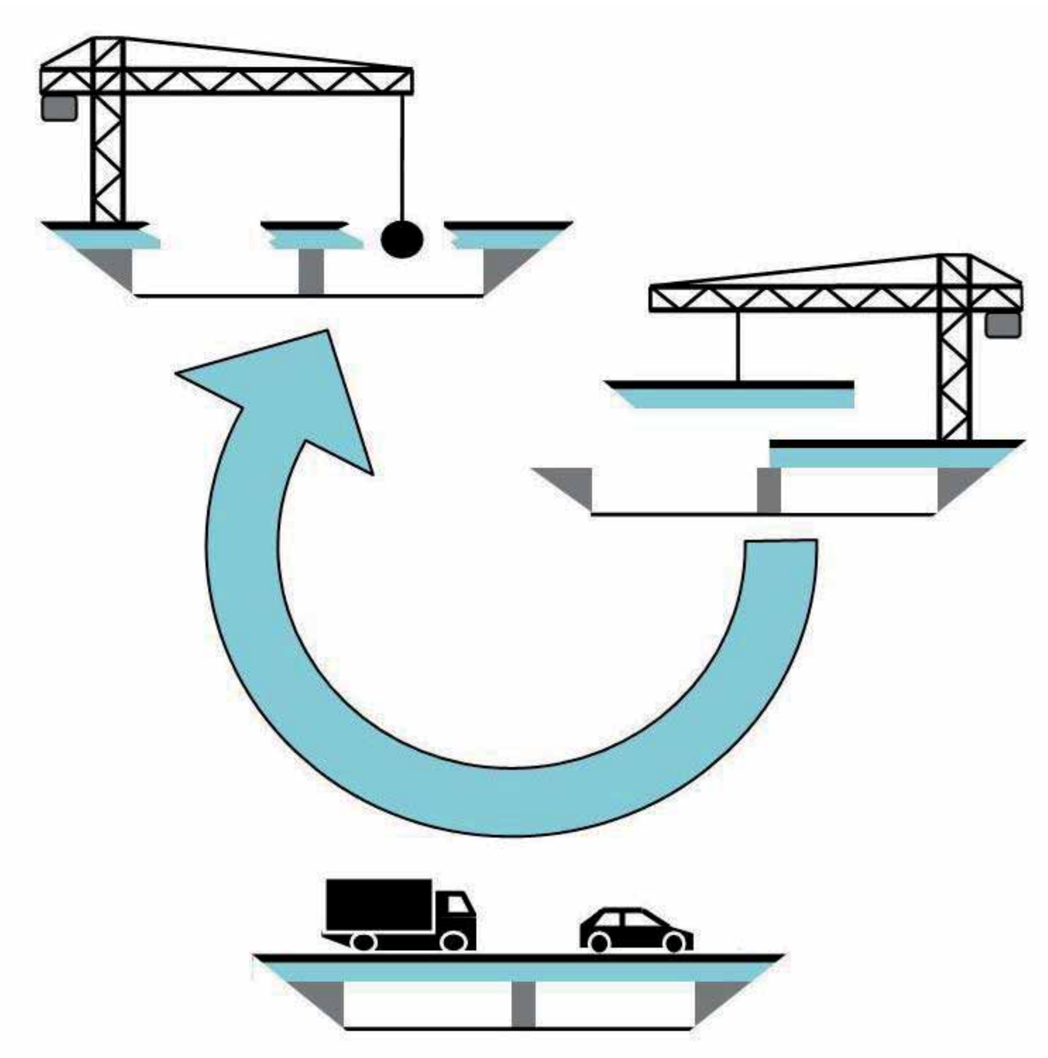
Sustainable
Steel-Composite Bridges



Handbook

Sustainable Steel-Composite Bridges

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Handbook

Abstract

In the worldwide infrastructure network especially bridges are of essential importance. The request for sustainable structures is urgent as for bridge lifecycle design it is intended to cover a lifespan of more than 100 years. Shifting from an initial cost-effective mode to a lifecycle cost-effective mode is demanding in regard of increasing importance of maintenance, rehabilitation and renewal of bridges also in view of the rapid growing traffic volume on bridges.

Within the European funded research project “Sustainable Steel-Composite Bridges in Built Environment” (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.

The present handbook describes a lifecycle model for a sustainable bridge design integrating environmental, economic and functional aspects. With Lifecycle Performance (LCP), Lifecycle Assessment (LCA) and Lifecycle Costs (LCC) the most relevant elements are introduced. The complete process is illustrated by a case study covering the entire lifespan, from the construction to the demolition of three different types of bridges crossing a motorway.

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1 Introduction

The present handbook is an essential result of the European funded research project SBRI "Sustainable Steel-Composite Bridges in Built Environment". The focus is placed on the introduction of a fully integrated lifecycle model integrating environmental, economic and functional aspects and illustrated by a case study. The objective of the handbook is to provide an overview about the most important relationships and to describe the complete process in essence. An overview is given in [1] and more detailed explanations including data compilation, background information and further case studies are published in the final report of the SBRI-project [2].

Traditionally bridges are designed to achieve minimal initial costs. But in regard of sustainability, not only the construction stage must be taken into account but the entire lifecycle of 100 years and more (Figure 1).

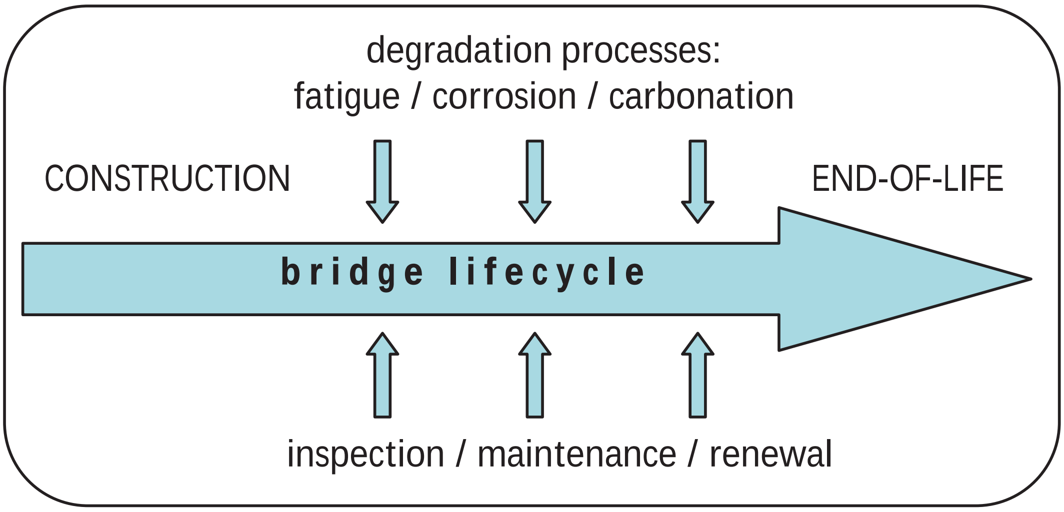

Figure 1: Sketch of the lifecycle of a bridge.

Bridges are facing different degradation processes throughout the years. The structural function of the details, and therefore the structure itself, can be preserved and improved by maintenance and/or renewal actions concerning defects discovered during inspections. The lifecycle of steel-composite bridges is analyzed from the **construction** over the **operation** of the bridge to the **end-of-life**.

A fully integrated lifecycle model which serves as a tool for evaluating new steel-composite bridges from a sustainability perspective is introduced – integrating environmental, economic and functional qualities. The so-called Lifecycle Analysis represents a new holistic approach including **Lifecycle Performance (LCP) and Maintenance Strategies**, **Lifecycle Assessment (LCA)** and **Lifecycle Costs (LCC)** (Figure 2).

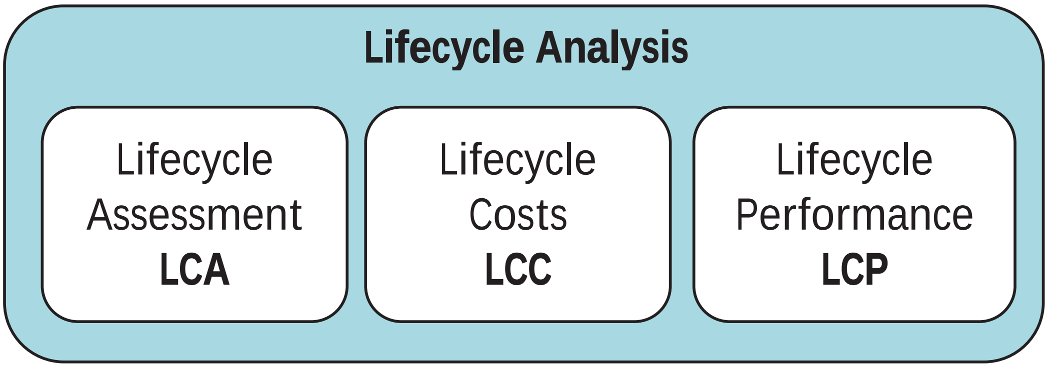

Figure 2: Holistic approach to Lifecycle Analysis.

The complete process is illustrated by a case study covering the entire lifespan, from the construction to the demolition of three different types of bridges crossing a motorway. Thus also an interesting comparison can be drawn.

2 Lifecycle Performance (LCP) and Maintenance Strategies

2.1 General

The evaluation of lifecycle performance starts with the construction of the bridge including also material production. The operation phase starts when the bridge goes into service and this stage ends when the bridge reaches the end of its functionality – end-of-life.

Lifecycle Performance concerns both: a) various degradation processes such as carbonation, corrosion and fatigue and b) the corresponding inspection and maintenance intervals and methods.

2.2 Construction

The information regarding the construction includes data from the production of raw materials to the erection of the bridge itself. To reflect realistic scenarios, this study uses real cases data which synthesize the actual experience of some partners involved in the management of their road infrastructure system, where bridges are a major asset. All information concerning the construction phase is based on the detailed design and structural solutions already tested and built. Therefore the timetables with detailed work plans with the chronological allocation of resources considered are realistic.

As we are not dealing with motorways built from scratch but in a built environment, the construction processes of the composite decks are strongly conditioned by the need to reduce the duration of the work done over the motorway. Thus, the structural steel is normally assembled near the work site and lifted in few pieces for its final position. The deck, for the same reason, is often entirely prefabricated to avoid concreting works over motorway traffic.

The concrete structures used for establishing a benchmark with the composite structures surveyed were built with traditional methods associated with this type of structures, always aiming to minimize the time gap in which the motorway service level will be reduced. Following this purpose it was considered a solution fully concreted on site with conventional formwork and scaffolding and another with precast beams.

Considering real data from built structures, means that the assumptions associated with each detailed design differ from each other. In order to address this particular feature, some assumptions were made for the benefit of this project, which allowed avoiding the contamination of the results with external factors that do not depend on the structural typology. As an example, it has been assumed that all structures are based over the same geotechnical horizon. Apart from the constructive aspects themselves, information regarding the legal framework that contextualizes such interventions was provided, in order to allow the estimation of all costs not directly related with materials or workloads.

2.3 Operation

2.3.1 General

The operation phase includes all maintenance and rehabilitation actions as well as the necessary regular bridge inspections that allow the monitoring of bridge condition rating and eventual need for rehabilitations actions. Three types of maintenance and inspections strategies were considered:

- Standard – a scenario with a 100-year service life, according to the normal service life of bridges, for which there will be enough money to undergo all the necessary inspections and maintenance/repair actions;
- Lack of money – along the bridge lifecycle, there is not enough money to undergo the necessary maintenance/repair actions and the bridge will be critically deteriorated and with traffic restrictions on year 100. Inspection activity will have to be increased in the last years for the knowledge of the real bridge condition, and also maintenance actions are introduced to extend the service life of some elements;
- Prolonged life – the decision of maintaining the bridge for an additional 30 years (130 years total and no more) is taken around year 80. After this year, inspection and maintenance actions are adapted to accomplish this service life extension.

In the following chapters the basic parameters for the three scenarios are condensed.

2.3.2 Standard scenario

For the operation phase, it was assumed that the average service life for each structural or non structural element of the bridge is the same for the standard, lack of money and prolonged life scenario, according to Table 1. Based on the average service life, a maintenance/repair works frequency was assumed – Table 2.

Table 1: Average service life assumed for bridge elements (for the standard, lack of money and prolonged life scenarios).

Element	Average service life (years)
Superstructure concrete	100
Concrete edge beam	40
Safety barrier	40
Superstructure steel	100
Steel corrosion protection	35
Expansion joints	40
Road surface	20
Water Proofing Layer	40
Metal cornice gutter	25
Elastomeric bearing	35
Railing	40

Table A1 with maintenance and repair actions works frequency for the maintenance or renewal for the standard scenario is shown in Annex A.

In order to perform an adequate maintenance strategy, inspection activity is necessary. The standard inspection strategy includes three types of inspection considered important to maintain a good condition rating for the bridge.

Table 2: Standard scenario - average maintenance/repair works frequency.

Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	25
Concrete edge beam	Minor repairs	25
Safety barrier	Partial replacement	25
Steel corrosion protection	Repainting of corrosion protection	25
Expansion joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0
Elastomeric bearing	Clean, painting, lubricating	20
Railing	Painting	20

(*) – Elements with no maintenance actions. Total replacement takes place when the service life is reached.

The outcomes of these inspections are the necessary maintenance, repair or rehabilitation works:

- Routine inspection – visual observation to detect small damage that can be promptly repaired;
- Principal inspection – detailed visual inspection with special means of access. The aim is the assessment

of the bridge condition rating evolution, with the definition of eventual repair / rehabilitation actions;

- Special inspection – detailed inspection when there is a need for a specific repair plan for the complete or partial rehabilitation of the bridge. Tests and laboratory analysis are also used to help evaluate damage conditions and allow recommendations for damage repairs.

The frequency assumed for each type of inspection for the standard scenario is shown in Table 3.

Table 3: Standard scenario - Inspection frequency and average occurrence.

Type of Inspection	Inspection frequency	Average occurrence during 100 years
Routine	annually	100
Principal	6 years	17
Special	2 in 100 years	2

2.3.3 Lack of money scenario

In this scenario, inspections in the early stages of the bridge will be less frequent, and as the estimated end-of-life approaches, inspections are more frequent, for the control of the structural safety of the bridge. Repair actions are therefore delayed and scheduled towards the end of the lifecycle. Based on this scenario, the assumed maintenance/repair works frequency is shown in Table 4.

Table 4: Lack of money scenario - average maintenance/repair works frequency.

Element	**Maintenance action**	**Standard maintenance frequency (years)**
Superstructure concrete	Small area repairs	50
Concrete edge beam	Minor repairs	50
Safety barrier	Partial replacement	20
Steel corrosion protection	Repainting of corrosion protection	25
Expansion joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0
Elastomeric bearing	Clean, painting, lubricating	20
Railing	Painting	20

(*) – Elements with no maintenance actions. Total replacement takes place when the service life is reached.

Table A2 with maintenance and repair actions works frequency for the maintenance or renewal for the lack of money scenario is shown in Annex A.

The frequency assumed for each type of inspection for the lack of money scenario is shown in Table 5. The special inspections will take place on years 35, 50, 75 and 90.

Table 5: Lack of money scenario - Inspection frequency and average occurrence.

Type of Inspection	Inspection frequency	Average occurrence during 100 years
Routine	annually	100
Principal	5 years	20
Special	4 in 100 years	4

2.3.4 Prolonged life scenario

Maintenance actions are kept the same as for the standard scenario up to around year 80 and are then prolonged to year 130. Up to year 80, maintenance and inspection activities frequencies will be the same as the assumed for the standard scenario. Maintenance repairs in some elements will be more frequent between year 115 and 130.

Regarding maintenance it is also assumed that the steel superstructure will have no fatigue problems, so no reinforcement actions have been considered in this maintenance strategy. This assumption has been confirmed by fatigue design. Based on the average service life, a maintenance/repair works frequency was assumed – Table 6.

Table A3 with maintenance and repair actions works frequency for the maintenance or renewal for the prolonged life scenario is shown in Annex A.

Table 6: Prolonged life scenario - average maintenance/repair works frequency.

Element	Maintenance action	Standard maintenance frequency (years)
Superstructure concrete	Small area repairs	25
Concrete edge beam	Minor repairs	40
Safety barrier	Partial replacement	20
Steel corrosion protection	Repainting of corrosion protection	25
Expansion joints	Partial replacement	10
Road surface	Minor repairs	10
Water Proofing Layer	No maintenance actions *	0
Metal cornice gutter	No maintenance actions *	0
Elastomeric bearing	Clean, painting, lubricating	25
Railing	Painting	20

(*) – Elements with no maintenance actions. Total replacement takes place when the service life is reached.

The frequency assumed for each type of inspection for the prolonged life is shown in Table 7. The special inspections will take place on years 50, 75, 90 and 115.

Table 7: Prolonged life scenario - Inspection frequency and average occurrence.

Type of Inspection	Inspection frequency	Average occurrence during 130 years
Routine	annually	130
Principal	6 years	22
Special	4 in 130 years	4

2.4 End-of-life

When the bridge reaches the end-of-life (100 years), the whole bridge is demolished. Recycling and discarding of the different materials is considered as well as the need for traffic restrictions under the bridge while the demolition of the deck and central pier takes place.

3 Lifecycle Assessment (LCA)

3.1 General framework

The framework for Lifecycle Environmental Analysis (LCA) adopted in this project is according to ISO standards 14040 [3] and 14044 [4]. These standards specify the general framework, principles and requirements for conducting and reporting lifecycle assessment studies. According to these standards, lifecycle assessment shall include (i) definition of goal and scope, (ii) inventory analysis, (iii) impact assessment, (iv) normalization and weighting, and (v) interpretation of results. The step of normalization and weighting are considered to be optional in ISO standards and it will not be addressed in the lifecycle environmental analysis. Thus, the complete flowchart for the environmental lifecycle analysis is represented in Figure 3.

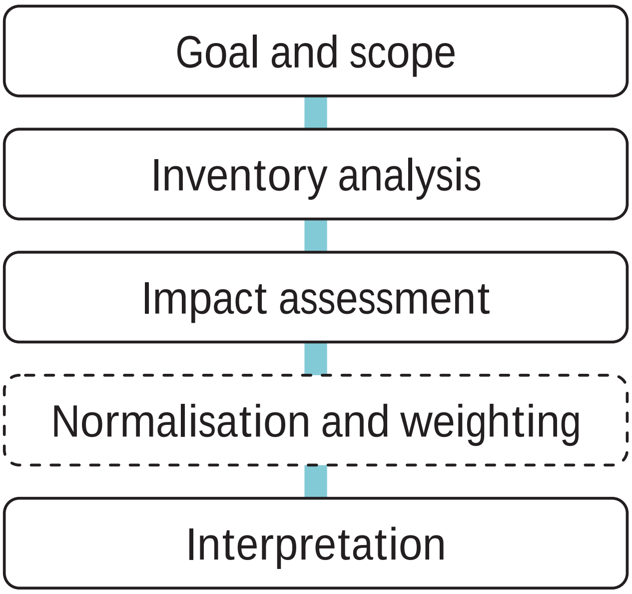

Figure 3: Scheme of the environmental lifecycle analysis.

3.2 Goal and scope of the LCA

3.2.2 Goal of the LCA

The general goal of the LCA is to evaluate the environmental performance of composite motorway bridges over their lifecycle. The period of analysis is assumed to be 100 years. The lifecycle analysis will highlight main advantages and disadvantages of this kind of structures and will allow to provide recommendations for further improvements.

3.2.2 Functional unit

In the aim of this project the general definition of the functional unit is a motorway bridge, designed for a service life of 100 years, to overpass a dual-carriageway. During the operation stage it is assumed that bridges are maintained according to the standard maintenance scenario described in the final report [2].

3.2.3 Scope of the LCA

The system boundaries determine which unit process shall be included within the LCA [3], [4]. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The system boundary adopted in this project is represented in Figure 4. All stages over the complete lifecycle of the bridges, from raw material extraction until end-of-life procedures, are included. Furthermore, the transportation of materials and equipments should also be included in the system boundary.

When the bridge is built (assuming that the motorway is under service) or it goes under repair, traffic congestion results from delays over the construction work zone. This construction related delay results in additional fuel consumption and related emissions. The effects of traffic congestion are also taken into account in the LCA.

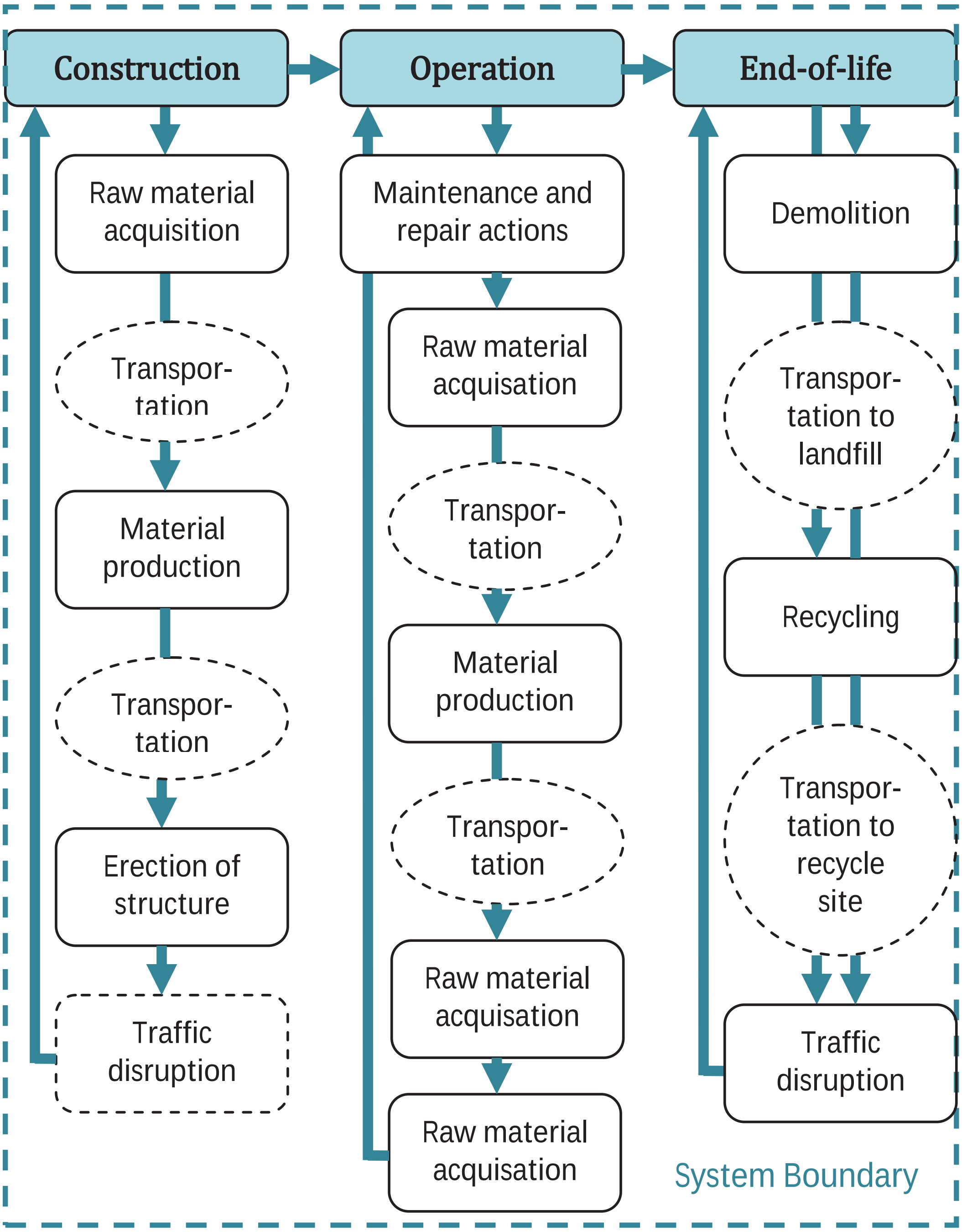

Figure 4: System boundary of the LCA [5].

3.3 Methodology for impact assessment

The impact assessment stage of a LCA is aimed at evaluating the significance of potential environmental impacts using the results of the lifecycle inventory analysis. In general, this process involves associating inventory data with specific environmental impact categories, and is made in two parts (i) mandatory elements, such as selection of environmental indicators and classification; and (ii) optional elements, such as normalization, ranking, grouping and weighting.

The classification implies a previous selection of appropriate impact categories, according to the goal of the study, and the assignment of inventory results to the chosen impact categories. Characterization factors are then used representing the relative contribution of an inventory result (m_i) to the impact category indicator result, as expressed by the following expression:

$$impact_{cat} = \sum_{i} m_i \times charact\_factor_{cat,i} \tag{1}$$

The environmental indicators adopted in the lifecycle approach are listed in the Table 8.

All the indicators represented in Table 8 are evaluated according to expression (1). The characterization factors adopted in this approach are provided from the methodology developed by the Centre of Environmental Sciences [6], in the University of Leiden.

Table 8: Environmental indicators for LCA.

Indicator	Unit	Time scale
Abiotic depletion (ADP)	kg Sb eq	-
Acidification (AP)	kg SO_2 eq	∞
Eutrophication (EP)	kg PO_4--eq	∞
Global warming (GWP)	kg CO_2 eq	100 yrs
Ozone layer depletion steady state (ODP)	kg CFC-11 eq	∞
Photochemical oxidation (POCP)	kg C_2H_4 eq	-

Normalization and weighting of environmental indicators will not be considered in the analysis due to the local dependency and the subjectivity of the values, respectively.

4 Lifecycle Costs (LCC)

4.1 General

The total lifecycle costs include not only construction costs but also other costs such as design, maintenance, dismantlement and user costs which may represent a significant portion of the total lifecycle costs of a steel-composite bridge (Figure 5).

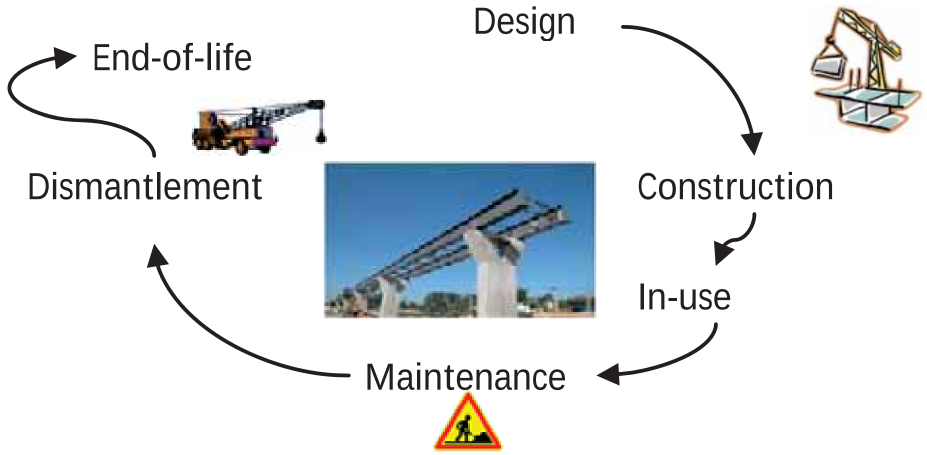

Figure 5: Lifecycle stages/costs from design to bridge end-of-life.

The ISO 15686-5 methodology [7] defines the lifecycle costing as a technique which enables systematic economic evaluation of the lifecycle costs over the period of analysis (Figure 6). In a whole life costing approach, the projected costs or benefits may include finance, business costs, income from land sale and user costs. One important motivation to use lifecycle cost analysis (LCCA) is to balance the decrease of operation and maintenance costs with a possible increase of initial costs [8].

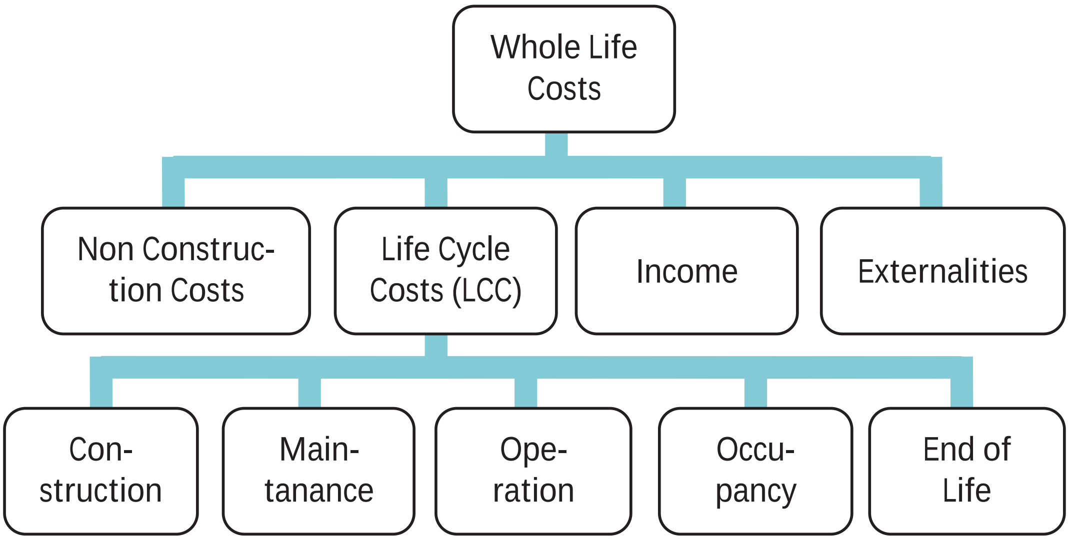

Figure 6: "Whole life costs" and "lifecycle costs" concept [6].

By considering all these costs in the decision process and ensuring performance constraints are satisfied, solutions that may be more expensive than others at the construction stage can finally be more attractive when considering the overall life service of the structure (see Figure 7).

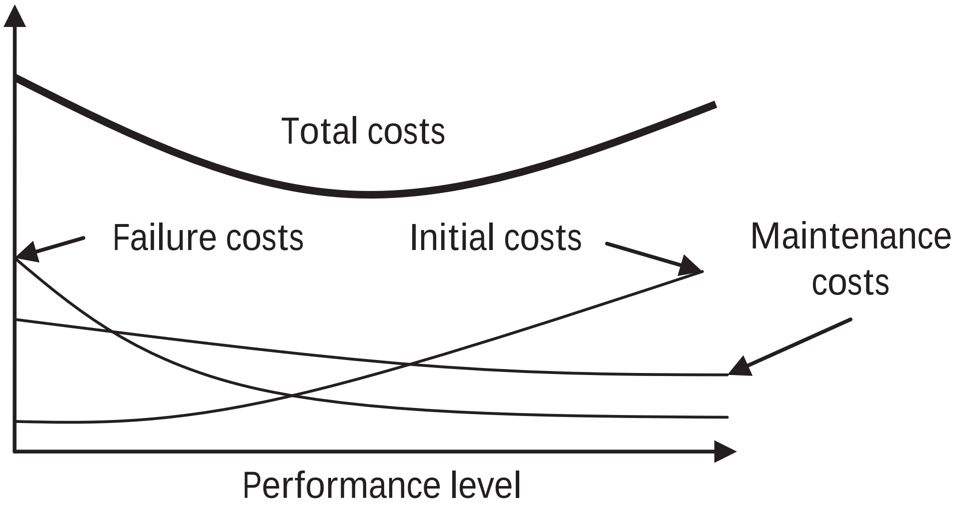

Figure 7: Schematic representation of lifecycle costs [9], [10].

4.2 Economic evaluation method for LCC

The costs included in a LCCA being incurred at varying points in time, there is a need to convert them into a value at a common point in time [11]. Several methods exist to lead to LCC among which:

- the payback method, which determines the time required to return to the initial investment,
- the equivalent annual costs, which express the costs per year of owning and operating an asset over its entire lifespan,
- the internal rate of return, which is the discount rate at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investments,
- the net present value approach which directly applies discount factors to each year projected cash flow.

The net present value approach mentioned above is one of the most used methods to compare past and future cash flows with those of today. To make costs time-equivalent, the approach discounts them to a common point in time, the discount rate of money reflecting the investor's opportunity costs of money over time. The net present value can be calculated as follows:

$$NPV = \sum_{k=1}^{N} \frac{C_k}{(1+r)^k} \tag{2}$$

NPV	lifecycle costs expressed as a present value,
k	year considered,
C_k	sum of all cash flows in year k ,
r	discount rate,
N	number of actions to be considered during the service lifetime.

The yearly profile of one unity of money is shown for illustration in Figure 8. It is noted that a steep drop of the discounted costs is observed for high discount rate values. Also, it is shown that choosing r = 6 or 8% leads to a monetary value close to zero after sixty years.

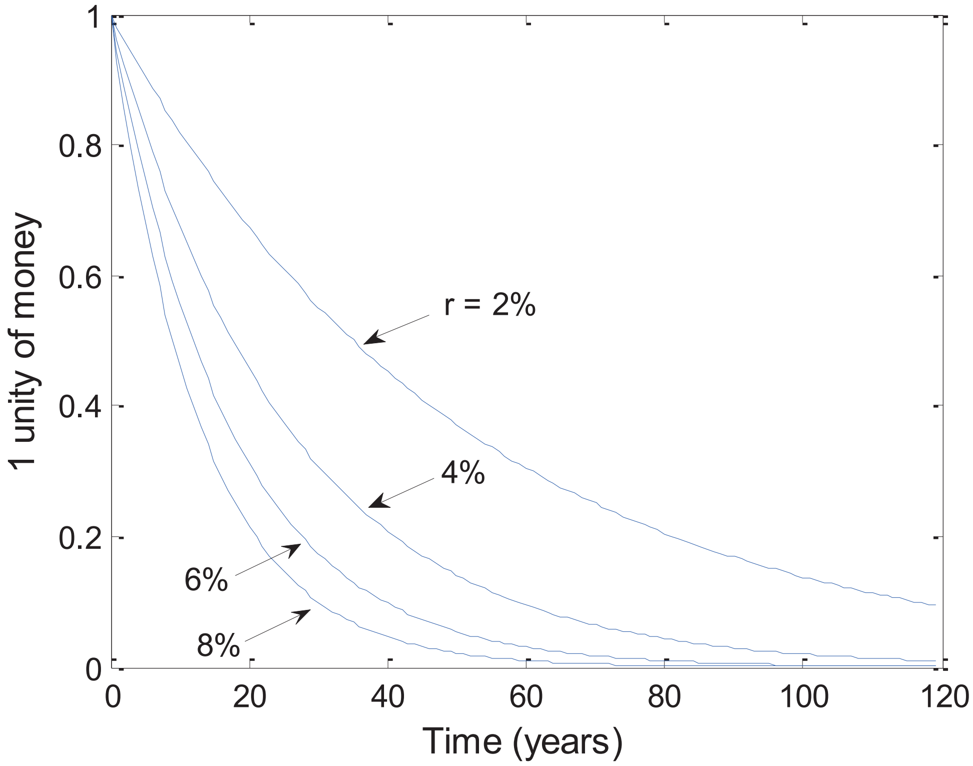

Figure 8: Profile of one unity of money for different values of r.

The value of the yearly discount rate used is crucial since the current worth of money (NPV) is highly sensitive to this parameter. Indeed, the higher the discount rate, the more importance is given to the near-present. Choosing a high discount rate may then promote management strategies with low initial costs and a costly end-of-life. Therefore, the choice of the discount rate is delicate and has to be in agreement with the time horizon. It is noted that the discount rate is fixed at 2% in the LCCA performed in the SBRI-project for a 100-year service life.

4.3 From design to end-of-life costs

4.3.1 Lifecycle

LCC extends the analysis over the whole life of the project, showing the real value of the investment. Such an analysis investigates the costs related to the entire lifecycle in combination with the assessment of structural performances over time. Initial costs (design, material production, fabrication), operation costs (inspection and repair costs) and end-of-life costs are then assessed (Figure 9).

It is mentioned that the costs of failure (which comprises costs associated with structural failure multiplied by their probability of occurrence) are not investigated in this project, which focuses only on standard operation scenarios during the service life. The application of LCC to steel-concrete composite bridges, according to the construction/operation/end-of-life-scheme is detailed in the following chapters.

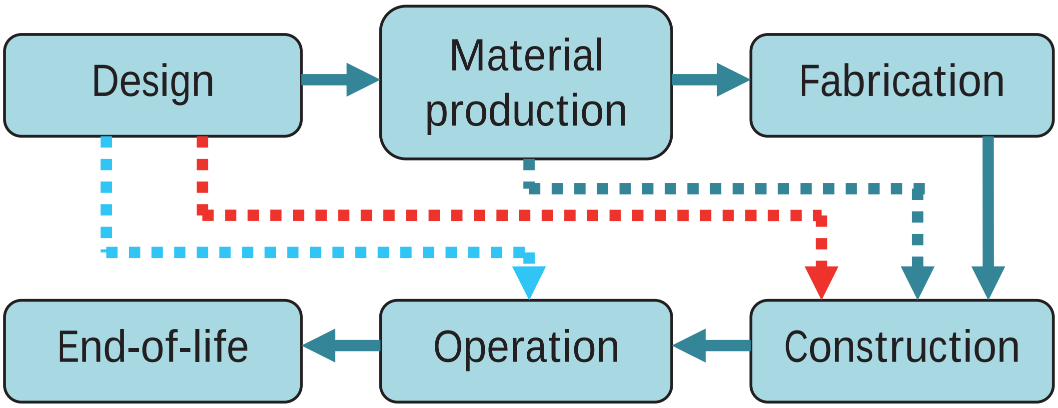

Figure 9: From design to end-of-life costs.

4.3.2 Construction

Expenses associated with steel-concrete composite bridge construction mainly include costs for (i) foundation, (ii) substructure with abutments, piles and bearings, (iii) superstructure with steel girder/box (for composite bridge), concrete deck and equipments (expansion joints, road surface, waterproofing layer, metal cornice gutter, railing and protection). These costs should include all materials and work costs needed for each component. Obviously, the different design solutions of a composite bridge are associated with different construction costs according to the type of materials used and the fabrication/erection process.

4.3.3 Operation

During the operation stage all bridges have to be inspected and maintained. In particular, bridge inspections are essential for determination of intervention strategies. The time intervals between these measures depend on the type of bridge, the experience in the different countries, the economic resources available, the average daily traffic value, the usage of de-icing salt and so on.

Also, inspection strategies (intensities and frequencies of inspections) may be different in each country based on climate conditions and prioritization strategies proper to each country [12].

The three basic types of inspection (routine, principle and special) and the three maintenance scenarios (standard, lack of money, prolonged life), described in chapter 2.3.2 are here considered for the operation stage.

The objective is that the performance of the bridge (associated with serviceability and safety concepts) always remains above a minimum threshold. This point corresponds to the end of the service life if no other rehabilitation action is conducted.

A regular interval between interventions is generally considered by highway agencies to assess the costs in the LCC analysis. For example, Irzik et al. [13] estimate future times at which maintenance actions/rehabilitation will be performed, based on the average service life of elements of the bridge. It is noted that intervals are updated in this model, based on the measures that are performed on the bridge. Figure 10 illustrates the link between the lifecycle performance and the lifecycle costs.

Depending on the minimum allowable performance threshold, preventive, essential and rehabilitation actions might be decided in a different way (compare cases (a) and (b) in Figure 10).

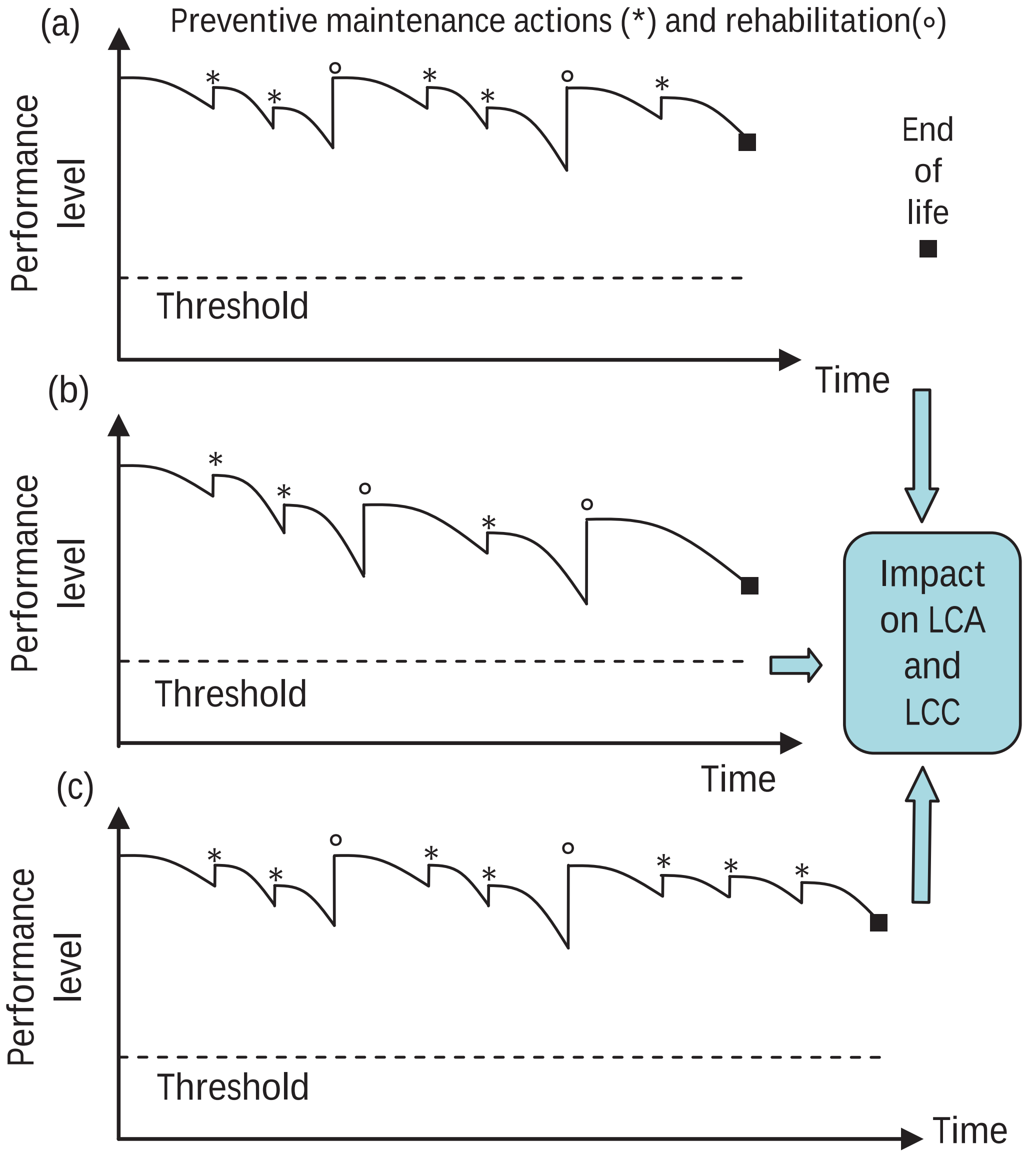

Figure 10: Schematic representation of the bridge performance profiles for (a) standard, (b) lack of money, and (c) prolonged life scenarios.

Besides, the definition of the time horizon might be crucial to orientate the choice to be made between different maintenance strategies (e.g., compare cases (a) or (b) with (c) in Figure 10). Many researchers and practitioners have proposed optimal maintenance strategies for critical structural elements [10], [14], [15]. In particular, Ferry and Flanagan [16] show that LCCA can be used as a management tool throughout the service life of the structure (for inspection, maintenance/rehabilitation and dismantlement) whenever different options are available to determine the lowest LCC.

4.3.4 End-of-life

In the end-of-life stage, it is assumed that the bridge is demolished and that the materials are sorted in the same place before being sent to their final destination. For steel-composite bridges, it is assumed that the steel structure is going to be reused. The remaining parts, which are generally concrete and bitumen materials, are cut down and transported to waste disposal areas. In this context, end-of-life costs should take into account the costs of bridge dismantlement (labour work, equipments, road warning signage), costs of transportation and costs for deposition of materials and/or revenue due to recycling of materials.

4.4 User costs

Contrary to the owner costs that are direct measurable costs, the user costs are indirect and hardly measurable. In the case of highway bridges, these costs are those incurred by the users due to maintenance operations of highway structure causing congestion or disruption of the normal traffic flow. These costs are not directly measurable but the traffic delays that lead to them can be measured. Traffic delay costs have, consequently, to be predicted on the basis of estimated delay and vehicle operation costs which include additional costs of fuel plus additional costs of vehicle maintenance. These costs are briefly described below:

- Traffic delay costs result from an increase in travel time through the work zone due to speed reductions, congestion delays or increased distances as a result of detour. These costs are influenced by many factors such as current and future traffic, bridge capacity, the timing, duration, and frequency of work-zone-induced capacity restrictions, and the unit costs for delay.
- Vehicle operating costs are due to the level of service loss caused by the maintenance operations on highway structures. The disruption of normal traffic causes speed reductions, increase of fuel and oil consumptions, tire wear and vehicle maintenance. In particular, additional costs of fuel are due to the fact that its consumption is significantly higher in congested conditions. Besides, vehicle maintenance costs increase since these items need faster replacement for vehicles travelling in congested conditions. Finally, the traffic disruption induced by maintenance works has a negative impact on road safety and consequently increases the accident rate on the road part affected by the works.

The current or future average daily traffic (ADT expressed in vehicles/day), based on the desired construction year, should be obtained from the traffic monitoring section. Due to factors such as population growth and economic prosperity, the volume of traffic on bridge may increase each year and can be estimated:

$$ADT_t = ADT \times \left(1 + r_{tg}\right)^{year_t - year_0} \tag{3}$$

ADT_t	average daily traffic to be used in the analysis at year t (vehicles/day),
r_{tg}	expected traffic growth rate,
$year_t$	year in which the ADT is calculated,
$year_0$	year in which the ADT is measured.

5 Case Study and Variations

5.1 General

Three types of motorway-crossings are considered: a traditional composite bridge (B0-1) a traditional concrete bridge (B0-2) and an integral composite bridge (B1-1).

Reference case B0.1 is a steel-concrete composite twin-girder bridge. The bridge has a symmetrical structure with two spans of 22.5 m (i.e. a total length between abutments of 45 m) (Figure 11). The total slab width is 12.40 m. The centre-to-centre spacing between main girders is 6.5 m and the slab cantilever either side is 2.6 m (Figure 12).

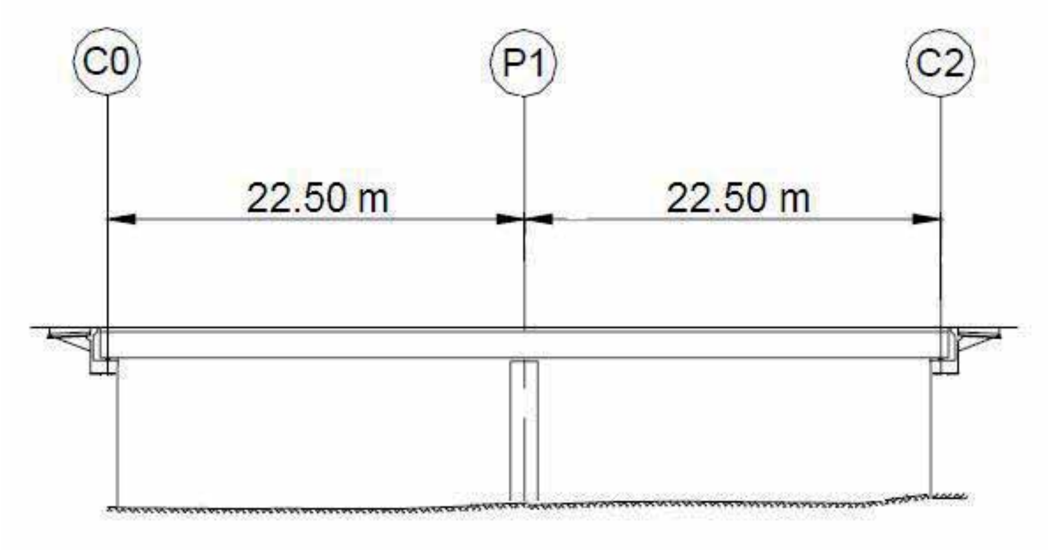

Figure 11: Case B0.1 : span distribution.

For the construction, the structural steel is first installed with a crane, then the 23 pre-cast concrete slab segments (1.95 m long each) are installed and keyed.

The standard design of case B0.1 leads to the redaction of a list of outputs (Table 9). The quantities refer only to the superstructure, abutment, foundation, and not the excavations or embankments. The estimate does not consider the equipments necessary for construction (formwork, scaffolding), nor supplies related to construction of structure. Moreover, the mentioned quantities are the ones actually in place during the service life, and therefore do not include the scrap and waste associated with their development and construction.

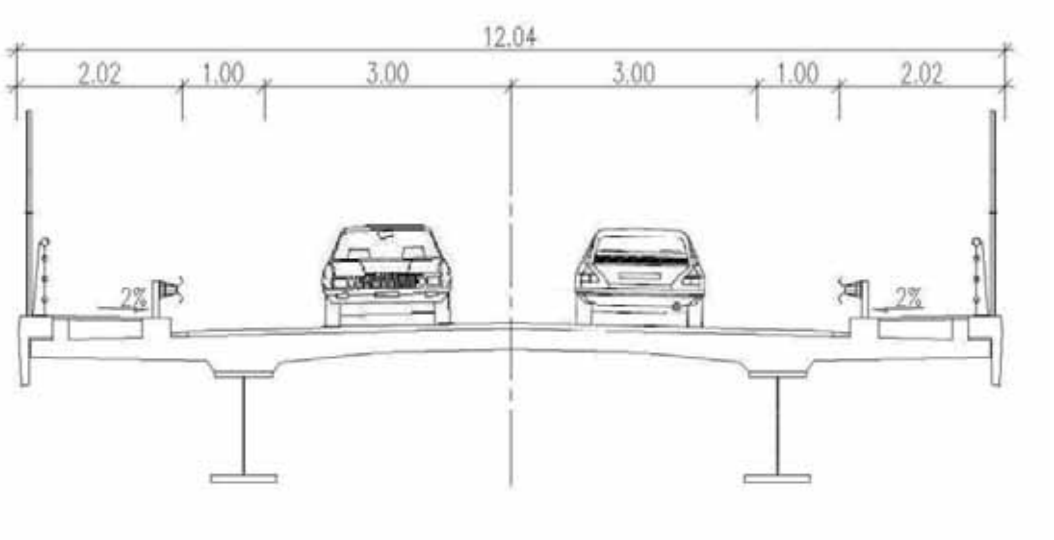

Figure 12: Case B0.1: cross-section.

Variant B0.2 is a concrete bridge cast in place. The bridge has a symmetrical structure with two spans of 22.5 m (i.e. a total length between abutments of 45 m). The total slab width is 13.10 m.

Table 9: List of design outputs for B0.1 provided to LCA and LCC analysis

	Quantity	*Unit*
Steel		
Structural steel (main girders + bracing frames) S355 N/NL	63 500	kg
Reinforcement steel bars f_{sk} = 500 Mpa – Concrete slab	31 000	kg
Reinforcement steel bars f_{sk} = 500 Mpa – Concrete support for the safety barrier	5 700	kg
Studs S235 f_u = 450	680	kg
Concrete		
Main slab C35/45	152	m^3
Concrete support for the safety barriers C35/45	29	m^3
Corrosion protection		
Paint class C4 ANV	450	m²
Non-structural equipments		
Steel S235 JR (galvanised) – Safety barrier	4 500	kg
Waterproofing layer (3 cm thick)	503	m²
Asphalt layer (8 cm thick - 360 m²)	72	t
Concrete cornice gutter – C25/30	12	m^3
Comb expansion joint (range of opening: 85 mm)	23.4	m
Supports		
Concrete C35/45	490	m^3
Reinforcement steel bars f_{sk} = 500 MPa	62 650	kg

Variant B1-1 consists of the use of integral abutments with a 40.8 m single span, that is to say no support in the middle of the highway (Figure 11). Main girders are made of plated steel. Figure 13 shows the span distribution of case B1-1.

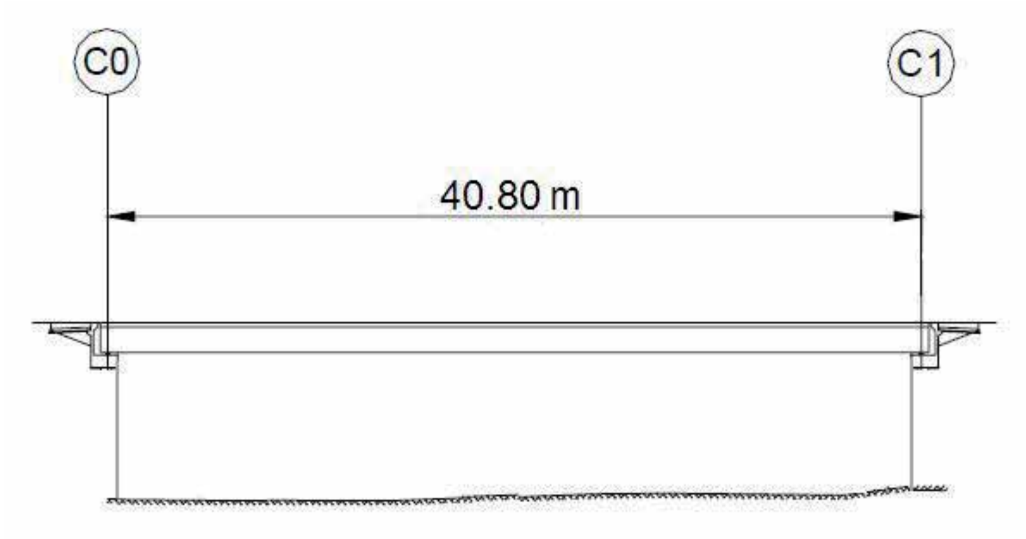

Figure 13: Case B1-1: span distribution.

This variant is 9.3 % shorter than case B0.1, but allows to save 11 % of structural steel and 21.5 % of concrete (mainly due to the elimination of the intermediate pier). Moreover, it eliminates some maintenance actions: replacement of expansion joints and bearings.

5.2 Lifecycle Performance (LCP)

As the chapters 5.3 “LCA” and 5.4 “LCC” are based on the considerations made in chapter 2 “Lifecycle Performance (LCP) and Maintenance Strategies”, this forms an important basis for the LCA and LCC evaluation.

5.3 Lifecycle Assessment (LCA)

5.3.1 General

This section describes the results of the LCA for case study B0-1. In addition, a comparative analysis is provided with the results of case studies B0-2 and B1-1.

All case studies provide the same functional unit. However, due to different geometric characteristics of the deck, it was decided to provide the results normalized by the area of each deck.

5.3.2 Material production

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 13.

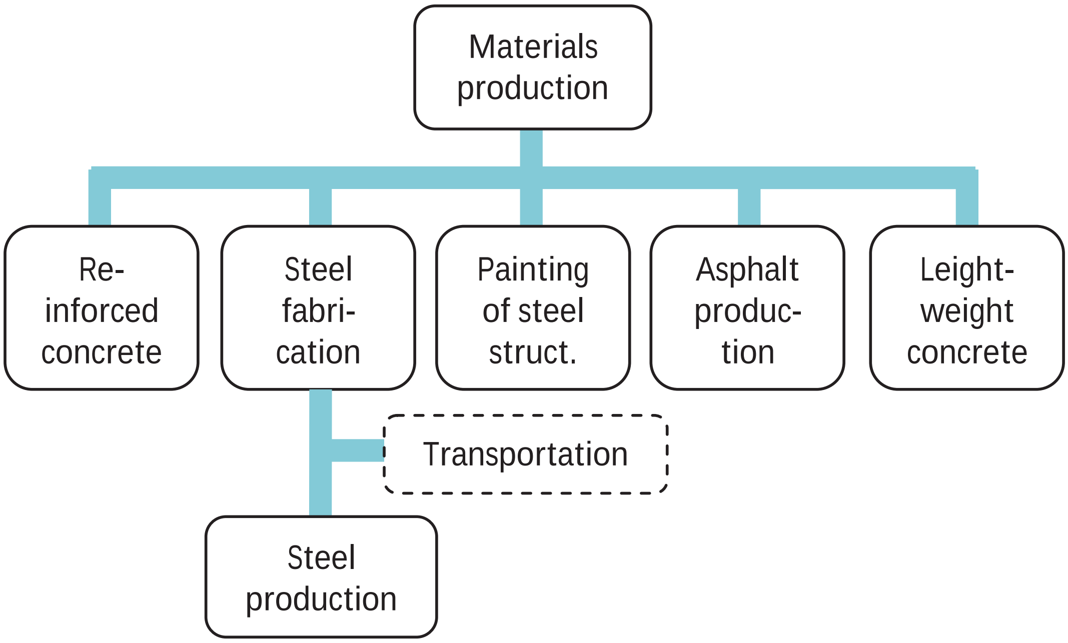

Figure 13: Contribution of each main process in the construction stage to each impact category.

The results obtained for all case studies are represented in Table 10. This table also indicates the variation of the results for each case study in relation to the reference case study B0.1.

Table 10: Variation of the results for the material production stage in relation to case study B0.1 (in m^2).

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4
B0-1	4,50	3,14	0,30	1056,96	2,53E-05	0,28
B0-2	-32,10%	-15,70%	-9,60%	-18,10%	-15,10%	-37,60%
B1-1	1,30%	-5,20%	-6,50%	-4,90%	-0,20%	-1,10%

5.3.3 Construction

The construction stage takes into account all the processes needed for the construction of the bridge and affected by it. Therefore, it should include the transportation of materials to the construction site, the transportation of equipment and the use of construction equipment.

However, due to the lack of environmental data, the use of equipment was not considered in the analysis. In addition, as the motorway and the bridge were built from scratch, no traffic was considered during this stage.

Construction materials have to be transported to the construction site. The travel distances were estimated due to lack of information and they are indicated in Table 11. The consumption of diesel is based on the travel distances displayed in Table 11.

Table 11: Transportation of materials and equipments for the construction stage.

Activity	Distance (km)
Transportation of steel structure	50
Transportation of fresh concrete	10
Transportation of steel reinforcement	50
Transportation of asphalt	20
Transportation of waterproof layer	20

The results obtained for all case studies are represented in Table 12. This table also indicates the variation of the results for each case study in relation to the reference case study B0.1.

Table 12: Variation of the results for the construction stage in relation to case study B0.1 (in m^2).

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4
B0-1	0,02	0,01	1,67E-03	3,11	4,95E-07	3,89E-04
B0-2	32,80%	32,80%	32,80%	32,80%	32,80%	32,80%
B1-1	112,40%	112,40%	112,40%	112,40%	112,40%	112,40%

5.3.4 Operation

In the operation stage, for the quantification of environmental impacts due to traffic congestion during maintenance activities, two alternative scenarios were considered: (i) a “day work” scenario, in which maintenance actions take place during the day (8 a.m. to 5 p.m.); and (ii) a “night work” scenario, in which maintenance actions take place during the night (9 p.m. to 6 a.m.).

However, the following maintenance actions required the closure of 1 lane all day (24h period):

- replacement of the waterproofing layer;
- replacement of the asphalt layer;
- replacement of coating system;
- maintenance of concrete deck.

The results obtained for all case studies are represented in Table 13. This table also indicates the variation of the results for each case study in relation to the reference case study B0.1, considering the “day work” scenario.

Table 13: Variation of the results for the operation stage in relation to case study B0.1 (in m^2).

	ADP	**AP**	**EP**	**GWP**	**ODP**	**POCP**
	kg Sb eq	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4
B0-1	13,46	3,72	0,39	510,61	2,60E-04	0,77
B0-2	-16,70%	-17,60%	-16,90%	-13,90%	-17,80%	-19,20%
B1-1	-2,00%	-1,90%	-1,70%	-1,30%	-2,00%	-5,20%

5.3.5 End-of-life

In the end-of-life stage, it is assumed that the steel structure is going to be recycled, assuming a recycling rate of 85% and a closed-loop approach. For the recycling of asphalt a cut-off rule was used due to the lack of data in relation to the respective recycling process, i.e., all processes related to the recycling process were excluded from the analysis. In relation to steel reinforcement, it was assumed that it was recycled using the same close-loop approach as for structural steel.

Due to the lack of environmental data, the use of equipment was not considered in the analysis. In addition, it was considered that during the demolition of the bridge, traffic was diverted to another route and thus no traffic was considered in this stage.

Moreover, it is assumed that the bridge is demolished and the resulting materials are sorted in the demolition place. After sorting, materials are sent for their final destination according to the respective end-of-life scenario. The estimated travelling distances between the sorting place and the final destination of the materials are indicated in Table 14. Furthermore, it is assumed that the transportation of materials is done by truck.

Table 14: Transportation of materials for the end-of-life stage.

Activity	Distance (km)
Landfill of inert materials	50 km
Recycling plant of steel reinforcement	50 km
Recycling plant of structural steel	50 km
Recycling plant of asphalt	20 km

The results obtained for all case studies are represented in Table 15.

Table 15: Variation of the results for the end-of-life stage in relation to case study B0.1 (in m^2).

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4
B0-1	-0,42	-0,10	0,05	-61,06	7,83E-06	-0,06
B0-2	-200,5%	-309,4%	58,7%	-277,8%	30,2%	-111,8%
B1-1	-17,8%	-28,1%	8,1%	-21,9%	16,5%	-3,3%

5.3.6 Lifecycle results

The results of the lifecycle analysis of the reference case study B0.1 are summarized in the contribution graph of Figure 14. In this report, only the results of the analysis considering the “day work” scenarios are provided. The detailed results of the analysis are provided in [17] and in the final report [2].

The material production stage is the stage that most contributes to the impact category of Global warming (GWP) with a percentage above 50%. On the other side, this stage has a minimum contribution to impact category Ozone Depletion (Ph), with a percentage of about 15%. The operation stage has a major contribution to most impact categories except GWP.

Stage of construction has a negligible contribution for all impact categories; while end-of-life stage has a global contribution of less than 10%.

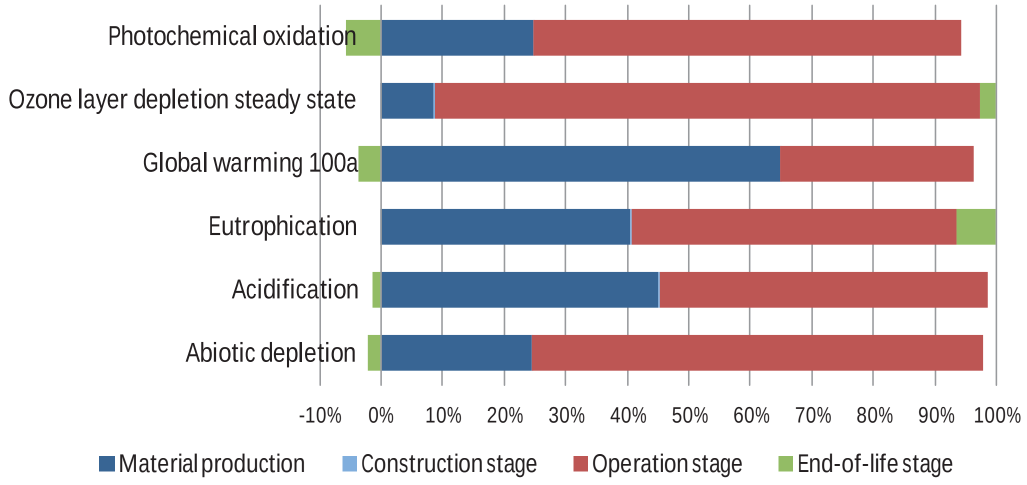

Figure 14: Contribution of each stage to impact category (B0-1).

The results presented in Figure 14 were rearranged according to the main process involved in the lifecycle analysis and the results are presented in Figure 15. Four main processes were identified: (i) production of material, (ii) transportation of materials, (iii) disposal of materials, and (iv) traffic congestion. According to Figure 15, the processes of production of materials and traffic congestion are dominant for most impact categories.

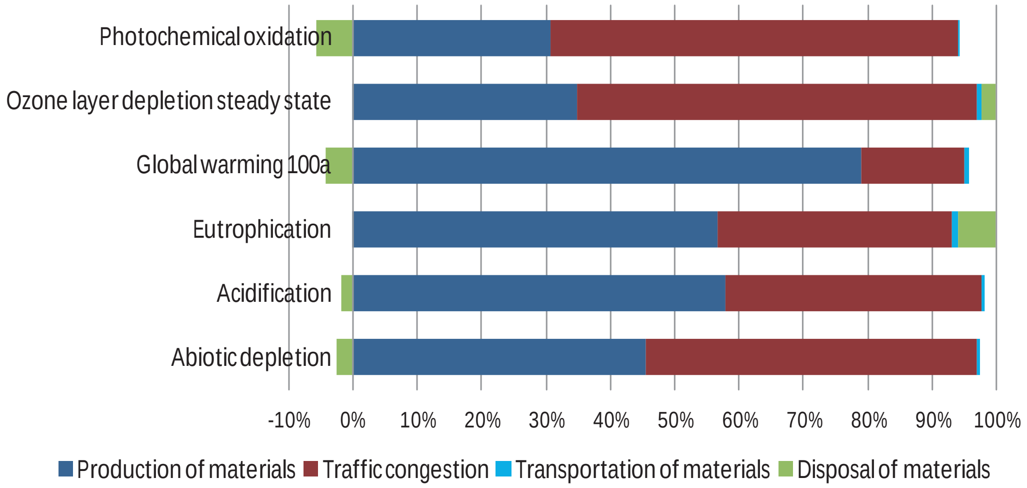

Figure 15: Contribution of each main process to impact category (B0-1).

The results obtained for all case studies are presented in Table 16. This table also indicates the variation of the results for each case study in relation to the reference case study B0.1.

Table 16: Variation of the aggregated results in relation to case study B0.1 (in m^2).

	ADP	AP	EP	GWP	ODP	POCP
	kg Sb eq	kg SO2 eq	kg PO4-eq	kg CO2 eq	kg CFC-11 eq	kg C2H4
B0-1	17,56	6,77	0,74	1509,62	2,93E-04	0,98
B0-2	-16,30%	-12,40%	-9,00%	-6,00%	-16,20%	-18,40%
B1-1	-0,60%	-2,90%	-2,70%	-2,80%	-1,20%	-4,10%

The comparative results for selected indicators are provided in Figure 16 and Figure 17.

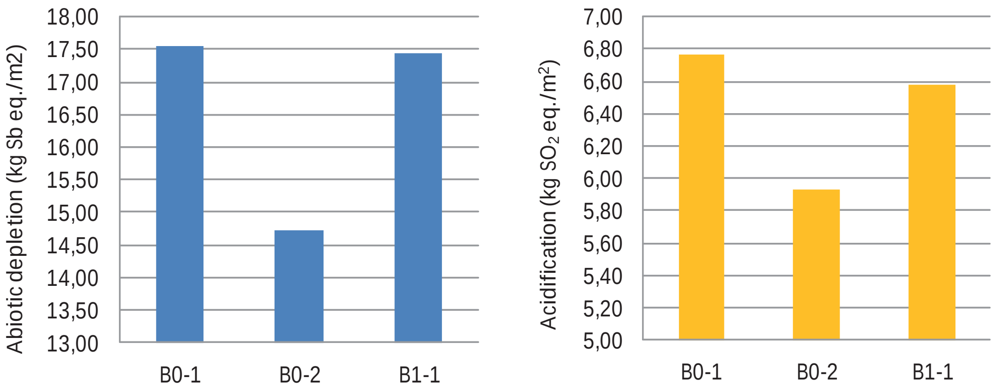

Figure 16: Comparative results for the impact categories of abiotic depletion and acidification.

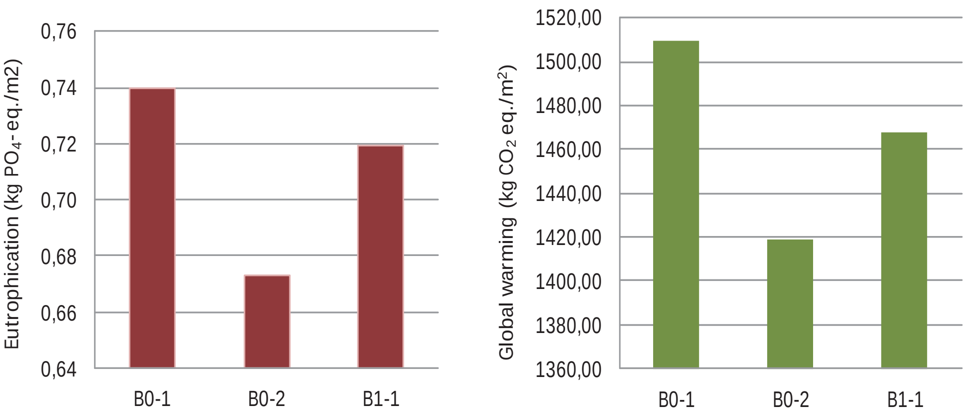

Figure 17: Comparative results for the impact categories of eutrophication and global warming.

5.4 Lifecycle costs (LCC)

5.4.1 Construction

Figure 18– a and b detail the total construction costs for solutions B0-1, B0-2 and B1-1 in € and in €/m^2, respectively.

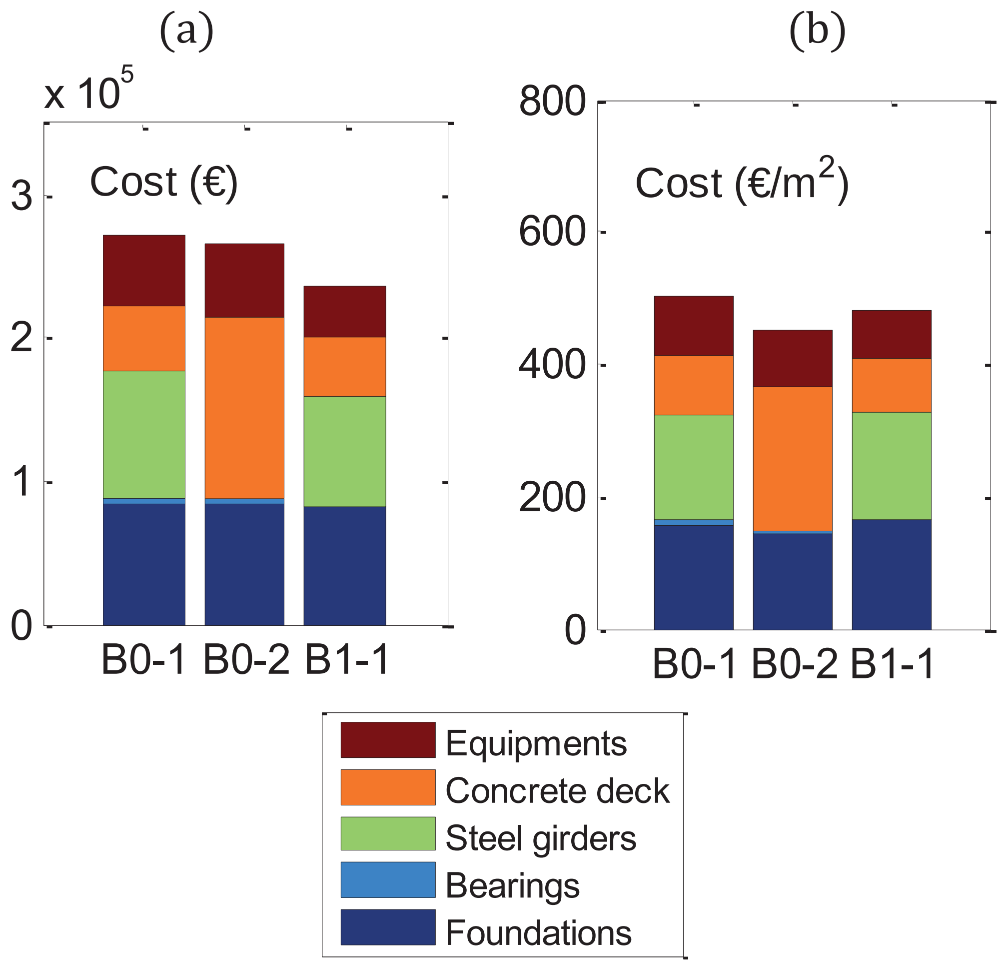

Figure 18: Construction costs (a) in € and (b) in €/m^2 for case studies B.

For each design solution, it is possible to assess the relative difference in construction costs compared with the reference case study B0-1. For concrete bridges B0-2 (-1.89%/B0-1), it is obviously noted that concrete represents a significant part of the construction costs. The case study B1-1 (-13.35%/B0-1) appears as the less expensive solution at the construction stage.

5.4.2 Operation

A lifecycle cost analysis associated with the different inspection/maintenance actions is carried out. The LCCs for case studies B0-1, B0-2 and B1-1 are shown in Figure 19 – (a) normal view and (b) zoomed view. It is noted that only the standard maintenance scenario described in section 2.3.1 is considered herein. Compared with the LCC (construction + operation costs) of case study B0-1, design solutions B0-2 and B1-1 are associated with lower LCCs: (-6.24%/B0-1 and -14.64%/B0-1, respectively). It is observed that B0-2 has lower operation costs than B0-1 due to the fact that concrete bridges do not require any maintenance actions for corrosion protection. However, it is reminded that there is more concrete surface to maintain. Besides, integral bridge B1-1 also allows significantly reducing operation costs due to the lack of maintenance actions concerning expansion joints.

5.4.3 End-of-life

A comparison of the total LCC including construction, operation and end-of-life actions is proposed in Figure 20.

It is observed that end-of-life costs are relatively lower for steel-composite bridges than for concrete bridges, which can be explained by the integration of steel as a partial revenue for the contractor of the bridge demolition (steel recycling).

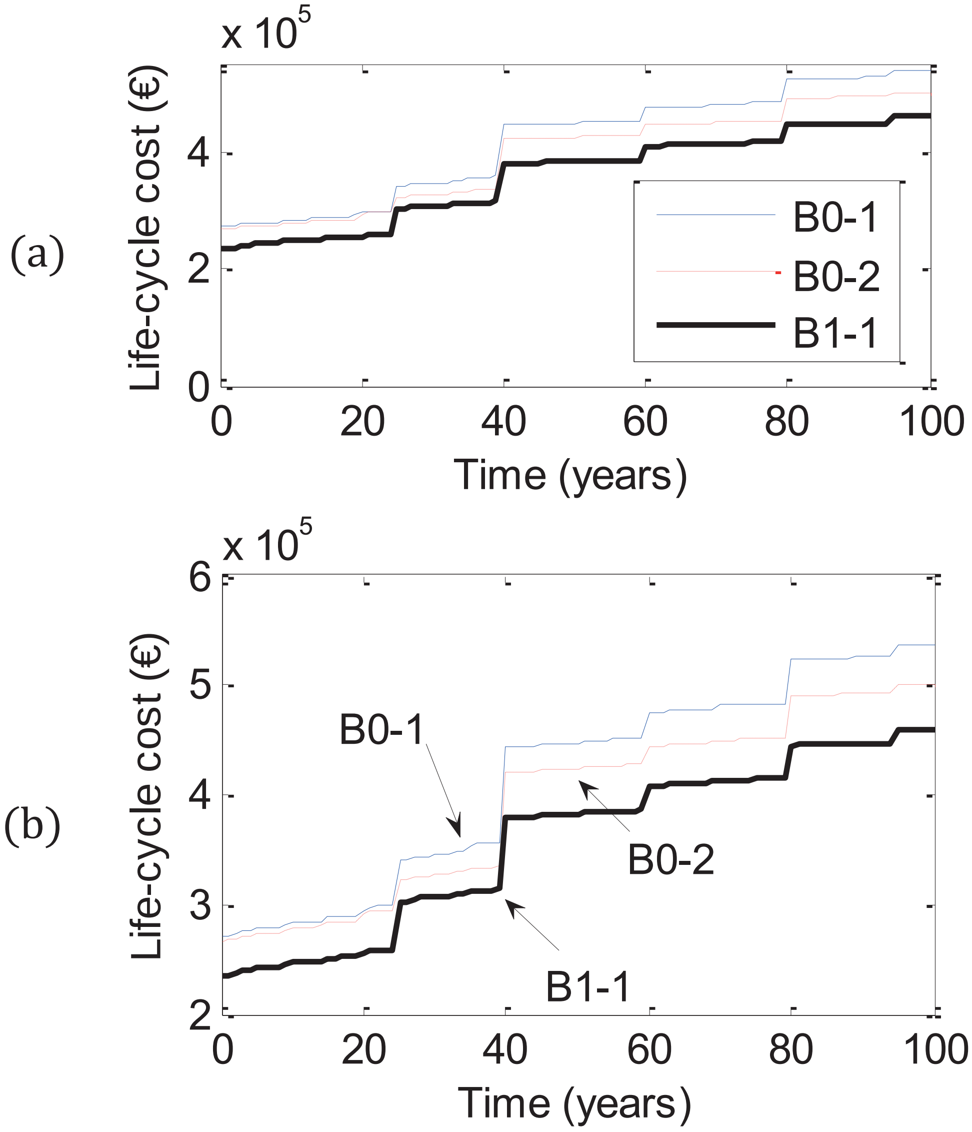

Figure 19: Lifecycle costs for case studies B0-1, B0-2 and B1-1 with (a) normal view and (b) zoomed view.

However, the end-of-life costs seem to be much lower than construction and operation costs due to the fact that they are discounted at year 100 with a yearly discount rate fixed at 2%.

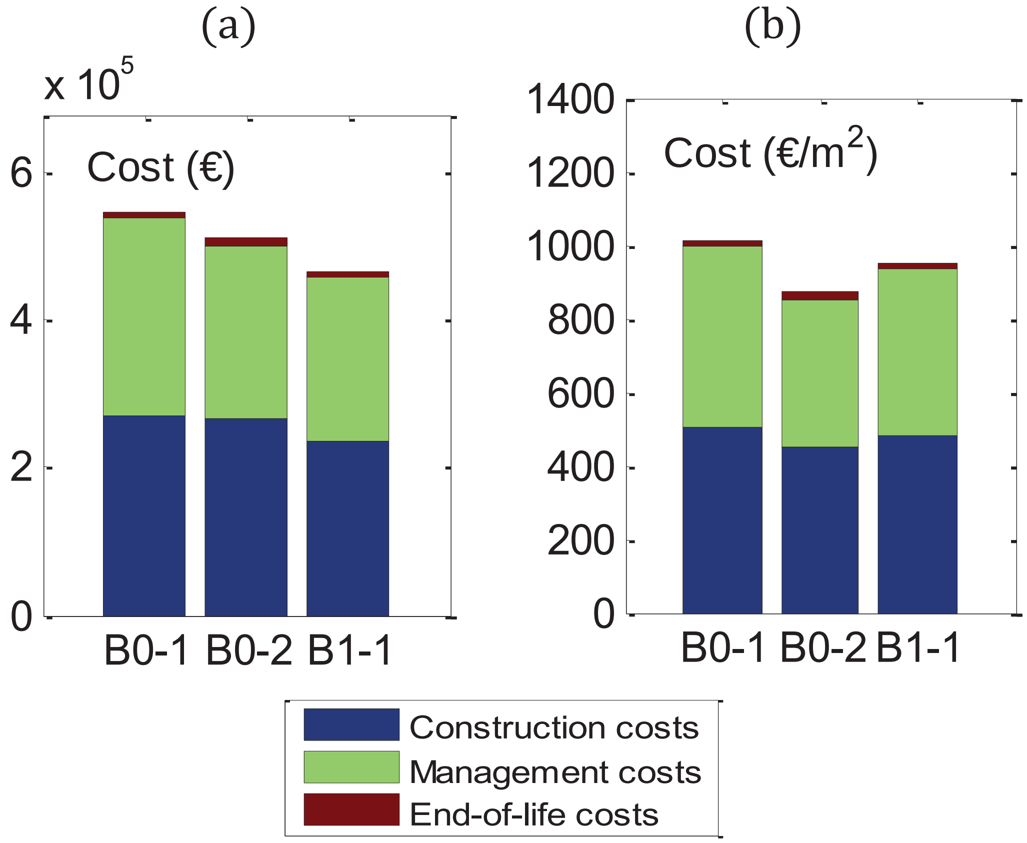

Figure 20: Total lifecycle costs for case studies B0-1, B0-2 and B1-1.

5.4.3 User costs

Both “day” and “night” maintenance scenarios described in section 5.3.4 are used herein. Figure 21 shows the user costs – scenario during (a) day and (b) night for case studies B.

It is observed that the integral bridge solution requires fewer maintenance actions due to its design and, consequently, leads to lower traffic disruption level during the lifetime. Besides, the user costs are higher for case study B0-2 (+14.67%/B0-1) since this bridge has more concrete surface to maintain, which requires traffic disruptions of the highway underneath the bridge.

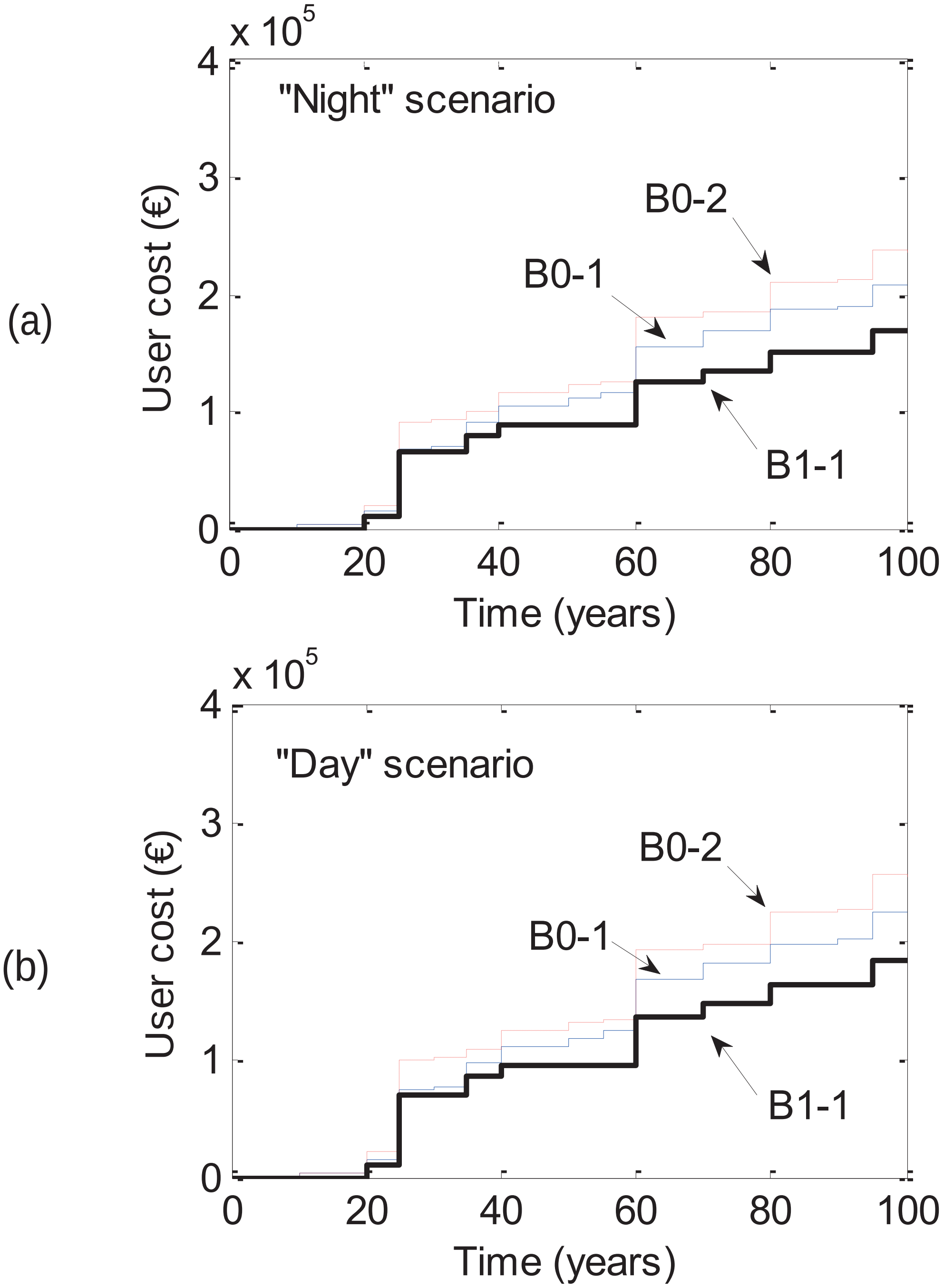

Figure 21: User costs for case studies B (a) "day" and (b) night scenarios.

5.5 Synopsis

The application of LCA and LCC analysis to the selected case studies obviously shows the interest of such tools.

Indeed, following a traditional point of view, based on the construction costs (normalized by the area of the deck) would lead to prefer the concrete bridge (case B0.2). The other bridges are then sorted as follow: the integral steel-concrete composite bridge (case B1.1) comes second and the usual steel-concrete composite bridge (Case B0.1) comes third. For the selected case studies, it appears that taking into account the whole Lifecycle Costs return exactly the same order. It is also interesting to notice that the Lifecycle Analysis also confirm this order.

Nevertheless, the consideration of user costs (for both "Day" and "Night" scenarios) completely changes the order. For this criteria the integral steel-concrete composite bridge (Case B1.1) comes first, the concrete bridge (Case B0.2) comes second and the usual steel-concrete composite bridge (Case B0.1) comes third.

To conclude, it appears that for such short spans, integral abutments should be preferred to usual abutments (with bearings and expansion joints). Then the choice between a concrete bridge and a steel-concrete composite bridge will be governed by the importance given to user costs and therefore to the position of the bridge in the transport network.

The method adopted in this research project for the combination of different criteria is the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE).

For the weighting of different criteria, there different scenarios were considered:

- Scenario 1 considered equal importance for the three main criteria: environmental, economical and user costs (1/1/1);
- Scenario 2 considered a higher importance to the environmental criterion in relation to economical and user costs (2/1/1);
- Scenario 3 considered a higher importance to the economical criterion in relation to environmental and user costs (1/2/1);
- Scenario 4 considered a higher importance to the user costs in relation to environmental and economical criteria (1/1/2).

Therefore, the combination of different criteria is illustrated in Figure 22, for the different weighting scenarios described above. Higher values correspond to higher rankings and thus better performance.

As observed from Figure 22, considering equal importance for the three main criteria (scenario 1), case study B1-1 has clearly the best rank. The same conclusion is taken in case of scenario 3.

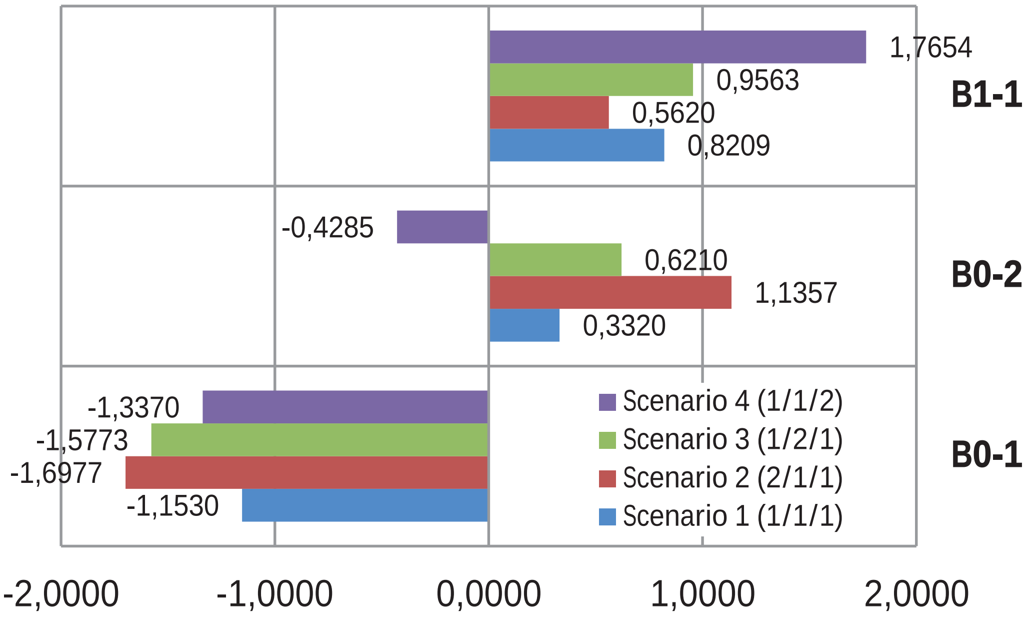

Figure 22: Multi-criteria decision analysis.

On the other hand, case study B0.2 has the best ranking taking into account scenario 2. Considering higher importance for the economical criterion (scenario 3), case study B1-1 has a slighter advantage in relation to case study B0-2.

Finally, case study B0-1 has the worst score, independently of the scenario considered.

6 Conclusions and Outlook

Sustainability in civil engineering is a fledging discipline in most European countries. As to the authors knowledge the SBRI-project represents the first approach to perform a lifecycle analysis of road bridges at an international level.

In this handbook the complete process is described in a concise way with the necessary information about the lifecycle performance and maintenance strategies as well as the approach for lifecycle assessment and lifecycle costs.

In the case study the integral steel-composite bridge shows obviously the best performance in regard of sustainability although it does not manifest the lowest construction costs per m^2. The investigations clearly showed the importance of the maintenance scenario for sustainable bridges.

Providing internationally harmonized parameters – such as basic types of inspection- and maintenance-strategies or the average service life for bridge elements – the SBRI-project might turn out to be a milestone for the future development of rules and guidelines for sustainable bridges in Europe.

The authors would highly appreciate if this handbook for sustainable steel-composite bridges would also contribute towards cultivating the idea of sustainability being a quantifiable criterion beyond bridges in general.

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Annex A: Tables

Table A1: Standard maintenance scenario.

Table A2: Lack of money maintenance scenario.

Table A3: Prolonged life maintenance scenario.

Table A1: Standard maintenance scenario.

Damage	Maintenance Actions	Years																		
		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Steels																				
Steel girder - used up																				
Corrosion (small points/small areas)	partial surface corrosion protection (1)				x							x							x	
Corrosion (complete renewal)	complete renewal corrosion						x							x						
Concrete																				
concrete slab - used up (A0, B0, C0)	demolition / replacement																			x
Corrosion of the reinforcement deck plate	partial renewal				x					x					x					x
Concrete edge beam	partial renewal							x								x				
Concrete edge beam	total replacement							x								x				
Concrete edge beam repairs	partial renewal				x								x							
Expansion joints																				
broken modules (considering a modular joint) B0	total replacement							x								x				
broken modules (considering a modular joint) A0,C0	total replacement							x								x				
broken concrete header (repair)	total/partial replacement	x		x		x				x		x		x				x		x
tightening of bolts	total/partial replacement	x		x		x				x		x		x				x		x
Cleaning		x		x		x				x		x		x				x		x
Bearings																				
Elastomeric bearing - used up - A0, B0	total replacement						x							x						
Elastomeric bearing - used up - C0	total replacement						x							x						
Elastomeric bearing (repair)	partial replacement			x							x							x		
Calote bearing - used up - B0	total replacement																			x
Calote bearing - maintenance	total/partial replacement																			x
Corrosion of metalic elements (Sa2/St3)	painting of metalic elements						x							x						
Road surface																				
cracks, ruts, excavation	total replacement			x				x				x				x				x
cracks, ruts, excavation	minor repairs	x				x				x				x				x		
Water proofing layer																				
cracks, ruts, excavation	total replacement							x								x				
Railings																				
used up	total replacement of railings							x								x				
painting	painting of metalic elements			x								x								
Gutters																				
replacement dewatewring	total replacement				x					x					x					x
Safety barrier																				
used up	total replacement of safety barrier							x								x				
safety barriers - minor repairs	total/partial replacement				x								x							x

Table A2: Lack of money maintenance scenario.

Damage	Maintenance Actions	Years																		
		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Steels																				
Steel girder - used up	demolition / replacement																			
Corrosion (small points/small areas)	partial surface corrosion protection (1)				x		x								x		x			
Corrosion (complete renewal)	complete renewal corrosion									x										
Concrete																				
concrete slab - used up (A0, B0, C0)	demolition / replacement																			
Corrosion of the reinforcement deck plate	partial renewal									x										
Concrete edge beam	total replacement									x										
Concrete edge beam	total surface treatment						x										x			
Concrete edge beam	partial renewal of surface treatment								x										x	
Concrete edge beam repairs	partial renewal				x										x					
Expansion joints																				
broken modules (considering a modular joint) B0	total replacement									x										
broken modules (considering a modular joint) A0,C0	total replacement									x										
broken concrete header (repair)	total/partial replacement	x		x		x		x				x		x		x		x		
tightening of bolts/ partial module replacement	total/partial replacement	x		x		x		x				x		x		x		x		
Cleaning		x		x		x		x				x		x		x		x		
Bearings																				
Elastomeric bearing - used up - A0, B0	total replacement						x							x						
Elastomeric bearing - used up - C0	total replacement						x							x						
Elastomeric bearing (repair)	partial replacement			x							x							x		
Calote bearing - used up - B0	total replacement																			
Calote bearing - maintenance	total/partial replacement																			
Corrosion of metalic elements (Sa2/St3)	painting of metalic elements						x							x						
Road surface																				
cracks, ruts, excavation	total replacement			x										x						
cracks, ruts, excavation	total survival road surface layer							x										x		
cracks, ruts, excavation	minor repairs	x				x						x				x				
Water proofing layer																				
cracks, ruts, excavation	total replacement									x										
Railings (only for case B.03 and B2)																				
used up	total replacement of railings									x										
painting	painting of metalic elements			x				x						x				x		
damage caused by corrosion	partial replacement							x										x		
Gutters																				
replacement dewatewring	total replacement				x					x					x					
Safety barrier																				
used up (steel)	total replacement of safety barrier									x										
safety barriers - minor repairs due to corrosion	total/partial replacement				x			x							x			x		
damage caused by accident (steel)	partial replacement																			

Table A3: Prolonged life maintenance scenario.

Damage	Maintenance Actions	Years																								
		10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130
Steels																										
Steel girder - used up	demolition / replacement																									
Corrosion (small points/small areas)	partial surface corrosion protection (1)				x							x						x						x		
Corrosion (complete renewal)	complete renewal corrosion protection(1)						x							x						x						
Concrete																										
concrete slab - used up (A0, B0, C0)	demolition / replacement																									
Corrosion of the reinforcement deck plate	partial renewal				x					x					x					x			x		x	
Concrete edge beam	total surface treatment																			x						
Concrete edge beam	partial renewal of surface treatment																						x			
Concrete edge beam	total replacement							x								x										
Concrete edge beam repairs	partial renewal				x								x							x			x		x	
Expansion joints																										
broken modules (considering a modular joint) B0	total replacement							x								x										
broken modules (considering a modular joint) A0,C0	total replacement							x								x										
broken concrete header (repair)	total/partial replacement	x		x		x				x		x		x				x		x		x		x		
tightening of bolts/ partial module replacement	total/partial replacement	x		x		x				x		x		x				x		x		x		x		
Cleaning		x		x		x				x		x		x				x		x		x		x		
Bearings																										
Elastomeric bearing - used up - A0, B0	total replacement						x							x							x					
Elastomeric bearing - used up - C0	total replacement						x							x							x					
Elastomeric bearing (repair)	partial replacement			x							x							x						x		
Calote bearing - used up - B0	total replacement																									
Calote bearing - maintenance	total/partial replacement																									
Corrosion of metalic elements (Sa2/St3)	painting of metalic elements						x							x							x					
Road surface																										
cracks, ruts, excavation	total replacement			x				x				x				x				x						
cracks, ruts, excavation	total survival road surface layer*																							x		
cracks, ruts, excavation	minor repairs	x				x				x				x				x				x				
Water proofing layer																										
cracks, ruts, excavation	total replacement							x								x										
Railings																										
used up	total replacement of railings							x								x										
painting	painting of metalic elements			x								x								x			x			
damage caused by corrosion	partial replacement																						x			
Gutters																										
replacement dewatewring	total replacement				x					x					x					x						
Safety barrier																										
used up	total replacement of safety barrier							x								x										
safety barriers - minor repairs due to corrosion	total/partial replacement				x								x							x			x			
damage caused by accident (steel)	partial replacement																									

* dense layer of asphalt containing a large amount of bitumen, that is placed on top of the existing damaged surface layer (and waterproofing layer).