DEVELOPMENT OF LIFETIME PROFILES FOR COMPOSITE BRIDGES WITH PROTECTIVE COATING

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Abstract

Life Cycle Analyses (LCA) have become the subject of research works in the recent decades. They have gained growing attention due to the economic crisis, regulations regarding the limitation of emissions and in general, the development of sustainable thinking. This field is very complex and it is used not only in civil engineering, but also in other engineering fields such as mechanical, chemical, biomedical etc.

The present thesis focuses on composite highway bridges with protective coating against corrosion. A Life Cycle Assessment Tool (LCAT) is developed in the framework of the thesis as well. This tool is able to study composite highway bridges over their lifetime (100 years) and includes three main modules: Life Cycle Cost (LCC), Life Cycle Environmental Assessment (LCEA) and Life Cycle Performance (LCP).

In general, LCA tend to predict the entire *lifetime* performance, cost, etc.; thus, some uncertainties cannot be avoided. Several probabilistic analyses were done in the present thesis, and in the end a probabilistic tool was developed based on the deterministic one. An optimization was also done for both types of the tools regarding the maintenance strategies, including re-coating and strengthening of the bridge.

A case study of a composite highway bridge in Portugal, which is analysed with both deterministic and probabilistic tools, is presented in the thesis. Also both non-optimized and optimized maintenance strategies are applied on it.

Finally, the conclusions are summarized emphasising the importance of probabilistic approach and optimization for Life Cycle Assessment Tools for composite bridges.

Resumo

As Análises de Ciclo de Vida (ACV) têm-se tornado objeto de trabalhos de investigação nas últimas décadas. Este tipo de abordagens tem vindo a ganhar uma atenção crescente devido à crise econômica, as regulamentações relativas à limitação das emissões e, em geral, ao desenvolvimento sustentável. Este campo de investigação é muito complexo e é utilizado não só na engenharia civil, mas também em outros campos da engenharia, tais como mecânica, química, biomedicina, etc.

A presente tese foca-se em pontes mistas de autoestradas com sistemas de revestimento de proteção contra a corrosão. No âmbito desta tese é também desenvolvida uma ferramenta de Avaliação de Ciclo de Vida (LCAT). Esta ferramenta é capaz de analisar pontes mistas de autoestradas ao longo da sua vida útil (100 anos) e inclui três módulos principais: custo do ciclo de vida (LCC), análise ambiental de ciclo de vida (LCEA) e desempenho estrutural de ciclo de vida (LCP).

Em geral, numa análise de ciclo de vida é necessário prever o desempenho estrutural, custos, etc, ao longo de todo o ciclo de vida; assim, as incertezas não podem ser evitadas. Na presente tese serão realizadas várias análises probabilísticas e, no final, será desenvolvida uma ferramenta probabilística com base numa ferramenta determinista. Em ambos os tipos de ferramentas será incluída uma otimização relativa às estratégias de manutenção, incluindo reaplicação do revestimento e reforço de uma ponte.

Nesta tese será ainda apresentado o caso de estudo de uma ponte mista numa autoestrada em Portugal, no qual serão utilizadas tanto a ferramenta determinística como a probabilística. Em ambos os casos será também realizada a otimização da manutenção da obra.

Finalmente, as conclusões serão apresentadas enfatizando a importância da abordagem probabilística e da otimização em ferramentas para a Avaliação do Ciclo de Vida de pontes mistas.

Organization of the Thesis

A short introduction is presented in chapter 1 including the motivation and the goals of the present thesis.

In chapter 2 a literature review can be found about corrosion, more accurately about the corrosion of steel girders. A method is also presented for modelling the effect of corrosion through estimating a uniform thickness loss due to corrosion.

Afterwards, in chapter 3, a review of protective coatings is presented. The main topics that are included in this chapter: the reason for using these coatings, the most common types and the possible faults of them. At the end, an analytical model for the degradation of these coatings is also presented.

Chapter 4 is dedicated to the degradation processes of reinforced concrete. A review of the relevant and widely recognized models is presented here. Finally, an analytical model is given assuming the degrading performance of a reinforced concrete element due to the corrosion of its reinforcement.

Chapter 5 gives a quick overview about Life Cycle Analysis (LCA), the main ideas connected to it and the most common methods to perform such analysis. The three pillars of LCA are also presented one by one.

Based on a similar tool that had been developed in the MAINLINE project (MAINLINE, 2013), a deterministic tool was developed in chapter 6. This tool is able to perform an LCA of composite motorway bridges with protective coating.

In chapter 7 the deterministic tool is further improved into a probabilistic one. Firstly, probabilistic approach is explained in general. Afterwards, the program @Risk used in the present thesis is described. Different kinds of simulations are presented to show how and regarding what principles the final tool was obtained.

Chapter 8 provides a short overview about optimization in general and a practical guide how to do it with the help of @Risk. This chapter also includes the description and results of the optimization of both deterministic and probabilistic tools.

In the last chapter of the thesis (chapter 9) a case study is presented. A Portuguese motorway overpass with composite structure is studied with the previously developed deterministic and probabilistic tools.

Finally, the conclusions and remarks of this thesis can be found in chapter 10. Additionally, potential future works regarding the topic and the desired improvements for the tool are summarized in this chapter.

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Notations

A and B	experimentally determined constants for calculating the corrosion rate
A_a	accident rate during work on road
A_n	accident rate during normal conditions
A_{pt}	residual protected area of steel element
A_{pt0}	initial protected area of steel element
A_s	area loss of rebar
C	corrosion rate
C_0	external CO_2 concentration in air
C_{0Cl}	equilibrium chloride concentration at the concrete surface
C_a	capital cost of an accident
C_{cov}	thickness of concrete cover
C_{cr}	critical chloride concentration
C_t	all the cash flows in year t
D_0	initial diameter of rebar
D_c	chloride diffusion coefficient
D_{co2}	effective CO_2 diffusion coefficient in concrete
D_g	CO_2 diffusion coefficient in the gaseous phase
D_s	diameter of rebar
HR_{ext}	external relative humidity
Kl	water permeability
L	length of the road affected by traffic congestion
N	number of days of traffic congestion
S	liquid water saturation degree
S_a	traffic speed during work on road
S_n	traffic speed during normal conditions
T	total number of years
T_L	half of the service life of the coating
T_i	time when corrosion initiates
a and b	coefficients for
d	coefficient assessed by a model of moisture
f_c	compressive strength of concrete

i_{corr}	corrosion rate density
n_i	initial carbon hydroxide $Ca(OH)_2$ content of concrete
r	discount rate
r_v	average cost of operating a vehicle for an hour
r_{tg}	expected traffic growth rate
t	time
t_d	length of drying period of concrete
t_w	length of the wetting period of concrete
w	parameter characterized by phenomenon of water inhibition
w_d	average cost of one hour of a driver's time
w/c	water/cement ratio
$year_0$	base year
$year_t$	year of study
α and β	Genuchten's coefficients
Φ	porosity

Abbreviations

AP	Acidification Potential
DDC	Driver Delay Cost
DRF	Dose Response Functions
EC	Eurocode
EP	Eutrophication Potential
GWP	Global Warming Potential
LCA	Life Cycle Analysis
LCAT	Life Cycle Assessment Tool
LCC	Life Cycle Cost
LCEA	Life Cycle (Environmental) Assessment
LCIA	Life Cycle Inventory Assessment
LCP	Life Cycle Performance
NPV	Net Present Value
ODP	Ozone-layer Depletion Potential
POCP	Photochemical Ozone Creation Potential
RH	Relative Humidity
SC	Safety Cost
SLCA	Social Life Cycle Assessment
TOW	Time of Wetness
VOC	Vehicle Operational Cost

1. Introduction

1.1. Motivation

In recent decades, 'sustainability', 'environment friendly', 'life cycle analysis' or 'renewable energy' are widely used concepts in several contexts. Environment consciousness and life cycle concepts are getting more and more important for individuals, researchers, companies or even countries. This trend has various reasons but the most obvious and well-known are the decreasing amount of fossil fuel energy sources, the deteriorating quality of the surrounding materials (i.e.: air, water, soil) that affect our lives, the global warming and all of its direct and indirect effects and at last but not least, the recent economic crisis.

With the passing of time, specialists tend to pay more attention on life cycle analyses results and consider not only the initial cost that has to be paid at the time of an investment but also the cost that is due during the lifetime of a product or an asset. Beside this, they have also started to pay attention on environmental and social impacts and recognize the importance of these. Additionally, thinking in a wider time horizon approaches has become popular in general. It is important to understand that even if it is about financial impact, environmental impact or performance of a structure, the main idea is the same: to think not only about the present moment, but to see the impact on the future and the consequences of our decisions for the following years and decades.

In civil engineering, structures often become subject of sustainability and life cycle analyses. Among all structures, bridges are in special focus. There are two main reasons for this: bridge inventory represents very high value and these assets are designed not for 50 years as buildings but for 100 years, according to Eurocode (EC) standards.

1.2. State of the art

In recent years, several extensive European projects aimed to establish Life Cycle Analysis (LCA) and to develop Life Cycle Assessment Tool (LCAT) for different types of bridges. Some of these are: MAINLINE – "MAINtenance, renewaL and improvement of rail transport INfrastructure to reduce Economic and environmental impacts; SBRI – Sustainable Steel-Composite Bridges in Built Environment; Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives.

The focus of the projects MAINLINE and Sustainable Bridges was on railway bridges. More precisely, these projects aimed to examine the entire railway system and bridges were observed as parts of this network. The main idea of Sustainable Bridges was to "assess the readiness of railway bridges to meet the demands of the 2020 scenario and provide the means for up-grading them if they fall short. The 2020 scenario requires increased capacities with heavier loads to be carried and bigger forces to be absorbed due to longer faster trains and mixed traffic. All types of bridges are being considered" (Sustainable Bridges, 2007). "The objective of MAINLINE was to develop methods and tools contributing to an improved railway system by taking into consideration the whole life of specific infrastructure – tunnels, bridges, track, switches, earthworks and retaining walls" (MAINLINE, 2013). In this project LCATs were developed for different assets. In case of bridges, the tool was developed for steel bridges consisting of I-, channel- and box-sections. The tool took into account the thickness loss of the cross-sections due to corrosion and provided three different types of curing interventions: re-coating, strengthening and replacing. This deterministic tool served as a basis for the LCAT that is developed in the present thesis.

"Within the European funded research project SBRI a holistic approach is applied by combining analyses of environmental, economic and functional qualities. The obtained results provide a basis for European recommendations for the design of sustainable bridges." (SBRI, 2013) This project concentrated specifically on composite highway bridges. Assumptions were made regarding the expected lifetime of different elements of a bridge and also several types of interventions were established for all of them. These main elements of the bridge were selected as it follows: steel, concrete, expansion joint, bearing, road surface, water proofing layer, railing, gutter, and safety barrier. It is also worth noting that in SBRI, user costs are calculated at an advanced level regarding the traffic congestions under and over the bridge. After performing surveys about maintenance practice for bridges in different countries, three scenarios were created: standard, lack of money, and prolonged life maintenance strategies. At the end of the project, case studies were done for short-, medium-, and long-span bridges.

1.3. Goals

The main aim of this thesis is to develop a probabilistic tool (using Microsoft Excel) that can be used for LCA of composite highway bridges. The probabilistic tool is based on a similar deterministic tool developed in the MAINLINE project, which focused on steel railway bridges. Therefore, the main goal of the present thesis is to adopt this tool for composite highway bridges, and further improve it by converting it into a more powerful probabilistic tool with the help of the software @Risk (see subchapter 7.2)

Figure 1.1 Composite bridge in Dobřichovice, Czech Republic

This LCA has three main parts: Life Cycle (Environmental) Assessment (LCEA), Life Cycle Cost (LCC), including Social Life Cycle Analysis (SLCA), and Life Cycle Performance (LCP). The probabilistic approach is important to be implemented as there are several uncertainties in these fields, e.g. in modelling the corrosion damage of steel or protective coating degradation. Furthermore, an optimization algorithm is considered which provides an additional advantage regarding decision making processes. The tool can be later integrated in bigger systems, so the users will be able to model and examine not only one bridge but a group of them and in general the entire highway network including bridges.

Figure 1.2 Corroded steel bridges in Budapest, Hungary; from the left to the right: Árpád bridge, Lágymányosi bridge and Petőfi bridge

Apart from developing the tool, the other aim is to have a clearer idea about how these highway bridges behave over their lifetime. Regarding composite bridges, there is currently a lack of historical data, as this type of structures can be considered relatively young. These structures have some characteristics that can lead to better life cycle performance (e.g. recyclability of materials, speed of construction, etc), therefore they are expected to have more significance importance in future highway constructions.

2. Corrosion of I-girders

2.1. *Phenomena and Types of Corrosion*

Corrosion has attracted a growing attention of the scientific community in the last decades as this phenomenon is related to significant economic, social and environmental losses. Additionally, beside fatigue phenomenon it is one of the main reasons for failures of steel and composite structures (Gerhardus H. Koch, 2002).

Corrosion can be defined as the deterioration of a substance (mostly metal) due to reactions with its environment. Many classifications exist regarding this phenomenon. One of them distinguishes chemical and electrochemical corrosion based on the reaction that occurs on the surface of the metal. Another classification focuses on the appearance and the forms of corrosion. Regarding this, the following types of corrosion can be distinguished (see also Figure 2.1) (Landolfo, et al., 2010):

- Uniform corrosion: corrosion that proceeds roughly at the same rate throughout the metal surface;
- Pitting corrosion: localized corrosion occurring in a small area, having similar shapes to pits;
- Crevice corrosion: localized corrosion occurring at, or close, to an area that has no contact with air and vapour (i.e. protected);
- Galvanic corrosion: electrochemical process when corrosion of a metal occurs due to having contact in presence of electrolyte with another metal that is more noble than itself;
- Erosion corrosion: combined action of erosion and corrosion involving a rapid flow of a turbulent fluid and leading to accelerated loss of the metal;
- Cavitation corrosion: corrosion induced by evolution and rapid collapse of gas or vapour bubbles at or near the metal surface;
- Stress corrosion: strength loss due to combined occurrence of applied tensile stress and corrosive environment, evidenced in brittle cracking of the metal;
- Fatigue corrosion: strength loss gained by repeated stresses in a corrosive environment, evidenced in brittle cracking of the metal.

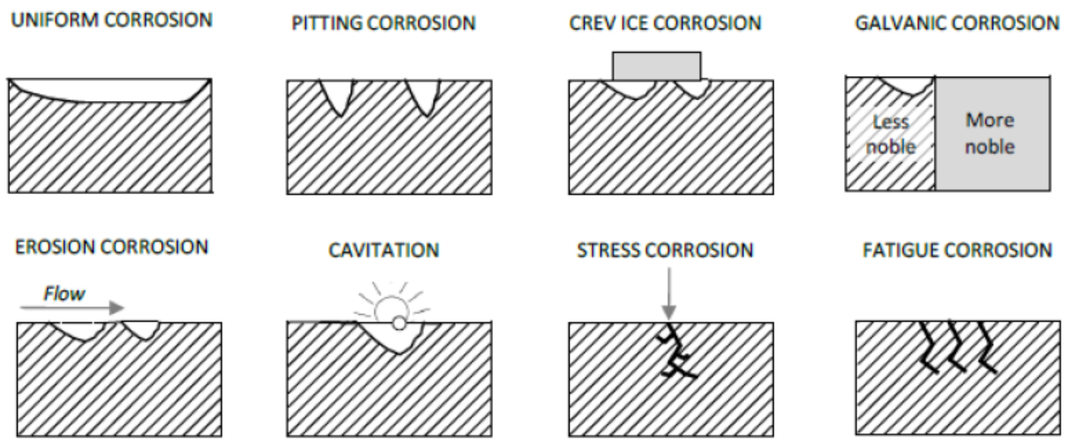


Figure 2.1 Types of corrosion **(Landolfo, et al., 2010)**

Corrosion, as an electrochemical process, can occur on the metal's surface in presence of water vapour (H_2O) and oxygen (O_2). The electrochemical reactions that occur to steel (iron) are the following (Zhifen Wang, 2013):

Anodic reaction:	$Fe \rightarrow Fe^{2+} + 2e^{-}$	(2.1)
Cathodic reaction:	$\frac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-}$	(2.2)
Overall reaction:	$Fe + \frac{1}{2}O_2 + H_2O \rightarrow Fe(OH)_2$	(2.3)
Reaction of rust development:	$2Fe(OH)_2 + \frac{1}{2}O_2 + H_2O \rightarrow 2Fe(OH)_3$	(2.4)

These reactions induce the loss of iron (Fe), therefore loss of steel of the element and increase of iron(III)oxide-hydroxide [$Fe(OH)_3$], i.e. rust. Hence, the useful cross-section and therefore its capacity reduced.

2.2. Classification of Environment

The occurrence of corrosion and the rate of damage for a particular element highly depend on the environmental conditions and effects. The main influencing parameters can be categorized as the following (BS EN ISO 9223, 2012) (F. Corvo, 1995):

- Climate factors:
  - Temperature;
  - Relative humidity;
- Levels of atmospheric pollutants:
  - Sulphur-dioxide (SO_2);
  - Chloride deposition (Cl^-).

Regarding the above parameters, in Table 2.1 (BS EN ISO 9223, 2012) six categories (C1-C5, CX) of the atmospheric corrosivity can be found. The table also shows examples for typical outdoor and indoor conditions regarding each category.

The standard (BS EN ISO 9223, 2012) provides guideline to decide about the corrosivity categories depending on the measurable environmental parameters, such as:

- Time of Wetness (TOW), which defines the period of time when the relative humidity is above 80% and the temperature is over 0°C
- SO_2 concentration;
- Cl^- deposition rate.

Knowing all these parameters it is possible to define the relevant corrosivity category of a structure or element according to the standard. However, it is worth noting that during the procedure of selecting the corrosivity category it is very important to take into account also the microclimate of the element, if relevant.

Another simplified classification of the environment, which is often used and does not require necessarily measurements, may consist of the following categories (Landolfo, et al., 2010):

- Rural atmosphere;
- Urban atmosphere;
- Industrial atmosphere;
- Marine atmosphere;
- Marine industrial atmosphere.

Table 2.1 – Corrosivity categories (extracted from Appendix C of (BS EN ISO 9223, 2012))

Corrosivity category [a]	Corrosivity	Typical environments — Examples [b] Indoor	Outdoor
C1	**Very low**	Heated spaces with low relative humidity and insignificant pollution, e.g. offices, schools, museums	Dry or cold zone, atmospheric environment with very low pollution and time wetness, e.g. certain deserts, Central Arctic/Antarctica
C2	**Low**	Unheated spaces with varying temperature and relative humidity. Low frequency of condensation and low pollution, e.g. storage, sport halls	Temperate zone, atmospheric environment with low pollution ($SO2<5µg/m3$), e.g. rural areas, small towns Dry or cold zone, atmospheric environment with short time of wetness, e.g. deserts, subarctic areas
C3	**Medium**	Spaces with moderate frequency of condensation and moderate pollution from production process, e.g. food-processing plants, laundries, breweries, dairies	Temperate zone, atmospheric environment with medium pollution (SO2: 5µg/m3 to 30µg/m3) or some effect of chlorides, e.g. urban areas, coastal areas with low deposition of chlorides Subtropical and tropical zone, atmosphere with low pollution
C4	**High**	Spaces with high frequency of condensation and high pollution from production process, e.g. industrial processing plants, swimming pools	Temperate zone, atmospheric environment with high pollution (SO2: 30µg/m3 to 90µg/m3) or substantial effect of chlorides, e.g. polluted urban areas, industrial areas, coastal areas without spray of salt water or exposure to strong effect of de-icing salts Subtropical and tropical zone, atmosphere with medium pollution
C5	**Very high**	Spaces with very high frequency of condensation and/or with high pollution from production from production process, e.g. mines, caverns for industrial purposes, unventilated sheds in subtropical and tropical zones	Temperate and subtropical zone atmospheric environment with very high pollution (SO2: 90µg/m3 to 250µg/m3) and/or significant effect of chlorides, e.g. industrial areas, coastal areas, sheltered positions on coastline
CX	**Extreme**	Spaces with almost permanent condensation or extensive periods of exposure to extreme humidity effects and/or with high pollution from production process, e.g. unventilated sheds in humid tropical zones with penetration of outdoor pollution including airborne chlorides and corrosion-stimulating particulate matter.	Subtropical and tropical zone (very high time of wetness), atmospheric environment with very high SO2 pollution (higher than 250µg/m3) including accompanying and production factors and/or strong effect of chlorides, e.g. extreme industrial areas, coastal and offshore areas, occasional contact with salt spray
Note 1 Deposition of chlorides in coastal areas is strongly dependent on the variables influencing the transport inland of sea salt, such a			
Note 2 Extreme effect by chlorides, which is typical of marine splash or heavy salt spray, is outside of the scope of this International Star			
Note 3 Corrosivity classification of specific service atmospheres, e.g. in chemical industries, is outside of the scope of this International			
Note 4 Surfaces that are sheltered and not rain-washed in marine atmospheric environments where chlorides are deposited and cumula			
Note 5 A detailed description of types of indoor environments within corrosivity categories C1 and C2 is given in ISO 11944-1. Indoor corr			
[a] In environments expected "CX category", it is recommended that atmospheric corrosivity classification from one-year corrosion losses			
[b] The concentration of sulphur dioxide (SO2) should be determined during at least one year and is expressed as the annual average.			

2.3. Analytical Modelling of Corrosion Damage

For estimating the future performance of an element or a structure that is influenced by corrosion, it is needed to assume the thickness loss due to corrosion. This affects the capacity of the element (e.g. shear, bending, buckling) and after its estimation, it is possible to predict the performance of the element over the lifetime of the bridge. The corrosion rate defines the thickness loss of an element over one year in mm. The corrosion rates for the first year of the exposure for an element in carbon steel, zinc, copper and aluminium are shown in Table 2.2 (BS EN ISO 9223, 2012). The values in the table are presented regarding each corrosivity category (C1-C5, CX) and are based on both full scale and laboratory tests.

Table 2.2 – Corrosion rates during the first year of exposure of an element for corrosivity categories C1 – C5, CX (extracted from (BS EN ISO 9223, 2012))

Corrosivity category	**Corrosion rates of metals, r_{corr}**				
	Unit	**Carbon steel**	**Zinc**	**Copper**	**Aluminium**
C1	g/(m²a)	$r_{corr} \leq 10$	$r_{corr} \leq 0{,}7$	$r_{corr} \leq 0{,}9$	negligible
	μm/a	$r_{corr} \leq 1{,}3$	$r_{corr} \leq 0{,}1$	$r_{corr} \leq 0{,}1$	—
C2	g/(m²a)	$10 < r_{corr} \leq 200$	$0{,}7 < r_{corr} \leq 5$	$0{,}9 < r_{corr} \leq 5$	$r_{corr} \leq 0{,}6$
	μm/a	$1{,}3 < r_{corr} \leq 25$	$0{,}1 < r_{corr} \leq 0{,}7$	$0{,}1 < r_{corr} \leq 0{,}6$	—
C3	g/(m²a)	$200 < r_{corr} \leq 400$	$5 < r_{corr} \leq 15$	$5 < r_{corr} \leq 12$	$0{,}6 < r_{corr} \leq 2$
	μm/a	$25 < r_{corr} \leq 50$	$0{,}7 < r_{corr} \leq 2{,}1$	$0{,}6 < r_{corr} \leq 1{,}3$	—
C4	g/(m²a)	$400 < r_{corr} \leq 650$	$15 < r_{corr} \leq 30$	$12 < r_{corr} \leq 25$	$2 < r_{corr} \leq 5$
	μm/a	$50 < r_{corr} \leq 80$	$2{,}1 < r_{corr} \leq 4{,}2$	$1{,}3 < r_{corr} \leq 2{,}8$	—
C5	g/(m²a)	$650 < r_{corr} \leq 1500$	$30 < r_{corr} \leq 60$	$25 < r_{corr} \leq 50$	$5 < r_{corr} \leq 10$
	μm/a	$80 < r_{corr} \leq 200$	$4{,}2 < r_{corr} \leq 8{,}4$	$2{,}8 < r_{corr} \leq 5{,}6$	—
CX	g/(m²a)	$1500 < r_{corr} \leq 5500$	$60 < r_{corr} \leq 180$	$50 < r_{corr} \leq 90$	$r_{corr} > 10$
	μm/a	$200 < r_{corr} \leq 700$	$8{,}4 < r_{corr} \leq 25$	$5{,}6 < r_{corr} \leq 10$	—
Note 1 The classification criterion is based on the methods of determination of corrosion rates of standard specimens for the evaluation of corrosivity (see ISO 9226)					
Note 2 The corrosion rates, expressed in grams per square metre per year [g/(m2·a)], are recalculated in micrometres per year [μm/a] and rounded.					
Note 3 The standard metallic materials are characterized in ISO 9226.					
Note 4 Aluminium experiences uniform and localized corrosion. The corrosion rates shown in this table are calculated as uniform corrosion. Maximum pit depth or number of pits can be a better indicator of potential damage. It depends on the final application. Uniform corrosion and localized corrosion cannot be evaluated after first year of exposure due to passivation effects and decreasing corrosion rates.					
Note 5 Corrosion rates exceeding the upper limits in category C5 are considered extreme. Corrosivity category C refers to specific marine and marine/industrial environments (see Annex C).					

For modelling the progress of corrosion rate the most well-known bilogarithmic equation is the following (Zhifen Wang, 2013):

$$C(t) = A \cdot t^{B} \tag{2.5}$$

where:

C(t) is the thickness loss in function of time, i.e. corrosion rate [mm];

t is the time length of exposure [year];

A and *B* are constants determined experimentally and are dependent on the material and environment.

It can be observed from the equation (2.5) that *A* is practically the thickness loss during the first year of exposure, affected mainly by the initial condition of the environment. On the other hand, *B* is related to the corrosion development with time. In Table 2.3 experimental values can be found for parameters *A* and *B* regarding both carbon and weathering steel (Kayser, 1988).

Equation (2.5) has strong limitations as it can hardly take into account the independent variation of each environmental parameter. Moreover, the entire corrosion rate function over time highly depends on the corrosion rate of the first year of exposure. This can cause inaccuracy examining a longer time profile as the initial conditions can change significantly.

Other possibility to model the corrosion rate over time are the Dose Response Functions (DRF), which involve environmental parameters directly; hence, their independent changes can also be tracked. Although these methods are able to provide more accurate results, this thesis does not examine them deeper due to the difficulties of finding input data and widely recognized formula for them.

Therefore, in this thesis, equation (2.5) is adopted to model the progression of corrosion.

Table 2.3 – Mean values, variations and correlations of statistical parameters *A* and *B* (Kayser, 1988)

Parameters	**Carbon Steel**		**Weathering Steel**	
	A	B	A	B
Rural Environment				
Mean value, μ	34.000	0.650	33.300	0.498
Coefficient of variation, σ/μ	0.090	0.100	0.340	0.090
Coefficient of correlation, ρAB	N/A	—	-0.050	—
Urban Environment				
Mean value, μ	80.200	0.593	50.700	0.567
Coefficient of variation, σ/μ	0.420	0.400	0.300	0.370
Coefficient of correlation, ρAB	0.680	—	0.190	—
Marine Environment				
Mean value, μ	70.600	0.789	40.200	0.557
Coefficient of variation, σ/μ	0.660	0.490	0.220	0.100
Coefficient of correlation, ρAB	-0.310	—	-0.450	—

3. Corrosion Protection

3.1. General Idea of Protection

It is widely known that steel tends to corrode, resulting in rust on the surface and consequently material loss of the element (as described in chapter 2). The main principle of preventing this harmful process is not to let steel (Fe) itself contact neither the oxygen (O_2) of the air, nor any humidity in the atmosphere. For this purpose, protective coatings are used.

However, right from the time of design it is important to think about corrosion and corrosion protection of any steel structure. It is not too difficult to achieve significant advantages regarding the life-cycle of the structure from a suitable and corrosion-conscious design. The main aspects that are needed to be taken into account are the following (Corus, 2002):

- Provide easy access for applying and maintaining the protective coatings along the steel structure;
- Avoid cope holes in web stiffeners or use circular ones with minimum radius of 40mm;
- Avoid moisture and debris traps;
- Avoid crevices, design bolted connection carefully;
- Ensure appropriate drainage and ventilation for each element to minimize TOW.

To make the protection of the steel complete, it is usually needed to apply proper protective coating to the steel structure. These coatings can be very effective and therefore are widely used nowadays. It is noted that in case of steel or composite bridges made of carbon steel, it is unavoidable to use such coatings. However, applying a protective coating does not necessarily lead to significant enhancement of performance without appropriate knowledge and carefulness for application of the protective system.

To achieve better quality and longer lifetime of the protective coatings, there are some aspects that should be taken into account and that can significantly affect the corrosion protection of the structure (Almeida, 2005):

- Application process;
- Environmental conditions during application;
- Surface preparation;
- Quality of environment/products.

3.2. Choice of Protective Coatings

There are different types of protective coatings. Previously, they consisted of more (5<) layers; however, with the development of the industry, the number of coats has decreased. Nowadays 2-3 layers coating systems are popular and even one single layer coating systems may be found. The most common classification of current coating systems is the following:

- Organic;
- Inorganic (non-metallic);
- Metallic:
  - Thermal spraying;
  - Hot-dip galvanizing;
- Mixed or “duplex”.

A coat usually consists of the following components: binders, pigments, additives, solvents. Binders are liquid and holding solid particles in place. The most used binders are: drying oils, alkyd resins, vinyl and acrylic emulsions, epoxy resins and polyurethanes. The solid particles are the pigments that can be either organic or inorganic. (Clark, 2002)

The typical layers of a coating system are listed below:

- Primer
- Intermediate or undercoat(s)
- Finish coat

Primer coat is applied directly on the (clean) surface of the steel. It has triple function as it provides adhesion between the coating and the steel element, it makes the surface wet and at last, it also provides corrosion inhibition already. Intermediate coat(s) gives the effective thickness of the painting following more or less the principle of ‘thicker paint means better protection’, hence it plays the main role of protection. Finish coat is responsible for both the surface resistance against weather: sun, condensation, etc. and the aesthetic of the painting. It is worth noting that the compatibility between the layers is essential to achieve the desired corrosion protection (Corus, 2002).

A metallic coat can be applied either by thermal spraying or by hot-dip galvanizing. For thermal spraying generally zinc (Zn) or aluminium (Al) metals are used. It can be applied either in shop or at site. Nevertheless, for obtaining proper adhesion with steel, the cleaning and appropriate roughening of the surface is unavoidable. The thickness of these coats is usually 100-200 µm for aluminium and 100-150 µm for zinc. In the hot-dip galvanizing method the element is sunk in a molten zinc bath with pickling and fluxing. It has to be noted that for this process, naturally there are size limitations for the elements, thus it cannot be used in every case. The thickness of these coatings depends on various things such as size and shape of the steel element or the preparation of the steel surface (Corus, 2002).

The right choice of coating is essential regarding the performance over the lifetime of a steel or composite structure, thus the decision has to be made carefully and taking into account mainly the following aspects (Hudson, 2002):

- The design life of the structure;
- The possibility and the actual planning of maintenance works during the lifetime of the structure;
- The environment of the structure (i.e. corrosivity category);
- The size and shape of the steel elements;
- The treatment facilities that the fabricator can offer;
- The conditions at the construction site that determine whether there is a possibility to treat the steel after erection;
- The budget that is available for the treatment of the steel structure;
- The restrictions or the goals regarding the sustainability of the structure.

After considering these aspects, additional decisions have to be made regarding the following points:

- The type of the protective coating to be used;
- The method to be used for surface preparation;
- The method to be used for application of the protective coating;
- The number of coats to be used and the thickness of each of them.

3.3. Protective Coating Degradation

It is possible to extend the life of the protective coating and thus of the steel structure with careful consideration of the conditions listed in subchapter 3.2. Mindful choice of the coating system, proper application and maintenance of it are very important issues. However, it is not possible to fully avoid the degradation of coating. The coating degrades in time whenever it has contact with the environment, and it has defects whenever it depends on any job made by humans (mainly regarding surface preparation and application of coating). The degradation happens in various forms, which may occur simultaneously. Some appear already during the application of the coating or directly after it, while others need time or some external effect (environmental or physical) to start developing. They differ also in appearance; for example, they can be: visible or not visible, local or global, changing in colour/shine or changing in roughness/smoothness of the surface.

The possible defects of coating systems are presented in (Fitzsimons, 1999), and the most significant defects are summarized in Table 3.1.

Table 3.1 – Defects of coating systems (adopted from (Fitzsimons, 1999))

Adhesion failure	Paint fails to adhere to substrate or underlying coats of paint.
Bleaching	Total loss of colour of a coating.
Bleeding	Staining of a paint film by diffusion of a soluble coloured substance from the underlying
Blistering	Dome shaped projections or blisters in the dry paint film through local loss of adhesion from the underlying surface.
Bloom	A hazy deposit on the surface of the paint film resembling the bloom on grape, resulting in a loss of gloss and a dulling of colour.
Bridging	The covering over of unfilled gaps such as cracks or corners with a film of coating material.
Bubbles/Bubbling	Bubbles within a paint film appear as small raised blisters. These may be intact or broken (to leave a crater).
Chalking	A friable, powdery layer on the surface of a paint film and a change of colour or fading.
Checking	Fine cracks which do not penetrate the topcoat of a paint system.
Cheesiness	Coating remains soft, even after prolonged drying time.
Cracking	Paint coatings with visible cracks which may penetrate down to the substrate.
Delamination	Loss of adhesion between coats of paint.
Dry spray	Rough and uneven finish to the surface of the paint film.
Erosion	Selective removal of paint films from areas or high spots.
Fading	Discoloration or gradual decrease in colour of a paint when exposed to sunlight/weather.
Flaking	A form of adhesion failure where paint literally flakes from the substrate.
Flooding	A defect which appears soon after application due to pigment separation.
Grinning	The underlying surface is visible through the paint film due to inadequate hiding power of the coating material.
Grit inclusions	Particles of grit and dust embedded within the coating system.
Growth	Growth and attachments of natural and organisms to surface of finished products.
Impact damage	Cracks which radiate from a point of impact.
Mud cracking	The dried paint film has the appearance of a dried-out mud bath.
Orange peel	The uniform pock-marked appearance resembles the skin of of an orange.
Pinholes	The formation of minute holes in the wet paint film during application and drying.
Rippled coating	A rippled effect on the surface of the paint.
Runs/sags	Downward movement and tears of paint which appear soon after application to vertical surfaces.
Rust spotting	Fine spots of rust which appear on a paint film, usually a thin primer coat.
Rust staining	A light staining on the surface of the paint caused by the precipitation of ferrous oxide.
Settlement	A term used to describe the settled pigment/solids in a liquid prior to application.
Undercutting	Visual corrosion beneath a paint film. Corrosion travels beneath the paint film and lifts the paint from the substrate.
Water spotting	The spotty appearance of the paint film caused by drops of water on the surface and which remains after the water has evaporated.
Wrinkling	The development of wrinkles in the paint film during drying / wrinkling / swelling and blistering of the coating.

3.4. Modelling of Coating Degradation

Deterioration of coating can be modelled by the polynomial equation (3.1) that takes into account the actual atmosphere through the expected life of the coating (MAINLINE, 2013). These values regarding each corrosivity category, should be provided by the company that produces the coating, or gathered from scientific papers and/or standards.

$$\frac{A_{pr}(t)}{A_{pr0}} = 1 - \left(\frac{0.6t^2}{T_L^{\ 2}} - \frac{0.1t}{T_L} \right) \tag{3.1}$$

where:

$A_{pt}(t)$ and A_{pt0} stand for the residual and initial protected area of steel, respectively;

t is the time [year];

T_L is the time when it is assumed that 50% of the coating becomes ineffective.

With this model it is possible to define the time T_U when the entire coating is lost and the whole steel area becomes without protection. It should be noted that $A_{pt}(t) \leq A_{pt0}$ for every value of t and $A_{pt}(t) = 0$ when $t > T_U$. This formula takes into account that the deterioration of the coating becomes more rapid with time; hence, T_U will be always smaller than $2 \times T_L$.

4. Degradation of the Reinforced Concrete

4.1. Phenomena of Carbonation

In general, reinforced concrete is considered as a durable structural material. Compared to other widely used materials in construction industry, such as steel or timber, the advantage of concrete regarding durability is undeniable. However, concrete does not have infinite durability and its deterioration has to be undoubtedly taken into account.

The most dangerous deterioration processes of concrete are connected with the corrosion of the steel rebar embedded in the element and the decomposition of concrete due to the phenomenon of spalling. Both of these deterioration processes involve transport phenomena through the pores of the concrete (Papadakis, et al., 1991).

The corrosion of the steel rebars can occur after carbonation of the surrounding concrete, penetration of chloride ions (Cl^-) or the combination of both (Papadakis, et al., 1991). In the first case, corrosion of steel rebars evolves from atmospheric carbonation of the concrete. When the structure has connection with the environment, it evidently has connection with air, and thus with carbon dioxide (CO_2) and oxygen (O_2). Therefore CO_2 can diffuse into the concrete cover and reach the pore water, in which it can dissolve. Through chemical reactions with hydration compounds, this leads to decreased value of pH (from over 12 to under 9) and thus to increased likelihood of corrosion of the steel rebars; more precisely: formation of rust, rust stains on concrete surface, cracks and spalling and decreased effective area of rebars (Mickaël, 2010).

In the second case, corrosion of steel rebars occurs when the chloride content reaches a critical value after penetration. This can result from de-icing salts or seawater and is the main reason for corrosion initiation in concrete elements of highway, marine and coastal structures. The chloride ions are transported in the network of the pores of concrete through micro cracks and start to accelerate the corrosion when they reach the steel rebars and passivate the protecting oxide-film of them (V. G. Papadikis, 2005).

Considering the above mentioned processes that lead to the deterioration of reinforced concrete, it can be stated that the durability of concrete depends mainly on four aspects (Papadakis, et al., 1991):

- The structure of its pores;
- The distribution of volume of pores between gaseous and aqueous phases;
- The evolution in time of the concentrations of the compounds that are expected to be involved in chemical reactions with external aggressive substances;

- The thickness of the concrete cover.

While these aspects are connected with the reinforced concrete element itself, another group of aspects influencing deterioration of concrete are connected with the surrounding environment, such as relative humidity.

4.2. Analytical Modelling of Carbonation

There are two widely known and acknowledged modelling approaches for carbonation of reinforced concrete. The model of Papadakis predicts the progress of carbonation in a square root of time law, while Bakker's model is improved by recognizing and involving the effect of wetting-drying cycles (Mickael & Christian, 2008). In the next paragraphs, both models are examined in detail.

4.2.1. Papadakis model

The assumptions of the Papadakis model are the following (Mickaël, 2010)

- Sharp carbonation front;
- Diffusion of CO_2 in a fully-carbonated and homogenous area;
- Moisture content uniform and steady in time;
- Moisture equilibrium between the concrete and the environment.

The function of the carbonation depth follows a square root of time law and can be calculated according to the equation (Mickael & Christian, 2008):

$$X_c(t) = \sqrt{\frac{2 \cdot C_0 \cdot D_{CO2}}{n_i}} \cdot \sqrt{t} \tag{4.1}$$

where:

D_{CO2} is the effective CO_2 diffusion coefficient, which is expressed in the equation (4.2);

n_i is the initial carbon hydroxide $Ca(OH)_2$ content;

C_0 is the external CO_2 concentration;

t is the time.

The following formula shows how the effective CO_2 diffusion coefficient is expressed:

$$D_{CO2} = D_g \cdot \phi^a \cdot (1-S)^b \tag{4.2}$$

where:

D_g is the CO_2 diffusion coefficient in the gaseous phase;

a and b are coefficients, equal to *2.74* and *4.20*, respectively;

S is the liquid water saturation degree;

Φ is the porosity.

The model can be considered reliable as the calculated depth of carbonation is coherent with the value measured by phenolphthalein-spray test. It is widely recognized that Papadakis described an analytical relationship between time and the progress of carbonation in reinforced concrete. On the other hand, the model considers sharp carbonation front that may not refer to reality and moreover, it is not able to take into account the effects of wetting-drying cycles (Mickaël, 2010).

4.2.2. Bakker's model

This model is based on the model of Papadakis but it is improved by taking into account the influence of drying-wetting cycles. In this approach, the basic assumptions are the following:

- Carbonation front is sharp;
- Carbonation is negligible as long as the moisture content of concrete is too high;
- Choice of a limit relative humidity (*RH*) for which carbonation is inhibited (RH_{lim}=80%);
- Drying happens faster than the carbonation process;
- Wetting is instantaneous.

During the drying process, the depth X_d where *RH* reaches RH_{lim} follows a square root of time law as it is shown in equation (4.3):

$$X_d = d \cdot \sqrt{t_d} \tag{4.3}$$

where:

d is kinetics coefficient assessed by a model of moisture transport and can be defined according to equation (4.4) (Mickael & Christian, 2008);

t_d is the length of the drying period.

$$d = d_0 \cdot \left(\frac{Kl}{Kl^0}\right)^{0.61} \cdot \left(\frac{\phi}{\phi_0}\right)^{-0.61} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{-0.61} \cdot \left(\frac{\beta}{\beta_0}\right)^{0.95} \cdot \left(\frac{HR_{ext}}{HR_{ext}^0}\right)^{0.51} \qquad (4.4)$$

where:

Φ is the variation of porosity;

Kl is the variation of water permeability;

α and β are the Genuchten's coefficients;

HR_{ext} is the variation external relative humidity;

Index 0 (^{0} *or* $_0$) indicates the mean value of any variable.

As carbonation is assumed to stop in wet concrete, the depth of carbonation cannot exceed the maximum depth of drying. The depth of drying is influenced not only by the properties of concrete but the environment as well. During the wetting process, the water absorption is defined in a similar way as during drying process using a square root of time law (see equation (4.5) (Mickael & Christian, 2008)).

$$X_w = w \cdot \sqrt{t_w} \qquad (4.5)$$

where:

w is a kinetics coefficient characterized by phenomenon of water inhibition;

t_w is the length of the wetting period.

Regarding Bakker's model the progress of carbonation starting from a sharp front is given by an algorithm that takes into account the effective CO_2 diffusion coefficient in the carbonated area, the environmental concentration of CO_2, the initial content of $Ca(OH)_2$, the kinetics coefficients, the length of the period of drying and wetting and the external relative humidity (Mickael & Christian, 2008).

The model results in a simple algorithm that makes it practical and easy to use. It takes into account the wetting-drying cycles and hence follows the real phenomenon of carbonation better than Papadakis' model. Despite these advantages, the model assumes instantaneous wetting, which cannot be realistic. The choice of RH_{lim} also results in unreliability and at last but not least, this model still considers a sharp carbonation front like the Papadakis model.

4.3. Analytical Modelling of Area Loss of Rebars

It has to be emphasised that Cl^- diffusion in concrete is dangerous or critical due to its effect on the rebars. The corrosion of the rebars can be initiated by diffusion of Cl^- either through the concrete cover or through cracks. This leads to capacity loss and also to micro cracks in concrete or even concrete spalling as the volume of the corroded rebars increases. (Vu & Stewart, 2000)

The performance degradation can be approximately modelled by calculating the area loss of the rebars by time due to pitting or general corrosion. Taking into account the latter and more severe one, the formulas (4.6), (4.7), (4.8), (4.9) and (4.10) can be used (Ma, et al., 2013).

The time when the corrosion initiates (T_i) is calculated in years according to the formula expressed by Thoft-Christensen:

$$T_i = \frac{{C_{\mathrm{cov}}}^2}{4 \cdot D_c} \cdot \left[erf^{-1}\left(\frac{C_{0Cl} - C_{cr}}{C_{0Cl}} \right) \right]^{-2} \tag{4.6}$$

where:

C_{cov} is the thickness of the concrete cover [cm];

D_c is the chloride diffusion coefficient [cm^2/year];

C_{cr} is the critical chloride concentration which initiates the corrosion [% of concrete weight];

C_{0cl} is the equilibrium chloride concentration at the concrete surface [% of concrete weight].

The water/cement ratio (w/c) has high importance in predicting the chloride diffusion in concrete and as a result, the corrosion rate of rebars. It can be estimated using the Bolomey's formula presented hereby:

$$w/c = \frac{27}{f_c + 13.5} \tag{4.7}$$

where:

f_c is the compressive strength of concrete [MPa].

The corrosion rate density (i_{corr}), which presents the "speed" of the corrosion phenomenon of steel reinforcement, for any time, is determined by the formula below:

$$i_{corr}(t) = \frac{32.13 \cdot \left(1 - w/c\right)^{-1.64}}{C_{\text{cov}}} \cdot \left(t - T_i\right)^{-0.29} \qquad (4.8)$$

Knowing the corrosion rate and the time when corrosion initiates, it is easy to find the diameter of rebars (D_s), at any time, applying the following formula:

$$D_s(t) = D_0 - 0.0232 \cdot \left(t - T_i\right) \cdot i_{corr}(t) \qquad (4.9)$$

where:

D_0 is the initial diameter of rebar.

Finally, the area loss of the steel reinforcement (A_s) is calculated with the expression presented below:

$$A_s(t) = \frac{\pi \cdot \left(D_0^2 - D_s^{\,2}(t)\right)}{4} \qquad (4.10)$$

5. Integration of Life Cycle Environmental Burdens and Costs

5.1. *Life Cycle Sustainability Assessment*

In the recent decades sustainability has been drawing more and more attention from both scientists and engineers. The word sustainability can be defined as 'the development that meets the needs of the present without compromising the ability of future generation to meet their own needs' (UN Document, 1987). In general, it can be stated that LCA is probably the best fitting tool to realize designs that fulfil the criteria of sustainability.

LCA is an approach to evaluate a product, a process or a structure regarding economic, social, and environmental aspects over its entire lifetime. These three aspects are often referred as the three main pillars of LCA. As they are naturally unique and usually dependent on each other, it is not easy to find a global methodology that results in a common solution for all. According to Koepffler (Gervásio, 2010) there are two ways to do this. The first one involves the development of independent assessments and then the use of the following formula[1]:

$$LCA = LCEA + LCC + SLCA \qquad (5.1)$$

where:

LCEA is the Life Cycle (Environmental) Assessment;

LCC is the Life Cycle Cost;

SLCA is the Social Life Cycle Assessment.

The other approach is an integral approach where the economic and social aspects are integrated in LCA during the impact assessment. This can be expressed using the following formula:

$$LCA = LCEA_{new} \qquad (5.2)$$

[1] In order to use a coherent abbreviation system in this thesis, the original formula has been changed in outlook, but not in meaning.

LCA covers all stages of a product life from raw material stage to the waste treatment or final deposition, as it is shown in Figure 5.1. In case of a more integrated system, such as a bridge or any other structure, the analysis becomes more complex. However, the scope of the analysis depends always on the goals that are defined. Regarding the goals, the specialists can decide which steps are affecting the results and which are not; hence, several steps of the analysis may be ignored. (Gervásio, 2010)

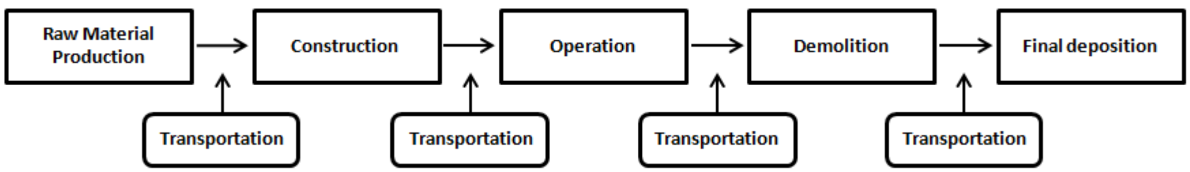


Figure 5.1 System boundary of the integral analysis adapted from (Gervásio, 2010)

The present thesis focuses mainly on environmental and economic aspects, while the social aspect is not too much detailed. This can be explained as for the latter there are less developed methodologies and the thesis focuses primarily on the lifetime profiles of bridges with protective coating, not on applying a whole LCA of bridges. Despite these, some social effects are taken into account through indirect costs included in LCC, see subchapter 5.3.

5.2. Environmental Impacts over the Lifetime of Bridges

5.2.1. LCEA approaches

LCEA includes impacts on the environment over the lifetime of a product or, of a (bridge) structure as in the present case. At every stage of the lifetime (see Figure 5.1) there are processes that have significant effect on the quality of our environment. LCEA intends to identify and quantify all these effects. In case of a bridge, these effects mainly come from the different products that are used and the activities that happen through the lifetime of the bridge.

The framework of the analysis according to (ISO14040, 2006) is shown in Figure 5.2.

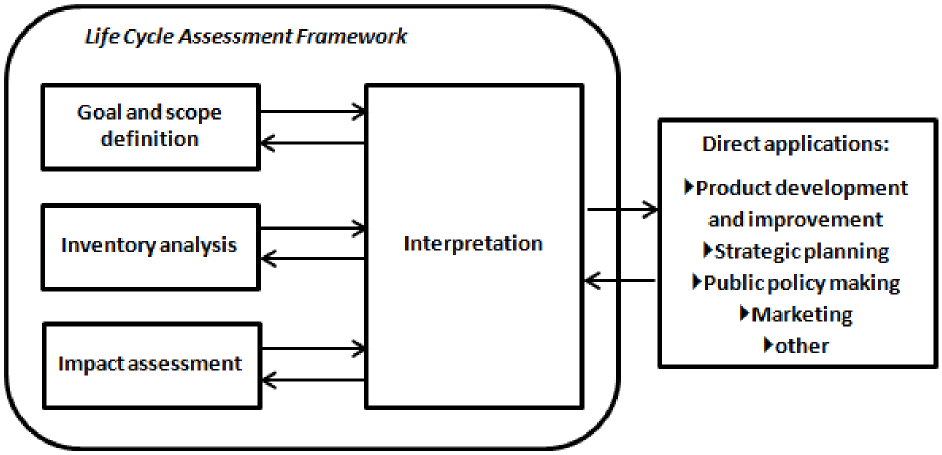


Figure 5.2 LCEA framework adapted from (ISO14040, 2006)

It is worth mentioning that regarding Life Cycle Impact Assessment (LCIA), two approaches can be identified: problem-oriented (i.e. bottom-up or mid-point) and damage-oriented (i.e. top-down or end-point). For the first one, impact categories are needed to be defined and by using a weighting system the final result can be obtained. In the later approach, damage categories are also needed to be defined and accounted for each impact that contributes on a chosen damage. Both methods are illustrated in Figure 5.3.

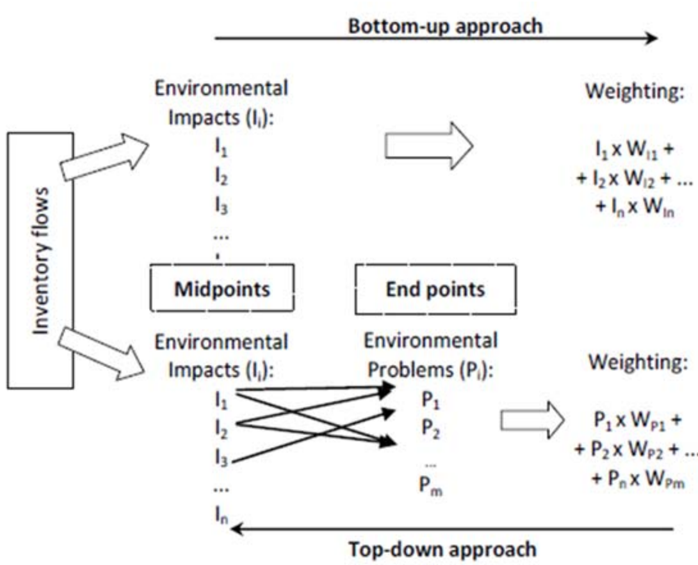


Figure 5.3 Bottom-up and Top-down LCIA approaches (Gervásio, 2010)

5.2.2. *Environmental impacts*

Many environmental impact categories can be considered. However, in the literature there are a reasonable number of impacts considered essential and widely recognized. The most common environmental categories are the following (Gervásio, 2010):

- Climate change;
- Ozone depletion;
- Photochemical ozone creation;
- Acidification;
- Eutrophication,
- Ecotoxity;
- Human toxicity;
- Resource consumption.

The impact assessment has mandatory steps (such as classification and characterization) and optional steps (such as normalization and weighting) as illustrated in Figure 5.4.

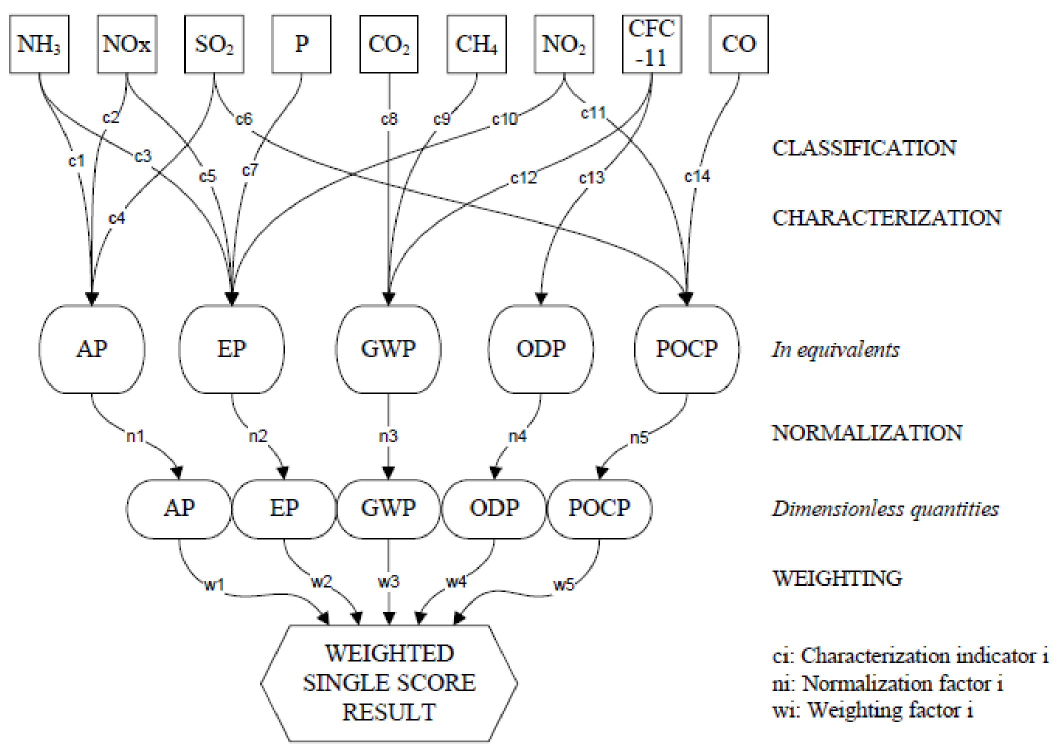


Figure 5.4 Life cycle impact assessment steps: classification, characterization, normalization and weighting (J. Hammervold, 2009)

The selection of the emission substances for the analysis has to be done regarding what impacts are desired to be taken into account. Following the steps described in Figure 5.4, firstly the emissions are classified according to the environmental impact categories that they contribute to (Acidification Potential: AP, Eutrophication Potential: EP, Global Warming Potential: GWP, Ozone-layer Depletion Potential: ODP, Photochemical Ozone Creation Potential: POCP), using the relevant characterisation indicators. For each category the total scores are summarized and normalized, and in the last step, these scores are weighted to make it possible to achieve one single result.

5.3. Life Cycle Cost of Bridges

LCC has always been the most developed aspect among the three pillars of LCA. Not too long time ago decision makers were taking into account only costs and ignoring social or environmental effects during the preparation process of any design. Fortunately this has been changing recently. However, more data and studies are available for LCC as its importance has been recognized for longer time.

It can be stated that in general, LCC includes all possible relevant costs of a product or an asset from the raw materials until the waste deposition at the end of life or over any other specified time horizon. Since in a LCC, costs occur in different stages, they are usually discounted into the present value. In other words, LCC results in the present value of all the costs and expenses that can occur during the chosen period of the study of a product or asset.

5.3.1. Classification of the costs

There are different options to classify the costs and these may vary regarding the subject of the study (Gervásio, 2010). In case of bridges, costs can be divided regarding the time they occur:

- Construction cost;
- Operational and maintenance cost;
- End of life cost.

Another way of grouping costs is by the entity that bears the cost:

- Agency;
- 3rd party;
- User.

Costs also can be distributed according to their root, i.e. what they refer to:

- Elements;
- Activities;
- New technologies.

Finally there is also a way to divide the costs simply into:

- Direct;
- Indirect.

5.3.2. Direct costs

The direct costs involve all the costs that come directly from the material production, construction, maintenance etc. These are the costs that can be measured easily and directly expressed in financial value, or with other words the costs that can be seen on any bill.

5.3.3. Indirect costs

Indirect costs include much more uncertainties than direct costs. They are rooted in activities indirectly connected to the asset (in our case: the bridge). It is generally difficult to express these costs in financial value or to define a limit how "far" the study needs to go, which cost still has to be included and which should not be anymore. These indirect costs mostly occur during the operation stage of the bridge's life, more precisely during maintenance activities. It should be noted that these costs can be referred as social impacts and thus indirect costs basically present an SLCA included in LCC. The most commonly defined indirect costs are called User costs and can be divided into the following categories:

- Driver Delay Cost (DDC): average unit cost of a driver's time;
- Vehicle Operational Cost (VOC): average unit cost of operating a vehicle;
- Safety Cost (SC): average unit cost of any accident that possibly happens on a road.

6. Deterministic Life Cycle Assessment Tool

6.1. Introduction

There are several LCAT developed for bridges nowadays. Among them, it is possible to find separate tools only for motorway or for railway bridges due to their differences both in structural systems and in the effect of traffic congestions. For obvious reasons usually these programs are also suitable for limited types of structures and/or materials. The main parameters that can differ among the tools are the following:

- Including or not the construction stage;
- Including or not the end of life stage;
- Calculation of costs (for interventions);
- Considered environment impacts (of interventions);
- Including or not the indirect impacts (e.g. user costs and extra emissions);
- Maintenance strategies;
- Degradation modelling of the structure.

In the present thesis an LCAT was developed for composite steel-concrete highway bridges. This Microsoft Excel tool was based on a similar LCAT developed as part of the MAINLINE project. The original tool of MAINLINE was developed for three types of railway bridges: half-through truss, I-girder and box-section. To determine the degradation of the steel elements, corrosion (i.e. thickness loss) is taken into account. The subject of the analysis is always one (type of) element, e.g. one I-girder. The maintenance strategies that can be applied are: strengthening of the elements with additional plating, repainting or replacing them. The costs and the environmental impacts (only CO_2 emission) of the interventions are defined mainly as user input data in the tool. This is done due to differences between countries and companies regarding prices (both materials and labour), commonly used equipment and products (e.g. paintings) and calculation of environmental impacts. The main outputs are costs, environmental impacts and performance of the bridge over its lifetime.

In this thesis, the deterministic tool was further improved in relation to the type of the bridge cross-section (composite section) and by the implementation of user costs. In the next subchapters the improved and modified LCAT, which is be able to deal with composite steel-concrete highway bridges, is explained in detail.

6.2. Input Data

Regarding the environment, a category has to be decided between C1 and C5. This can be done knowing if the environment of the asset is rural, urban or industrial and if the element is "exposed" (side girders) or "protected" (inner girders). After, the corrosivity category can be defined according to Table 6.1.

Table 6.1 – Defining corrosivity categories for bridge elements

Bridge environment		**Element exposure**		**Box**
		Exposed	***Protected***	**Section**
Rural	(C2)	C2	C1	C1
Urban	(C3)	C3	C2	C2
Industrial	(C5)	C5	C3	C2

The tool enables it to consider that the environment of the bridge may become more aggressive by the time. For instance, it is possible to set the corrosivity category of the bridge to C2 until the 30th year, then to C3, and from year 70th to C4 till the end of the bridge's lifetime (see Table 6.2).

Table 6.2 – Parameters for deterioration of coating and corrosion

Bridge Environment		
Element corrosivity	**first year**	**category**
	0	C2
	30	C3
	70	C4
	-	C1

The geometry for both the concrete slab and the steel girder(s) has to be defined. It is also necessary to provide information about the protective coating of the steel and its initial condition. In other words the service life of the coating needs to be defined for the different corrosivity categories and also the age or the actual quality (in percentage related to a perfectly new coating) of it. The required parameters for the calculation of coating degradation and corrosion rate are shown in Table 6.3.

Table 6.3 – Parameters for deterioration of coating and corrosion

Element Exposure	Parameters					
	Coating servide life (L)			Corrosion		
	NC	M27.4	Hem	A	B	t1 [yrs]
C1	0	7	13	0.0013	0.5490	20
C2	0	7	13	0.0250	0.5490	20
C3	0	6	10	0.0500	0.5490	20
C4	0	5.5	7	0.0800	0.5490	20
C5	0	5	5	0.2000	0.5490	20

All three types of intervention (strengthening, repainting, replacing) can be triggered in the following ways:

- Depending on the exposure of the element (i.e. quality of coating);
- Depending on the corrosion depth of
  - the web,
  - the top flange,
  - the bottom flange;
- Depending on the performance of the section:
  - shear performance of web,
  - local buckling of the bottom flange,
  - bending resistance of the section both at support or in mid-span;
- Defining directly the years (one by one) of relevance.

Firstly, it has to be chosen which triggering method(s) are desired to be used and then, define the required parameters for those. The effect of the interventions can also be partially decided by the user. This means e.g. to decide about painting that should be used after any of the interventions (it can be different than the one initially applied to the bridge) or what is the extent of the thickness increase in case of strengthening intervention.

For LCC analysis the costs of the interventions have to be calculated and the relevant data have to be entered. For all the three intervention it is necessary to define the costs that can include the labour, plant, material and taxes or any other four categories defined by the user. There is also an option to decide about the budgets and enter the relevant proportion ratios of the total amount that has to be spent for each type of interventions. The user can also introduce a discount rate for these direct costs.

Apart from these there are other expenses that have to be taken into account and these are the indirect costs, i.e. user costs. In the tool, three main types of them are considered: DDC, VOC and SC. As the tool is designed for highway overpasses, each of the above listed costs has to be calculated for both roads that go over and under the bridge. The discount rate for the indirect costs can be defined independently from the one used for direct costs but this is not recommended. The required input data for both roads are the following:

- Traffic speed during *both* normal and disturbed conditions*;
- Average daily traffic (ADT) in year '0';
- Value of one hour of a driver's time;
- Value of operating a vehicle for an hour;
- Capital cost of an accident;
- Accident rates during *both* normal and disturbed conditions*;
- Length of the work zone*;
- Number of days of the interventions*.

The ones on the list signed by asterisk are expected to be given separately for the three different types of interventions.

The environmental impacts of the interventions shall be introduced by the user.

6.3. Principles of the Tool

The main principle of the tool is to assume deterioration for the plates of the steel element regarding the environmental conditions and the coating applied on them. The tool provides the results of LCP, LCC and LCA analyses according to the maintenance strategy determined by the user.

The degradation of the coating is calculated through the given service life (the year when exactly 50% of the steel area is protected by the coating) and it is assumed to be uniform all over the surface of the steel section. The protective coating is assumed to be totally effective at age 0 and become totally ineffective at the end of its life, calculated according to the equation (3.1).

For the modelling of corrosion damage of steel (i.e. average thickness loss) the recommendation of (BS EN ISO 9223, 2012) (BS EN ISO 9224, 2012)is used. Hence, the actual depth of corrosion is calculated simply regarding the corrosivity category of the element according to the equation (2.5) up to the 20^{th} year of exposure in case there is no coating applied. For the determination of parameters A and B the following procedure is used. Parameter A is chosen as the upper limit of the corrosion rate of the first year of exposure as it can be seen in Table 2.2 and the parameter B is the mean value plus the standard deviation defined in Table 6.4 for carbon steel. (BS EN ISO 9224, 2012)

Table 6.4 – Statistical properties of the coefficient *B* (BS EN ISO 9224, 2012)

Metal	Mean, μ_B	Standard deviation, σ_B
Carbon steel	0.523	0.026
Zinc	0.813	0.03
Copper	0.667	0.0295
Aluminium	0.728	0.0395

Beyond 20 years of exposure the function continues linearly with the gradient it has reaching the 20th year. This linear function is expressed using the following formula: (BS EN ISO 9224, 2012)

$$C(\mathrm{t} > 20) = \mathrm{A}[20^{B} + B(20^{B-1})(t-20)] \tag{6.1}$$

where:

C(t>20) is the corrosion rate from year 21;

A and *B* are parameters;

t is the considered year.

The exact values for the parameters *A* and *B* are indicated in Table 6.3. The corrosion rate curves are shown in Figure 6.1, regarding each corrosivity category (C1-C5).

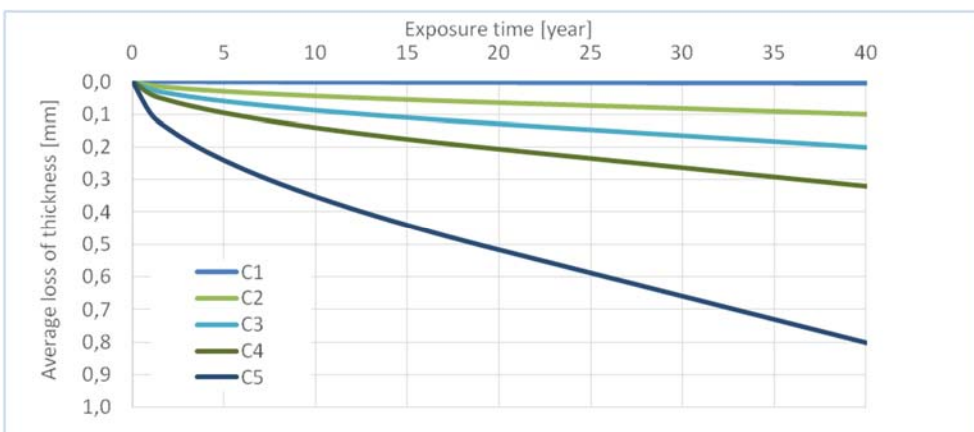


Figure 6.1 Base corrosion damage (i.e. rate) curves for corrosivity categories C1-C5

The deterioration of steel is assumed to be uniform along the exposed surface of the element. The thickness loss calculated according to above paragraphs gives the result for one surface of an element. Hence, for the bottom flange and for the web the results need to be multiplied by two to obtain the entire thickness loss. For the top flange, on the other hand, the formula gives the result directly as it is assumed that the top surface of the flange, which is connected to the concrete slab, does not suffer from corrosion.

When a protective coating system is applied on the element obviously the corrosion rate curves are modified. When there is a totally effective and undamaged coating, it does not result in thickness loss of the steel. However, as the painting starts to degrade, simultaneously the thickness of the steel element starts to decrease. First the tool calculates the size of the steel area that becomes unprotected and then, the increment of this between the actual and the previous years. This is followed by the calculation of the sum product of increments and the respective corrosion rates regarding the corrosivity category of the element. The tool is able to follow the variation in the depth of the corrosion even after several interventions as it 'remembers' the depth of corrosion before any intervention and adds the value of it in any stage of the life of the element later.

The degradation of the coatings is expressed with the polynomial formula given in equation (3.1). An example of the effect of different coatings can be seen on the graph of Figure 6.2. It is evident that when the coating is fully degraded, the curve of the thickness loss becomes parallel to the original curve (case of no coating). In reality, it is only shifted up with a value that depends on the quality of the coating, i.e. the service life of it. While the coating is partially still effective the gradient of the curve is proportional to the exposure of the element, i.e. the quality of the coating.

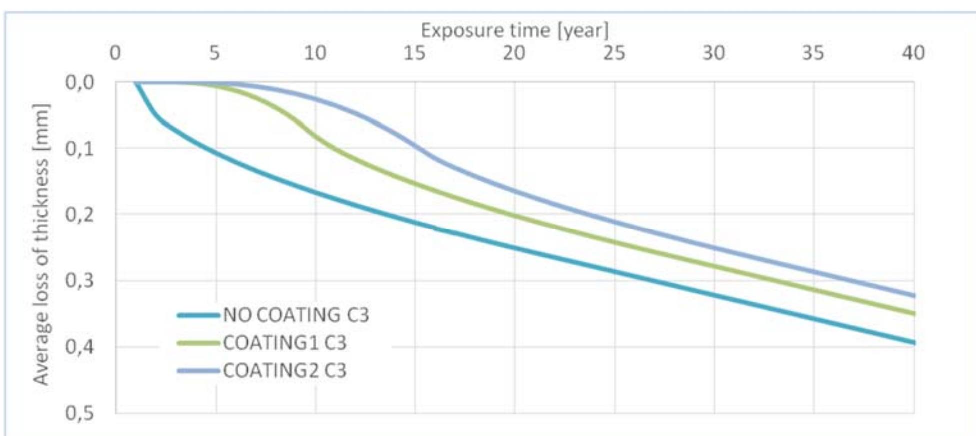


Figure 6.2 Corrosion damage curves for Corrosivity Category C3 applying different coatings

As it was mentioned in subchapter 6.2, the tool considers three types of interventions. These interventions have priority order (replacing > plating > recoating) and if two of them (or even three) would happen in the same year than the tool would choose the one that has higher (or the highest) priority and ignore the other(s). All the interventions in their triggered year make improvement of the element, but these improvements differ and can be explained in the following ways:

- Re-coating the element results in new protective coating (which coating can differ from the initial one);
- Plating the element results in additional thickness (given in mm) and optionally in new protective coating as well;
- Replacing the element results in recovering the thickness of the initial cross-section and optionally in new protective coating as well.

The replacement and the painting interventions have the same effect on the three types of plate elements (i.e. top flange, bottom flange and web) while the strengthening intervention has different influence on the top flange as it can be only plated on one side.

In the improved approach, since the replacement of elements in a composite bridge is not usual and adequate intervention, this intervention option was not taken into account.

As the direct costs have to be given by the user for each intervention, the tool only groups them according to different criteria and calculates the discounted values.

The indirect costs, on the other hand, are calculated by the tool using the input data listed in subchapter 6.2 and the following equations (Ehlen, 2003):

Driver Delay Cost $$DDC = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \cdot ADT \cdot N \cdot w_d \quad (6.2)$$

Vehicle Operational Cost $$VOC = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \cdot ADT \cdot N \cdot r_v \quad (6.3)$$

Safety Cost $$SC = L \cdot ADT \cdot N \cdot (A_a - A_n) \cdot C_a \quad (6.4)$$

where:

L is the length of the affected road [m];

S_a is the traffic speed during work activities [km/h];

S_n is the traffic speed in normal conditions [km/h];

ADT is the average daily traffic [number of cars/day];

N is the number of working days;

w_d is the average cost of one hour of a driver's time [€/h];

r_v is average cost of operating a vehicle for an hour [€/h];

A_a is the accident rate during work activities [number of accidents/(number of vehicles × km];

A_n is the accident rate in normal conditions [number of accidents/(number of vehicles × km];

C_a is the capital cost of an accident [€].

The ADT cannot be assumed to be constant over time as the traffic, i.e. the number of cars on the roads, is increasing. Therefore for the estimation of the traffic increase the following formula is used in the tool: (SBRI, 2013)

$$ADT_t = ADT \cdot (1 + r_{tg})^{year_t - year_0} \tag{6.5}$$

where:

r_{tg} is the expected traffic growth rate;

$year_t$ and $year_0$ are respectively the considered year of study and the base year.

Three different stages of the function are considered. The value of r_{tg} decreases with time, which means that the growth of the traffic is slowing down in the future regarding the capacities of the Earth itself. This phenomenon is considered in the following way (SBRI, 2013):

- From year 0 to year 10 $r_{tg} = 2.0\%$
- From year 11 to year 20 $r_{tg} = 1.0\%$
- From year 21 $r_{tg} = 0.5\%$

In the tool all the user costs are expressed for both roads over and under the bridge. Figure 6.3 shows the development of ADT for a busy highway and a less busy overpass.

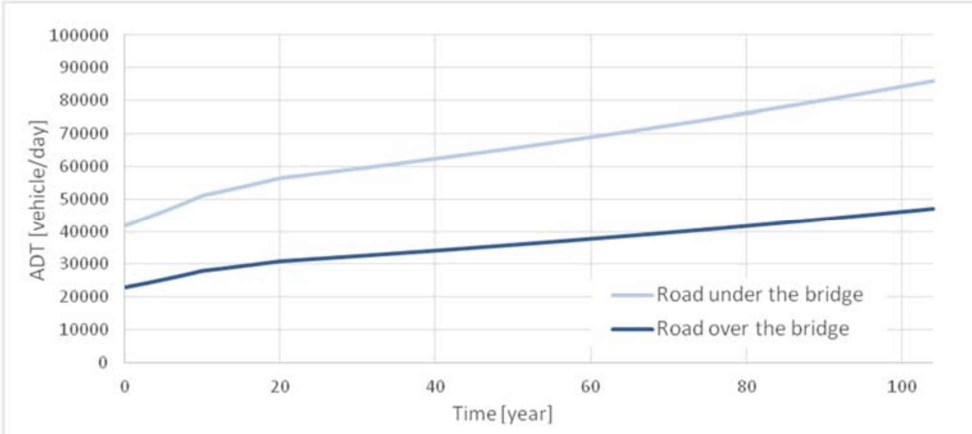


Figure 6.3 Assumption of the growth of ADT between year 0 and year 104 for the roads under and over the bridge (in case of a highway overpass)

The tool calculates the Net Present Value (NPV) for both direct and indirect costs using the following widely known formula (SBRI, 2013):

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \tag{6.6}$$

where:

t is the considered year;

C_t is all the cash flows in the year t;

r is the discount rate;

T is the total number of years.

The discount rate can be defined separately for the direct and the indirect costs.

6.4. Environmental Impacts

The tool for the environmental analysis takes only into account greenhouse emissions. However, other substances can be defined manually by the user. In case of appropriate input data, the tool enables to consider any indicator and it is also easy to develop in such form to make classification, characterization, normalization and weighting automatic. However, for the time being the tool does not contain extended inventory data.

By providing an appropriate conversion rate to convert CO_2 emissions into money, the tool is able to achieve the cost of the environmental impacts and include it in the calculation of the total cost.

6.5. Final Output

After the introduction of the desired input data the tool performs the calculations and provides the user with the following results:

- Financial output
  - Costs for each time period (5 years or user defined)
  - Discounted costs for each time period
  - Total cost for each categories:
    - Direct cost
    - User cost
    - Cost converted from environmental impacts
  - Summarized total cost
  - Discounted summarized total cost
- Environmental output
  - Environmental impacts by categories for each time period
  - Environmental impacts converted into cost
- Performance output
  - Exposure of steel over the bridge's lifetime (i.e. coating performance)
  - Thickness loss of the plates of the steel section over the bridge's lifetime due to corrosion
  - Performance of the steel section over the bridge's lifetime (relative strength in %):
    - Bending resistance (Second moment of inertia);
    - Shear resistance (Area of the web);
    - Local buckling resistance (Area of the bottom flange).

7. Probabilistic Approach

7.1. Monte Carlo Simulation

Regardless the field of study, researchers often face problems when they do not know exact initial data and thus they cannot obtain accurate result. In other words, they are not able to establish deterministic results due to the lack of certainty of input data. In these cases, probabilistic approach is required.

Different probabilistic approaches are available nowadays. However, they have the same goal. They are supposed to replicate the real world by using a set of assumptions and conceived models of reality. The simulation may be either performed theoretically or experimentally. The latter approach has become much more used since computers appeared and their capacity has continuously improved.

The essential members of such simulations are the design variables or parameters. Repeated simulation process makes it possible to examine the sensitivity of the system to each design variable and it can be also used to find alternative or optimal designs. Monte Carlo simulations may be appropriate if a problem involves random variables with known or unknown probability distributions. This is a repeating simulation process. In each repetition, different set of values of the random variables is chosen regarding their probability distributions. A sample of solution can be obtained with this process and each solution will correspond to a different set of values of the random variables; hence, the final result will not be an exact value but a distribution function. It is worth noting that the result of Monte Carlo simulation is comparable with the result of any experimental test and thus can be treated statistically. The most important process of the simulation is choosing the random variables because after, for a given set of values of them the calculation is done deterministically (Ang & Tang, 1984). Shortly summarizing, Monte Carlo simulation is a technique to obtain distribution function of a desired output using uncertain inputs which are defined by probability distribution functions.

As it is mentioned above, the key process of Monte Carlo simulation is the random sampling of the variables in accordance with their distributions. For this, a random number generator is needed. In the earlier times it was common to use techniques for finding random variables such as dice rolling, card shuffling or wheel spinning. Nevertheless, nowadays computers are used for generating random numbers. As the first step, it is necessary to generate a uniformly distributed random number between 0 and 1, which means generating values U_i that are uniformly distributed between 0 and 1 and are mutually independent. Widely known random number generators are pseudo-random number and linear congruential generators. The next step in the process is using appropriate transformation regarding the defined distribution for each variable to obtain the desired random numbers. With the available techniques, one can generate both continuous (e.g. normal, beta-distributed, gamma-distribute) or discrete (e.g. binomial, Poisson) random variables. These techniques are referred as sampling methods and most commonly they are either the inversion method or the acceptance-rejection method (Karayalcin, 2007).

It is also worth noting that as Monte Carlo simulation can be considered as a sampling process, sampling errors are likely to appear. However, there are different approaches to reduce these errors or variance without increasing the size of the sample (Ang & Tang, 1984).

In the present thesis, Monte Carlo simulation is performed by using the software @Risk, which is a Microsoft Excel based program used for probabilistic simulations, and it is described further in details in subchapter 7.2.

7.2. @Risk Software

@Risk is a user-friendly tool, which applies Monte Carlo simulation for probabilistic analysis, risk analysis, optimization etc. It works as a Microsoft Excel extension, a so-called "add-in", and after installation and launch, it appears as an additional tab with the "@Risk ribbon" as shown in Figure 7.1.

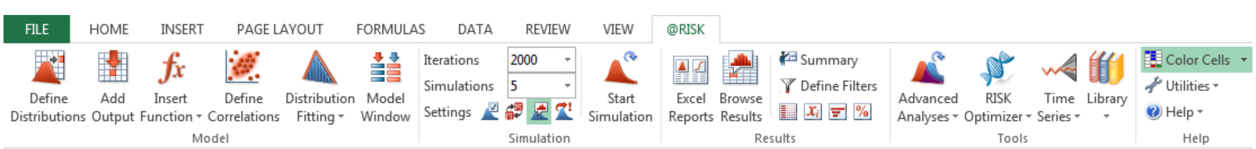


Figure 7.1 @Risk ribbon in Microsoft Excel

After one becomes familiar with the program, the first step to use @Risk for a particular case is to define the input data. This, in other words, mean to go through and answer the following questions:

1. What are the uncertain input data?
2. Are the uncertainties relevant regarding our desired output data?
3. Do we know a specific distribution of the values?
4. If not, what kind of distribution can be adequate to use?

After answering these questions, it is possible to establish the probability distribution functions for each uncertain (and relevant) input data. In @Risk there are several ways to define probability distributions:

- Manually
  - Defining the values and their probability one by one;
- Using continuous distribution, such as
  - Uniform,
  - Beta,
  - Normal,
  - Gamma,
  - Weibull etc;
- Using discrete distribution, such as
  - Binomial,
  - Poisson,
  - Bernoulli etc.

The most commonly used distribution functions (according to @Risk) are shown in Figure 7.2.

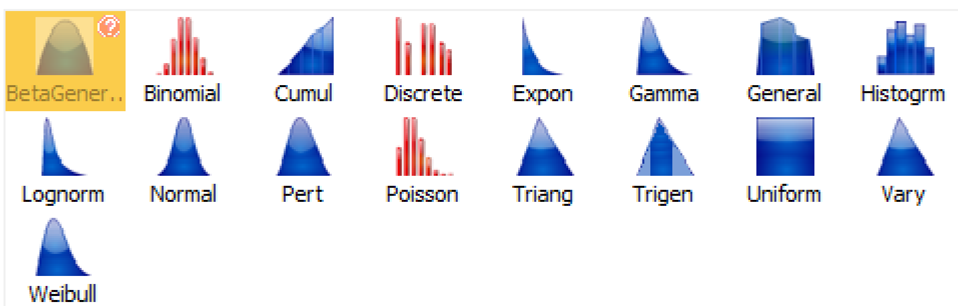
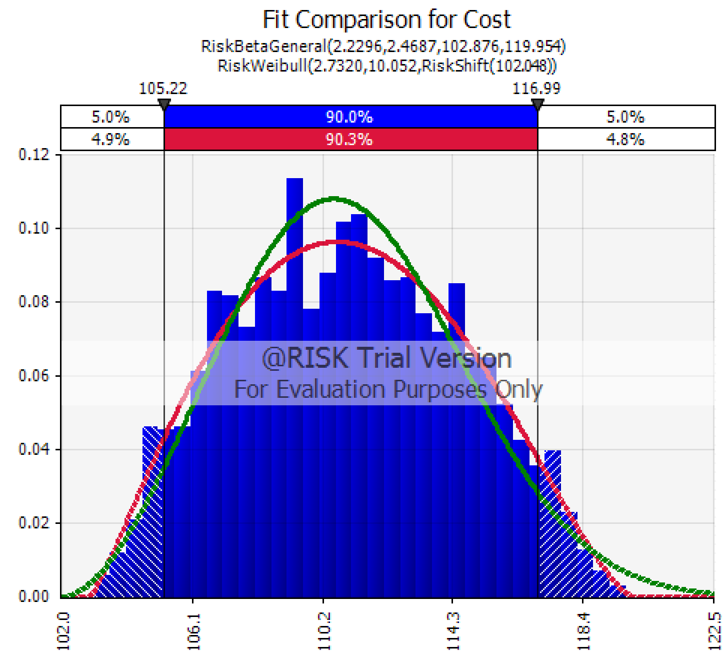


Figure 7.2 Common probability distributions for input data in @Risk

When all uncertain input data are defined with a probability distribution function, the second step is to define the desired output(s). After that it is already possible to run a simulation. At the end of the simulation, there will not be a single result for the chosen output, but a range of data, more precisely: a distribution of the results. From these results one can obtain data such as the mean value of the results, the standard deviation, the value of any percentile, and the sensitivity of the output to any input datum. It is also possible to fit a known distribution to the distribution of the results. An example of fitting two different distributions to the values of a chosen output is presented in Figure 7.3. However, before running a simulation it is advised to look through the default settings and make changes where it is necessary. For example, despite @Risk is using Monte Carlo simulation, Latin Hypercube and not Monte Carlo, is the default sampling method. Latin Hypercube method is often used in such computer programs. This method is more efficient than Monte Carlo sampling as it can be seen as a method that possesses desirable features of both random and stratified samplings and results in more stable outcomes even for smaller sample sizes (Helton & Davis, 2002). One can also decide about the desired random number generator. As a default, @Risk uses Mersenne Twister generator. Also the number of both iterations and simulations and other features that are not relevant for the simulations of the present thesis are chosen by the user.



Statistics

	Input	BetaGeneral	Weibull
Minimum	103.017	102.876	102.048
Maximum	119.759	119.954	+∞
Mean	110.979	110.980	110.991
Mode	≈112.118	110.658	110.556
Median	110.917	110.914	110.838
Std Dev	3.584	3.572	3.534
Skewness	0.0788	0.0726	0.2627
Kurtosis	2.1910	2.2275	2.7778
Left X	105.22	105.22	105.22
Left P	5.0%	4.9%	4.2%
Right X	116.99	116.99	116.99
Right P	95.0%	95.2%	94.8%
Dif. X	11.772	11.772	11.772
Dif. P	90.0%	90.3%	90.6%
1%	104.181	103.986	103.914
5%	105.223	105.245	105.437
10%	106.230	106.203	106.459
15%	106.941	106.961	107.217
20%	107.493	107.623	107.853
25%	108.238	108.228	108.419
30%	108.770	108.797	108.940
35%	109.295	109.343	109.433
40%	109.749	109.873	109.909

Figure 7.3 Distribution fittings to the values of a specified cost output

There are several features how one can make the simulation more precise and thus more realistic. It often happens that input variables are not independent from each other. In these cases, the software lets the user define correlations between two or more variables. Another advanced feature of the program is that it is possible to run analyses changing one variable. In other words, if there are simulations that differ only in changing one parameter, the analyses can be ran in one file and the results for the different values of the chosen parameter can be obtained simultaneously. For this, "Risksimtable" function is used. It can be also used to choose the best distribution of an input variable, by obtaining results for different distributions and comparing them.

It is worth mentioning that @Risk is able to make optimization with a built-in tool. For the optimization, a target (using a previously defined "output") and adjustable cells must be defined. Adjustable cells contain the parameters that are desired to be optimized aiming either to minimize or maximize the value in the target cell. Apart from this, it is possible to define any constraints for the analysis as well. After running the optimization one gains the optimal set of values of the adjustable cells regarding the previously defined target and all the constraints. During the run of any kind of analysis the program allows the user to follow the results both in a result graph (e.g. a probability function of the output) and in the Excel sheet. This will be further detailed in chapter 8.

@Risk is a very powerful tool. Together with other similar programs it is acknowledged because it provides the user with additional information that have high importance without the demand of extensive extra work, effort and time. The application of @Risk in the present thesis is described in the following subchapters.

7.3. Probabilistic Simulations

The base of all the following simulations is the deterministic tool described in chapter 6. Both the deterministic and the probabilistic analyses were done in Microsoft Excel and thus, their bases are identical. All the changes that were made for presenting probabilistic analyses are described in the following paragraphs. It should be noted that the deterministic input data of the probabilistic analyses are not discussed here but they are chosen realistically and based on the case study's input data, presented in chapter 8.

7.3.1. General sensitivity analysis

This sensitivity analysis was made to see the effect of input variables to some chosen output results. The desired outputs were selected to be:

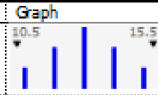
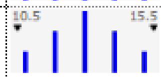
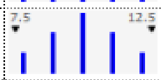
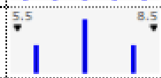
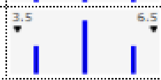
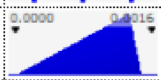
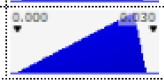
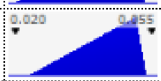
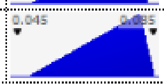
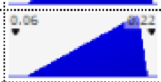
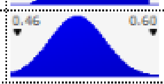
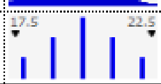
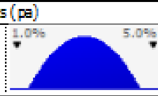
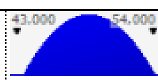
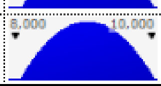
- Total Discounted Cost;
- Minimum Performance over the bridge's lifetime,
- Total number of interventions,
- Average exposed area of steel over the bridge's lifetime.

Afterwards the input variables were:

- Parameter A, B and t_1 for Corrosion Rate Function;
- Coating Service Life (T_L);
- Discount rate;
- ADT.

The chosen probability distributions regarding each variable are shown in Table 7.1. After running the analysis, two output results were examined. For sensitivity analysis, tornado graphs were used. Examples of these graphs can be seen in Figure 7.4 and Figure 7.5. Moreover the program can create a tornado graph with the correlation coefficients of the input variables (see in Figure 7.6). It is clearly observed from Figure 7.4 that the Discount rate and the Service life of the coating have the most significant effect on the Total discounted cost.

Table 7.1 – Probability distributions of input variables for sensitivity analysis

Name	Graph	Function	Min	Mean	Max
Service life C1 for HEM		RiskDiscrete({11,12,13,14,15},{1,2,3,2,1},RiskStatic(13),RiskName("Service life C1 for HEM"))	11	13	15
Service life C2 for HEM		RiskDiscrete({11,12,13,14,15},{1,2,3,2,1},RiskStatic(13),RiskName("Service life C2 for HEM"))	11	13	15
Service life C3 for HEM		RiskDiscrete({8,9,10,11,12},{1,2,3,2,1},RiskStatic(10),RiskName("Service life C3 for HEM"))	8	10	12
Service life C4 for HEM		RiskDiscrete({6,7,8},{1,2,1},RiskStatic(7),RiskName("Service life C4 for HEM"))	6	7	8
Service life C5 for HEM		RiskDiscrete({4,5,6},{1,2,1},RiskStatic(5),RiskName("Service life C5 for HEM"))	4	5	6
Parameter A for C1		RiskTriang(0.0001,0.0013,0.00143,RiskStatic(0.0013),RiskName("Parameter A for C1"))	0.0001	0.0009	0.0014
Parameter A for C2		RiskTriang(0.0013,0.025,0.0275,RiskStatic(0.025),RiskName("Parameter A for C2"))	0.0013	0.0179	0.0275
Parameter A for C3		RiskTriang(0.025,0.05,0.0525,RiskStatic(0.05),RiskName("Parameter A for C3"))	0.0250	0.0425	0.0525
Parameter A for C4		RiskTriang(0.05,0.08,0.084,RiskStatic(0.08),RiskName("Parameter A for C4"))	0.0500	0.0713	0.0840
Parameter A for C5		RiskTriang(0.08,0.2,0.21,RiskStatic(0.2),RiskName("Parameter A for C5"))	0.0800	0.1633	0.2100
Parameter B for C1-C5		RiskNormal(0.523,0.026,RiskStatic(0.523),RiskName("Parameter B"))	-∞	0.5230	+∞
Parameter t1 for C1-C5		RiskDiscrete({18,19,20,21,22},{1,2,3,2,1},RiskStatic(20),RiskName("Parameter t1"))	18	20	22
Category: Discount rate for Financial costs (pa)					
Discount rate for financial costs		RiskBetaGeneral(2,2,0.015,0.045,RiskStatic(0.035))	1.5%	3.0%	4.5%
Category: Average Daily Traffic					
ADT on road under the bridge		RiskBetaGeneral(2,2,43975.8,53748.2,RiskStatic(48862))	43975.8	48862.0	53748.2
ADT on road over the bridge		RiskBetaGeneral(2,2,8157.6,9970.4,RiskStatic(9064))	8157.6	9064.0	9970.4

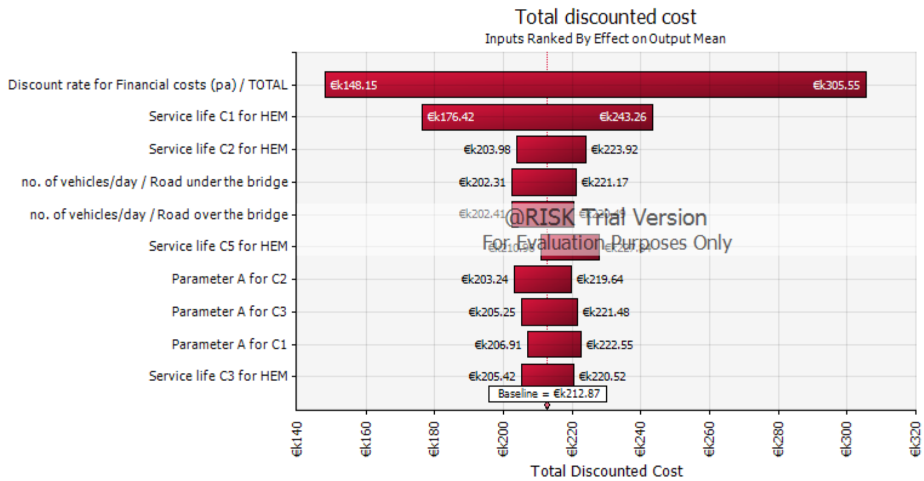


Figure 7.4 Tornado graph for the Total discounted cost

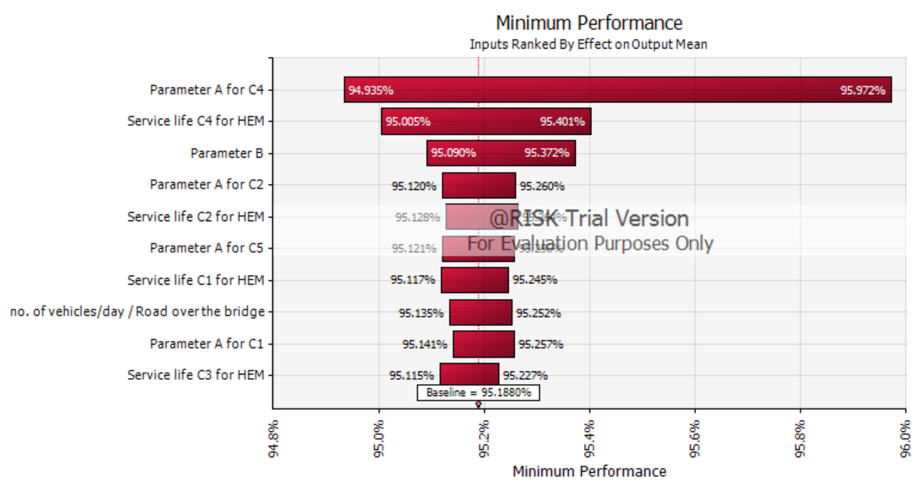


Figure 7.5 Tornado graph for the Minimum performance over the bridge's lifetime

Examining the results in Figure 7.5, it can be stated that parameter *A* has far more importance on the Minimum Performance over the bridge's lifetime than any other variable. For the Total number of interventions and for the Average exposed area of the steel over the bridge's lifetime, the Service life of the coating has undoubtedly the greatest effect. Scattered diagrams for correlations are also provided by @Risk and an example for these is given in Figure 7.7.

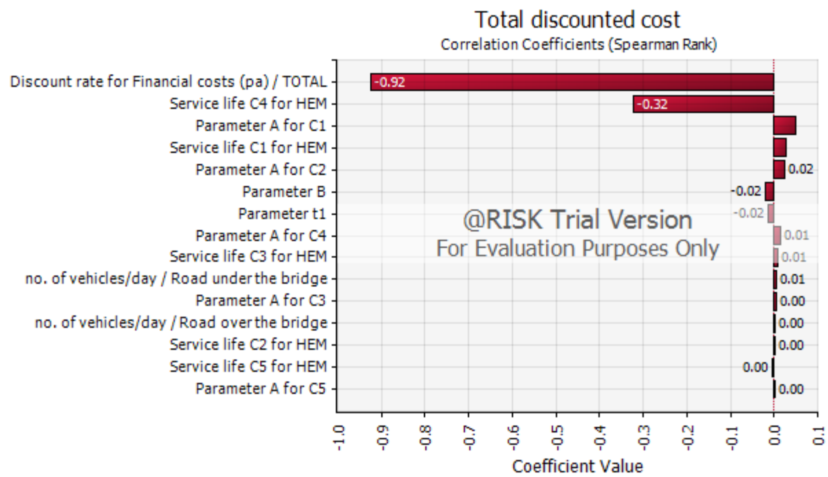


Figure 7.6 Correlation coefficient tornado graph for the Total discounted cost

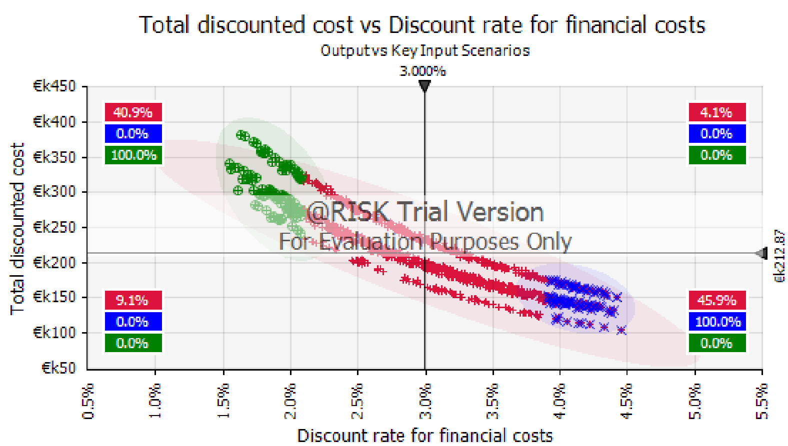


Figure 7.7 Scattered diagram of sensitivity for Total discounted cost versus Discount rate

The results of sensitivity analysis show that the most important variables regarding cost and performance are the following:

- Service life of the coating;
- Parameter *A* for corrosion rate function;
- Discount rate.

7.3.2. Sensitivity analysis for probability distributions

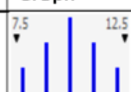
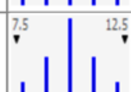
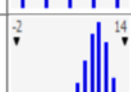
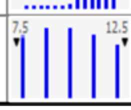
Based on the results of the general sensitivity analysis (see paragraph 7.3.1), a similar but more specific analysis is presented in this section. After deciding about the most important variable parameters, as a next step it is important to see the effect of their distribution functions. This is essential as these functions are usually assumed and the aim of this paragraph is to find appropriate shapes for them. For these analyses a basic scenario is used for triggering interventions in every case. This basic scenario includes repainting whenever 80% of the steel area is exposed and strengthening whenever the corrosion depth of any element reaches 5% of its nominal thickness.

For the **Service life of the coating**, the analysis was made for corrosivity category C3 and for 5 different distributions. Corrosivity category C3 was chosen for mainly two reasons: it is a quite probable environmental condition for a random bridge and according to the general sensitivity analysis, the Service life of the coating has the second highest relative influence in this case. For defining distributions, the following principles were followed:

- The distribution had to be discrete;
- 90% of the values of the distribution had to be between 8 and 12 years;
- The mean value of the distribution had to be 10 years (the rounded value at least).

Regarding the above listed principles, the chosen distributions are presented in Table 7.2. The results of the simulations are presented in Table 7.3 and Table 7.4.

Table 7.2 –Different probability distributions for the Service life of coating (in case of C3)

Name	Graph	Function	Min	Mean	Max
Discrete triangle 1		RiskDiscrete({8,9,10,11,12},{1,2,3,2,1},RiskStatic(10),RiskName("Discrete triangle 1"))	8	10	12
Discrete triangle 2		RiskDiscrete({8,9,10,11,12},{1,3,6,3,1},RiskStatic(10),RiskName("Discrete triangle 2"))	8	10	12
Discrete uniform		RiskDiscrete({8,9,10,11,12},{1,1,1,1,1},RiskName("Discrete uniform"))	8	10	12
Binomial		RiskBinomial(12,0.8,RiskName("Binomial"))	0	9.6	12
Poisson		RiskPoisson(10,RiskTruncate(8,12),RiskName("Poisson"))	8	9.91768	12

It can be seen from the results of Table 7.3 and Table 7.4 that the different distributions of the Service life of the coating do not have the same effect on the different outputs. However, the "worst" (most costly) mean value for the Total discounted cost and the "worst" (highest) mean value for the Average exposed steel area both appear when Binomial distribution is applied. This distribution gives small probability also for extreme situations, such as fully wrong application of coating (even with service life 0 years). This is not common and reasonable situation in engineering, therefore it cannot be taken into account. After examining the results it was decided to avoid those distributions leading to the worst and best results regarding the Total discounted cost. Therefore the final decision had to be made only between Discrete uniform and Poisson distributions. Looking at the results of Table 7.4, it is clear that **Poisson** distribution has slightly worse result and thus it can be considered safer. Consequently it was chosen to be implemented in the probabilistic tool for all corrosivity categories.

Table 7.3 – Main properties of the Total discounted cost probability functions for different distributions of the Service life of coating

Distribution	Discrete triangle 1	Discrete triangle 2	Discrete uniform	Binomial	Poisson
Mean value	€k 289	€k 289	€k 294	€k 306	€k 295
Standard Deviation	€k 74	€k 74	€k 84	€k 91	€k 81
Value for 10%	€k 202	€k 202	€k 195	€k 206	€k 201

Table 7.4 – Main properties of the Average exposed steel area over the bridge's lifetime probability functions for different distributions of the Service life of coating

Distribution	Discrete triangle 1	Discrete triangle 2	Discrete uniform	Binomial	Poisson
Mean value	0.273	0.274	0.268	0.275	0.270
Standard Deviation	0.018	0.016	0.020	0.018	0.019
Value for 10%	0.244	0.254	0.244	0.254	0.244

For the **Parameter *A***, the analysis was made for corrosivity category C2 and for 5 different distributions like in the case of the Service life of the coating. Corrosivity category C2 was chosen for similar reasons as C3 had been in the previous case: the results of the general sensitivity analysis have shown that the relatively highest influence of the Parameter *A* occurs in this case, moreover C2 can be also considered as common environmental condition for bridges. For defining distributions, the following principles were followed:

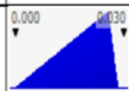
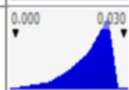
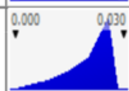
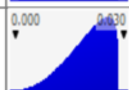
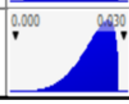
- The distribution is continuous;

The minimum and maximum values are fixed at 0.0013 and 0.0275 (which is 0.025+10%), respectively; these values come from Table 2.2;

- The mean value is around 0.02, meaning that higher (and worse regarding progress of corrosion) values are more probable.

The probability distributions used for this sensitivity analysis are presented in Table 7.5.

Table 7.5 – Different probability distributions for the Parameter *A* (in case of C2)

Name	Graph	Function	Min	Mean	Max
Asymmetric triangle		RiskTriang(0.0013,0.025,0.0275,RiskStatic(0.025),RiskName("Asymmetric triangle"))	0.0013	0.0179333	0.0275
Polygonal 1		RiskGeneral(0.0013,0.0275,{0.01,0.015,0.02,0.025},{1,3,6,12},RiskStatic(0.025),RiskName("Polygonal 1"))	0.0013	0.0203671	0.0275
Polygonal 2		RiskGeneral(0.0013,0.0275,{0.01,0.015,0.02,0.025},{1,2,3.5,8},RiskStatic(0.025),RiskName("Polygonal 2"))	0.0013	0.0199697	0.0275
Beta Subjective		RiskBetaSubj(0.0013,0.025,0.02,0.0275,RiskName("Beta Subjective"))	0.0013	0.02	0.0275
PERT		RiskPert(0.0013,0.025,0.0275,RiskName("PERT"))	0.0013	0.0214667	0.0275

The results of the analysis are shown in Table 7.6. It is noted that the effect of the distribution of Parameter *A* is negligible for all the highlighted output results other than the Minimum performance over the bridge's lifetime. Therefore the decision was made only according to the content of Table 7.6. The idea was to choose a distribution with an average mean value and standard deviation. This thinking lead to selecting the **Beta subjective** distribution for parameter *A* to be implemented in the probabilistic tool for all corrosivity categories.

Table 7.6 – Main properties of the Minimum performance functions for different distributions of the Parameter *A*

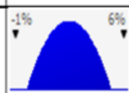
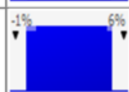
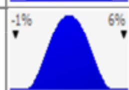
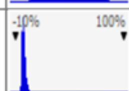
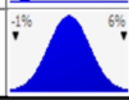
Distribution	**Asymmetric triangle**	**Polygonal 1**	**Polygonal 2**	**Beta subjective**	**PERT**
Mean value	**98.92%**	**98.78%**	**98.80%**	**98.80%**	**98.71%**
Standard Deviation	**0.37%**	**0.31%**	**0.33%**	**0.32%**	**0.27%**
Value for 10%	**98.48%**	**98.43%**	**98.44%**	**98.42%**	**98.40%**

The sensitivity analysis for the **Discount rate** was made for corrosivity category C2 and C3 to represent the usual environmental conditions. The probability distribution of this variable is the most difficult to decide about as it is not scientific but fiscal parameter. Moreover it is hard to find a mean value and a probability distribution that are widely recognized. Nevertheless, for defining distributions, some principles were established in this thesis:

- The distribution is continuous;
- At least 90% of the values of the Discount rate are between 0% and 5%;
- The mean value of the Discount rate is 2.5%

The five different probability distributions that were defined for the Discount rate are shown in Table 7.7.

Table 7.7 – Different probability distributions for the Discount rate

Name	Graph	Function	Min	Mean	Max
Beta general		RiskBetaGeneral(2,2,0,0.05,RiskStatic(0.025))	0	0.025	0.05
Uniform		RiskUniform(0,0.05,RiskStatic(0.025))	0	0.025	0.05
PERT		RiskPert(0,0.025,0.05,RiskStatic(0.025))	0	0.025	0.05
Johnson		RiskJohnsonMoments(0.025,0.015,1.3,6,RiskStatic(0.025))	-0.00933	0.025	0.939628
Normal		RiskNormal(0.025,0.012,RiskStatic(0.025))	-∞	0.025	+∞

The results did not show significant differences between the two corrosivity categories that were involved in the study (C2 and C3). It can be seen in Table 7.8 that the "worst" mean value was obtained using uniform distribution while the "best" was obtained using PERT distribution. However, examining the value of 10% it can be seen that the worst value was derived from PERT and the best was from Uniform distribution, exactly in the opposite way as for the mean value. It seems these two distributions are providing with all the extreme values thus they are avoided to consider further. Applying **Normal** distribution for the Discount rate gives an average mean value with reasonably high standard deviation and acceptable value for 10%; hence, this was chosen to be implemented in the probabilistic tool for all corrosivity categories.

Table 7.8 – Main properties of the Total discounted cost functions for different distributions of the Discount rate (in case of C2)

Distribution	Beta general	Uniform	PERT	Johnson	Normal
Mean value	€k 275	€k 300	€k 266	€k 289	€k 284
Standard Deviation	€k 123	€k 169	€k 101	€k 133	€k 162
Value for 10%	€k 149	€k 131	€k 158	€k 134	€k 147

7.3.3. *Correlation study*

According to (Kayser, 1988), a correlation exists between parameters *A* and *B* of the corrosion rate function. It is easily understandable that if one parameter increases, the other does as well, meaning the environment is harsher. However, these two parameters have positive correlation only in rural environment while in marine they have negative correlation. This can be seen in Table 2.3. It is worth noting that not only Parameters *A* and *B* but the Service life of the coating may also be correlated. It was decided to make correlations for all three variables but put always higher value for the correlation coefficient between *A* and *B*.

During the correlation study, four different cases were established beside the case with no correlation as it follows:

- Weak positive correlation;
- Strong positive correlation;
- Weak negative correlation;
- Strong negative correlation.

Correlation matrices can be seen in Table 7.9.

Table 7.9 – The four different correlation matrices for Parameter *A* and *B* and Service life of coating

Weak positive correlation	Service life	Parameter A	Parameter B	**Weak negative correlation**	Service life	Parameter A	Parameter B
Service life	1	0.2	0.2	Service life	1	-0.2	-0.2
Parameter A	0.2	1	0.4	Parameter A	-0.2	1	-0.4
Parameter B	0.2	0.4	1	Parameter B	-0.2	-0.4	1
Strong positive correlation	Service life	Parameter A	Parameter B	**Strong negative correlation**	Service life	Parameter A	Parameter B
Service life	1	0.5	0.5	Service life	1	-0.4124039	-0.4124039
Parameter A	0.5	1	0.8	Parameter A	-0.4124039	1	-0.6598461
Parameter B	0.5	0.8	1	Parameter B	-0.4124039	-0.6598461	1

After running the analysis, it became immediately visible (see Table 7.10) that the possible correlations do not affect significantly the distribution functions of the desired outputs. The difference between the results of the above cases was mainly in sensitivity analysis, although even those results have no severe relevance. Therefore, it was decided not to use any correlation matrix in the probabilistic tool, as their effect is negligible while it makes the model more complicated, increases the time of run and the risk of any error.

Table 7.10 – Results of the correlation study

Total Discounted Cost					
Correlations	**No correlation**	**Weak positive c.**	**Strong positive c.**	**Weak negative c.**	**Strong negative c.**
Mean	€k 289	€k 290	€k 290	€k 290	€k 290
St. Dev.	€k 74	€k 76	€k 76	€k 79	€k 77
10%	€k 203	€k 200	€k 202	€k 203	€k 203
Minimum Performance					
Correlations	**No correlation**	**Weak positive c.**	**Strong positive c.**	**Weak negative c.**	**Strong negative c.**
Mean	0.9715	0.9715	0.9715	0.9715	0.9715
St. Dev.	0.0049	0.0049	0.0048	0.0047	0.0047
10%	0.9654	0.9655	0.9656	0.9656	0.9653

8. Optimization procedure

In the previous chapter one fixed scenario was considered regarding triggering interventions. In this chapter the variance of these maintenance scenarios are examined and through an optimization the optimal scenario is found. To make the explanation of the optimization procedure clear, the input data of the case study described in chapter 9 are used. Also the distributions for the important uncertain input data, chosen in the previous chapter, are used.

8.1. Optimization of the Maintenance of Bridges

Optimization can be defined in one short sentence: 'the process of making something as good or effective as possible' (Cambridge Online Dictonaries, -) However, it is necessary to go further in details of defining the optimization of the maintenance strategies of bridges.

Five categories of any optimization (or variation reduction) problems can be distinguished (Tylora, 1992):

- Larger the better;
- Smaller the better;
- Target value;
- Target function;
- Uniform around the average.

In case of maintenance strategies, mostly the following principles are used:

- Minimize costs:
  - for some period of time;
  - for all the life of asset;
- Maximize performance of asset.

Maintenance strategies have achieved high importance and attention simultaneously with LCA. Deciding about the triggering of maintenance actions (and inspections) has severe influence in LCA. Bridges are more in focus since they are designed for 100 years according to EC and usually they appear as part of a network and not only as a single, independent asset.

The companies who are responsible for maintaining highways or other roads have already realised their responsibilities regarding bridges. Nowadays, many Bridge Management Systems (BMS) are available and used around the world. These systems are able to handle networks of bridges and support decision making processes about the right timing and ordering of interventions in the network. These tools are slightly different in purposes, capacities and level of development.

However, the main goal is the same for all: to optimize the maintenance strategy for the bridges of a specified road network.

In the present thesis a single bridge is examined instead of a network of bridges. This can be seen as the first step of studying the entire network. In the next subchapters the important of steps of optimizing the previously presented tools are discussed.

8.2. Optimization with @Risk

In the present thesis, @Risk was used not only for probabilistic simulations but also for optimization. The so-called RISKOptimizer is a powerful module included in @Risk. The main advantage, compared to other optimizing tools, is that it makes it possible to count on uncertainties in the model. It is worth noting that the tool is able to minimize runtime with convergence monitoring after a desirable number of iterations and with generating new trials (set of adjustable cells) moving toward an optimal solution as quick as possible.

From a user's point of view the following steps needed to be done to achieve optimization results using RISKOptimzer:

- Building up the model with specified distributions for uncertain inputs;
- Defining the target as minimizing or maximizing any statistic property of the distribution of the target cell;
- Identifying adjustable cells that have fix values (fix combination of values) for each trial during simulation;
- Determining the ranges of the values of the adjustable cells;
- Identifying constraints:
  - "Iteration constraints" – constraints applied for each international step;
  - "Simulation constraints" – constraints applied for each trial step;
- Running analysis;
- Observing the results of the optimization.

During the run of an optimization, RISKOptimizer is follows specific steps:

- Setting a combination of the values of the adjustable cells;
- Sampling the distributions of uncertain input cells;
- Calculating and storing value for target cell;
- Checking iteration constraints (and discard values if they do not meet);
- Repeating the previous 3 steps until the specified number of iteration is done;
- Building the statistic of the target cell regarding the iterations;

- Checking simulation constraints (and discard simulation results if they do not meet);
- Repeat the previous 7 steps until one of the following happens (according to the decision of the user)
  - The specified number of simulation is done;
  - The specified time for optimization is expired;
  - The specified progress (maximum change for an exact number of trials) is reached;
  - The specified formula is true;
  - An error occurred;
- Identifying the optimal values for the target cells.

Note that all constraints can be defined either soft or hard. The former, in case of not meeting, does not discard but only disfavour the target value, meanwhile the latter does discard it.

After running an optimization, the results can be observed directly. These results are the statistical properties of the target value, the relevant values of the adjustable cells and the values for the applied constraints for each trial. In a different table, the progress of the optimization is also presented, where the steps that lead to a new “best” trial are listed. In addition, a graph is provided to give a quick and clear idea about the progress steps of the optimization.

In the next subchapters, the details of the optimization for both deterministic and probabilistic analyses are described.

8.3. Optimization of the Deterministic Analysis

For the optimization done with RISKOptimizer, the first step is to define the target of the analysis. After that it is necessary to choose the adjustable parameters for the analysis. In other words, to choose the variables that one wants to optimize. In addition some constraints may be defined as well.

As the tool provides several ways to trigger interventions accordingly, for the optimization one way (or one combination) needs to be chosen. Considering the possible ways, different basic scenarios were selected and optimization was done separately for each of them. The basic scenarios are listed below:

- Scenario 1 (SC1): only recoating is triggered regarding the exposed area of steel;
- Scenario 2 (SC2): recoating and strengthening are triggered regarding the exposed steel area and the corrosion depth of the web in percentage, respectively;

- Scenario 3 (SC3): only strengthening is triggered regarding the corrosion depth of the web in percentage.

For all these cases optimization analyses were ran for corrosivity categories C2, C3, C4 and C5. In Scenario 1, it was decided to use only recoating intervention and to trigger according to the exposed area of steel, which means that at latest, an intervention will be triggered when the full coating becomes ineffective. This was decided following an aesthetical principle, which states that if it is assumed that the full coating is ineffective, it is aesthetically unbearable and thus a recoating is unavoidable. In Scenario 3, only strengthening intervention can be triggered. It was decided to assume that an intervention is triggered only when it is needed for achieving 100 years of structural life at an acceptable level of performance. The triggering is done according to the thickness loss (in percentage) of the web as this is the most sensitive element of the I-beams due to its slenderness. In Scenario 2, SC1 and SC3 are combined and results in a more realistic but also more complex approach.

The target is defined as minimizing the Total discounted cost. The used constraint is a limit value for the worst performance (shear, buckling, bending at support or in mid-span) level in percentage along the timeline profile of the bridge. This limit value may vary depending on the corrosivity category. The results of these analyses can be seen in Table 8.1, Table 8.2, and Table 8.3 respectively for each Scenario.

Table 8.1 – Deterministic optimization results for Scenario 1

C2			
Trial	Result	Adjustable Cells	Hard Constraints
		L24	0.95 <= OutPer!B47
1	€k 310	0,60	98,7%
2	€k 267	0,80	98,4%
3	€k 257	1,00	98,2%
C3			
Trial	Result	Adjustable Cells	Hard Constraints
		L24	0.95 <= OutPer!B47
1	€k 437	0,60	97,5%
2	€k 372	0,80	96,6%
3	€k 313	1,00	95,8%
C4			
Trial	Result	Adjustable Cells	Hard Constraints
		L24	0.93 <= OutPer!B47
1	€k 611	0,60	95,4%
9	€k 513	0,85	94,1%
C5			
Trial	Result	Adjustable Cells	Hard Constraints
		L24	0.90 <= OutPer!B47
9	€k 944	0,50	91,5%

Table 8.2 – Deterministic optimization results for Scenario 2

C2				
Trial	Result	Adjustable Cells		Hard Constraints
		L24	L17	0.95 <= OutPer!B47
1	€k 310	0,60	10	98,7%
2	€k 267	0,80	20	98,4%
3	€k 257	1,00	30	98,2%
C3				
Trial	Result	Adjustable Cells		Hard Constraints
		L24	L17	0.95 <= OutPer!B47
1	€k 437	0,60	10	97,5%
2	€k 372	0,80	20	96,6%
3	€k 313	1,00	30	95,8%
C4				
Trial	Result	Adjustable Cells		Hard Constraints
		L24	L17	0.93 <= OutPer!B47
1	€k 611	0,60	10	95,4%
15	€k 513	0,85	30	94,1%
C5				
Trial	Result	Adjustable Cells		Hard Constraints
		L24	L17	0.90 <= OutPer!B47
4	€k 1 116	0,60	0	98,1%
6	€k 870	0,70	6	93,7%
7	€k 832	0,75	4	95,7%
26	€k 776	1,00	8	91,9%

Table 8.3 – Deterministic optimization results for Scenario 3

C2			
Trial	Result	Adjustable Cells	Hard Constraints
		L17	0,95 <= OutPer!B47
1	€k 0	10	97,6%
C3			
Trial	Result	Adjustable Cells	Hard Constraints
		L17	0,95 <= OutPer!B47
1	€k 0	10	95,1%
C4			
Trial	Result	Adjustable Cells	Hard Constraints
		L17	0.93 <= OutPer!B47
3	€k 341	0	98,8%
8	€k 127	4	96,0%
10	€k 64	6	93,9%
C5			
Trial	Result	Adjustable Cells	Hard Constraints
		L17	0.90 <= OutPer!B47
3	€k 341	0	97,0%
5	€k 159	8	92,0%

8.4. Optimization of the Probabilistic Analysis

In case of the probabilistic analysis the optimization is done in a very similar way as it was done for the deterministic tool. However, in this case more advantage is taken from the power of RISKOptimizer. The used scenarios are the same to make them comparable. The target is to minimise the mean value of the Total discounted cost. The standard deviation of the results can be examined as well; although, it is not set as a criterion to minimize it. The constraint was chosen to be the 10 percentile value of the Minimum performance level. It means that it is not allowed to have lower performance than the limit for more than 10% of the results. In Table 8.4, Table 8.5, and Table 8.6 one can see the results for all corrosivity categories and for each scenario. L17 adjustable cell stands for the triggering of strengthening intervention, while L24 adjustable cell stands for the triggering of re-coating intervention.

Table 8.4 – Probabilistic optimization results for Scenario 1

C2						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	0,95 <= OutPer!B49
1	€k 385	€k 231	€k 98	€k 2 102	0,60	98,68%
2	€k 330	€k 193	€k 74	€k 1 683	0,80	98,33%
3	€k 296	€k 181	€k 67	€k 1 778	1,00	97,95%
C3						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	0,95 <= OutPer!B49
1	€k 512	€k 301	€k 120	€k 2 442	0,60	97,30%
2	€k 447	€k 271	€k 96	€k 2 571	0,80	96,35%
3	€k 394	€k 238	€k 92	€k 2 035	1,00	95,42%
C4						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	0,93 <= OutPer!B49
1	€k 734	€k 485	€k 199	€k 7 354	0,60	94,89%
2	€k 644	€k 420	€k 186	€k 5 868	0,80	93,07%
C5						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	0,90 <= OutPer!B49
9	€k 1 095	€k 587	€k 368	€k 6 647	0,50	91,33%

Table 8.5 – Probabilistic optimization results for Scenario 2

C2							
Trial	Goal Cell Statistics				Adjustable Cells		Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	L17	0,95 <= OutPer!B49
1	€k 385	€k 237	€k 89	€k 2 460	0,60	10	98,68%
2	€k 332	€k 198	€k 64	€k 1 726	0,80	20	98,31%
3	€k 296	€k 179	€k 63	€k 1 870	1,00	30	97,89%
C3							
Trial	Goal Cell Statistics				Adjustable Cells		Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L39	L17	0,95 <= OutPer!B49
1	€k 524	€k 484	€k 150	€k 9 150	10	0,60	97,27%
2	€k 457	€k 414	€k 139	€k 7 657	20	0,80	96,39%
3	€k 405	€k 402	€k 111	€k 7 744	30	1,00	95,38%
C4							
Trial	Goal Cell Statistics				Adjustable Cells		Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L24	L17	0,93 <= OutPer!B49
1	€k 732	€k 444	€k 207	€k 5 119	0,60	10	94,89%
2	€k 646	€k 416	€k 201	€k 5 100	0,80	16	93,13%
16	€k 634	€k 414	€k 186	€k 5 100	0,85	30	93,05%
C5							
Trial	Goal Cell Statistics				Adjustable Cells		Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L17	L24	0,90 <= OutPer!B49
7	€k 1 265	€k 499	€k 608	€k 4 186	0	0,60	98,03%
9	€k 1 005	€k 558	€k 282	€k 4 550	8	0,70	91,72%
10	€k 950	€k 541	€k 256	€k 4 143	8	0,75	91,66%
15	€k 947	€k 466	€k 296	€k 3 634	4	0,85	95,59%
25	€k 878	€k 489	€k 203	€k 3 755	8	1,00	91,62%

Table 8.6 – Probabilistic optimization results for Scenario 3

C2						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L17	0,95 <= OutPer!B49
1	€k 0	€k 0	€k 0	€k 0	20	97,42%
C3						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L17	0,95 <= OutPer!B49
2	€k 341	€k 3	€k 334	€k 348	0	99,24%
6	€k 147	€k 85	€k 15	€k 679	2	97,96%
10	€k 56	€k 108	€k 0	€k 1 570	4	95,96%
C4						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L17	0,93 <= OutPer!B49
2	€k 341	€k 3	€k 333	€k 348	0	98,72%
4	€k 80	€k 114	€k 0	€k 1 556	6	93,94%
C5						
Trial	Goal Cell Statistics				Adjustable Cells	Hard Constraints
	Mean	Std. Dev.	Min.	Max.	L17	0,90 <= OutPer!B49
3	€k 341	€k 3	€k 333	€k 348	0	96,79%
5	€k 195	€k 76	€k 34	€k 591	6	93,85%
11	€k 154	€k 87	€k 13	€k 702	8	91,85%

8.5. Results of the Optimization

A summary, including the results for both the deterministic and the probabilistic tools, is presented in Table 8.7. Some points that the table shows are worth noting:

- SC1 is less economical than SC2 only for C5;
- Results of SC2 do not differ from SC1 for C2, C3 and C4, meaning that for the most common atmospheric conditions for a bridge (C2 and C3) only re-coating interventions are satisfying;
- For the deterministic tool SC3 gives no intervention for C2 and C3, while for probabilistic tool it gives no intervention for C2 and gives relatively small probability for any intervention for C3.This means that desirable performance level over the lifetime of a bridge, ignoring aesthetical aspects, can be achieved without any intervention for C2 and possibly even for C3;
- In most of the cases the mean value (regarding the probabilistic tool) of the Total discounted cost is higher than the value of the deterministic tool. This means that by using deterministic tool, it is possible to severely underestimate the Total discounted cost.

All findings are based on the unique assumption that only corrosion is taken into account as reason for the deterioration of a composite bridge. Therefore the above conclusions should not be understood as general recommendations for composite bridges. It has to be kept always in mind that in reality, corrosion is only one of the reasons that leads to the deterioration or failure of a composite bridge.

Table 8.7 – Summary table for optimization

			C2		C3		C4		C5	
			Det	Prob	Det	Prob	Det	Prob	Det	Prob
Scenario 1	Adjustable cell for recoating		1,00	1,00	1,00	1,00	0,80	0,80	0,50	0,50
	Number of intervention for	Mean	5	4,89	6	6,45	10	10,3	17	17,17
		Standard dev.	-	0,81	-	0,99	-	1,64	-	2,41
	Total discounted cost	Mean	€k 257	€k 296	€k 313	€k 394	€k 513	€k 644	€k 944	€k 1 095
		Standard dev.	-	€k 181	-	€k 238	-	€k 420	-	587
	Minimum performance	Constraint	95%		95%		93%		90%	
		Result	98,2%	97,9%	95,8%	95,4%	94,1%	93,1%	91,5%	91,3%
Scenario 2	Adjustable cells	for recoating	1,00	1,00	1,00	1,00	0,85	0,85	0,95	1,00
		for strengthening	-	-	-	-	-	-	8	8
	Number of intervention for	Mean	5	4,89	6	6,45	10	10,11	12	11,69
		Standard dev.	-	0,81	-	0,99	-	1,84	-	1,88
	Number of interventions for	Mean	0	0	0	0	0	0	1	1,00
		Standard dev.	-	0	-	0	-	0	-	0
	Total discounted cost	Mean	€k 257	€k 296	€k 313	€k 405	€k 513	€k 634	€k 776	€k 714
		Standard dev.	-	€k 179	-	€k 402	-	€k 414	-	€k 380
	Minimum performance	Constraint	95%		95%		93%		90%	
		Result	98,2%	98,0%	95,8%	95,3%	94,1%	93,0%	91,9%	91,6%
Scenario 3	Adjustable cell for strengthening [%]		-	-	-	4	6	6	8	8
	Number of intervention for	Mean	-	0	-	0,66	1	0,88	1	1,00
		Standard dev.	-	0	-	0,48	-	0,33	-	0,00
	Total discounted cost	Mean	€k 0	€k 0	€k 0	€k 56	€k 64	€k 80	€k 159	€k 154
		Standard dev.	-	€k 0	-	€k 108	-	€k 114	-	€k 87
	Minimum performance	Constraint	95%		95%		93%		90%	
		Result	97,6%	97,4%	95,1%	96,0%	93,9%	93,9%	92,0%	91,9%

9. Case Study

9.1. Description of the Bridge

In the present case study a composite steel-concrete bridge is examined. It is an overpass over the dual carriageway of "A1 – *Auto Estrada do Norte"* motorway in Portugal (see Figure 9.1). The motorway consists of three lanes in each direction, 3.75 m wide each. In the middle there is a reservation of 4.05 m width. On the sides there are hard shoulders of 1.0 m width each. Hence, the overall width of one carriage way of the motorway is 16.3 m (SBRI, 2013).

The overpass composite bridge has one lane of 3.0 m, one hard shoulder of 1.0 m and one side walk for pedestrians of 1.65 m width in both directions. The total width of the bridge is 12.04 m, while the effective width is 11.3 m. The total area of the deck is 936.71 m^2. The bridge has three spans: the side spans are 18.5 m and the inner span is 40.8 m long. While the two middle piers supports the bridge fully restrained against displacement, the side abutments serve as simple supports to the deck (see Figure 9.2) (SBRI, 2013).

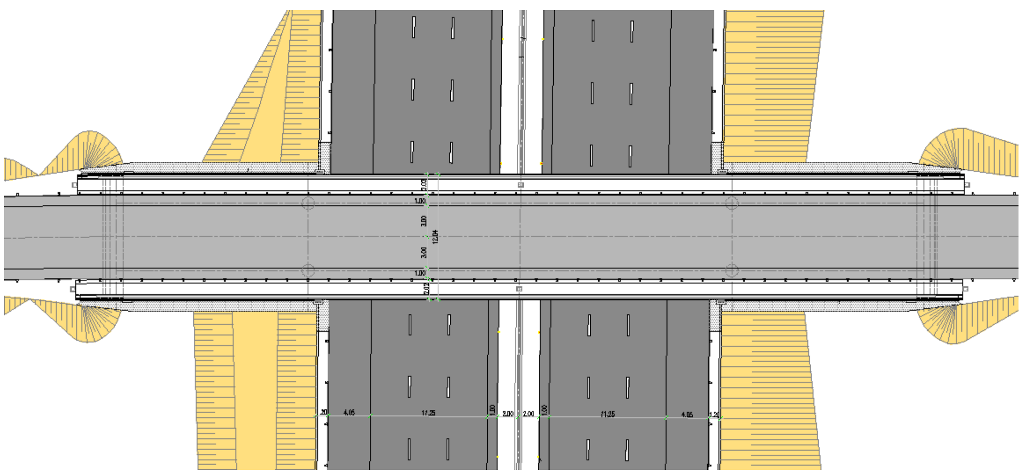


Figure 9.1 Plan view of A1 the motorway and the composite bridge (subject of the case study) (SBRI, 2013)

The structure of the bridge is composite steel-concrete. The steel part consists of two I girders and the overall height of these girders is 1.35 m and the width of the top and bottom flanges are 700 and 800 mm, respectively. The thickness of the web varies from 14 to 18 mm, while the thicknesses of the top and bottom flanges vary from 30 to 80 and 40 to 80 mm, respectively along the length of the bridge. The cross-section can be seen in Figure 9.3 and the dimensions of these elements are given in Table 9.1 (SBRI, 2013).

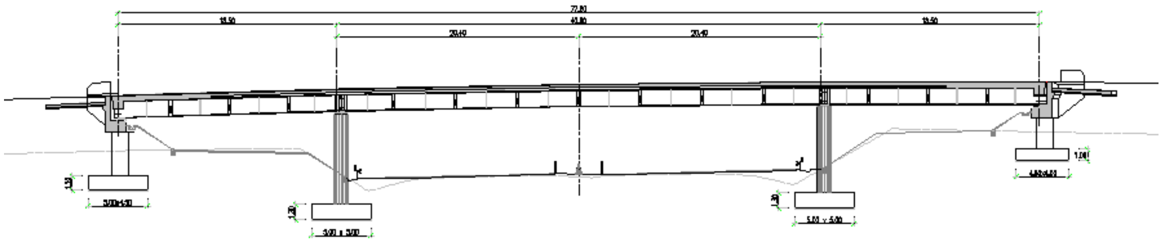


Figure 9.2 Elevation view of the composite bridge (SBRI, 2013)

The I-girders are braced along the mid span in every 5.2 m and along the side spans in every 5.0 m with IPE500 profiles. Over the mid piers and the side abutments steel profiles are placed serving as bracings with the height of 800 and 500 mm, respectively (SBRI, 2013).

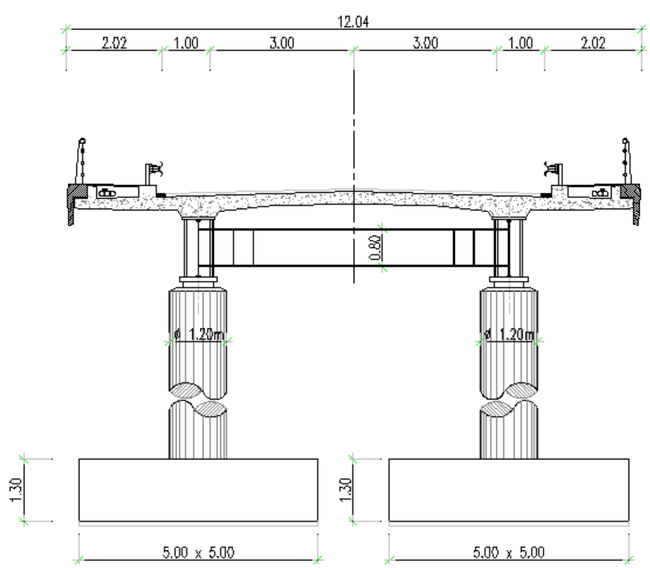


Figure 9.3 Cross-section of the composite bridge (SBRI, 2013)

Table 9.1 – Data of the steel I-girders

	Thickness [mm]			Depth/Breadth [mm]
	Min.	Max.	Mean	
Top Flange	30	80	**55**	**700**
Bottom Flange	40	80	**60**	**800**
Web	14	18	**16**	**-**
Overall	-	-	**-**	**1350**

The precast concrete slab placed on the top of the steel girders is 44 cm thick above the girders, 20 cm at the edge of the cantilevers and 25 cm in the mid-span. The connection between the two elements (steel girder system and concrete slab) is provided by shear connectors, i.e. studs welded to the top flanges of the girders, and "cast in situ" concreting around them. The mid piers have circular cross-sections of 1.2 m diameter and are made of "cast in situ" concrete (SBRI, 2013).

9.2. Coating of the Steel Girders

The coating of the steel structure is made in four stages. At first the cleaning of the surface is done according to ISO 5801-1 standard using abrasive blast cleaning method at level Sa 2½, i.e. "near white metal" (ISO 8501-1, 1988). After cleaning, three coating layers are applied that are from the primer to the top coat the following:

- "Hempadur Zinc 15360" coating from Hempel or similar (thickness: 50 µm)
  - 2 component polyamide cured Zn-riched epoxy primer
  - 2.3 kg/l
- "Hempadur 15570" coating from Hempel or similar (thickness: 100 µm)
  - 2 component polyamide-adduct cured epoxy paint
  - 1.4 kg/l
- "Hempathane 55210" top coating from Hempel or similar (thickness: 50 µm)
  - 2 component semi-gloss acrylic polyurethane finisher
  - 1.2 kg/l – white

The coating system has a total thickness of 200 µm and it is a paint system with both organic and inorganic components.

9.3. Traffic Conditions

The road over the bridge has one carriage way with two lanes of traffic in the same direction. The ADT in the base year of the study was assumed to be equal to 9 064 vehicles/day. The predicted growth rate for the traffic is following the principles described in subchapter 6.2. The road under the bridge consists of two carriageways including 3-3 lanes in each direction. In the base year of the study the ADT is assumed to be equal to 24 431 vehicles/day/carriageway. The assumed speed of vehicles during an average day is considered to be 120 km/h, which is equal to the speed limit of the highways in Portugal.

9.4. Data for Interventions

9.4.1. Direct cost

The cost of interventions are calculated with the help of projects (SBRI, 2013) and (MAINLINE, 2013) and their values are shown in Table 9.2. In the table, he cost for each item in the table includes all the relating activities.

Table 9.2 – Direct costs for the applied interventions

Strengthening intervention	
Team 4 men 2 months	€160 000
Paint	€5 000
Steel	€80 000
Scaffold	€10 000
Sand blaster	€2 500
SUMMA	**€257 500**
Re-coating intervention	
Team 4 men 1 month	€80 000
Paint	€5 000
Scaffold	€10 000
Sand blaster	€2 500
SUMMA	**€97 500**

9.4.2. *User cost*

All the input parameters needed for the calculation of the user cost are taken according to (SBRI, 2013). The main parameters used for re-coating and strengthening interventions can be found in Table 9.3.

Table 9.3 – Parameters for calculating User costs

	Length of the workzone		Number of days of intervention (8 hour working day)		Traffic speed during disturbed traffic conditions		Accident rates during work conditions	
	Under	Over	Under	Over	Under	Over	Under	Over
	m		day		km/h		no. of acc./(million veh*km)	
Plating of Element (Strengthening)	1011,7	1000,0	8,0	8,0	70,0	80,0	1,1	0,9
Re-coating of Element (Painting)	1011,7	1000,0	4,0	4,0	70,0	80,0	1,1	0,9

For the calculation of DDC and VOC, the unit values used in SBRI (SBRI, 2013) were taken, as shown in Table 9.4. For VOC the unit values are given in [€/km] instead of [€/h], therefore equation (6.3) is modified to:

$$VOC = \left(L - \frac{S_a \cdot L}{S_n} \right) \cdot ADT \cdot N \cdot r_v \tag{9.1}$$

Table 9.4 – Unit values for calculating DDC and VOC

Vehicle category	Proportion	DDC [€/h]	VOC [€/km]
1	80%	€ 7,75	€ 0,17
2	8%	€ 6,20	€ 0,12
3	10%	€ 62,90	€ 0,83
4	2%	€ 9,30	€ 0,67
SUMMA	100%	€ 13,16	€ 0,24

9.4.3. *Environmental impacts*

Among environmental impacts only greenhouse emissions are taken into account in the case study. The values are chosen according to the project (MAINLINE, 2013) for the following scenarios: for the re-coating intervention it is assumed to be 1 075.1 kg of CO_2 eq. considering 4 days of equipment usage, while for the strengthening intervention it is assumed to be 3 779.7 kg of CO_2 eq. considering 8 days of equipment usage. The values include the effect of all the required material production, equipment usage and transportation.

For the conversion of CO_2 emission into cost, the observations of (Maibach, et al., 2008) were used. At the end it was decided to use 100 €/tonne CO_2 as a rounded value for the central value in year 2050 (see in Table 9.5).

Table 9.5 – Recommended values for the external costs of climate change (in €/tonne CO_2), expressed as single values for central estimate, lower and upper values (Maibach, et al., 2008)

Year of application	Converted cost for CO_2 (€/tonne CO_2)		
	Lower value	Central value	Upper value
2010	7	25	45
2020	17	40	70
2030	22	55	100
2040	22	70	135
2050	20	85	180

9.5. Deterministic LCA of the Composite Bridge

9.5.1. Result graphs before optimization

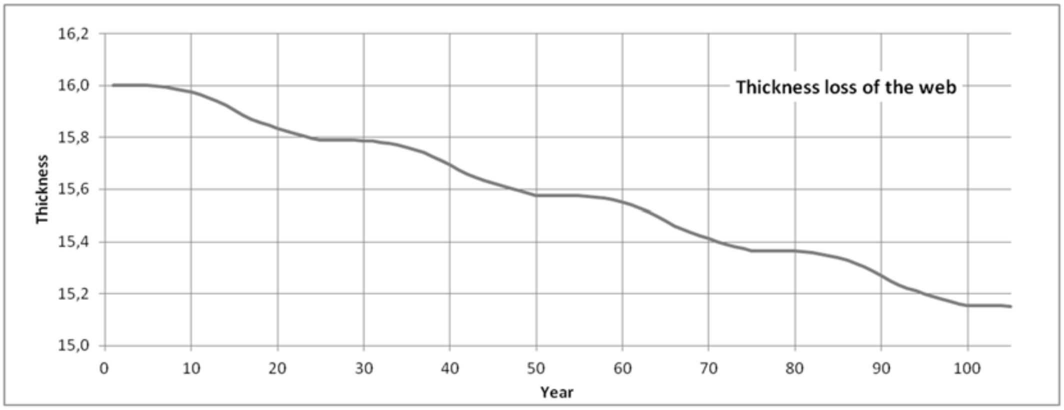


Figure 9.4 Thickness loss of the web over the bridge’s lifetime

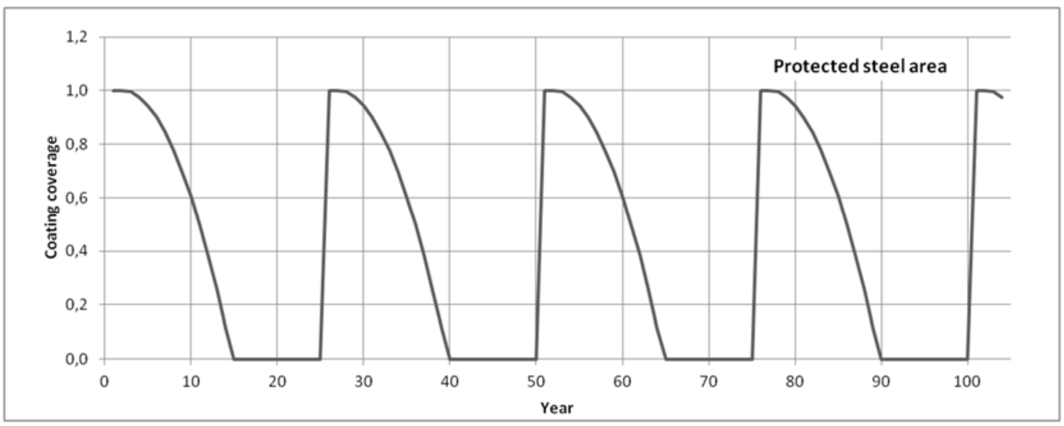


Figure 9.5 Protected steel over the bridge’s lifetime

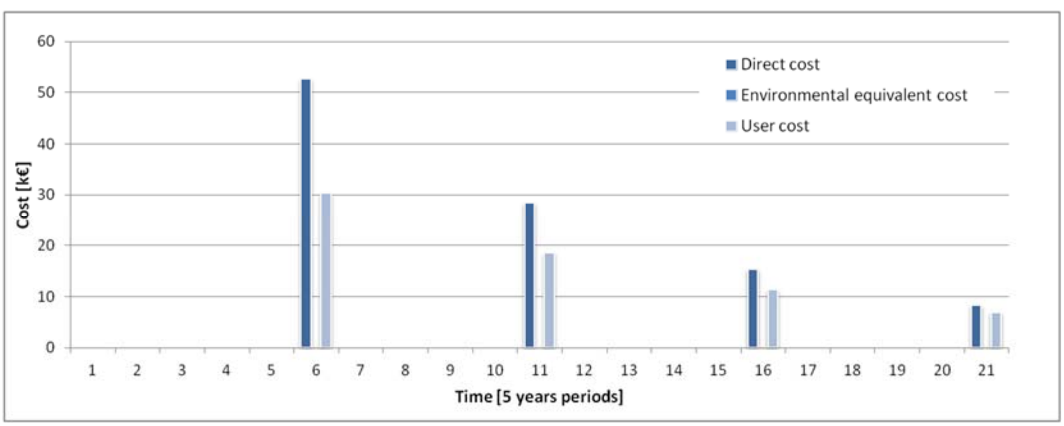


Figure 9.6 Discounted costs over the bridge’s lifetime

9.5.2. Result graphs after optimization

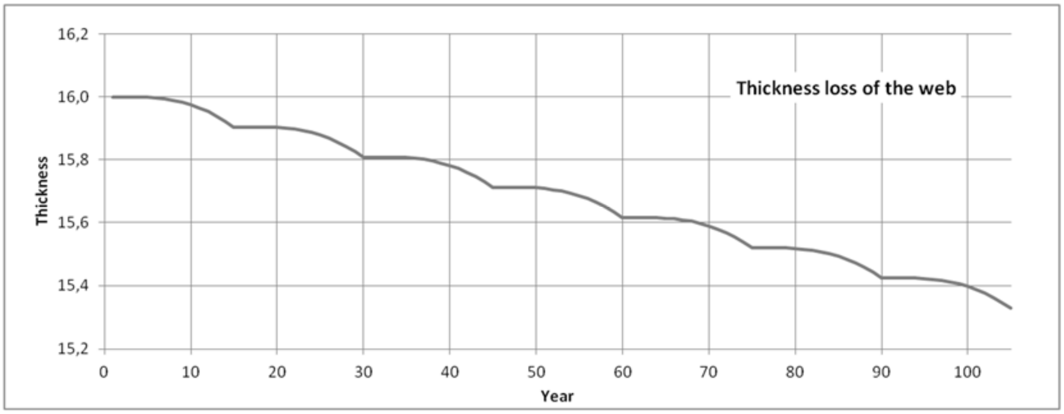


Figure 9.7 Thickness loss of the web over the bridge's lifetime

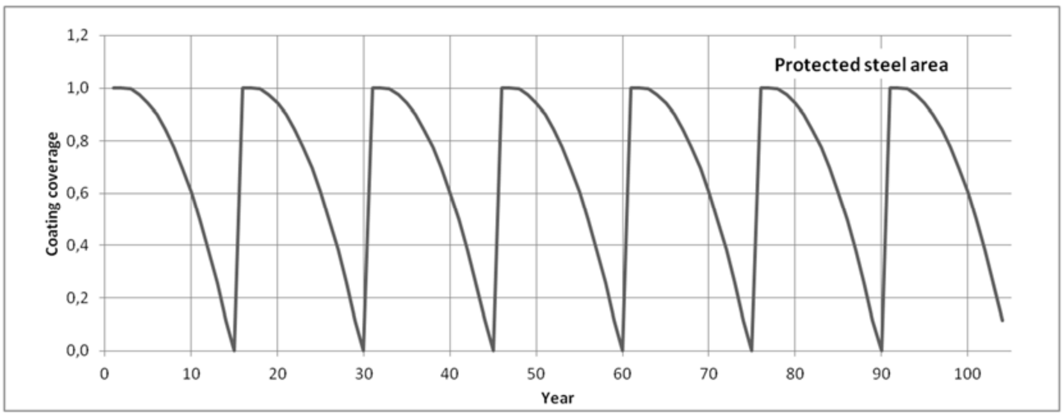


Figure 9.8 Protected steel over the bridge's lifetime

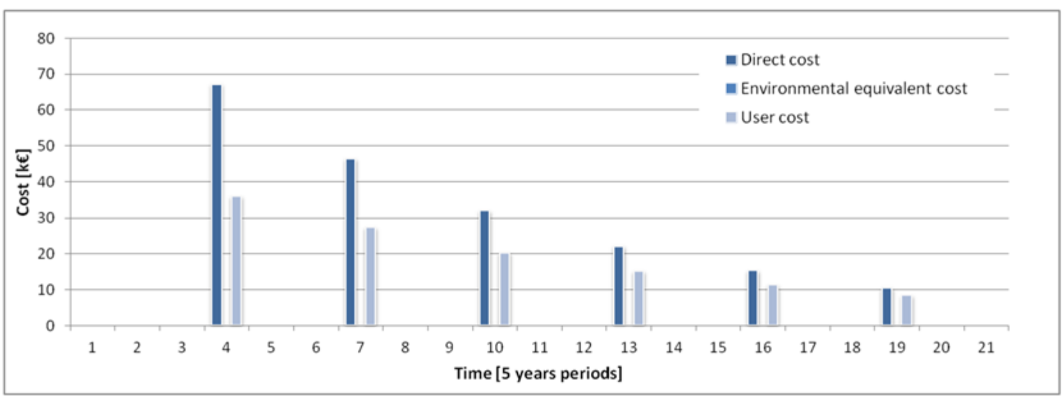


Figure 9.9 Discounted costs over the bridge's lifetime

9.5.3. Comparing the results

It can be easily observed from Table 9.6 that optimization does not lead to lower LCC for the case study. It leads however to higher performance level along the bridge's lifetime. At first, the observer can say the tool is not able to help to achieve economic advantage and therefore optimization has no relevance. This statement is true but misleading as other aspects and reasons are needed to be considered. The tool only takes into account the corrosion of the steel girders and does not take into account other deterioration process of the bridge (e.g. fatigue or concrete carbonation). Therefore for this study only observing LCC can be ambiguous. It is important to understand that there are more ways for degradation of a composite bridge that the tool does not take into account yet. The aim of the optimization done in subchapter 8.2 is to gain the most economical maintenance strategies taking into account constraints, like aesthetical aspect and performance level. It can be seen that the performance level is higher after optimization, which is the main achievement in this case and the consequence of a more frequent intervention scheduling. Also it can be stated that regarding aesthetical aspects the optimized tool is better and it identifies the time, which it is necessary to repaint the bridge after. It is worth noting that the relevance of optimization will be increased after improving the tool to take into account other types of degradation of composite bridges and other possible intervention techniques.

Applying optimized maintenance strategy can be also helpful in case of unexpected events, such as change of design code or increase of loading. With optimized maintenance strategy, one can achieve continuously higher performance level for the structure; therefore, it is easier in any case to verify the structure for increased loading or stricter requirements throughout its lifetime.

Table 9.6 – Comparison of the main results of the deterministic analyses

Total discounted cost		**Minimum performance**	
Before Op.	**After Op.**	**Before Op.**	**After Op.**
€k 172	€k 313	94,70%	95,79%

9.6. *Probabilistic LCEA of the Composite Bridge*

9.6.1. Result graphs before optimization

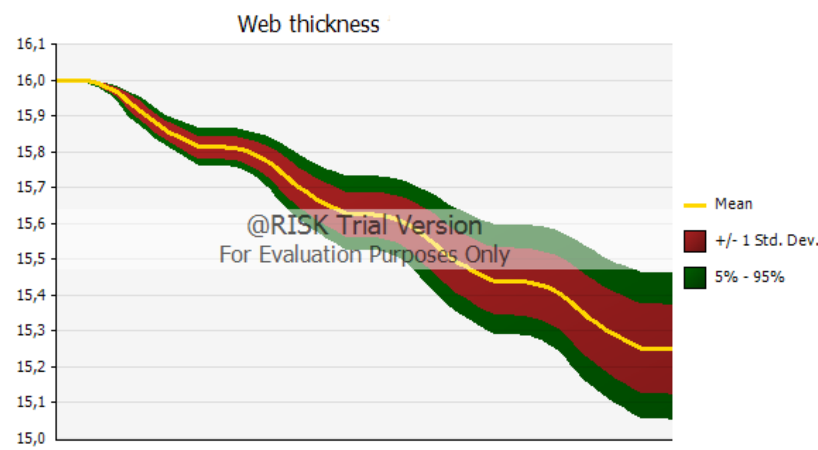


Figure 9.10 Web thickness over the bridge's lifetime

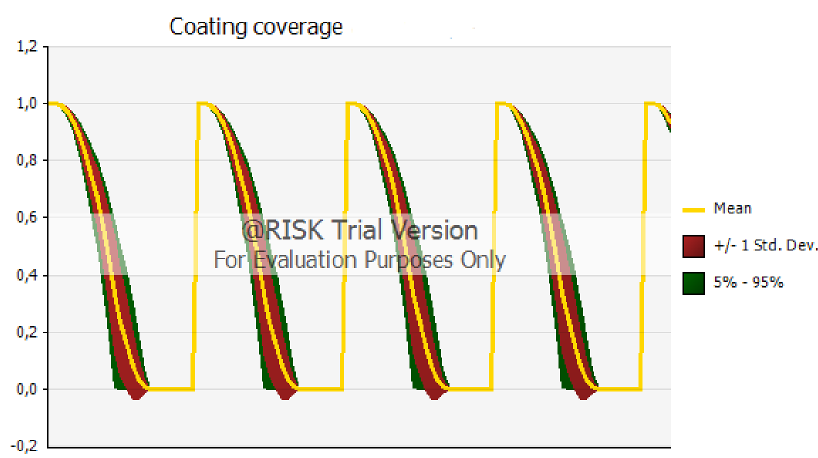


Figure 9.11 Coating coverage over the bridge's lifetime

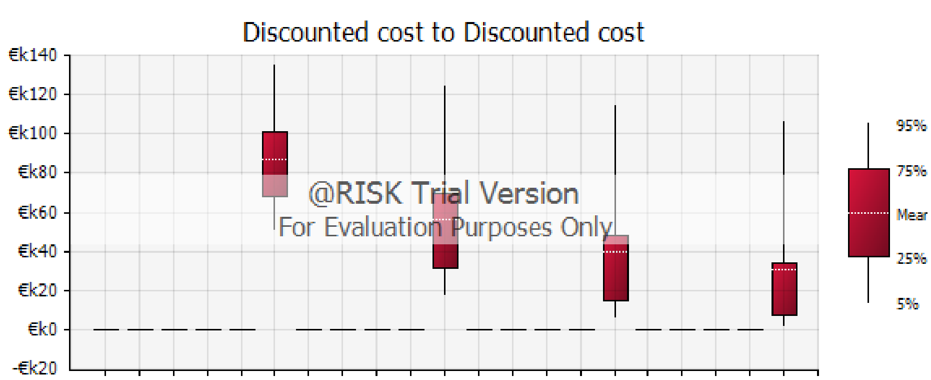


Figure 9.12 Discounted costs over the bridge's lifetime

9.6.2. *Result graphs after optimization*

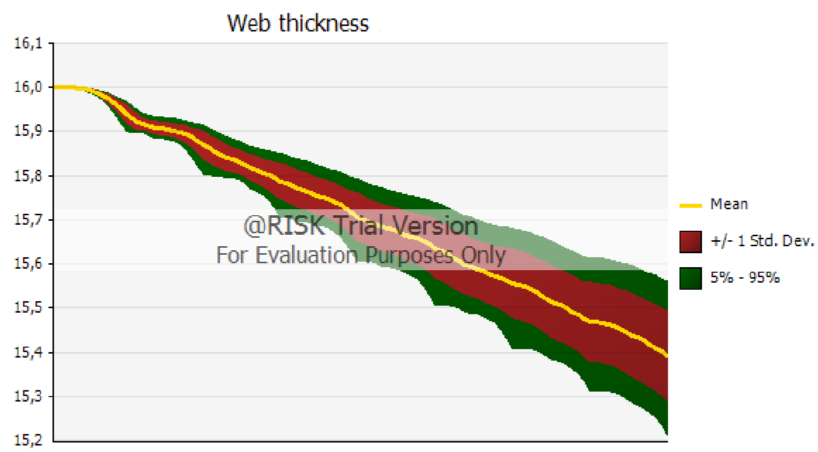


Figure 9.13 Web thickness over the bridge's lifetime

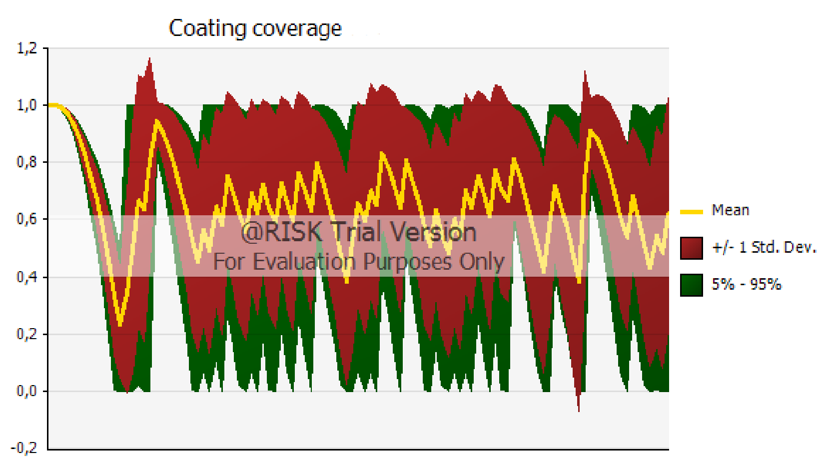


Figure 9.14 Coating coverage over the bridge's lifetime

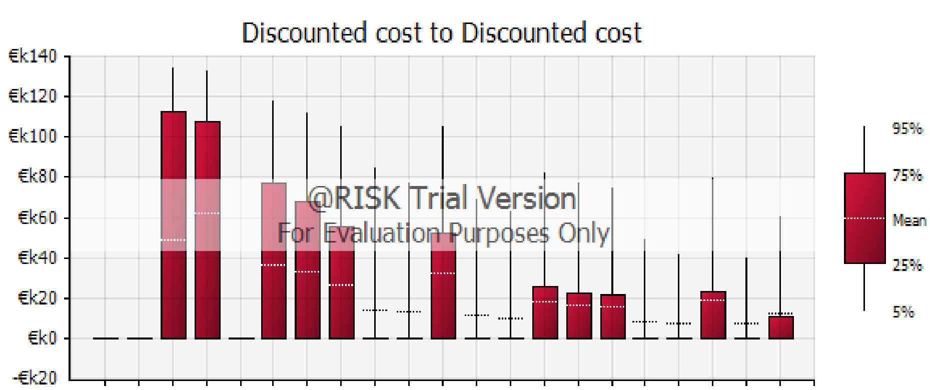


Figure 9.15 Discounted costs over the bridge's lifetime

9.6.3. Comparing the results

It can be stated for the probabilistic tool, as well as it was for the deterministic one, that the primary achievements of optimization are not economical for the case study. However, by comparing Figure 9.10 and Figure 9.13, the relevance of optimization for the performance of the bridge can be seen. Using the optimized maintenance strategy, the function of mean value of the performance of the coating is much closer to a constant value. In other words the amplitudes are much smaller of the function, meaning the performance is more reliable. Looking at Table 9.7 it is possible to conclude that optimization affects all the statistical values of the Total discounted cost and the Minimum performance. For any probabilistic results severe importance is given not only on the mean value but also on the standard deviation, i.e. minimizing the risks. The standard deviation of Minimum performance using the optimized tool is 4/5 of the standard deviation using the basic tool (see Table 9.7), which can be considered as relevant achievement. Also the results for any percentile can be studied. For 5 and 95 percentiles the results are shown in Table 9.7. The conclusion can be made that with optimization not only the mean value but the values for any percentile can be increased, resulting in an overall more reliable performance.

Table 9.7 – Comparison of the main results of the probabilistic analyses

	Total discounted cost		Minimum performance	
	Before Op.	**After Op.**	**Before Op.**	**After Op.**
Mean	€k 213	€k 392	95,31%	96,16%
Std. Dev.	€k 153	€k 243	0,76%	0,63%
5%	€k 78	€k 165	94,11%	95,09%
95%	€k 476	€k 810	96,62%	97,25%

9.7. Benefits of the Probabilistic Tool

After studying 'before and after optimization' cases, separately for the deterministic and the probabilistic tool, in this paragraph emphasis is put on the benefits of applying probabilistic tool instead of deterministic.

The traditional way of engineering calculations is deterministic, meaning that engineers like to work with single values, usually the expected values, and obtain a single value as result also. However, generally there are many uncertainties in engineering calculations. Commonly engineers work with data coming from experimental or numerical tests; hence, these data cannot be identified with single values (most probable or mean values) without risks. To take into consideration these risks it is essential to build a probabilistic model that is able to deal not only with single values but also with distributions of values.

The advantages of using a probabilistic approach can be clearly seen in the results of the case study in this thesis. To make a decision about the maintenance strategy, in case of following a deterministic way, some aspects are ignored. It is not possible to take into account any uncertainties in the input data; therefore, the decision can be done wrongly and reality can be far from the estimations. However, by using the probabilistic tool it is possible to count on the most relevant uncertainties and model the probable outcomes of the results. Like this, the decision maker has to face much less unexpected events, and with much more data available he can attain a more complete picture of all possible scenarios to count on them.

For example, if the goal was to know the expenses for maintenance during the time period 8 (years 35-40), using deterministic approach and looking at Figure 9.9 it could be said that there wouldn't be any. However, observing Figure 9.15 of the probabilistic results, it is evident that there would be a high chance that expenses would occur during that period. Hence, it would lead to serious consequences in the decision making process to assume that there will not be any expenditure during that time period.

10. Conclusions and Future Works

10.1.Conclusions

In the scope of this thesis, a probabilistic Life Cycle Assessment Tool (LCAT) was developed for optimizing the maintenance strategies of composite highway bridges with protective coatings. In the developed tool only corrosion is taken into account. Therefore, all the findings have to be considered carefully regarding this limitation.

Obtaining the results of different probabilistic analyses the following findings can be articulated:

- General sensitivity analysis showed that the most important input data regarding:
  - Life Cycle Cost (LCC) is the discount rate;
  - Life Cycle Performance (LCP) are the parameter *A* (the most important parameter of corrosion rate) and the service life of the coating.
- Sensitivity analyses were also done to find the most appropriate distribution function for the relevant input data:
  - For the discount rate Normal,
  - For the parameter A Beta subjective,
  - For the service life of the coating Poisson distribution was chosen.
- Correlation studies lead to the conclusion that:
  - Establishing correlation between the parameters of the corrosion rate and the service life of the coating is not essential and thus avoidable.

Both the deterministic and the probabilistic LCAT were applied to a case study. Hereby the observed advantages of the probabilistic tool are listed:

- Counting on uncertainties, which is extremely important when input data come from experiments or many assumptions are made regarding the future;
- Gaining no single values but statistical properties of distributions of the results;
- Providing complete picture of all possible scenarios with the help of statistical output data;
- Introducing the idea of risk in the decision making process.

Using the same case study, a comparison was also made between general and optimized maintenance strategies. It is important to note that optimization can be done in many ways. The target and the constraints of the optimization can vary regarding the principles that are chosen to follow. In the present thesis three optimizations were done. For all of them, the target was to minimize the Total discounted cost and constraints were identified regarding the Minimum level of performance at any time over the bridge's lifetime. The principles of the different scenarios however slightly differ and are summarized below:

SC1) Scenario 1 focuses on aesthetical aspect and includes re-painting of the bridge whenever the painting is assumed to be entirely lost;

SC2) The principle of Scenario 1 is still valid in Scenario 2; in addition, a strengthening intervention can be triggered also if it is better economically or if it is needed due to the performance constraints;

SC3) In Scenario 3 aesthetical aspects are ignored; only strengthening intervention can be triggered regarding the performance of the bridge at any time.

It is concluded that in case of a composite highway bridge with the previously mentioned limitations, only triggering re-coating interventions is satisfactory for all corrosivity categories. Only for category C5, it can be more economical to trigger also strengthening intervention.

Both tools were applied to the case study twice: at first, using a basic scenario (re-coating in every 25 years) and then an optimal scenario (rooted from SC2). After attaining results for all four scenarios the following conclusions are made:

- Due to the limitations of the tool and the chosen principles for the optimization, the achievements of the optimal strategies are not minimizing LCC, but maximizing LCP;
- Optimal strategies lead to better performance of the bridge in terms of resistance as well as in terms of aesthetics;
- As a consequence of the previous statement, using optimal strategies can help to face unforeseen events in the future, such as load increase or performance requirement changes;
- Regarding the probabilistic tool, an additional achievement of optimization is the *continuously* high performance level of the coating and hence the bridge's aesthetics;
- It is also concluded that not only the mean value of the Minimum performance level is higher applying the optimal strategy but the standard deviation is lower, which results in higher reliability.

10.2.Future developments

The limitations of the tool developed in the present thesis were already mentioned previously. Hereby, these and desirable future improvements are discussed more specifically.

The biggest limitation of the tool is that it takes into account only corrosion of the steel structure as deterioration of the composite bridges. Additionally, the interventions included in the tool affect solely the steel structure. An important future development would be taking into account deteriorations such as: fatigue of steel structure, carbonation of concrete and corrosion of steel rebars in reinforced concrete. Note, that for the deteriorations of the concrete slab some research was already done in this thesis; however, due to time shortage these could not be implemented in the tool. Regarding the interventions, beside full re-coating and full-strengthening of the bridge, it would be necessary to take into account partial re-coating and partial strengthening as well because in reality these interventions are more often applied. Apart from these, entirely new interventions are desired to be implemented due to the appearance of new deterioration processes in the tool. These interventions would affect the performance of the reinforced concrete slab, i.e. the concrete and the rebars.

In terms of Life Cycle Environmental Assessment (LCEA), other emissions could be taken into account, apart from greenhouse emissions, enabling for the quantification of other impact categories. The goal is to develop a powerful LCEA to be included in the present LCAT and thus to enable a more realistic balance between LCEA, LCC and LCP modules.

Another possible improvement would be also to allow specialists to use different types of cross-sections and cross-sectional systems, e.g. trapezoidal sheets.

For the optimization of the tool, a deeper research should be done by realizing several scenarios and following various principles in order to establish optimal maintenance strategies for numerous possible requirements. This optimization study, after the implementation of additional deterioration processes, interventions and environmental impact categories, would be a really complex and interesting task.

It is observed that the LCAT presented in this thesis provides a solid basis for a future powerful tool. As a final remark it can be stated that the present tool is promising and it is worth to be subject of future development.

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