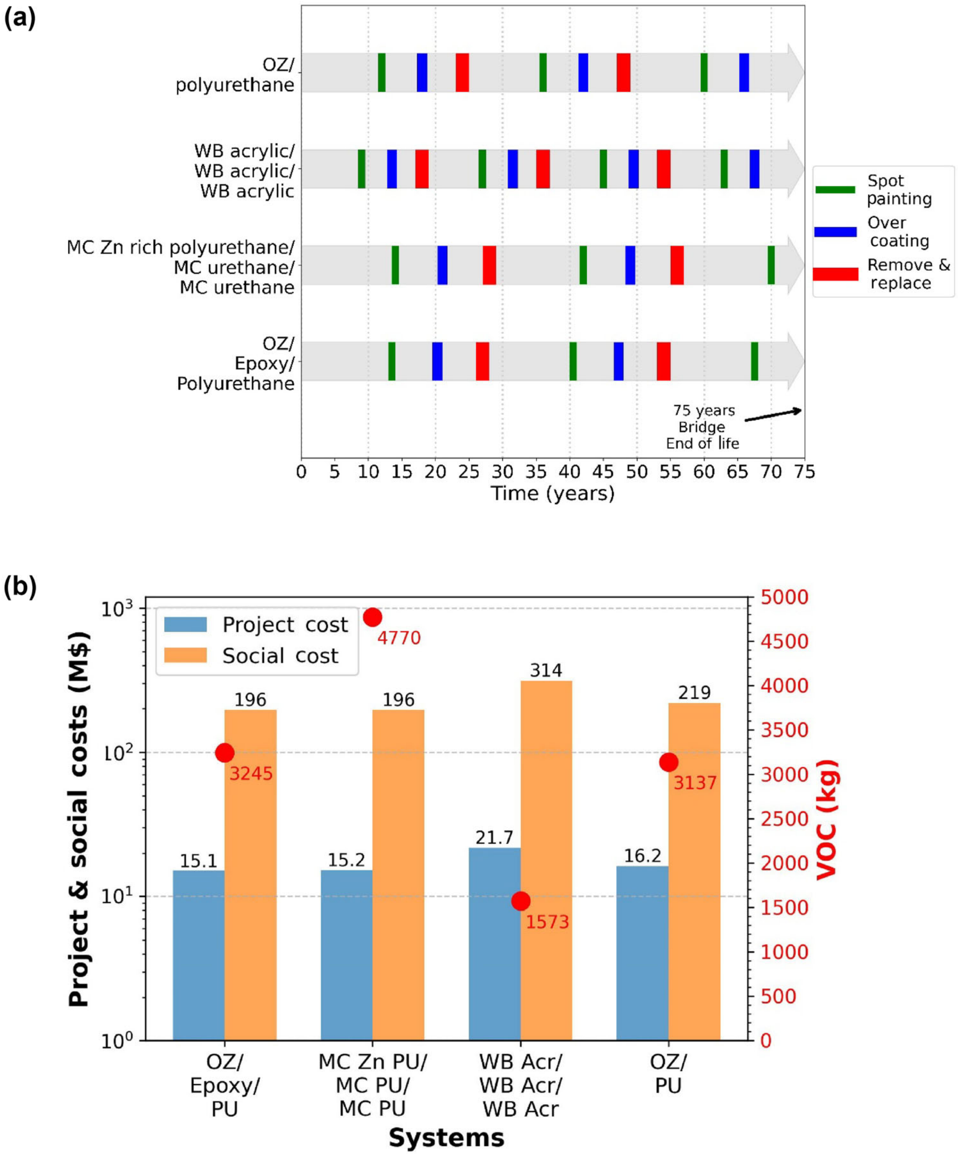

Fig. 3: Sustainability analysis of coatings in a C5 environment with SP10 surface preparation: (a) the timeline for the maintenance services and (b) cost and VOC emissions

coatings containing organic zinc primers (the two-coat system in the C2 environment and the three-coat system in the C3 and C5 environments) result in project costs that are nearly identical to those using the zinc-rich moisture-cured polyurethane primers. The primary reason lies in the other costs associated with the coating system.

As highlighted in Kogler's work,[10] coating materials, surface preparation, and coating application collectively account for only 25% of the total project cost, aligning well with the findings presented in this study. For example, the pie charts in Fig. 4 show the proportion of material costs compared to other associated costs for a coating system in a C5 environment with an SP10 surface finish. The data reveals that only about 4–6% of the project cost is due to the material itself, 10–11% of the costs are assigned to surface preparation, and 6–9% to coating application; the rest (75–78%) is attributed to access and HSE costs.[28] When comparing the relative costs of the four coating systems analyzed in this study, Figs. 1, 2 and 3 reveal that, overall, in aggressive C3 and C5 conditions, the OZ/Epoxy/Polyurethane three-coat system demonstrates a cost advantage. Its closest competitor, the moisture-curing system, is priced at a similarly low cost but exhibits significantly higher VOC emissions (32% more VOCs than the OZ/Epoxy/Polyurethane system, in both C3 and C5 environments). Additionally, it is important to note that regardless of the environmental conditions or coating system used, the results of this simulation (with most values summarized in Tables 8 and 9) indicate that social costs are approximately an order of magnitude higher than the project costs. This highlights the significant impact of social factors in the overall cost evaluation.

Another important factor in evaluating the cost of a coating system is ensuring that the level of protection provided by the coating is suitable for the environment in which it will be applied. It is well established that surface preparation significantly impacts coating performance.[55] However, as demonstrated in the C2 environment, even an SP6 surface finish can provide satisfactory corrosion protection over the lifespan of a bridge. Opting for the less expensive SP6 finish, rather than the more costly SP10 option, can effectively reduce surface preparation costs. Although other coating systems may offer superior corrosion protection compared to a two-coat system with an SP6 surface finish in a C2 environment, the additional costs associated with their application may be unnecessary.

As previously mentioned, not all parameters were considered in this analysis. However, the discussion above highlights two key points. First, the higher initial cost of a coating component may become less significant when viewed in the context of all the steps and expenses required to ensure a 75-year lifespan. Second, overprotecting a bridge can led to increased costs without offering substantial additional benefits. This second point should be approached with caution, as designers must always prioritize safety when making decisions.

Social impact considerations

Traditional LCCA and LCA frameworks primarily focus on economic and environmental factors, often overlooking the significant social impacts. This oversight can lead to suboptimal decision-making that fails to account for broader impacts on communities and individuals. It is important to recognize that the historical development of infrastructures, such as bridges, has been driven by societal demands. Therefore, when deciding to build a bridge or develop a corrosion maintenance protocol, it is essential and unavoidable to consider the social impacts of these decisions.

In this study, social impacts were systematically classified to evaluate how corrosion protection projects affect society. The analysis focused solely on direct impacts, while indirect impacts were omitted and out of the scope of this analysis. By monetizing these social impacts, this study provides a framework for translating them into quantifiable social costs.

The analysis results highlight that time is the most significant factor impacting society. One of the key objectives of Figs. 1a, 2a and 3a is to illustrate the intensity of bridge maintenance requirements, particularly in aggressive C5 environments. The downside of this maintenance, as demonstrated through the equations presented in this paper, is its association with high social costs. For example, waterborne coating systems, while offering low VOC emissions, require the most frequent maintenance and consequently impose the highest social costs. Each maintenance event partially or completely restricts public access to the bridge, causing those who rely on the bridge to travel to spend more time and/or money, as they may face delays or increased accident risks in construction zones.

This social cost analysis supports the conclusions drawn from the cost analysis: maintaining a bridge's anti-corrosion system requires substantial investments and incurs significant social costs, even when performed properly and in accordance with a maintenance schedule. The analysis assumes that any attempt to cut costs by extending the time between maintenance stages would likely result in greater damage, leading to even higher social costs. Ensuring that a coating system provides adequate protection and performing maintenance at scheduled intervals helps keep the bridge accessible with minimal restrictions, thereby mitigating the social costs associated with maintenance activities.

Toward sustainable maintenance

The sustainability of coating systems for steel bridges involves evaluating cost, environmental impact, and social factors over the bridge's lifespan. For a hypothetical steel bridge with a 75-year service life, the cost and environmental impact of each coating system were analyzed, and the primary factors affecting these were discussed. However, the key remaining question is: How can bridge designers and owners determine the most sustainable corrosion protection plan? Among the three pillars of sustainability—economic, environmental, and social—which one is the most important? The answers to these questions appear to depend on several factors, including:

Climate Change: The environment in which the bridge operates affects the performance of coatings, impacting associated costs and VOC emissions. With the global warming and warmer than normal winters, the need for deicing processes during winter commutes are less demanded.[56,57] As the deicing agents are known to contribute significantly to the corrosion processes, the change in their application can affect the corrosivity of the environment [58]. The other way that the climate change may affect corrosion behavior of the steel bridges is the wetter than normal summers[59,60]. The increase in the rain falls as the result of climate change can provide the electrolyte required during the atmospheric corrosion of the steel bridges. This will lengthen the wetting period during the atmospheric corrosion cycle and increase the corrosion rate [61]. Therefore, climate change can cause both an increase or a decrease in the corrosion rate. As climate change progresses over the coming decades, it may influence the most sustainable option for corrosion protection.

Societal Priorities: Ideally, the most sustainable coating system would minimize project costs, social

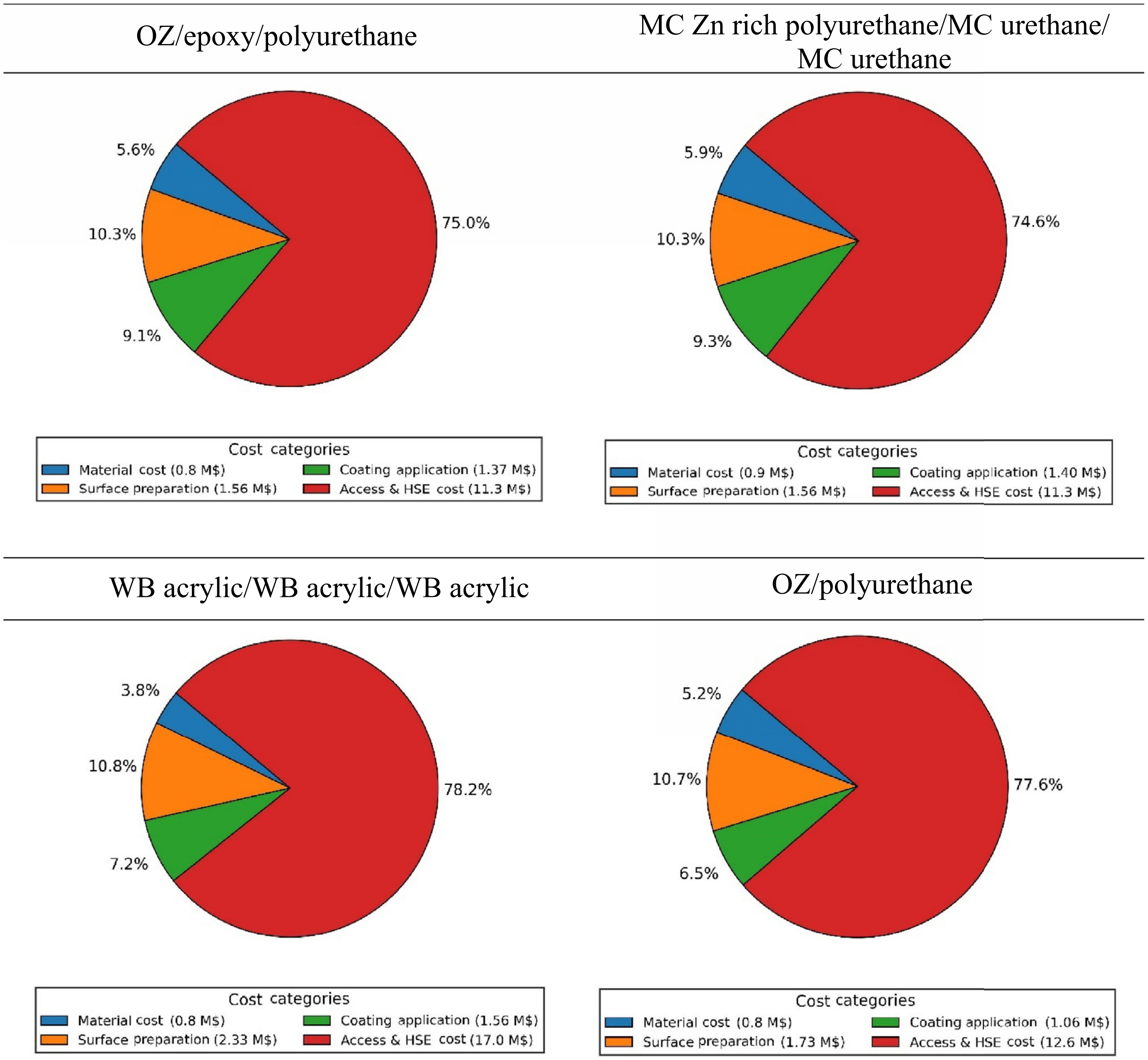

Fig. 4: Contribution of different factors in the project cost in a C5 environment with SP10 surface finish

costs, and VOC emissions simultaneously. However, as seen in this analysis, this optimal solution is not always attainable. In such cases, government policies and societal priorities become the primary factors guiding designers and owners in balancing the three pillars of sustainability.

These policies often reflect broader societal values, such as environmental protection, public health, and economic stability. Consequently, designers and owners must navigate these priorities to make informed decisions that align with both regulatory requirements and community expectations.

Technological Advancements: The availability of advanced technologies significantly influences decision-making. Over the past few decades, coating technology has evolved, providing more cost-effective and environmentally friendly products [62]. The analysis conducted in this study assumed the use of current technology over the bridge's 75-year lifespan. However, future technological advancements could introduce coatings with lower costs and VOC emissions, potentially altering the weighting of the sustainability pillars by authorities.

Changes in Demographics and Societal Norms: Demographic shifts and societal changes can also impact the environment's corrosiveness and the associated costs of corrosion protection. For instance, an industrial region typically has a more corrosive environment than a rural area. If the demographics of the region where the bridge is located change over its service life, this could significantly affect the authorities' decisions regarding corrosion protection plan. Additionally, changes in business practices, such as the rise of hybrid and remote working, could reduce societal dependence on the bridge, influencing the related costs.

Considering these factors, it is possible to introduce a Sustainable Decision Index (SDI) that integrates all three pillars of sustainability with adjustable coefficients that can vary over time and by region to help compare two options for sustainability:

$$\begin{aligned}\mathrm{SDI} &= k_{\mathrm{VOC}} \times \frac{\mathrm{VOCCost,\,Initialoption}}{\mathrm{VOC\ Cost,\ Option\ 2}} + k_{\mathrm{Project}} \\ &\quad \times \frac{\mathrm{ProjectCost,\,Initialoption}}{\mathrm{Project\ Cost,\ Option\ 2}} + k_{\mathrm{Social}} \\ &\quad \times \frac{\mathrm{Social\ Cost,\,Initial\ option}}{\mathrm{Social\ Cost,\ Option\ 2}} \end{aligned} \tag{17}$$

where

k_{VOC}, k_{Project}, and k_{Society} are the coefficients assigned by authorities to VOC emissions, project, and social costs, respectively. VOC Cost represents the cost of VOC emissions, directly related to the total VOC emissions.

The VOC Cost can be further formulated as:

$$\mathrm{VOC\ Cost} = A_{\mathrm{VOC}} \times \mathrm{VOC} \tag{18}$$

where A (\$/kg) is the unit cost of VOC emissions, and VOC (kg) represents the total weight of the emissions.

While some governments, such as Canada, have introduced carbon taxes that simplify calculating the cost associated with CO_2 emissions, there is still insufficient data on the costs of VOC emissions.[63] Consequently, a comprehensive life cycle assessment (LCA) is necessary and recommended to fully assess the total VOC emissions and other pollutants, as well as to assign their associated costs. While the proposed framework offers a systematic method for evaluating the sustainability of corrosion protection strategies, it is important to note that this study is not an LCA but rather focuses on providing a flexible approach for adapting to changing priorities and conditions.

Conclusions

In conclusion, this research underlines the necessity of adopting a complete and adaptable framework for the sustainability evaluation of anti-corrosion systems for steel bridge infrastructures. By integrating the three pillars of sustainability—economic cost, environmental impact, and social implications—through the proposed sustainable decision index (SDI), the study provides a dynamic mechanism to guide decision-making over a bridge lifespan. The findings highlight that while low VOC materials are crucial, the overall effectiveness of corrosion protection and maintenance requirements hold substantial weight in determining long-term sustainability. Moreover, social costs such as public inconvenience from maintenance activities must also be factored into the decision-making process. The SDC's flexible coefficients allow for regional and temporal adjustments, ensuring that the evaluations remain relevant in a variety of contexts and evolving environmental and societal landscapes. This comprehensive approach will aid in selecting the most sustainable corrosion protection strategies, balancing immediate project goals with long-term societal benefits and environmental stewardship.

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