Comparative life cycle cost assessment of painted and hot-dip galvanized bridges

Authors: B. Rossi¹, S. Marquart², G. Rossi³

1 Corresponding author: Department of Civil Engineering, KU Leuven, Belgium –
Barbara.Rossi@kuleuven.be

2 Nuremberg Institute of Technology Georg-Simon-Ohm, Nuremberg, Germany

3 Chênée Royal College, Liège, Belgium

Abstract

The study addresses the life cycle cost assessment (LCCA) of steel bridges, focusing on the maintenance activities and the maintenance scenario. Firstly, the unit costs of maintenance activities and their durability (i.e. the time between two activities) are evaluated. Pragmatic data are provided for the environment category C4 and for three activities: Patch Up, Overcoating and Remove & Replace. A comparative LCCA for a typical hypothetical steel girder bridge is carried out, either painted or hot-dip galvanized (HDG), in the environmental class C4. The LCC versus the cumulated life is provided for both options. The initial cost of the steel unpainted option is only 50.3% of the HDG option. It is shown that after 'Overcoating' occurring at 18.5 years, the total Net Present Value (NPV) of the painted option surpasses that of the HDG option. A sensitivity analysis of the NPV to the cost and service life parameters, the escalation and discount rates is then performed. The discount and escalation rates, considerably influences the total LCC, following a non-linear trend. The total LCC decreases with the discount rate increasing and, conversely, increases with the escalation rate increasing. Secondly, the influence of the maintenance scenario on the total LCC is assessed based on a probabilistic approach. A permutation of the three independent maintenance activities assumed to occur six times over the life of the bridge is considered and a probability of occurrence is associated to each unique scenario. The most probable scenarios are then classified according to their NPV or achieved service life. This approach leads to the definition of a cost-effective maintenance scenario i.e. the scenario, within all the considered permutations, that has the minimum LCC in a range of lifespan. Besides, the probabilistic analysis also shows that, whatever the scenario, the return on investment period ranges between 18.5 years and 24.2 years. After that period, the HDG option becomes economic.

Keywords

Life cycle cost assessment; Steel bridge; Painted; Hot-dip galvanizing; Maintenance scenario.

1. Introduction

This paper is divided into three main parts. Following this brief introduction, Section 2 describes the two coating systems and their respective maintenance activities. Section 3 mainly focuses on the determination of the cost and service life parameters necessary to perform the life cycle cost assessment (LCCA) and on the description of the hypothetical bridge. These parameters are based on the literature and on interviews with experts and are independent from the presently chosen hypothetical bridge. Two hypothetical bridges are considered as functional units: a painted steel bridge and a hot-dip galvanized steel bridge. A comparative LCCA is then achieved in Section 4, in which three maintenance events are considered. The variables of the LCCA are (1) the nominal maintenance event costs, (2) the moment of maintenance, which itself depends on the durability of the protection system, (3) the discount and escalation rates and (4) the maintenance scenario. Concerning the maintenance scenario, two cases are envisaged: the Model sequence (Section 4.1, fixed scenario) and the probability approach (Section 4.2, 729 scenarios), in which the plausibility of the considered scenarios is assessed by corroborating it to a probability of occurrence.

2. Considered coatings and their maintenance over time

2.1 Exposure categories

Every kind of structural steelwork is attacked by corrosion, the type and speed of which as well as distribution over the surface (generalised or localised) are influenced by environmental factors (Hempel, 2012). The standard EN ISO 12944-2 (ISO, 1998) defines six exposure categories for paint

coatings, as provided in Tab. 1. This study considers the category C4. A similar classification scheme exists for the corrosion of metals and is defined in EN ISO 9223:2012.

Tab. 1: Exposure categories for paint coatings according to EN ISO 12944-2

Categories		Typical exposure
C1	negligible	-
C2	low	Low pollution, mostly rural areas
C3	medium	Moderate pollution, urban/industrial areas, coastal areas with low salinity
C4	severe	Industrial areas, coastal areas with moderate salinity
C5-I	industrial	Industrial areas with high humidity and aggressive atmospheres
C5-M	maritime	Coastal and offshore regions with high salinity

2.2 Surface preparation

Several methods of protection against corrosion exist, but the most often used for steel bridges is the application of protective coatings, the maintenance of which causes cost. The surface preparation (solvent cleaning, hand and power tool cleaning, abrasive blast cleaning or water jetting) ensures the adhesion of the first coat layer, also known as primer, on the substrate (Hudson, 2000; International Paint Ltd., 2011). It significantly affects the performance of the whole coating system, no matter the system or application method. Surface preparation is the leadoff act in any coating operation. Generally, there are three initial surface conditions: the bare, shop primer covered and painted steel surfaces. For the latter, the surface condition must be assessed before the surface preparation can occur. Therefore, a rating system based on the rusted surface and its distribution is provided by the standards. In the present paper, depending on the maintenance events, different surface preparation according to EN ISO 8501-1 and EN ISO 8501-1 (ISO, 2007; ISO, 1994) will be considered.

2.3 Paint system

For paint systems, a zinc-rich primer is applied onto the prepared surface, followed by one or more undercoat(s) and the finish. The primer ensures the adhesion of the subsequent layer as well as the corrosion protection with the contained noble metallic particles. Organic (such as zinc epoxy) and inorganic zinc-rich (zinc ethylsilicate solvent-based, or alkali silicate water-borne) primers exist. In both category, solvent-based and water-borne coatings are present. Solvent-based are less susceptible to the atmospheric conditions (such as high humidity) during the curing phase, they contain a high content of volatile compounds and are flammable. Water-borne solvents have the advantage to contain less to no volatile compounds but humidity can prevent the water from evaporating, increasing the development of spot rusting. The undercoats accomplish the barrier function. The purposes of the finish are chiefly the UV-radiation protection and aesthetics. The primer and the undercoats are often applied in paint shops and the finish on site. This information will be important when the cost of the initial painting operations and of the subsequent maintenance activities will be evaluated.

In general, the maintenance of deteriorated coatings differs with the intensity of corrosion and the dimension of the surface to be treated. The literature distinguishes three main activities corresponding to three states (Berman, 2013), cleaning is not considered herein:

- 'Patch Up', also known as 'Touch up', is the activity with the lowest impact on the original coating system. Surface cleaning and preparation is made on localized areas and, subsequently, an application of a compatible new coat patch is done. According to (El Sarraf et al., 2008), this causes higher labour cost compared to other maintenance activities due to the size of the treated surface. 'Patch Up' is usually required directly after the erection to repair damages that occurred during construction or transportation, or simply to paint surfaces that were left uncoated on purpose (before welding on site for instance). The area maintained by 'Patch Up' ranges between 2% to 5% of the whole surface.

- 'Overcoating' consists of either the removal of small deteriorated areas or of a whole layer of coating. Afterwards the whole surface gets a new compatible coating layer. According to (American Iron and Steel Institute, 2007), this yields to a service life extension of 12 to 15 years, with no indication of the environment category. It is often the most economic technique, especially for lead based painted bridges (American Iron and Steel Institute, 2007; NZ Transport Agency, 2014).

- In the case of 'Remove & Replace', all rusted areas and existing coatings are removed, the whole surface is prepared and a new coating system is applied. The containment activities (to avoid environmental contamination and to protect the job during painting) usually cause a drastic increase of the cost.

2.4 Metal coating system

Metal coatings are applied via thermal metal spray or batch hot-dip galvanizing. In the latter, steel members to EN ISO 1461 (ISO, 2012) are dipped into a bath of molten zinc (with minimum 98.5% zinc and minor elements for process control or present as impurities) at a temperature of 450°C (Bauen mit Stahl, 2001).

Compared to on site painting which is quite flexible to demand and today not strongly limited due to its flexible nature, the galvanizing industry does not have the capacity to galvanize all the steel bridges that are built today mostly due to the size of the involved section. But the available capacity is sufficient to cope with the type of steel bridges that are viable for galvanizing. Besides, if the size exceeds the bath geometry, so called double dipping can be applied, by partly immersing the member.

Two associations, Zincinfo NL and EGGA, report that the total tonnage of steel galvanized in Europe is 7 million tonnes per annum with a current capacity utilisation of 56%. If we estimate that 20% of the current production is capable to process steel sections longer than 12m (i.e. for bridges), the relevant capacity is 1.4 million tonnes. Scaled up to 100% capacity, the total capacity is 2.5 million tonnes.

In (NZ Transport Agency, 2014) and EN ISO 14713-2 (ISO, 2009), guidance for the maintenance of metallic coatings, either thermal metal sprayed or hot-dip galvanized, is provided. If galvanized steel needs to be maintained, 'Patch Up' (as for paint system) is generally used. There are three options provided in Tab. 2:

Tab. 2: Repair techniques for damaged hot-dip galvanized steel surfaces

Option	Repair using:	Dry Film Thickness (microns)	Required Surface
1	Organic zinc-rich primer	50 at affected areas	SSPC-SP 11
2	Inorganic zinc silicate paint	30 greater than the local zinc coating	Sa 2½
3	Zinc metal spray	30 greater than the local zinc coating	Sa 2½

3. Life-cycle cost assessment (LCCA)

3.1 Principles and boundaries of the study

The life-cycle cost of the steelwork is the cost calculated throughout its life cycle while fulfilling technical and functional requirements. It is used to identify the economic impacts of the construction and to enable the client, user and designer to make decisions and choices that will help to address the need for sustainability (Kwang-Min, 2006). Among the European suite of standards intended to assess the sustainability of construction works (Fig. 1), EN 15643-4:2012 (CEN, 2012a) provides a framework with principles, requirements and guidelines for the assessment of the economic performance of a building. According to the general framework, the life-cycle analysis is subdivided into 4 information modules A to D, which also applies in the assessment of economic performance of a building:

- Modules A0 to A5 concerns the stage before the use phase: raw material supply, transport, manufacturing, associated processes and construction are included (CEN, 2012b);
- Modules B1-7: use, maintenance, repair, replacements and refurbishment;
- Modules C1-4: demolition, waste processing and disposal;
- Module D: reuse, recovery and/or recycling potentials, are optional modules.

Fig. 1: European standard suite for the assessment of the sustainability of building

According to EN 15643-4:2012, the object of assessment shall be the building, its foundations, the external works within the area of the building's site and the temporary works associated with the building's construction. Presently, the object of assessment will be one hypothetical steel bridge in the environment category C4, Tab. 1. The system boundary includes costs related to Module A, specifically the *Cost of products supplied at factory gate ready for construction*, all other costs (i.e. purchase or rent of land, earthworks such as excavation, foundations, professional fees related to the design and calculations, sales taxes) are disregarded; and costs related to Module B2, specifically the *Cost of repairs and replacement of minor components/small areas* and the cost of *Replacement or refurbishment of major systems and components*. No economic impacts and aspects related to the end-of-life (Modules C1-C4 i.e. deconstruction, demolition, recycling and disposal of materials) are presently considered. Traffic congestion costs occur during the construction of the bridge, when the traffic is either delayed or detoured. These additional costs will not influence the results of the comparison provided in Section 4 based on the assumption that both bridges are built at the same speed. Therefore, traffic congestion costs are presently not included in the study.

According to (NCHRP, 2003), there is no commonly accepted methodology for LCCA in the U.S. particularly for bridges. Part 1 of this report provides guidelines to undertake life cycle costing analysis for bridges. Nevertheless, since the publication of this report, the 6th edition of the ASTM Standards on Building Economics was published, in which guidelines are also given for bridge elements. A thorough description of these standards is given in (Kasi et al., 2012). Amongst other topics, the report illustrates the use of ASTM standards to achieve a balance between performance and life-cycle economics for the Gateway Arch bridge.

3.2 Net Future Value and Net Present Value

LCCA considers the time value of money over the project life utilizing the net present value (NPV) and the net future value (NFV), requiring the estimated discount and escalation rates. The net future value (NFV) measures the profitability at the end of the planning horizon compared to what might have been gained by investing elsewhere. The discount rate is used for discounting the cash flow to the present. The NPV of the estimated cost over the planning horizon is the discounted value of the NFV to the present. The NFV and NPV of events occurring in year n are calculated using the following formulas:

- Net Future Value: $NFV = C(1 + i)^n$

- Net Present Value: $NPV = C \left(\frac{1+i}{1+d} \right)^n$

where C is the current cost, i is the escalation rate, d is the discount rate (both held constant over the time horizon) and n as year of occurrence of the cost (study period). As initial values, the escalation rate is set to 2% and the discount rate to 5% according to (Lee, 2015; Tietz, 1987). The sensitivity analysis will include both the escalation and discount rates, due to the uncertainty of these parameters.

3.3 Service life data

The service life and cost data are the key factors to an informative and meaningful LCCA. The data presented here below are based on the literature and experience values. Scientific papers as well as information provided by experts from Royal Hashkoning DHV, Tata Steel Construction Centre NL, Zincinfo NL, Deacon FTSC, FICorr. and Infosteel were used. For paint systems, these data depend on many parameters:

- The surface preparation;
- The type of coating, layer composition and dry film thickness (DFT);
- The exposure category.

The durability of paint systems is classified according to EN ISO 12944 as shown in Tab. 3. The standard also indicates paint systems (classified by their type of binder and their expected service life) and their durability for each environment categories.

Tab. 3: EN ISO 12944-2 durability classification for paint systems

Category		Durability (in years)
L	Low	2 – 5
M	Medium	5 – 15
H	High	> 15

In (Santos, 2005), the authors tested and investigated four systems with the recommended properties indicated for high durability (H) in class C5. The performance was evaluated on site and under laboratory conditions. The result shows that none of the tested systems met the requirements. Besides, the durability of paint systems indicated by industries is evaluated under circumstances guaranteeing their best performance. Consequently, in the present paper, these data are disregarded.

The results of a performance investigation of bridge coatings by the Board of Roads and the Technical Research Centre of Finland (VTT) are published in (Saloranta, 1993). The paper states that the first maintenance i.e. 'Patch Up' is recommended when reaching the rust grade Ri 2 or Ri 3 and the average service life for the environment category C4 can then be calculated as 17.5 years. Besides, the coat must be renewed when the rust grade Ri 4 or Ri 5 is reached, which can be considered as a 'Remove & Replace' at an average age of 39.5 years.

In (Helsel, 2008), 36 records of generic used paint systems are reported, including their total DFT and their expected practical service life (PSL) in the environment categories C2, C3 and C5-I/M. Multipliers to estimate the time to the next maintenance event are also provided. The time to first maintenance i.e. 'Patch Up' is the practical service life (PSL) of the initial coat. The time to the second maintenance event i.e. 'Overcoating' equals 1.33 x PSL, thus the service life extension of 'Patch Up' is 0.33 x PSL. The time to the third maintenance i.e. 'Remove and Replace' is PSL x 1.33 + 0.50 x PSL. Therefore, the service life extension of 'Overcoating' is 0.50 x PSL. Since there is no indication for the environment category C4, the mean of the values for C3, C5-I and C5-M will presently be used.

Besides, interviews with experts allowed us to collect additional information about the maintenance horizon in the environment categories C4 and C5. As a conclusion, the average of the collected maintenance time for 'Patch Up', 'Overcoating' and 'Remove & Replace' are summarized in Tab. 4, for the environment C4.

Tab. 4: Service life data for each maintenance events (years)

Maintenance Event	System age in environment C4			Average Service Life Extension	Std. Dev.
	Literature	Experts	Average		
Patch Up	15.2	10.5	12.8	5.7	3.0
Overcoating	17.1	19.3	18.5	12.5	2.2
Remove & Replace	31.6	30	31.0	12.8	8.6

The sensitivity analysis in Section 4 includes the service life data, due to the unpredictability of these data.

The service life of metal coatings is generally higher than for traditional paint systems. The achieved service life largely depends on the chosen metal and its thickness and is slightly influenced by the application method (Corus Construction & Industrial, 2005; Corus Construction & Industrial, 2004). Service life of metallic zinc coatings, such as hot-dip galvanizing, according to the exposure categories are given in EN ISO 14713-1 (ISO, 2009). A minimum and a maximum service life higher than 40 years is indicated when the coating thickness reaches 200µm. According to experts from Zincinfo NL and Deacon FTSC, the service life of the initial hot-dip galvanizing coating is, on average, 40 years. Furthermore, actual information is available on galvanized steel coatings for steel bridges that have been in service for more than 40 years (Deacon, 2015). A service life value of 40 years is hence selected in the present study. Conservatively, 'Patch Up' will nonetheless be assumed to occur after a shorter period of 20 years.

3.4 Cost data

In this study, for the considered bridge, 80% of the bridge profiles are assumed to be heavy, 10% medium-heavy, and 10% medium to medium-light leading to a unit material cost (according to metalprices.com, in September 2015) of \$650 per ton of steel.

In (Yunovich et al., 2001), the author reports costs for painting jobs on bridges. Their wide extent can be explained by the uniqueness of each bridge and therefore by the associated maintenance costs.

In (Helsel, 2008), average material costs for several types of paints at their specific DFT are also listed. Besides the material costs, the authors provide several tables listing records for surface preparation and paint application costs. The tables are divided into shop painting and field painting costs. The shop painting table states the cost of 11 surface preparations and 4 coating applications. Depending on the job size, the calculated subtotal should be multiplied by a factor, which is for medium job size (as the considered bridge as described in Section 3.5) assumed to equal 1.10. The field painting table states the cost of 15 different cleaning grades, while 13 of them are determined as actual surface preparation. In addition, the costs of 5 paint applications are indicated. Certainly, the type and shape of the structure will influence the field cost. Consequently, the author indicates multipliers, depending on the complexity and height of the structure, which should be applied to the labour cost. The complexity is either 'simple' or 'complex' and the height ranges from below 50 to above 100 feet. The corresponding multiplier ranges from 1.20 to 1.50. Presently, the studied structure is assumed to have a medium height (i.e. from 50 to 100 feet). Labour costs are also included and assumed, according to (Helsel, 2008), to be a third of the subtotal. This preliminary total is then modified according to the surface condition. Four categories of surface conditions are listed and, in the present study, the category '1) *Light rusting, pitting and paint breakdown*' is used for 'Patch Up' and '2) *Heavy paint breakdown, severe rusting and pitting*' for 'Remove & Replace'. As the other two proposed categories are inappropriate for 'Overcoating', an average coefficient is calculated. In addition to this, multipliers related to the size of the maintenance jobs are indicated. The lowest maintenance surface ranges from 10 000 to 25 000 ft², our case-study falls in this range as it will be highlighted afterwards, and the corresponding factor is 1.15. The other two events are characterized by a factor of 1.05, which is the same as in shop painting. As final step, the containment during the maintenance is considered. The multipliers vary, depending on the surface preparation method, the structure's complexity and the emission-control class. To ensure a consistent calculation, the presently used factor will be a weighted average. The weighting is done using the 13 records of surface preparation, which have been used for the determination of the costs. According to (American Iron and Steel Institute, 2007), 'Overcoating' is usually an option for up to 10% deterioration and is therefore applied to 10% of the subtotal cost.

In (Bauforumstahl, 2013), cost data for structural steelwork are provided, including data for painting jobs, separated into field and shop application. The information is related to a member size via a surface-to-weight ratio. As the surface of a profile significantly depends on its shape, the relation is provided as a range. If a bridge is made using a relatively high amount of heavy plates/profiles for the load-bearing structure and a lower amount for the other parts, a weighted average cost can be calculated. The shop painting cost is used for 'Initial Coating' and the field painting cost for 'Overcoating', because the abrasive blasting cost is considered whereas the related cost for existing coating removal or containment are not. Assuming an average specific surface of 14.25 m²/t (verified against the weight-surface conversion data in (Helsel, 2008), the cost is expressed in function of the area and ranges between 'Large Structural – 9.30' and 'Medium Structural – 18.58'.

In (El Sarraf et al., 2008), two paint systems are compared along their life cycle. For the cost analysis, the price of the two systems is indicated for the following events: 'Initial Coating', 'Patch Up' and 'Remove & Replace'. The much higher cost for 'Patch Up' compared to 'Remove & Replace' is due to the higher labour cost occurring during reparation of small areas. A summary of the collected data is provided in Tab. 5, showing that the cost is highly variable for each operation.

Tab. 5: Estimated cost range for painting operations (cost conversion at exchange rate 1.139 \$/€, February 2015) (\$/m²)

	Initial painting		Patch Up		Overcoating		Remove & Replace	
(Yunovich et al., 2001)	17.12	- 53.70	17.12	- 53.70	11.00	- 86.00	43.00	- 215.25
(Helsel, 2008)	11.05	- 44.67	23.96	- 220.34	13.25	- 116.93	27.94	- 258.83
(Bauforumstahl, 2013)	17.70	- 36.97	n.a.	- n.a.	35.79	- 74.97	n.a.	- n.a.
(El Sarraf et al., 2008)	37.50	- 57.45	82.70	- 122.95	n.a.	- n.a.	50.50	- n.a.
(Kwang-Min Lee, 2006)	n.a.	- n.a.	n.a.	- n.a.	n.a.	- n.a.	n.a.	- 236.00
(AISI, 2007)	n.a.	- n.a.	n.a.	- n.a.	43.06	- 64.58	129.20	- 150.69
Experts	n.a.	- n.a.	56.95	- 68.34	n.a.	- n.a.	113.90	- 170.85
Min/Max	11.05	57.45	17.12	220.34	11.02	116.93	27.94	258.83
Average	20.84	48.20	45.18	116.33	25.77	85.62	72.90	206.32
Std. Dev.	11.5	9.2	30.5	75.5	16.1	22.5	45.5	44.9

The initial coating (in shop) for HDG has been evaluated based on (Helsel, 2008) and on interviews with experts, see Tab. 6. In this paper, 'Patch Up' costs for the HDG option are taken as the average between the minimum and maximum costs in Tab. 5. It could also be approximated using the data provided in (Helsel, 2008). In this case, the 'Patch Up' cost would range from 374.7 \$/m² to 384.5 \$/m². It will nevertheless be demonstrated that, in either case, 'Patch Up' activities have a low influence on the total NPV. Contrarily, the cost for 'Overcoating' is taken to be the maximum cost indicated in Tab. 5, which is coherent with the higher material costs related to metallic coating.

Tab. 6: Estimated costs for HDG operations (\$/m²)

	Initial HDG	Patch Up	Overcoating
Literature	39.39	-	-
Experts	34.12	-	-
Average	36.75	118.73	116.93
Std. Dev.	3.7	-	-

3.5 Description of the hypothetical bridge

The overall dimensions (deck surface, length and width) of the hypothetical bridge are chosen according to (Yunovich et al., 2001). The steel structure's weight is calculated following the statistical analysis carried out in (Toma, 2000), in which the steel weight-to-deck surface ratio is provided for all bridge types. Both (Yunovich et al., 2001) and (Toma, 2000) provide highway bridges data, which is the object of the present study. Hence, this hypothetical bridge can be considered as representative of most highway bridges. A 'Continuously supported plate girder bridge', Fig. 2, is considered with a deck length of 36.9m and a specific weight of 0.18t/m² (Toma, 2000).

Fig. 2: Hypothetical bridge

As the average deck area is 583m², it leads to a total steel weight of 105t. According to experts, the total weight of the components (girders, joints...) for a HDG steel bridge is higher than for a traditionally painted bridge mainly because it is impractical to weld the components. Herein, the HDG option's initial material weight is assumed to be 10% higher than the painted option, hence, 116t. This leads to a total initial price of the HDG option (including initial coating) of 135 483.5\$. In all future calculations, the costs will be expressed as a percentage of this reference value, see Tab. 7.

Tab. 7: Basic parameters for the analysis

Bridge Overall Dimensions			Steelwork Data			Total initial cost		
Length	Width	Area	Steel Weight	Specific Surface	Total Surface	HDG option	Painted option (before initial coating)	Painted option (after initial coating)
(m)	(m)	(m ²)	(t)	(m ² /t)	(m ²)			
36.9	15.8	583	105	14.25	1495	135 483.5\$ = Reference value	68 211.1\$ ⇒ 50.3%	119 428.3\$ ⇒ 88%

In (Bauforumstahl, 2013), the average specific surface is provided and allows to evaluate the application area of coatings. It was achieved under the same assumptions that for the weight calculations i.e. 80% are heavy profiles, 10% medium-heavy, and 10% medium to medium-light. Contrarily to the initial coating application, not the whole steel surface needs to be maintained. It is presently assumed that 90% of the total steel surface should be maintained, when 'Overcoating' or 'Remove & Replace' occurs. This assumption is consistent with a steel I-profile painted all over its external surface, except on the top surface of its top flange. For both options (painted and HDG), 'Patch Up' is done over 5% of the surface of the bridge. The summary of these assumptions is provided in Tab. 8.

Tab. 8: Chosen Event, surfaces and costs

Maintenance activity	Event	Painted Area		Cost		
		Relative (%)	Absolute (m ²)	Relative (\$/m ²)	Absolute (\$)	Relative to HDG (%)
Initial Coating	E0	100%	1495	34.25	51 217.3	38%
Patch Up	E1	5%	67.3	118.73	7 990.5	6%
Overcoating	E2	90%	1346	63.97	86 096.9	64%
Remove & Replace	E3	90%	1346	143.39	192 996.2	142%

4. Results and sensitivity analysis

4.1 Fixed scenario – Model sequence

The maintenance activities are, from now on, labelled as E0 ('Initial coating'), E1 ('Patch Up'), E2 ('Overcoating') and E3 ('Remove & Replace') as in Tab. 8. For the LCCA, a maintenance scenario must be chosen. The present scenario, namely 'Model sequence', represents a maintenance sequence in the sense of (Helsel, 2008). The sequence of events is: E0 followed by 2 cycles of E1, E2 and E3. The costs (as provided in Tab. 5) are discounted to obtain the NPV. The NPV significantly depends on the time of occurrence, which are chosen according to Tab. 4. For the HDG option, it is considered that 'Patch Up' occurs after 20 years, followed by 'Overcoating' after 40 years and then again 'Patch Up' after 20 years. Fig. 3 depicts the LCC versus the cumulated life. The initial cost of the steel unpainted option is only 50.3% of the HDG option. For both options, 'Patch Up' has a relatively low influence on the total NPV and that, after 'Overcoating' at 18.5 years, the NPV of the painted option surpasses the NPV of the HDG option.

Fig. 3: Life cycle cost – Model sequence – Painted bridge versus HDG bridge ($d = 0.05$, $i = 0.02$)

The sensitivity of the NPV to the maintenance costs and to the service lives of each event was studied. The total LCC (Cumulated NPV) varies linearly with a simultaneous increase of the costs parameters, Fig. 4. The slope is nevertheless different for both options. Because of the numerous maintenance activities included in the painted option, the increase of the LCC is always more noticeable, widening the gap between the painted and the hot-dip galvanized options. For the painted bridge, an increase of the costs of 10% leads to a total NPV increase of 14% whereas for the HDG option, this increase is 4%, Fig. 4.

Fig. 4: Model sequence – Painted option versus HDG option – Sensitivity of the NPV to the events' costs and time of occurrence

The influence of, respectively, a decrease or an increase of the cost data, is analogous for, respectively, an increase or a decrease of the service lives although the service lives parameters dominates the cost data. Therefore, the NPV for a simultaneous increase of both parameters tends to remains nearly unchanged.

Additionally, the discount and escalation rates, presently selected according to (Lee, 2015), significantly influences the total LCC, following a non-linear trend, Fig. 5. The total LCC decreases with the discount rate increasing and, conversely, increases with the escalation rate increasing. A careful handling of these rates is recommended to achieve realistic results.

Fig. 5: Model sequence – Painted option versus HDG option – Sensitivity of the NPV to the escalation and discount rates

In conclusion, the total LCC as well as the lifespan are of course influenced by the service lives and costs data presented above. Although, none of the above-mentioned parameters, except the time at which E2 occurs, significantly change the conclusion drawn from the study of the Model sequence i.e. the age at which investment return is reached (18.5 years). Keeping the scenario unchanged, to increase that period, the initial coating costs must be considerably decreased (up to 29%). It is worth pointing out that in Tab. 4, the standard deviation for the time to first overcoating value is 2.2 years.

4.2 Probabilistic approach of the scenario

Herein, the influence of the maintenance scenario is studied assuming that the bridge is submitted to two series (1st and 2nd series) of sequences, each of them including three maintenance events, as suggested in (Frangopol et al., 1997). All possible permutations of E1, E2 and E3 are considered. Hence, for three events and six occurrences the total amount of possibilities is 3⁶. The NPV varies depending on the event cost and its moment of occurrence over the planning horizon.

As stated in the literature (Helsel, 2008; Nicolai et al., 2008; El Sarraf et al., 2008; Zayed et al., 2002), the Model sequence is more probable. Besides, an extraordinary long service life with a relatively low cost is highly improbable. This can be highlighted through the choice of the probability of occurrence of an event. This probability also depends on when this event occurs i.e. after E1, E2 or E3 and in the 1st series or in the 2nd series, see the 18 cases in Tab. 9.

Tab. 9: Probabilities of occurrence depending on the previous event

Event	Probability of occurrence after:					
	E1		E2		E3	
	1 st series	2 nd series	1 st series	2 nd series	1 st series	2 nd series
E1	$P(E1/E1) = 0.20$	0.30	$P(E1/E2) = 0.15$	0.25	$P(E1/E3) = 0.70$	0.50
E2	$P(E2/E1) = 0.70$	0.50	$P(E2/E2) = 0.15$	0.25	$P(E2/E3) = 0.20$	0.30
E3	$P(E3/E1) = 0.10$	0.20	$P(E3/E2) = 0.70$	0.50	$P(E3/E3) = 0.10$	0.20

Each scenario contains six events and follows one path, as illustrated in Fig. 6. As a result, the probability of occurrence of one scenario is the product of the probability of each six independent event, as in $P(A \text{ and } B) = P(A) \times P(B)$ and the total probability of all the 729 scenarios evidently equals 1. All results are presented in Fig. 7, together with the Model sequence (the scenario with the highest probability). The records are crowded around the Model sequence, the selected probability scaling the original cloud accordingly.

Fig. 6: Possible path and probability

Fig. 7: Life cycle cost cost expressed as Net Present Value dots (729 records) and the associated achieved service life ($d = 0.05$, $i = 0.02$)

Fig. 8: Life cycle cost cost expressed as Net Present Value dots (43 records with $P > 0.5\%$) and the associated achieved service life ($d = 0.05$, $i = 0.02$)

In Fig. 8, the NPV is plotted versus the achieved service life for the scenarios with a probability higher than 0.5%. It can first be seen that, for the same range of cost, the achieved service life is highly variable, ranging (for all cases with $P < 0.5\%$) from 60.9 to 93 years. Similarly, for nearly the same achieved system life (as for instance 68 years), the LCC is highly variable (ranging from 177% to 235%). Therefore, using Fig. 8, a cost-effective scenario can be highlighted for a chosen lifespan, see Tab. 10. For instance, for 75 years, the minimum total NPV reaches 207% when the chosen scenario is E0 followed by E1 E2 E1 - E2 E3 E1.

387

Tab. 10: 43 scenarios with P>0.5% arranged by lifespan

Average lifespan (years)	# of cases with P>0.5% within the 43 cases	Min. possible LCC (%)	Corresponding scenario					
64.3	2	179	E1	E2	E3	E1	E2	E3
67.8	12	177	E1	E2	E3	E3	E1	E2
74.7	16	198	E1	E2	E1	E2	E3	E1
81.3	10	210	E1	E3	E1	E2	E3	E1
87.3	2	227	E1	E2	E3	E3	E2	E1
93	1	193	E1	E2	E3	E3	E2	E2

388 And, more importantly, when the lifespan equals 60.9 (respectively 93 years), the minimum total NPV
 389 of the painted steel option equals 179% (respectively 193%). For the HDG option, it equals 141%.
 390 Hence, for an increase of only 7.8% of the total LCC, the maintenance scenario can be judiciously
 391 chosen such that the lifespan increases by 32 years for the painted option. For the cases with
 392 P>0.5%, the relative difference between both options' LCC ranges from 26% to 84%.

393 The probabilistic analysis also shows that, when E2 for the HDG option occurs, the painted option
 394 becomes cost-effective again for a short period. Also, whatever the scenario, under these hypotheses,
 395 the return on investment period ranges between 18.5 years and 24.2 years.

396 The results presented for this hypothetical case-study are based on several hypotheses among which:
 397 the environment category is C4; 'Patch Up' is made over 5% of the total bridge surface; 'Overcoating'
 398 occurs on 90% of the surface; the bridge is supposed to be a 'complex' structure of 'medium height' in
 399 the sense of (Helsel, 2008) and its surface (583 m² for the deck surface and 1346 m² for the
 400 maintained surface) and weight (105 t for the painted bridge and 116t for the HDG bridge) are
 401 evaluated according to (Bauforumstahl, 2013; Yunovich et al., 2001; Toma2000). The results are
 402 therefore reproducible for steel bridges falling within this category of bridges.

403 5. Conclusions

404 In the present paper, the life cycle cost assessment (LCCA) of one hypothetical steel bridge in the
 405 environmental class C4 is achieved. The bridge is successively considered as painted or hot-dip
 406 galvanized (HDG). To this purpose, the cost of the maintenance activities and their durability is firstly
 407 determined. Secondly, a reasonable sequence of maintenance events (i.e. scenario) is defined. In the
 408 present study, each permutation of three independent maintenance activities ('Patch Up',
 409 'Overcoating' and 'Remove & Replace'), assumed to occur six times, is considered. To each activity, a
 410 probability of occurrence is associated, allowing to classify the scenarios according to their total Net
 411 Present Value (NPV) or achieved service life. Through this analysis, within a relatively short range of
 412 lifespan, a maximum and a minimum total maintenance LCC is calculated and a judicious
 413 maintenance scenario can therefore be highlighted. The paper gives the most cost-effective scenario
 414 i.e. the scenario that, according to this analysis, should be followed to achieve the longest lifespan at a
 415 minimum cost.

416 Besides, a sensitivity analysis of the LCC to the maintenance costs and service life parameters, the
 417 escalation rate and the discount rate is also considered, for both the painted and HDG options. It is
 418 shown that extending the events service lives or their individual maintenance costs leads to a similar
 419 (but opposite in sign) alteration of the total LCC (the NPV for a simultaneous increase of the
 420 parameters tends to remain unchanged). When comparing the painted and HDG options, it is also
 421 shown that none of the above-mentioned parameters, except the time at which 'Overcoating' occurs,
 422 significantly change the conclusion drawn from the study i.e. the age at which investment return is
 423 reached. The sensitivity analysis furthermore shows that, because of the numerous maintenance
 424 activities occurring during the life the painted bridge, the increase of the LCC is always more
 425 noticeable, widening the gap between the painted and the HDG bridges. Besides, the subsequent
 426 probabilistic analysis also shows that, whatever the scenario, the return on investment period ranges
 427 between 18.5 years and 24.2 years. After that period, the HDG option becomes economic.

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