SBRI+ Design Manual I

General information

and

Worked examples

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General information and Worked examples

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PREFACE

1st Edition

This First Edition of the Design Manual I has been prepared by Constança Rigueiro of the University of Coimbra as part of the RFCS project Valorisation of Knowledge for Sustainable Steel-Composite Bridges in Built Environment (SBRIPLUS) (contract 710068)

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Executive Summary

Bridges are of vital importance for the European infrastructure network. Due to their significance in the political economy the request for sustainable, meaning highly advanced, cost-effective, environmentally friendly and long-living structures is outstanding. Therefore, during the SBRI – Sustainable Steel-Composite Bridges in Built Environment – project, steel-composite road bridges were analyzed by means of a holistic approach combining Lifecycle Assessment (LCA), Lifecycle Costs (LCC) and Lifecycle Performance (LCP) analyses and thereby promote steel in the bridge construction market.

The aim of this Design Manual I is to provide practical information about the design method developed in SBRI in order to give a better understanding of the benefits gained by the application of lifecycle approaches. This would also allow the users to make rational decisions based on the possibilities and design variations and give the background necessary for the discussions in the decision-making process when dealing with authorities like road ministries and concessionaires.

This Design Manual I is divided in by two main parts: Part A: General information and Part B: Worked Examples. In Part A basic information is given including background information in order to allow the reader to follow the worked examples. To promote the sustainable bridge design, the applications of the lifecycle approach developed in SBRI project were included in Part B. It comprises several worked examples which are presented in a comprehensive way. For that several worked examples are presented in a traceable and comprehensible way. The worked examples cover the entire lifecycle of bridges from the construction over the operation and the maintenance stage till the demolition at the end-of-life.

PART A: GENERAL INFORMATION

1 INTRODUCTION

1.1 General

In the SBRI research project, standard situations of deck bridges were analyzed and investigated. A holistic approach was applied to steel-composite bridges by combining the analysis of environmental, economic and functional impacts. It has been recognized that the idea of sustainable design needs to be transferred to practice. The current project (SBRI+) aims the valorization, dissemination, and extension of the method developed in SBRI for advanced applications, in order to increase the acceptance of this new way of sustainable thinking especially among bridge owners and planners.

Sustainability requires lifecycle thinking. In the context of sustainable construction, the design of a bridge goes beyond the traditional requirements of safety and initial costs. It comprises all lifecycle stages of the bridge, from raw material production to the bridge's demolition [1]. This implies the prediction of the structural behavior of the bridge over its lifespan, the estimation of bridge maintenance and repair, etc. Moreover, non-traditional aspects of the environment, economy, and society shall be considered together with traditional ones and currently, most engineers are rarely prepared for these new requirements.

Lifecycle analyses are usually time-consuming and thus costly and the lack of data is a problem often encountered. In addition, the benefits brought by a sustainability perspective are often perceived only in the long-term, which makes its effective implementation difficult to promote. Moreover, lifecycle methodologies have been developed for the analysis of simple products. The application of such approaches to more complex systems, like a construction system, entails specific problems that need to be addressed in order to make them feasible [1]. In light of this, extensive data regarding Lifecycle Cost Analysis (LCC), Lifecycle Environmental Assessment (LCA) and Lifecycle Performance (LCP) for all the lifecycle stages of bridges were collected in the SBRI research project. The database forms then the basis for the detailed investigations on LCC, LCA, and LCP. Focus is given to the Lifecycle Performance in regard to different degradation processes in composite bridges. As bridges are designed to cover a lifespan of more than 100 years, inspections and maintenance actions need to be given a special focus. The analysis of complete case studies aims at possible comparisons and improvements by variations.

1.2 Framework of the SBRI-Tool

The aim of this tool is to provide means to assess and compare the sustainability of different bridge types, in the early stages of design, implementing a holistic Lifecycle analysis methodology. This would help select the best option by considering the pros and cons of each alternative in the construction, operation and end-of-life stages of the bridge's life – contrary to comparing mere initial construction costs.

The sustainability assessment is undertaken in accordance with the most recent European standard CEN TC350 and ISO standards 14040 [2] and 14044 [3]. The overall Lifecycle analysis incorporates three major sub-analyses: Lifecycle Environmental Assessment (LCA), Lifecycle Cost Analysis (LCC) and Lifecycle Social Analysis (LCS), at the different stages of the bridge's service life.

Steel-concrete composite bridges are currently built in a lot of various situations with various possible designs. With the aim of simplifying the routine task of picking between common alternatives, the tool is organized by subgrouping projects into three representative bridge types: Type A – Crossings of motorway, Type B – Big motorway bridges and Type C – Small and medium motorway bridges.

The tool features three essential modules. The first one allows for the computation of Lifecycle Analysis for a single bridge alone - given parameters and data on the bridge properties. The second module enables users to run a Multi-criteria analysis when choosing between different elements/alternatives within the same bridge design type. Comparison of the Lifecycle Analysis of different bridge types can be performed by using the third module - Comparative Lifecycle Analysis.

1.3 Goals and Scope

The current situation in the European bridge market is dominated by concrete bridges. Steel and steel-composite bridges only represent an interesting alternative if additional criteria count such as e.g. aesthetics, construction time or reduced overall weight. That is because the choice of orders is mostly made according to minimum initial construction costs only. However, with rising traffic volume and increasing vehicle gross weight, this approach does no longer seem to be adequate, especially considering that bridges are in general long-living structures where the lifecycle is planned for more than 100 years.

Therefore, a new holistic approach was investigated by combining analyses of Lifecycle Environmental Assessment (LCA), Lifecycle Costs (LCC) and Lifecycle Performance (LCP). For steel-composite bridges, innovative solutions were analyzed to give alternatives to concrete bridges. Throughout the project, the approach is applied to three realistic types of bridges and a multitude of variants which represent the standard situations of steel-composite road bridges identified according to the span length and bridge functionality. The analyses of these examples as case studies mainly aim to familiarize the users with the application of the method and also allow comparisons and improvements.

2 SUSTAINABILITY BY LIFECYCLE ANALYSIS OF BRIDGES

2.1 General Definitions

The traditional design of a bridge is based on the requirements of codes and rules that have been developed for that purpose. These requirements are related to the safety of the structure and usually include rules for resistance, durability, and serviceability. In this approach, the initial safety of the structure, according to the requirements of the Structural Eurocodes, is assumed to be fulfilled. In addition, it is assumed that major failure of the bridge does not occur over the time span of the analysis (100 years). Such an approach is limited in a lifecycle analysis, though. Bridges start to deteriorate immediately after they enter into service. The rate of deterioration depends on many factors for different types of bridges. In order to keep the bridge above some condition, maintenance and rehabilitation actions are required.

Looking at bridges from the point of view of sustainability, not only the construction stage must be taken into account but the entire lifecycle of 100 years. These long-living structures are facing different degradation processes throughout the years. Degradation can be divided into several processes as among which fatigue, corrosion of steel girders and carbonation having an impact on various details. 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.

Each time an intervention to the bridge is needed, it implies environmental and economic impacts that need to be considered in a lifecycle analysis. Hence, the lifecycle environmental and economic analyses of bridges are directly dependent on the lifetime structural performance and this relationship is addressed by integrating the structural performance of the bridge over its lifespan as illustrated in Figure 1.

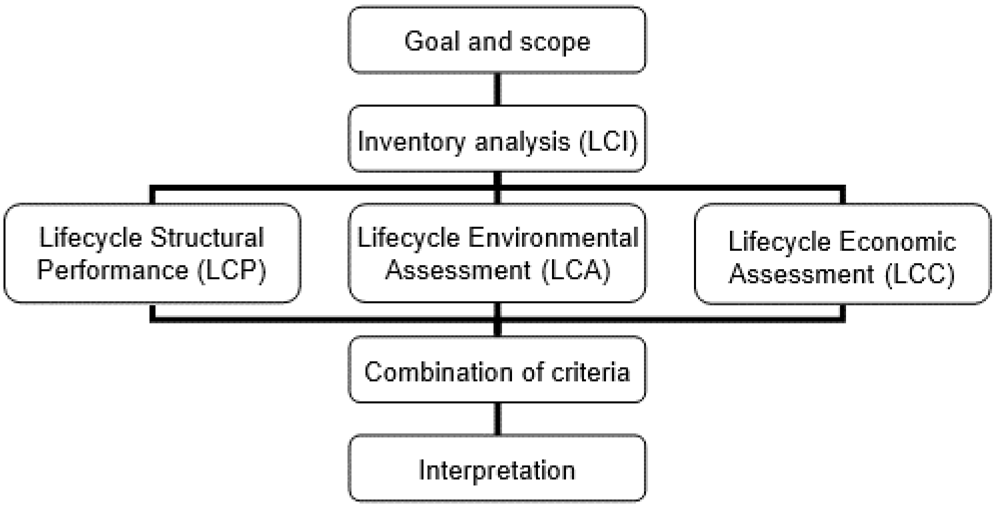


Figure 1: Flowchart of the Lifecycle Integral Analysis

The impact assessment stage of the three main categories is made separately for each criterion. The following step, the combination of criteria, depends on the aim of the analysis. If the aim of the analysis is to identify the improvement possibilities of the processes contributing to major impacts, then the structural, environmental and costs performances may be interpreted individually. On the other hand, if the aim of the analysis is to solve the decision-making problems, then the balance between the individual performances may be achieved by a multi-criteria decision analysis. It should be emphasized that a lifecycle analysis is not a decision-making approach; however, it can provide valuable information for decision-makers in the process of decision-making [1].

The lifecycle performance of steel-composite bridges is analyzed starting from the stage of production of raw materials, followed by construction, the operation of the bridge (including maintenance etc.) and until the demolition at the end-of-life. Under the participation of scientists, bridge owners, consultants, and industry as project partners the lifecycle performance of steel-composite bridges was analyzed in the SBRI project employing a holistic approach as described in the following.

An integral lifecycle approach for the assessment of motorway bridges was developed in the framework of this project. The aim of the approach is the lifecycle assessment of a bridge in the context of sustainable development and, in particular, in the context of sustainable construction. Therefore, the approach aims at balancing environmental and economic aspects.

Currently, there is not a standardized methodology providing guidance for an integral lifecycle analysis of a construction system [1]. The lifecycle environmental analysis has currently the most well established standardized framework, although there is still no generalized acceptable methodology in the scientific community. In a decreasing order of development follows the lifecycle economic analysis. For this reason, the development of the general framework for the integral lifecycle analysis was based on the standardized framework for Lifecycle Environmental Analysis (LCA), according to the series of ISO standards 14040 [2], with further adaptation in order to include economic criteria.

Therefore, the generalized framework proposed in this manual entails the four main steps of the ISO standard 14040 [2]: the goal and scope step; the inventory step; the impact assessment step; and the interpretation step. However, as already referred, each step of the analysis was adopted in order to allow the integration of economic aspects in the lifecycle analysis.

2.2 Holistic Approach

Lifecycle analysis which aims at sustainable bridge structures is divided into three main categories of consideration, see Figure 2. First, the environmental quality represents the analysis of emissions within the lifecycle assessment (LCA). The economic quality comprises costs occurring during the entire lifecycle (LCC) and is defined in the second category. The social and functional quality is involved as the third main category of lifecycle social analyses (LCS). Applying the holistic approach to the entire lifecycle of bridges, the influence of the outlined parameters to the structure and society is taken into account throughout the service life.

Figure 2: Holistic approach to lifecycle analyses.

The description of the lifecycle performance (LCP) of the structure and its details is the all-embracing condition to determine any inspection measurement during operation needed to guarantee a functional structure. The initial design and construction strongly interact with the inspection and repair measurements needed during the service life and the scenario at the end-of-life of bridges. Possible effects of degradation and renewal actions may lead to additional emissions (LCA), costs (LCC) and restricted social and functional quality (LCS).

The application of this holistic approach over the entire lifecycle is the basis for a shift from bridge designs based on construction costs to a sustainable design taking into account the advantages of steel-composite bridges such as construction time, durability and exploration of material properties in an efficient way.

2.3 Lifecycle Performance

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 as among which carbonation (initiation of corrosion of concrete rebars), corrosion of steel girders and fatigue and b) the corresponding inspection and maintenance intervals and methods.

The lifecycle performance of each bridge is mainly described by the performance of critical details. Therefore, a good knowledge of the behavior of the details during the entire lifespan of a bridge is essential for holistic analyses. Degradation can be divided into several processes. For bridges, fatigue, corrosion and carbonation are the processes that were investigated in the SBRI project, see Figure 3.

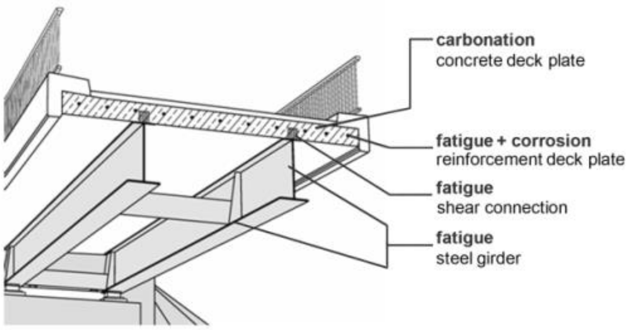


Figure 3: Degradation processes

Scheduling inspections and maintenance actions should be done based on a detailed description of the lifecycle performance of the affected details. Thus, lifecycle costs and emissions can be reduced. Intervals of bridge inspections can also be optimised by the knowledge of the adequate non-destructive testing methods to early detect defects. Knowing and being able to describe the lifecycle under deterioration processes of bridge details gives the possibility to optimise the structure in regard to sustainable aspects.

2.3.1 Fatigue behavior

Bridges are subject to traffic loading over a long lifespan. Traffic loading is recurrent and beyond that, due to increasing traffic volume, it must be calculated with an increased loading till the end of the lifecycle. Fatigue, therefore, cannot be neglected in bridges as it is one of the main degradation processes.

Various details can be affected by fatigue and cause deterioration of bridges. A classification by the severity of the induced damage can lead to the identification of the most critical details during the lifecycle. Literature shows that critical spots are not only located in steel but also in composite details. The transverse stiffener was selected as a typical detail in steel. Transverse stiffeners are used in both steel bridges and in composite bridges and are a common detail which faces crack problems due to fatigue. Post-weld treatment by high frequent hammering was found to improve that crucial resistance.

An effective shear connection in composite bridges is horizontally lying shear studs in combination with an omitted steel flange, e.g. for prefabricated composite bridge girders or connections of the concrete slab to the outer main girder in typical arch bridges. The existing degradation models for these details were analyzed and improved by results from own prototype tests in order to be included in the overall assessment.

2.3.2 Corrosion

A common problem found in composite bridges is corrosion attacks in the joint between the steel beam and the concrete deck. Rust stains may occur in the joint between the steel beam and the concrete deck and/or on the surface of the sealant in the areas where the sealant is used in the interface zone. Rust stains are caused by corrosion on the steel surface behind the sealant or by corroding binding wire. In the latter case, the stains have no direct influence on the condition of the steel beam. Once corrosion is noticed, a proper repair is needed in order to stop the process and avoid future major problems. To repair the corrosion problem in the joint between the steel beam and the concrete deck different methods can be used, such as the application of surface coatings or of elastic sealants to the joint.

2.3.3 Carbonation

Carbonation processes impact the reinforced concrete structure of composite bridges leading to degradation. Long-term durability of reinforced concrete (RC) structures has become one major concern in view of the vast amounts of money required to maintain the infrastructures in a serviceable state. Regarding the steel RC corrosion, resulting from chloride ingress and/or atmospheric carbonation, the traditional approach to the concrete design has been to follow deemed-to-satisfy rules which set requirements on mix-parameters, the thickness of the concrete cover, crack width limitations, etc. However, these requirements are no longer appropriate because of the complexity and the variety of the binders used today, and even stifle the designers who have nowadays numerous possibilities in terms of mix-design parameters (use of admixtures like superplasticizers, air-entraining agents, etc., and use of cement blended with supplementary cementitious materials like fly ash, slag, silica fume, etc.).

That is why a need is currently appearing for performance-based approaches [4] [5] in which the rules are associated with the performance to be achieved in terms of durability properties (i.e., porosity, permeability, etc.). Corrosion of the embedded reinforcement steel, resulting from atmospheric carbonation, is a matter of considerable concern which irreversibly affects the serviceability of RC structures. Most concrete structures are exposed to the action of CO_2 which diffuses into the concrete cover, dissolves in the pore water, and reacts with the hydration compounds, causing a reduction in the pH-value which thus makes corrosion of the steel reinforcement possible [6]. This issue is particularly pronounced for cementitious materials with a low portlandite content (CH) since CH is the main supplier of alkaline buffering capacity. Therefore, an ordinary concrete (medium to high porosity) made of a binder with a large amount of supplementary cementitious materials is likely to be more sensitive to carbonation. This is why the quantification of the carbonation mechanism for these kinds of concrete is crucial, all the more since their use will drastically increase in the next decades to fulfill commitments related to the mitigation of the CO_2 footprint.

The simplest and most effective way of enhancing service life (SL) of RC structures is to increase the length of the corrosion initiation period which is defined as the time required for the first layer of steel rebars to become depassivated. To make the prediction of this induction period possible, mathematical models can be used. Most of the time, a deterministic approach is adopted. Even if a deterministic approach can provide an acceptable assessment of the carbonation penetration for accelerated conditions, the predictions for durations of more than fifty years are very uncertain given that most input data of the model show a great variability which rejects any idea of absolute reliability.

2.4 Inspection and Maintenance Strategies

During the operation phase of a bridge, regular inspections are necessary to allow the continuous monitoring of the bridge condition, evaluation and eventual need for maintenance and rehabilitation actions. The definition and aim of each the types of inspections are:

- *Routine inspection – visual observation to detect small damage that can be promptly repaired; The team is formed by one or two members of the maintenance staff with specific training;*

- *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 potential 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 1.

Table 1: 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

Regarding maintenance during the operation stage, a list of maintenance strategies was compiled for different European countries [7]. Maintenance activities can be divided into categories regarding the intensity of maintenance. In this research three types of maintenance scenarios 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 actual 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.*

Basic definitions for the three scenarios are described in the following chapters.

2.4.1 Standard scenario

In the standard scenario, the types and inspection frequencies shown below are considered necessary to maintain the knowledge of the bridge condition and average service life of bridge elements. The frequency of maintenance/repair actions is considered essential in maintaining a good condition rating for the bridge. Regarding maintenance/repair, in the standard scenario, it is assumed that maintenance actions take place before the end of the average service life of the elements of the bridge. Structural elements are replaced when the average service life is reached.

For the operation phase, it is 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 2. Based on the average service life, a maintenance/repair works frequency was assumed.

Table 2: 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 3: Standard scenario - average maintenance/repair work 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 bearings	Clean, painting, lubricating	20
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In the Annex – Table A1 summarises data that were assumed for the definition of the standard Inspection scenario.

2.4.2 Lack of money scenario

In this scenario, it is assumed that in the early stages of the bridge, inspection actions will be less frequent, due to the lack of money, and as the estimated end of the bridge service life approaches, inspection actions are more frequent for evaluation of bridge condition rating and control of structural safety.

Repair actions are delayed and scheduled towards the end of the service life and new maintenance actions are introduced to extend the service life of some bridge elements, in order to delay or remove other maintenance actions.

Regarding the assumptions in the previous sections, the average service life for the bridge elements is the same for all scenarios but the assumed frequency for maintenance/repair actions is shown in Table 4.

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

Bridge 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 bearings	Clean, painting, lubricating	20
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In Annex A – Table A2 summarises data that were assumed for the definition of the lack of money scenario.

2.4.3 Prolonged life scenario

In this scenario, the decision of maintaining the bridge for an additional 30 years (130 years of service life and no more), is made around year 80. Inspection and maintenance frequencies and actions are similar to the standard scenario up to year 80 except for the following elements: superstructure concrete, edge beams, safety barriers, and bearings. After this year, inspection and maintenance actions are adapted to accomplish the service life extension. Maintenance actions in some elements will be more frequent between year 115 and 130. It is also assumed that there will be no fatigue problems in the steel superstructure and therefore no strengthening actions will be considered.

The average service life for bridge elements is the same as the one considered for the standard and lack of money scenarios and the assumed frequency for maintenance/repair actions is shown in Table 5.

Table 5: Prolonged life scenario - average maintenance/repair work 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 bearings	Clean, painting, lubricating	25
Railing	Painting	20

(*) - Elements with no maintenance actions. Total replacement takes place when the element's service life is reached.

In Annex A – Table A3 summarises data that were assumed for the definition of the prolonged life scenario.

3 LIFECYCLE ENVIRONMENTAL ANALYSIS (LCA)

3.1 General

The framework for Lifecycle Environmental Analysis (LCA) adopted in this project is according to ISO standards 14040 [2] and 14044 [3]. These standards specify the general framework, principles, and requirements for conducting and reporting lifecycle assessment studies. According to these standards, the 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 is considered to be optional in ISO standards and will not be addressed in the lifecycle environmental analysis. Thus, the complete flowchart for the environmental lifecycle analysis is detailed in Figure 4.

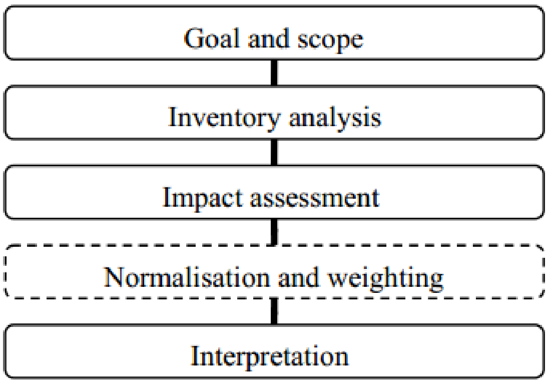


Figure 4: Scheme of the environmental lifecycle analysis

Sustainability requires lifecycle thinking. In the context of sustainable construction, the design of a bridge goes beyond the traditional requirements of safety and initial costs. It comprehends the lifecycle of the bridge, from raw material acquisition to the bridge's decommissioning [1]. This implies the prediction of the structural behavior of the bridge over its lifespan, the estimation of bridge maintenance and repair, etc. Moreover, non-traditional aspects of environment, economy, and society shall be considered together with traditional ones and currently, most engineers are not prepared for these new requirements.

Lifecycle analyses are usually time-consuming and thus costly, and the lack of data is a problem often encountered. In addition, the benefits brought by a sustainable perspective are often perceived only in the long-term, which makes its effective implementation difficult to promote.

Finally, lifecycle methodologies have been developed for the analysis of simple products. The application of such approaches to more complex systems, like a construction system, entails specific problems that need to be addressed in order to make them feasible [1].

3.2 Goal and Scope of the LCA

The 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 providing recommendations for further improvements.

The system boundaries determine which unit process shall be included within the LCA [2]. 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 introduced in Figure 5. All stages of the complete lifecycle of the bridges, from raw material extraction until end-of-life procedures, are included. Furthermore, the transportation of materials and equipment are also within the system boundary.

When the composite 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 were also taken into account in the LCA.

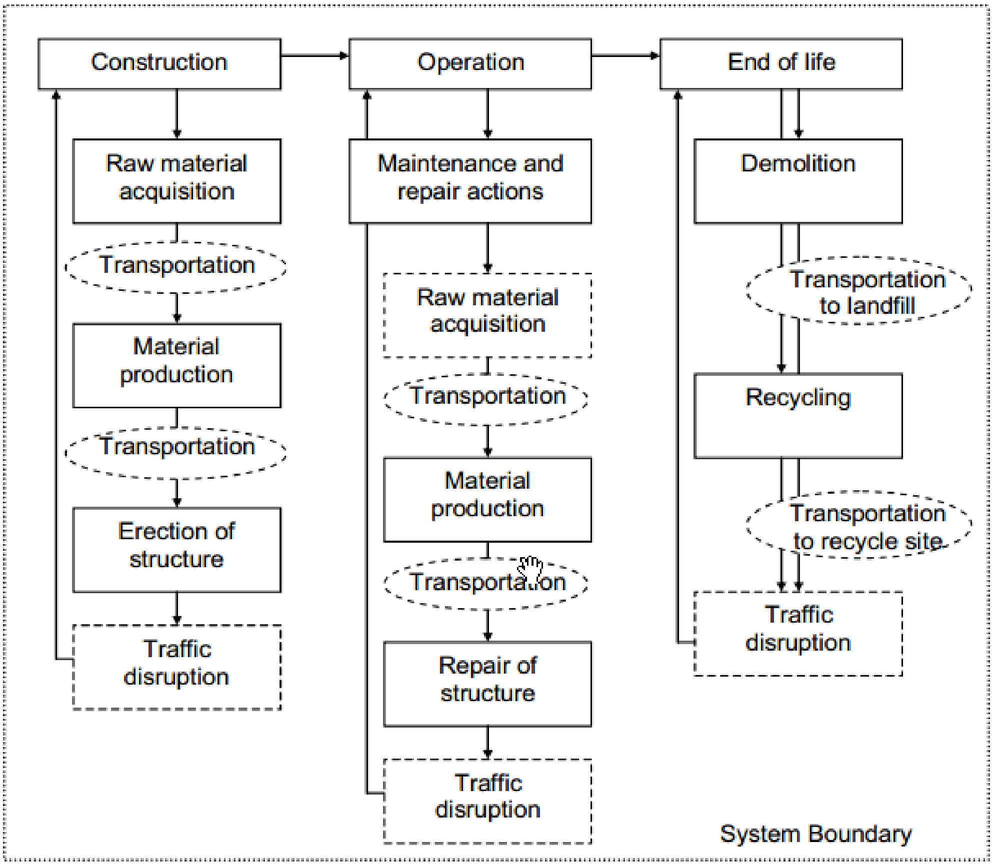


Figure 5: System boundary of the LCA

3.3 Methodology for Impact Assessment

The impact assessment stage of an 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 equation:

$$impact_{cat} = \sum_i m_i \times charact\_factor_{cat.i} \quad (1)$$

The environmental indicators adopted in the lifecycle approach are listed in Table 6.

Table 6: Environmental indicators for LCA

Indicator		Unit	Timescale
Global Warming Potential	GWP	Kg CO_2 eq.	100 years
Acidification Potential	AP	Kg SO_2 eq.	∞
Eutrophication Potential	EP	Kg PO_4 eq.	∞
Photo Ozone Creation Potential	POCP	Kg C_2H_4 eq.	-
Ozone Depletion Potential	ODP	Kg CFC eq.	∞
Abiotic Depletion Potential	ADP	Kg Sb eq.	-

3.4 Environmental Indicators

3.4.1 Global Warming Potential (GWP)

The global warming indicator measures the impact of human emissions on the radiative forcing of the atmosphere. GWPs are defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas [8]. For the definition of GWPs, the reference gas is carbon dioxide (CO_2).

3.4.2 Ozone Depletion Potential (ODP)

An ozone depletion indicator is derived from several properties of a gas, which include its stability to reach the stratosphere and the amount of bromine or chlorine the gas carries. These properties are then compared to CFC-11 (although CFC-11 is now banned by the Montreal Protocol in industrialized nations, it is still manufactured in many developing economies). The properties of each gas are then compared to the properties of CFC-11 and converted into CFC-11 equivalents. Then the individual equivalents are added together for the overall ozone depletion indicator score, which represents the total quantity of ozone-depleting gases released.

3.4.3 Photochemical Ozone Creation Potential (POCP)

Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) [9]. This chemical reaction is "non-linear," meaning that sometimes the NOx concentration will drive the reaction, and other times, it's the VOC that drive the reaction. Various indicators take low, average and high NOx concentrations to calculate an overall score. Photochemical ozone creation potentials assess various emission scenarios for VOCs. Therefore, the photochemical ozone creation potential of a VOC (POCP) is given by the ratio between the change in ozone concentration due to a change in the emission of that VOC and the change in the ozone concentration due to a change in the emission of ethylene (C_2H_4) [9].

3.4.4 Acidification Potential (AP)

Acidification in one of the impact categories in which local sensitivity plays an important role. The characterization factors adopted in this work are based on the model RAINS-LCA, which takes fate, background depositions and effects into account [10]. Based on this model, Huijbregts [10] developed characterization factors for 44 regions in Europe and average European factors, by a weighted summation of the regional factors for each acidifying emission. This indicator is expressed in kg of SO2 equivalents.

3.4.5 Eutrophication Potential (EP)

The eutrophication indicator is given by the aggregation of the potential contribution of emissions of N, P and C (given in terms of chemical oxygen demand, COD) to biomass formation [9]. The Eutrophication Potential of substance i reflects its potential contribution to biomass formation. This indicator is expressed in kg of PO4 equivalents.

3.4.6 Abiotic Depletion Potential (ADP)

The indicator abiotic depletion aims to evaluate the environmental problem related to the decreasing availability of natural resources. By natural resources, it is understood the minerals and materials found in the earth, sea, or atmosphere and biota, that have not yet been industrially processed [11].

The model [11] adopted for abiotic depletion in this work, assumes that ultimate reserves and extraction rates together are the best way to represent the seriousness of resource depletion. This model is a global model based on ultimate reserves in the world combined with yearly depletion on a world level.

4 LIFECYCLE COST (LCC)

4.1 General

Lifecycle cost (LCC) is an economic evaluation method that takes account of all relevant costs over the defined time horizon (period of study), including adjusting for the time value of money. The total lifecycle costs include not only construction costs but also other costs such as design, maintenance and dismantlement which may represent a significant portion of the total lifecycle costs of a steel composite bridge as illustrated in Figure 6.

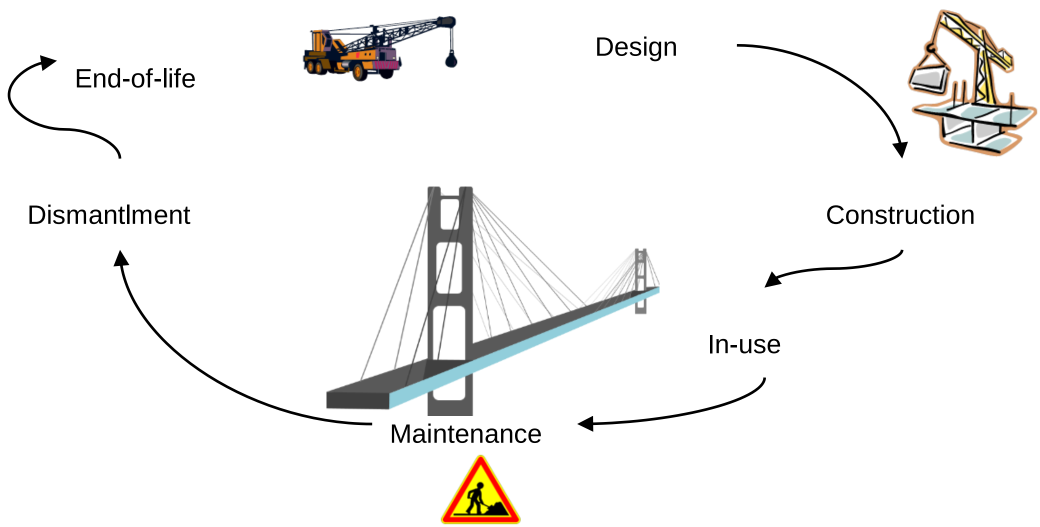


Figure 6: Lifecycle stages/costs from design to bridge end-of-life

The ISO 15686-5 methodology [6] defines the lifecycle costing as a technique which enables systematic economic evaluation of the lifecycle costs over the period of analysis. Figure 7 summarises the concept of whole life and Lifecycle cost. 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 (LCC) is to balance the decrease of operation and maintenance costs with a possible increase of initial costs [7].

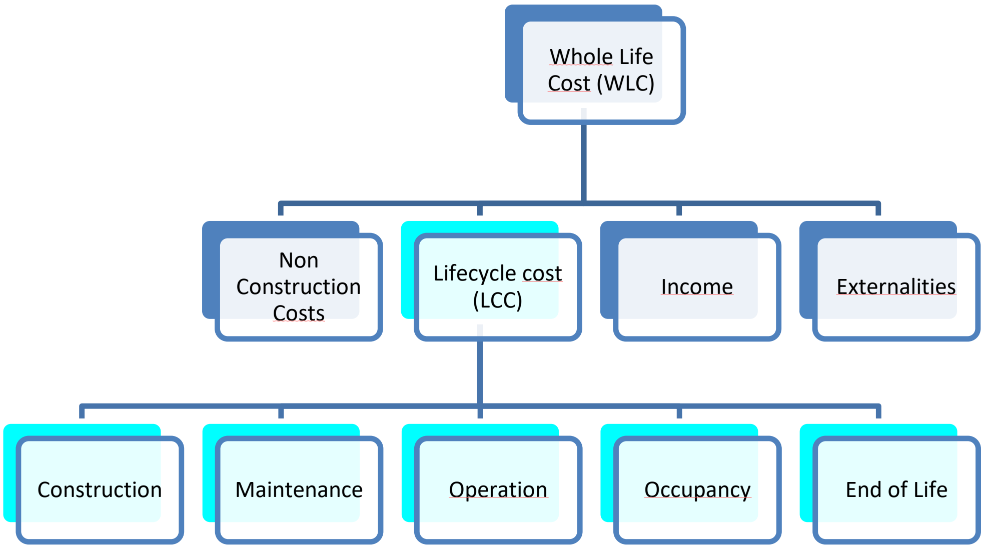


Figure 7: "Whole life costs" and "lifecycle costs" concept [6].

4.1.1 Construction stage

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 equipment (expansion joints, road surface, waterproofing layer, metal cornice gutter, railing and protection). It is noted that these costs should include all materials and work costs needed for each component as illustrated in Figure 8 to Figure 12.

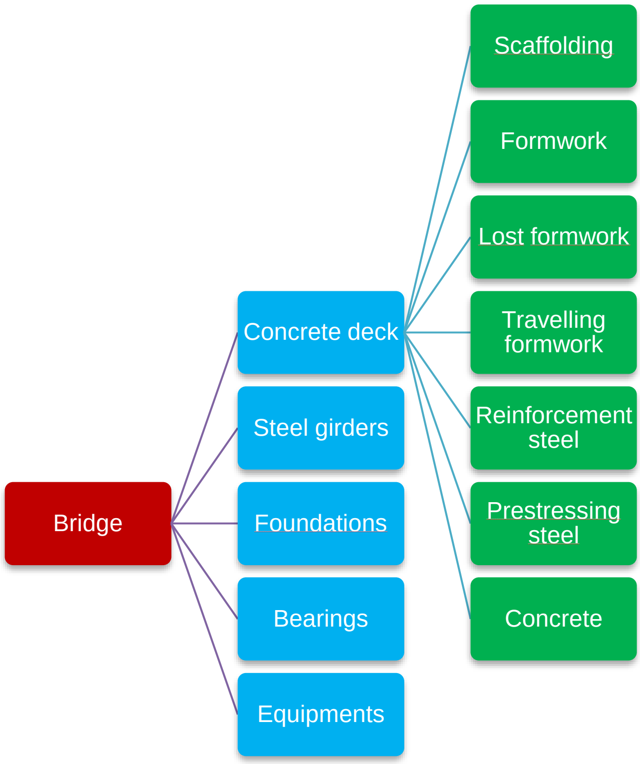


Figure 8: Concrete deck elements

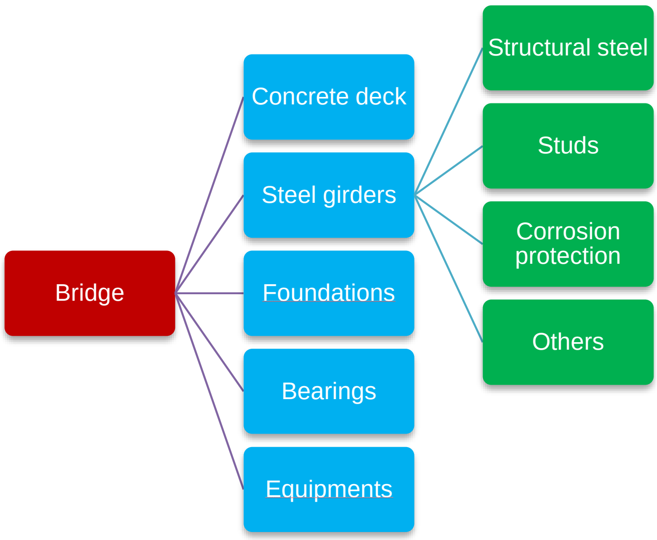


Figure 9: Steel girders elements

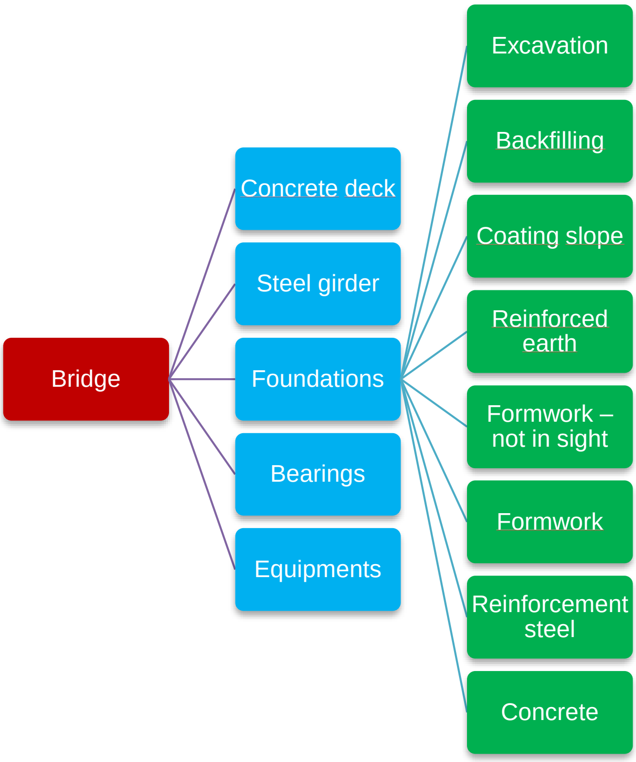


Figure 10: Foundation elements.

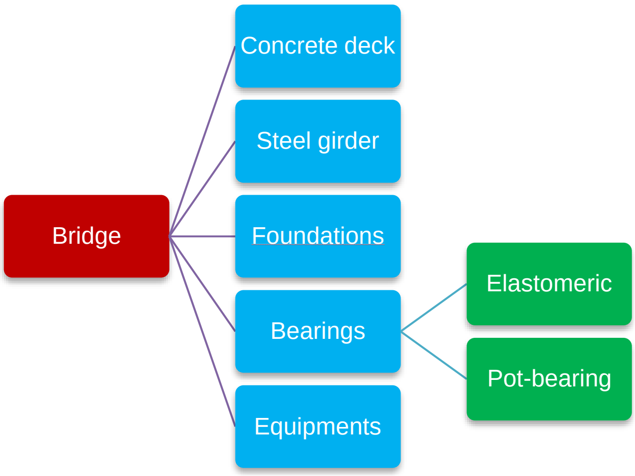


Figure 11: Bearing elements

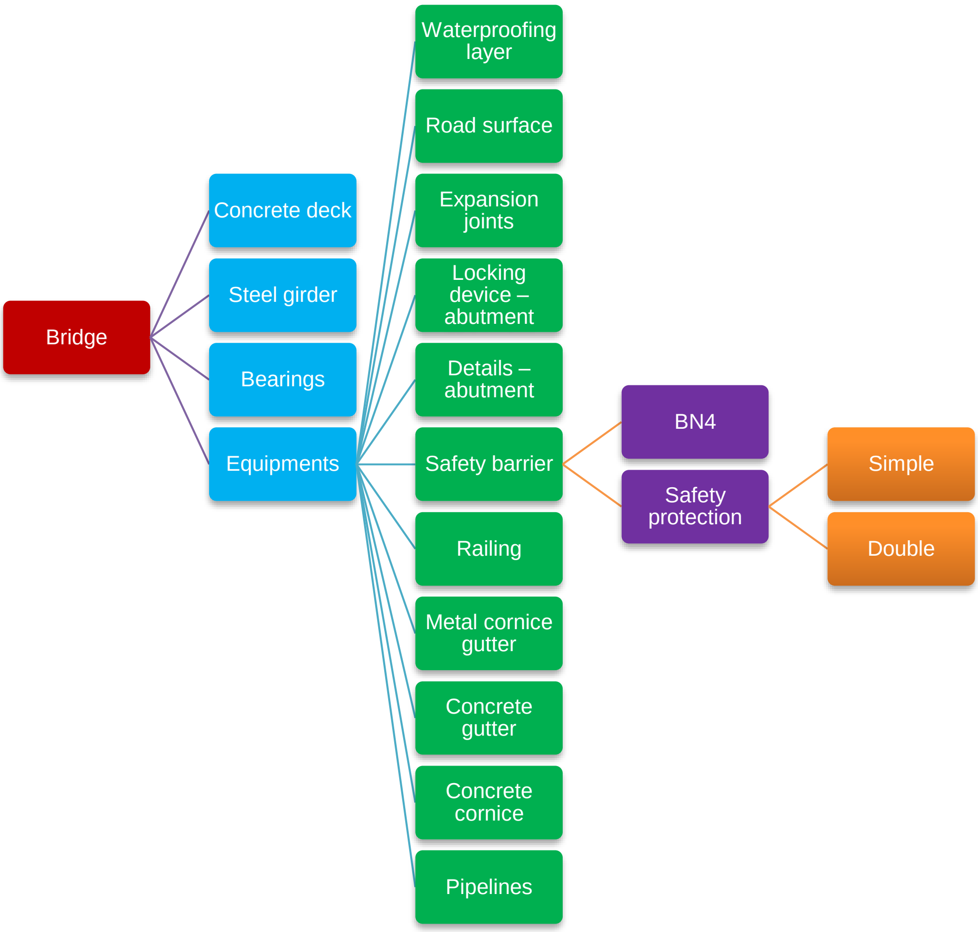


Figure 12: Detail of equipment

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. [12] states that with the choice of the appropriate steel grade and concrete quality, the conditions for economic construction are provided. The use of steel in composite construction represents a great economic potential developed with the use of cost-effective construction techniques and advanced construction procedures. It is noted that most construction materials consume energy for production and transportation. This aspect is taken into account in [13] by multiplying all costs for materials for construction and repair with some factor due to energy consumption for manufacturing and transportation. The use of non-renewable materials is also considered by involving costs for reproducing or reusing materials when the structure is decommissioned.

4.1.2 Operation stage

All structures have to be inspected and maintained. In particular, bridge inspections are essential for the 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 use 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 (Woodward 1997). The three basic types of inspection considered were discussed in section 2.4.

During the bridge operation stage, some maintenance activities are taken into account, the objective being that the bridge performance (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.

4.1.3 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 cost of bridge dismantlement (labor work, equipment, road warning signage), cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

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 (Figure 13).

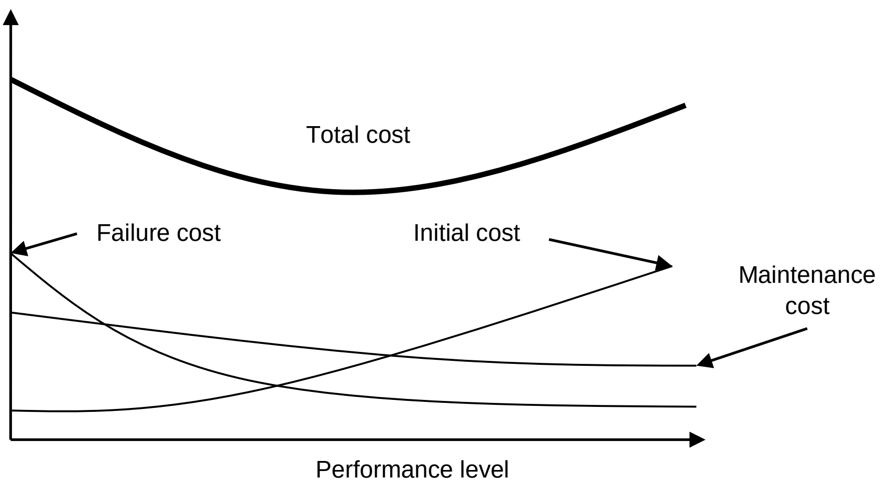


Figure 13: Schematic representation of lifecycle costs.

4.2 Economic Evaluation Method for LCC

Understanding the time value of money and the fact that the costs reflected in an LCC analysis are incurred at varying points in time, a need to convert all cost values into a value at a common point in time arises. Several methods exist to lead to LCC some of which are:

- *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:

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

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 unit of money is shown for illustration in Figure 14. It is noted that a steep drop in 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.

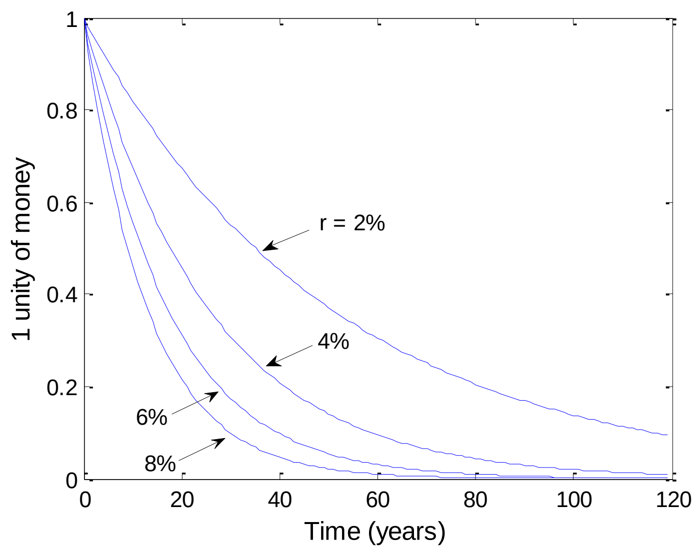


Figure 14: Profile of one unit of money for different values of r.

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. The discount rate is fixed at 2% in the LCCA performed in the SBRI-project for a 100-year service life.

5 LIFECYCLE SOCIAL ANALYSIS

The evaluation of the social criteria fully respects the boundary system of the integral analysis (see Figure 5). Social criteria enable us to quantify the impacts of the bridge on its direct users and surrounding population. Users of the bridge are all people traveling through the roads, beneath and above the bridge.

For the social Lifecycle analysis two types of indicators are considered: mandatory, those which are recommended to be always included in the Lifecycle analysis; and optional, those that can be included or not, depending on the aim of the analysis.

5.1 Mandatory indicators

Mandatory indicators aim to quantify the impacts due to any construction activity on the users of the bridge. In this case, three types of indicators are considered: driver's delay cost, vehicle operation cost, and road accident cost. Another impact could be included in this group, which is the impact on users due to detours. If for any specific reason, the traffic over and/or beneath the bridge has to be stopped for a certain period of time, then traffic needs to be diverted to an alternative road. In this case, the additional time spent by drivers and the additional length of road traveled can also be taken into consideration by the three indicators referred before. Thus in the LCS presented in this chapter, only the three basic indicators are considered.

5.1.1 Driver's delay cost

The cost of the time lost by a driver while traveling through a work zone is here denominated as Driver's Delay Cost (DDC). This cost is given by the difference between the cost of the time lost by a driver while traveling at normal speed and the time lost while traveling at a reduced speed due to construction works on the same length of the motorway.

5.1.2 Vehicle operation costs

A vehicle traveling through a work zone is subjected to delays. These construction-related delays result in additional costs for the owner of the vehicle. These additional costs are hereby denominated Vehicle Operating Costs (VOC). This cost is given by the difference between the cost of the operation of the vehicle while traveling at normal speed and the operation of the vehicle while traveling at a reduced speed due to construction works on the same length of the motorway.

5.1.3 Accident costs

Accident costs represent the additional costs due to a work zone in a road or motorway; thus, they are calculated by the difference between the cost of accidents in a length of motorway with no work activity and the cost of accidents in the same length when there is work activity.

5.2 Optional Indicators

Two indicators are here introduced as optional because its importance depends on the analyzed situation. These two indicators are hereby considered as optional as they differ from the other indicators. The first difference between these two impacts and the remaining is that, although they can be quantified over the Lifecycle of the bridge, there is no sense of adding their effects over that period of time. The other difference is that the two optional indicators have a strong subjective nature and this should be taken into account in its quantification.

The first indicator is noise, which may become important if the working place is located near a sensitive area and if the work is estimated to take place during the night. The other indicator is aesthetics. This indicator may be important if the bridge is intended to have an aesthetic function besides its normal function. Although, the aesthetics of a bridge should also be considered part of its conceptual design problem. However, in particular cases such as special types of bridges, bridges built in urban environments, etc., then the aesthetic value of the bridge may become an important criterion. These two indicators have some characteristics in common. They are not usually assessed based on a Lifecycle approach and they are both subjective, which implies another approach for their quantification and interpretation.

5.2.1 Noise

Noise can be defined as an undesirable sound thus implying that it has an adverse effect on human beings and their environment. Noise affects a large number of people and it is usually perceived as one of the major environmental problems. It can affect people in both physiological and psychological ways, interfering with basic activities such as sleep, rest, study and communication. Noise is associated with many human activities, but it is road, rail and air traffic noise that has the highest impact.

5.2.2 Aesthetics

The evaluation of aesthetics is commonly understood as a highly subjected issue. Aesthetics can be defined as (i) a set of principles concerned with the nature of beauty (especially in art), and (ii) the branch of philosophy which deals with questions of beauty and artistic taste. Different persons have different perceptions of beauty, and what is pleasant and acceptable to one might be offensive and unacceptable to others. Naturally, this makes the evaluation of aesthetics a highly subjective and often controversial issue.

5.3 User Costs

Contrary to the owner costs that are directly 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 resulting from an increase in travel time through the work zone due to speed reductions, congestion delays or increased distances as a result of a 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 the delay.*

- *Vehicle operating costs due to the level of service loss caused by the maintenance operations on highway structures. The disruption of normal traffic causes speed reductions, an increase in 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 a faster replacement for vehicles traveling 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 the 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 is the average daily traffic to be used in the analysis at year t (vehicles/day),

r_{tg} is the expected traffic growth rate,

$year_t$ is the year in which the ADT is to be calculated,

$year_0$ is the year in which the ADT is measured.

6 MULTICRITERIA ANALYSIS

Once different solutions are defined for the bridge, the final step of the approach is the comparison between different solutions. The lifecycle approach proposed in the scope of this project aimed at the integration of different criteria in the context of sustainability. To fulfill the aim of the proposed approach, outranking based methods are preferred to aggregating methods (or single criterion methods) because they involve weaker trade-offs, [14].

The method adopted in this research project is the Preference Ranking Organization Methodology of Enrichment Evaluation (PROMETHEE) developed by Brans [15] and further extended by Vincke and Brans [16]. PROMETHEE belongs to the family of outranking methods and although not being the most non-compensatory approach. PROMETHEE is a quite simple ranking method in conception and application compared with the other methods for multi-criteria analysis [17], [18]. One of the extensions of PROMETHEE (PROMETHEE II) enables a complete ranking of alternatives, while other approaches provide partial rankings including possible incomparability. PROMETHEE has a widespread use in decision-making situations varying from environmental management to business and financial management, medical applications, etc. A comprehensive review of PROMETHEE methodologies and applications is provided in [19].

6.1 PROMETHEE

In order to use PROMETHEE, it is necessary to provide additional information between the criteria and within each criterion, as described in the following paragraphs. Three main criteria were considered: environmental, economic and user costs. The environmental criteria considered in the analysis included abiotic depletion, acidification, eutrophication, global warming, ozone depletion, human toxicity, ecotoxicity and photo-oxidant formation. The economic criteria included construction cost, management costs, and end-of-life costs. For user costs, a single criterion was considered representing traffic delay costs, vehicle operation costs, and accident costs. Information between criteria is given by a set of weights (w_j = 1, 2,…, k) representing the relative importance of the different criteria. The higher the weighting factor the more important the criterion. It is up to the user to define the set of weighting factors to be assigned to each criterion. The information within each criterion, the preference structure, is based on pairwise comparisons. The deviation between the evaluations of two alternatives on a particular criterion is considered. For small deviations, the decision-maker allocates a small preference to the best alternative or possibly no preference if the deviation is negligible. The larger the deviation, the larger the preference.

For analysis, different scenarios are considered for the weighting of different criteria:

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

7 SBRI-TOOL – SOFTWARE TOOL

An enhanced and user-friendly software tool was developed in the iOS operating system in the context of this project. A new interface was implemented so that input data will be introduced in an easier way. The software and the user manual will be available for free download on various websites (i.e. sections.arcelormittal.com, www.infosteel.com, www.constructalia.com, www.steelconstruct.com, https://isise.net/smct/site/)

In the software, three pre-defined maintenance scenarios will be provided to the user, according to the service life of the different bridge components. Likewise, end-of-life scenarios were made available for different materials, enabling an easier assessment.

The worked examples described in the next sections of this manual are provided in the tool as application examples. This will enable an easier understanding of the tool based on the detailed description of the examples, provided in Design Manual I. Nevertheless, a simplified user manual will be included in the tool, describing the features of the program and guiding the user throughout the lifecycle assessment. The reader is referred to the user manual of the software for a detailed description of the software capabilities and functionalities.

Figure 15: SBRI+ Application interface

PART B: WORKED EXAMPLES

The Part B of this manual focuses on worked examples, which cover the entire lifecycle of bridges, from the construction, over the operation and maintenance stage, until the demolition at the end-of-life. The worked examples are classified into three different types: Bridges of type A, which are overpasses with single and double spans, type B that is a long span highway bridge, and type C representative for short to medium span motorway bridges. Note that the deductions drawn from LCA for each case study presented in this manual are case specific and are not meant for generalization.

1 WORKED EXAMPLES - BRIDGE TYPES

1.1 Description of the bridges types LCA

The worked examples focus on motorway bridges with different span distributions and different types of cross-sections (steel-concrete composite solutions and for reasons of comparison precast concrete beams). The examples of the bridges are described in Table 7.

Table 7: Bridges types – Case studies

Bridge type	Number of examples	Case Study	Material and typology Descriptions
Case A	3	A1	Composite and single span
		A2	Prestressed Concrete with two spans
		A3	Composite with two spans
Case B	1	B1	Composite with three spans
Case C	4	C1.1	Composite (multi-span)
		C1.2	Concrete (multi-span)
		C2.1	Composite and single span
		C2.2	Concrete and single span

One three span composite bridge is analyzed in case B; and this solution is not compared with another bridge.

1.2 Scenarios and assumptions for Lifecycle Environmental Analysis

1.2.1 Material Production stage

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 16. The data sources are as indicated in Table 8.

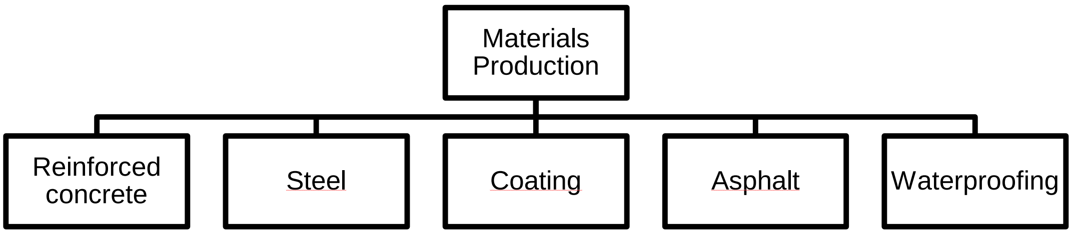


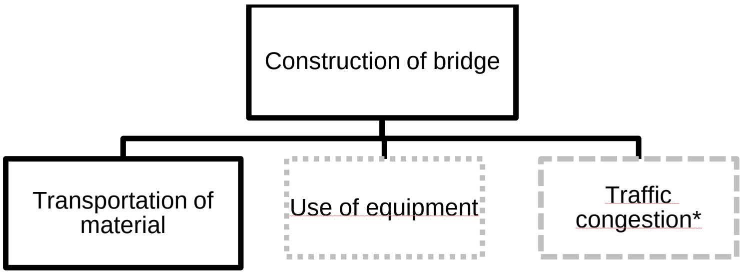
Figure 16: Material production stage

Table 8: Sources of data for materials and transportation

Material/Process	Source
Concrete (several grades)	GaBi [20]
Structural steel	GaBi/World Steel [20]
Reinforcement steel	GaBi [20]
Coating and Painting	GaBi [20]
Asphalt	GaBi [20]
Waterproof layer	GaBi [20]

1.2.2 Construction Stage

The construction stage covers all the processes needed for and affected by the construction of the bridge. Hence, as shown in Figure 17, the transportation of materials to the construction site is considered as well.



(*) Traffic congestion under the bridge is considered only for the overpass bridges which accommodate traffic on the motorway underneath during the construction stage

Figure 17: Construction stage

However, due to the lack of data, the use and transport of construction equipment were not considered in the analysis. In addition, as all the bridges are newly constructed, no traffic was considered over the bridges at this stage.

- *Transportation of the materials*

Construction materials have to be transported to the construction site. The traveling distances estimated for each case are indicated in Table 9. The consumption of diesel is also calculated based on the travel distances displayed in this table.

Table 9: Transportation of materials for the construction stage

Activity	Distance (km)
Transportation of steel structure	50
Transportation of reinforcement steel	50

Transportation of fresh concrete	10
Transportation of precast concrete	10
Transportation of asphalt	20
Transportation of waterproof layer	20

- *Traffic over the bridge*

As already referred, as all the bridges are new, no traffic was considered at this stage.

1.2.3 Operation Stage

It is hereby assumed that no major damage or failure of the bridge would occur over the bridge's service life taking into account the scenarios for maintenance and rehabilitation plans defined in Part A – section 2.4 of this manual. Accordingly, three different maintenance scenarios have been considered in this case study, namely Standard, Lack of Money and Prolonged Life scenarios. Apart from this, two work scenarios, day work and night work have been studied. Detailed plans of these scenarios have been presented in Annex A. The maintenance plans are based on the estimated service life of different components of the bridges.

- *Transportation of the materials*

Each time the bridge undergoes an activity of maintenance or rehabilitation, materials have to be transported to the bridge site. The traveling distances considered at this stage are the same as in the construction stage unless indicated otherwise.

- *Traffic over the bridge*

For the calculation of fuel consumption and vehicles' emissions for each combined activity, different scenarios are considered. In all cases, there will always be (at least) one lane of traffic open in each direction. When it is required to close a lane, two different scenarios are considered: work during the day (from 6:00 AM to 10:00 PM) and during the night (from 10:00 PM to 6:00 AM).

The maintenance schemes provided in Annex A indicate the traffic restraints over and under the bridge over the years in which maintenance activities take place.

1.2.4 End-of-life Stage

In the end-of-life stage, it is assumed that the bridges are demolished and that the materials are sorted in the same place before being sent to their final destination. Hence, no transport is necessary between the demolition place and the sorting plant. 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 (labor work, equipment, road warning signage), costs of transportation and costs for deposition of materials and/or revenue due to recycling of materials.

The steel structure is assumed to be recycled at a recycling rate of 90%. A closed-loop approach is assumed where scrap is remelted to produce new steel with little or no change in its inherent properties. As for the steel reinforcement, it was assumed that it will be recycled using the same closed-loop approach as the structural steel but at a recycling rate of 70%. Figure 18 illustrates the general unit processes included in this stage.

However, the use of equipment was not considered in the analysis due to lack of data. In addition, traffic congestion was neglected as traffic is expected to be diverted to an alternative route during the end-of-life stage.

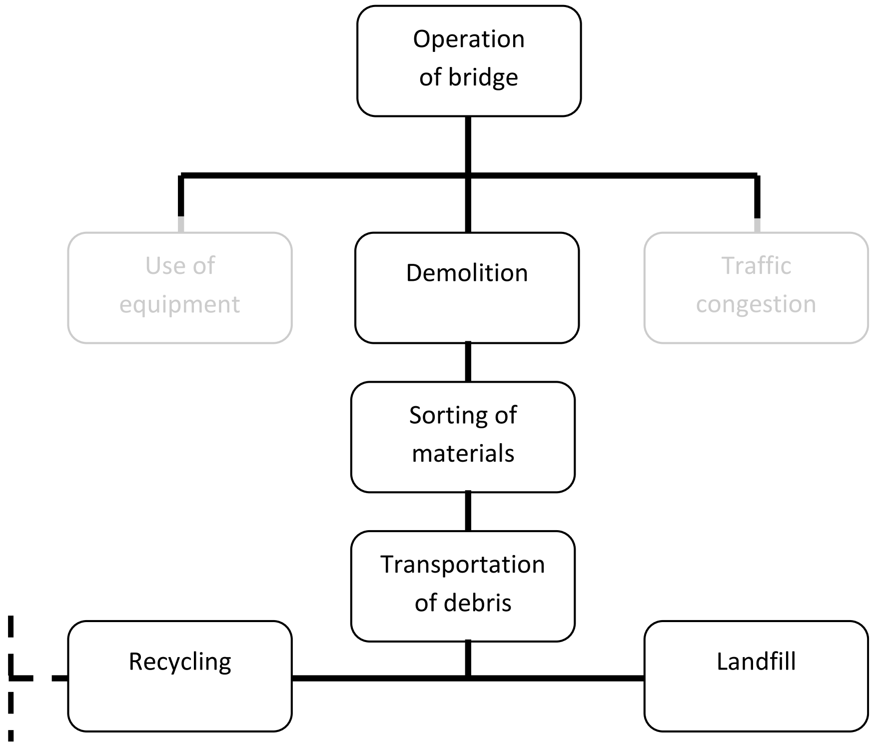


Figure 18: Processes included in the end-of-life stage

- *Transportation of the material*

In the end-of-life stage, it is assumed that the bridges will be demolished and the resulting materials will be sorted right at the demolition site. After sorting, materials were assumed to be loaded on trucks and transported to their final destination according to their respective end-of-life scenario. The estimated traveling distances between the sorting place and the final destination of the materials are indicated in Table 10.

Table 10: Transportation of materials for the end-of-life stage

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

- *Traffic over the bridge*

During the demolition of the bridge, it is assumed that traffic over the bridges will be diverted to an alternative road or that traffic is already flowing through an alternative bridge. Hence, no emissions and fuel consumption are considered at this stage.

1.2.5 Environmental category of $ADP_{Elements}$

The environmental categories adopted in the methodology (as indicated in section 3.4 of Part A) are calculated according to the CML methodology [21]. In relation to the environmental category of $ADP_{elements}$, the Characterization Factors (CF), which are used in the calculation method, are based on the extraction rate and ultimate reserve of each element. However, for many materials used in construction, the CFs cannot be defined due to the lack of data on material configurations and ultimate reserves [22]. Therefore, this indicator should be used with care and acknowledging its limitations. Moreover, in case of comparative assertions between different construction materials, the indicator should not be used. As a result, environmental impacts for this indicator are not presented in the following analysis.

1.2.6 Environmental category of POCP (Transport by truck)

According to the CML methodology [21], for the calculation of the environmental category of POCP of trucks, NO_x emissions are split into two single emissions, NO_2 and NO. The reason for a negative value is due to Nitric Oxide (NO) emissions, which have a counter effect on the environmental category of POCP as it helps reduce high concentrations of ozone near ground level which can be harmful to people, animals, and crops.

1.2.7 Assumptions for inspection and maintenance scenarios

Three maintenance scenarios (standard, lack of money and prolonged life) are considered in this manual. A further distinction was made based on the times where maintenance was carried out in the operation stage. The environmental impacts due to traffic congestion were quantified considering two alternative scenarios: (i) a day work, in which maintenance actions take place during the day (6:00 AM. to 10:00 PM.); and (ii) a night work, in which maintenance actions take place during the night (10:00 PM. to 6:00 AM.).

1.3 Assumptions for end-of-life cost analysis

End-of-life costs encompass the cost of labor work, cost of equipment, and cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

The cost for demolition is taken to be 100 €/m^2 [1]. This cost includes the cost of labor, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

Construction and Demolition Waste (C&DW) is sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the efficiency of the trucks and the price of fuel. In the case of the waste sent to a disposal site, the facility operator charges a fee to assume possession of the demolition waste. The cost for disposal of C&DW varies according to the type of material and the degree of contamination of the C&DW.

In the case of steel, it is assumed that the dealer pays the contractor 100 €/tonne (this price usually depends on the price of steel, according to the information from the U.S. recycling institute a price of $120/ton of steel may be considered). This figure has a negative sign since it is a revenue and not a cost for the contractor.

2 CASE STUDIES – BRIDGE TYPE A

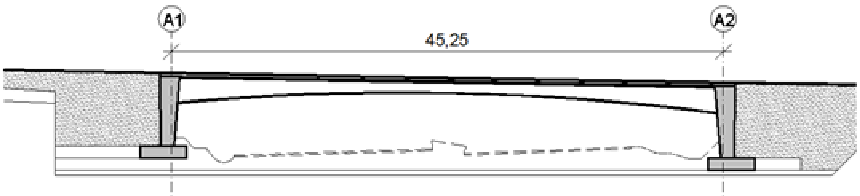
2.1 Description of the Case Studies

2.1.1 Definition of bridge systems, geometry, and parameters

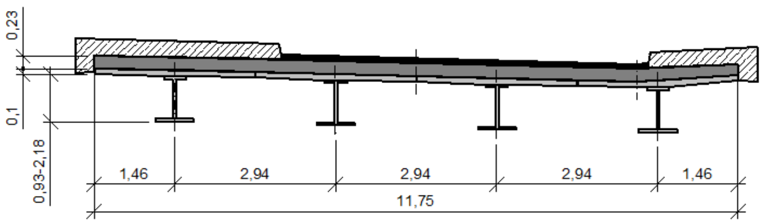
Three types of motorway crossings of two traffic lanes are considered here: an integral composite bridge (A1), a traditional prestressed concrete bridge of two spans cast in situ (A2) and a traditional composite bridge (A3), of two spans as well. [23] The three bridges are existing bridges - already built and their length and width are in the same range but not equal. In order to compare the three alternatives, bridges A2 and A3 have been "scaled" to the dimensions of bridge A1: 45.25 m length and 11.75 m width.

Case A1 is an integral bridge with a 45.25 m single span, which means it has integral abutments and there is no support in the middle of the highway. The deck consists of four composite girders (Figure 19), which are made of plated steel S355 J2 G3 with variable height ranging from 0.93m at mid-span to 2.18m in the abutments. The girders are transversally separated 2.94 m. The upper flange is 400 mm wide and the lower one 700 mm. The deck slab (C35/45) consists of a 0.23 m layer cast in-situ on precast slabs 0.01-0.12 m thick.

a1)



a2)



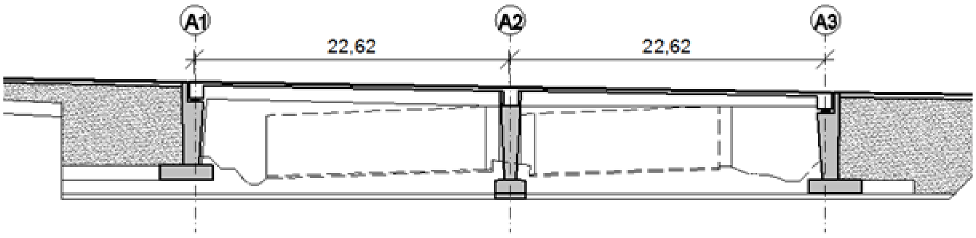
b)

Figure 19: Case A1: Integral composite bridge: a1) and a2) Longitudinal view; b) Cross section with girders of variable height.

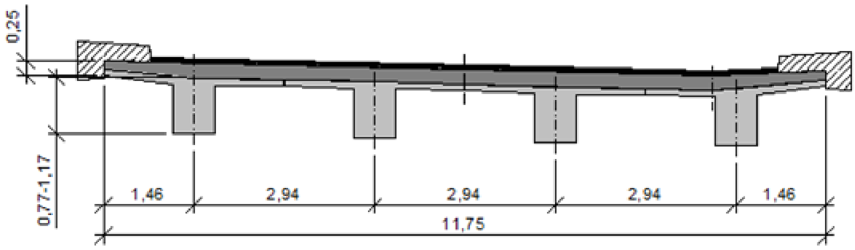
The bridges in these case studies overpass a motorway of dual carriage. Each carriageway has a capacity for 4 lanes with a width of 3.15 m. Each carriageway has a width of 20.05 m and it contains a main running surface of 15 m, a hard shoulder along the inner lane with a width of 4.05 m and a hard shoulder along the outer lane of 1 m width. 2 × (1+ 4 × 3.75 + 4.05 = 20.05) = 40.1 m.

Case A2 is a prestressed concrete bridge (Figure 20) the original dimensions were two spans of 25.20 m and 26.70 m and a slab width of 7.9 m. But it was scaled for the comparison, the total length between abutments of 51.90 m to 45.25 m. The slab has been scaled to 11.75 m. The deck consists of rectangular cast in-situ girders (C45/55) 0.68 m width and 0.77 m height. On the girders, a 25 mm thick concrete cast in-situ slab (C35/45) is lying.

a1)



a2)



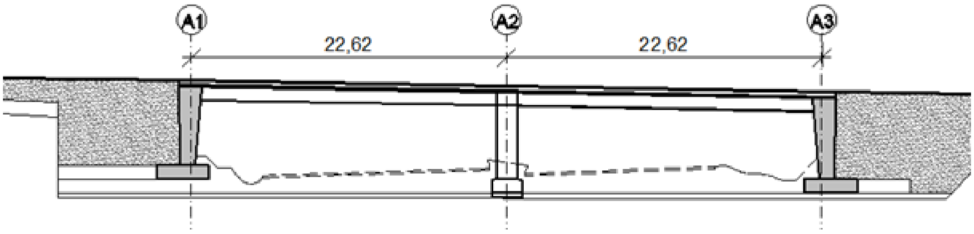
b)

Figure 20: Case A2: Prestressed cast in-situ concrete girder. a1) and a2) Longitudinal view; b) Cross section with girders of variable height.

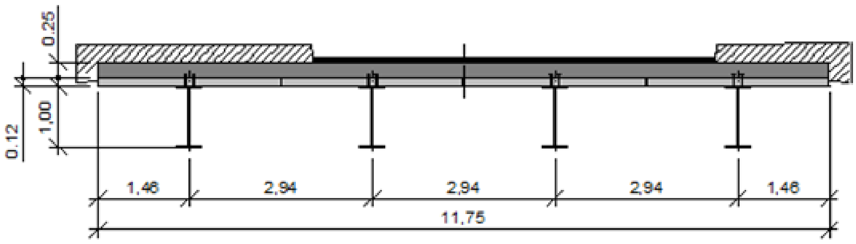
Case A3 is a four girdered steel-concrete composite bridge (Figure 21). The bridge has a symmetrical structure with two spans of 22.62 m (i.e. a total length between abutments of 45.25 m). The total slab width is 11.75 m. The girders are HL 1000 A S355 J2 G3 steel profiles. The deck slab (C35/45) consists of a 0.25 m layer cast in-situ on precast slabs (C45/55) 0.12 m thick.

The bearings are placed below each main girder in the bridge cases A2 and A3. The integral bridge case A1 does not present any bearings.

a1)



a2)



b)

Figure 21: Case A3: Composite bridge. a1) and a2) Longitudinal view; b) Cross section.

2.1.2 Design considerations

Table 11 shows a summary of the main quantities for the three cases of bridges under analysis. [23]

Table 11: Quantities of cases A1, A2, and A3 provided to perform LCA and LCC analysis

Description	Unit	Case A1	Case A2	Case A3	Unit	Unit cost (Germany 2008)
Substructure						
Excavations	[m³]	4500	4800	4800	[€/m³]	5.88
Backfilling	[m³]	2320	2520	2520	[€/m³]	7.60
Foundations' concrete C25/30	[m³]	254	223,81	-	[€/m³]	77.67
Abutments' + piles concrete C30/37	[m³]	746,20	681,97	969,6	[€/m³]	84.47
Reinforcement S500	[kg]	90600	90690	64326,6	[€/kg]	0.99
Superstructure						
Structural steel S355 J2 G3	[kg]	81800	-	-	[€/kg]	2.49
Structural steel S355 J2 G3 in HL1000A	[kg]	-	-	58084,35	[€/kg]	2.49
Corrosion protection	[m²]	896	-	575,58	[€/m²]	14.27
Concrete precast C30/37	[m³]	58	-	52,26	[€/m³]	588.73

Concrete C35/45	[m³]	144,20	571,20	130,66	[€/m³]	84.47
Concrete C45/55	[m³]	-	172,82	-	[€/m³]	588.73
Reinforcement S500	[kg]	44600	63038,3	44266,58	[€/kg]	0.99
Steel connectors	[kg]	1382	-	748,7	[€/kg]	2.31
Bearings Elastomeric	[pcs]	-	12	12	[€/u]	812
Bearing Calote	[pcs]	-	2	2	[€/u]	750
Roadway						
Pavement's asphalt layers	[m²]	309	309	309	[€/m²]	6
Pavement's waterproofing member	[m²]	309	309	309	[€/m²]	11.40
Safety barriers	[kg]	7429,20	7429,20	7429,20	[€/kg]	1.2

2.2 Traffic analysis

For study cases A, all bridges are new and they overpass a motorway. Therefore, during the construction phase, there is no traffic over the bridges and thus no emissions are considered at this stage. Later at the end-of-life stage also, it was considered that the traffic would be diverted to an alternative route; therefore, there would not be traffic on the bridge. The bridge roadway consists of one traffic lane for each direction and safety barriers border the whole bridge.

However, during the period of construction, the traffic under the bridge is affected due to restrictions in the traffic speed and the narrowing of the carriageway. Traffic congestion due to work activity in the surrounding area of the bridge has two major types of impacts: (i) the impacts due to direct emissions from vehicles, and (ii) the impacts due to the amount of fuel consumed.

- *Traffic under the bridge*

The motorway accommodates an Average Daily Traffic (ADT) of 49485 vehicles/day in the base year of the study. It is also considered that the percentages of lightweight vehicles and heavyweight vehicles are 88% and 12% of the ADT, respectively. The hourly traffic distribution presented in Figure 22 was assumed for the motorway.

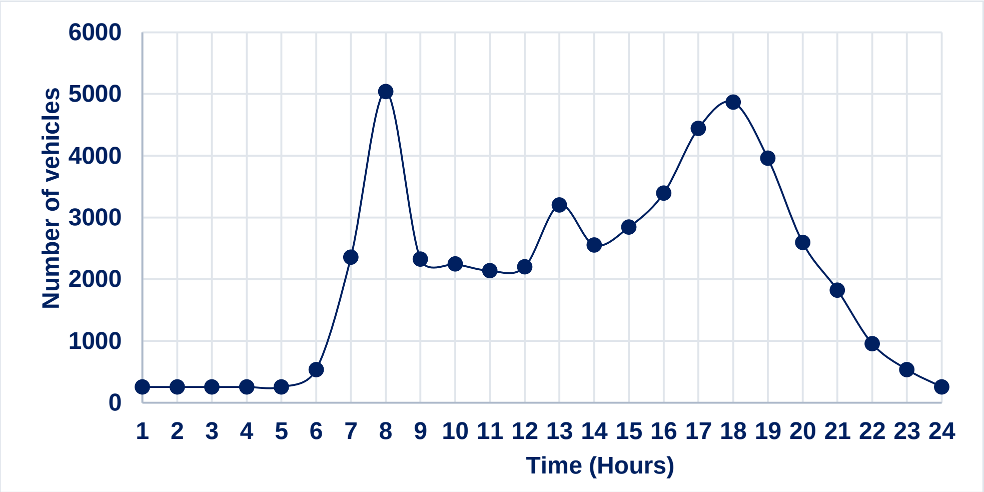


Figure 22: Hourly traffic distribution for cases A1, A2, and A3.

It is important to note that the traffic growth over time follows equation (3) (See section 5.3 of Part A) where a growth rate of 0.5% is considered. Hence, the traffic growth over a period of 100 years is presented in Table 12.

Table 12: Estimated Average Daily Traffic (ADT) under the bridge

	Base year	Base year + 50 years	Base year + 100 years
ADT(Vehicles/day)	49485	63500	81485

- *Traffic over the bridge*

The bridge is assumed to accommodate an Average Daily Traffic (ADT) of 5000 vehicles/day in the base year of the study. The traffic is assumed to grow linearly over a period of 100 years as indicated in Table 13.

Table 13: Estimated Average Daily Traffic (ADT) over the bridge

	Base year	Base year + 50 years	Base year + 100 years
ADT(Vehicles/day)	5000	7500	10000

2.3 Lifecycle Environmental Analysis

2.3.1 Material production stage

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 23.

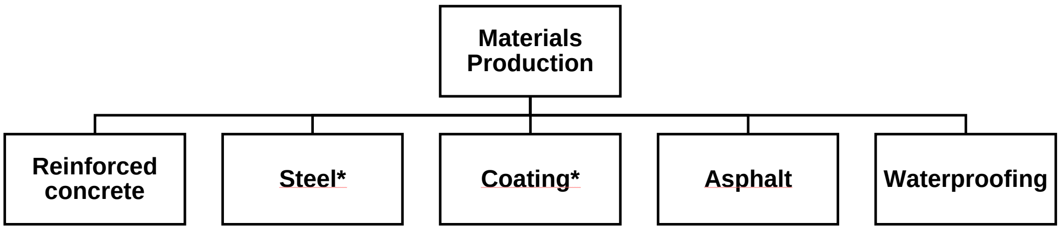


Figure 23: Material production stage

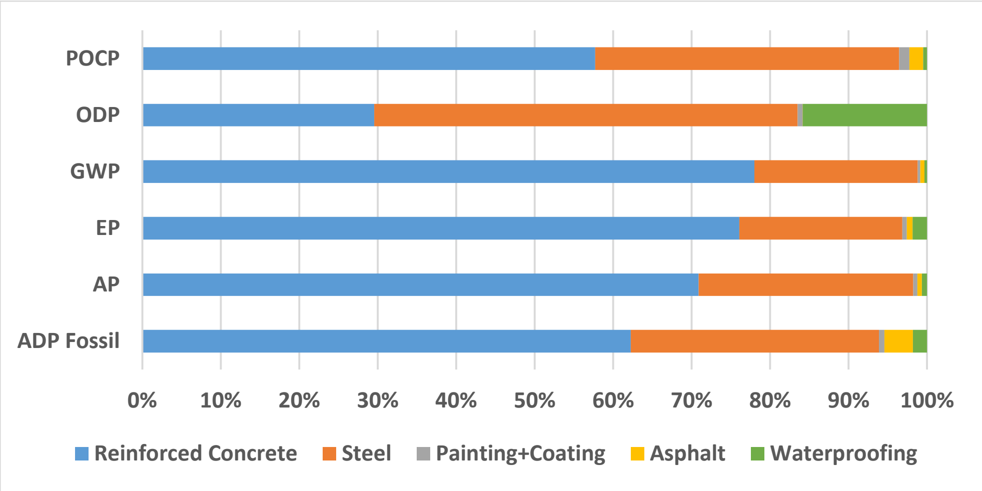
(*) All materials used in the current case study [A] are shown here. However, structural steel and corrosion protection are not present in case A2 as it is a concrete bridge.

- *Environmental analysis of reference case study A1*

The results obtained for the production stage are presented in Table 14. It is concluded that the production of structural steel and reinforced concrete are the main processes contributing to global impacts in the material production stage. The same results are plotted in Figure 24.

Table 14: Environmental impacts at the material production stage per impact category [A1]

Impact Category	Unit	Total	Reinforced Concrete	Structural Steel	Coating + Painting	Asphalt	Waterproofing
ADP Fossil	MJ	5,22E+06	3,25E+06	1,65E+06	3,48E+04	1,90E+05	9,41E+04
AP	Kg SO_2 eq.	1,54E+03	1,10E+03	4,22E+02	7,97E+00	8,84E+00	9,84E+00
EP	Kg PO_4 eq.	1,58E+02	1,20E+02	3,28E+01	9,21E-01	1,11E+00	2,91E+00
GWP	Kg CO_2 eq.	7,04E+05	5,50E+05	1,47E+05	2,14E+03	3,79E+03	2,27E+03
ODP	Kg R11 eq.	5,98E-03	1,77E-03	3,23E-03	3,90E-05	3,18E-09	9,46E-04
POCP	Kg C_2H_4	1,92E+02	1,11E+02	7,45E+01	2,51E+00	3,35E+00	9,17E-01



Note: Results for painting and coating include the environmental impacts coming from painting applied to non-structural elements such as protective equipment.

Figure 24: Contribution analysis of processes at the material production stage [A1]

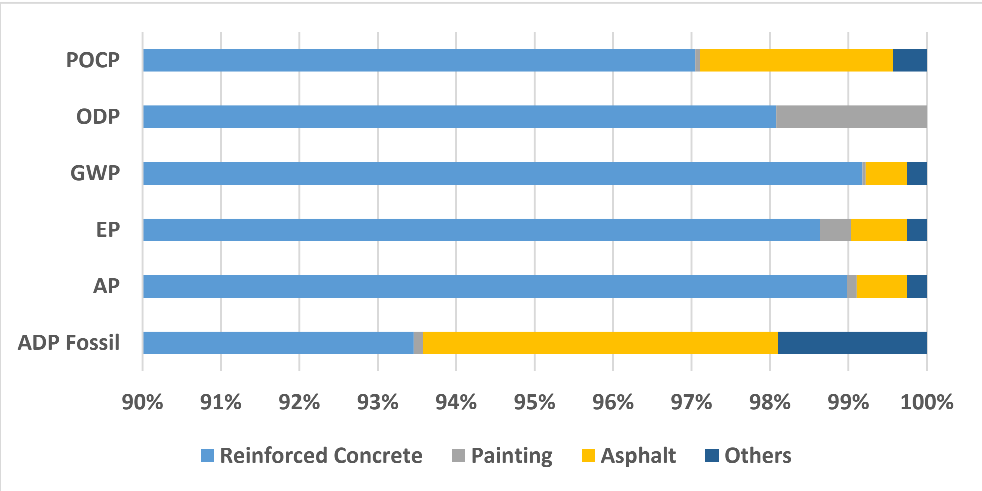
- *Environmental analysis of variant A2*

The results obtained for the variant case study A2 are presented in Figure 25 and Table 15. Table 16 indicates the variation of the results in comparison to the reference case study A1.

Table 15: Environmental impacts at the material production stage per impact category [A2]

Impact Category	Unit	Total	Reinforced Concrete	Painting	Asphalt	Others
ADP Fossil	MJ	4,19E+06	3,91E+06	4,99E+03	1,90E+05	7,94E+04
AP	Kg SO_2 eq.	1,38E+03	1,37E+03	1,73E+00	8,84E+00	3,47E+00
EP	Kg PO_4 eq.	1,56E+02	1,53E+02	6,18E-01	1,11E+00	3,83E-01
GWP	Kg CO_2 eq.	7,14E+05	7,08E+05	2,85E+02	3,79E+03	1,78E+03
ODP	Kg R11 eq.	2,04E-03	2,00E-03	3,90E-05	3,18E-09	5,11E-09
POCP	Kg C_2H_4	1,36E+02	1,32E+02	8,05E-02	3,35E+00	5,81E-01

Note: Results summarized under 'others' come from covering/sealing/protective layers mainly gussasphalt or bituminous sealant.



(*) Results for painting came from the paints applied to the protective equipment (railings), not from a structural steel element.

Figure 25: Contribution analysis of elements at the material production stage [A2]

Table 16: Environmental impacts of A2 at the material production stage relative to A1

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	5,22E+06	4,19E+06	-19,8%
AP	Kg SO_2 eq.	1,54E+03	1,38E+03	-10,7%
EP	Kg PO_4 eq.	1,58E+02	1,56E+02	-1,5%
GWP	Kg CO_2 eq.	7,04E+05	7,14E+05	+1,4%
ODP	Kg R11 eq.	5,98E-03	2,04E-03	-66,0%
POCP	Kg C_2H_4	1,92E+02	1,36E+02	-29,2%

Reinforced concrete is the main contributor to emissions (> 90%) in the construction phase for case A2. When compared with A1, reduced impacts were calculated in every category for case A2 in the material production phase.

- *Environmental analysis of variant A3*

The results obtained for the variant case study A3 are presented in Figure 26 and Table 17. Table 18 shows the variation of these results in comparison to the reference case study A1.

Table 17: Environmental impacts at the material production stage per impact category [A3]

Impact Category	Unit	Total	Reinforced Concrete	Structural Steel	Coating + Painting	Asphalt	Others
ADP Fossil	MJ	4,97E+06	2,82E+06	1,86E+06	2,42E+04	1,90E+05	7,94E+04
AP	Kg SO_2 eq.	1,49E+03	9,90E+02	4,80E+02	5,74E+00	8,84E+00	3,47E+00
EP	Kg PO_4 eq.	1,50E+02	1,11E+02	3,60E+01	8,13E-01	1,11E+00	3,83E-01
GWP	Kg CO_2 eq.	6,89E+05	5,15E+05	1,67E+05	1,48E+03	3,79E+03	1,78E+03
ODP	Kg R11 eq.	3,77E-03	1,44E-03	2,29E-03	3,90E-05	3,18E-09	5,11E-09
POCP	Kg C_2H_4	1,91E+02	9,66E+01	8,93E+01	1,64E+00	3,35E+00	5,81E-01

Note: Results summarized under ‘others’ come from covering/sealing/protective layers mainly gussasphalt or bituminous sealant.

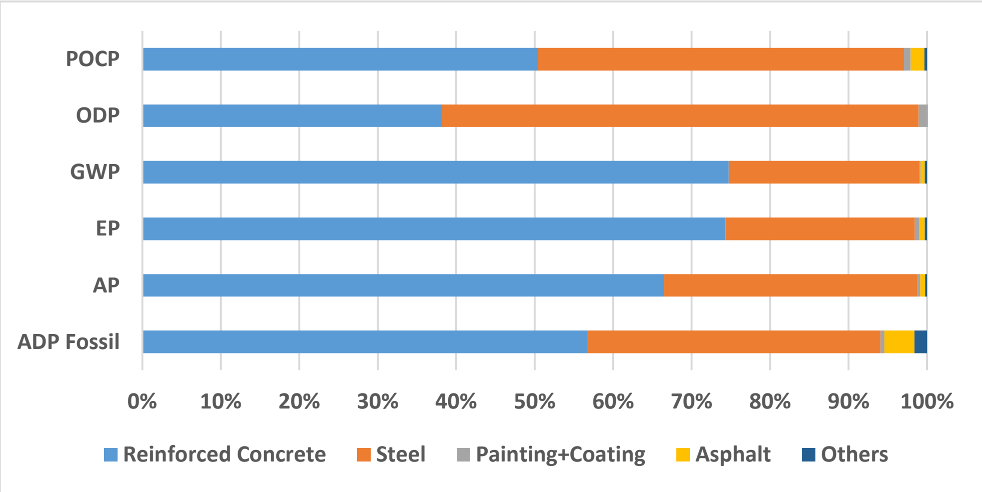


Figure 26: Contribution analysis of elements at the material production stage [A3]

Table 18: Environmental impacts of A3 at the material production stage relative to A1

Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	5,22E+06	4,97E+06	-4,8%
AP	Kg SO_2 eq.	1,54E+03	1,49E+03	-3,6%
EP	Kg PO_4 eq.	1,58E+02	1,50E+02	-5,3%
GWP	Kg CO_2 eq.	7,04E+05	6,89E+05	-2,1%
ODP	Kg R11 eq.	5,98E-03	3,77E-03	-37,0%
POCP	Kg C_2H_4	1,92E+02	1,91E+02	-0,4%

It can be seen that the production of reinforced concrete and structural steel are the main processes contributing to global impacts in the material production stage. When compared with A1, reduced impacts were calculated in most categories for case A3 in the material production phase.

2.3.2 Construction stage

The construction stage takes into account all the processes needed for the construction of the bridge and affected by it. Hence, as highlighted in Figure 27, it includes also the transportation of materials to the construction site (according to the distances indicated in Table 10).

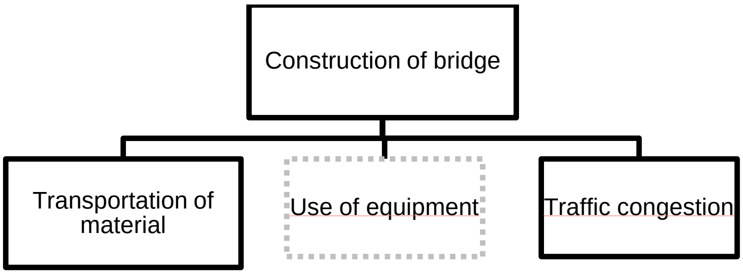


Figure 27: Construction stage

However, due to the lack of data, the use and transport of construction equipment were not considered in the analysis. In this subsection, only the traffic congestion due to the construction activity is analyzed. This bridges in this case study are new; therefore, during their construction, there is no traffic over the bridge and thus no emissions are considered.

During the period of construction, however, the traffic under the bridge is affected due to restrictions in the traffic speed and the narrowing of the carriageway. Traffic congestion due to work activity in the surrounding area of the bridge has two major types of impacts: (i) the impacts due to direct emissions from vehicles, and (ii) the impacts due to the amount of fuel consumed. The impacts due to direct emissions from vehicles are quantified based on the QUEWZ-98 model [24]. The Queue and User Cost Evaluation of Work Zones model analyzes traffic flows through motorway work zones and allows to estimate the traditional road user costs and air pollution on various lane closure strategies. The impacts due to the excess of fuel consumed, which include the upstream burdens due to the production of fuel, are quantified based on data from GaBi [20]. In both cases, the quantification of the impacts is given by the difference between the impacts of the vehicles passing through the work zone and the impacts of the vehicles passing through the same zone but without any delays due to work activity.

- *Traffic over and under the bridge*

As already referred, all the bridges in this case study are new. Therefore, there is no traffic over the bridge during the construction phase and thus no emissions are considered at this stage. However, the traffic on the motorway under the bridge is affected either due to restrictions in the traffic speed (as discussed above) or the narrowing of the carriageway. The average daily traffic volume of the motorway during the construction phase of the overpass bridge is taken to be 49485 as discussed in section 2.2. The duration of construction for each bridge, considering parallel building activities, is indicated in Table 19 along with the number of days with obstruction to traffic underneath the bridge.

Table 19: Traffic obstruction underneath the bridges in case B

	Case A1 Integral bridge	**Case A2 Concrete bridge (cast in situ)**	**Case A3 Composite bridge**
Construction duration (days)	154	273	196
Days with obstruction to traffic underneath the bridge	154 (1 lane closed per direction)	119 (1 lane closed per direction)	154 (1 lane closed per direction)
		42 (2 lanes closed per direction)	42 (2 lanes closed per direction)
		112 (One direction fully closed)	

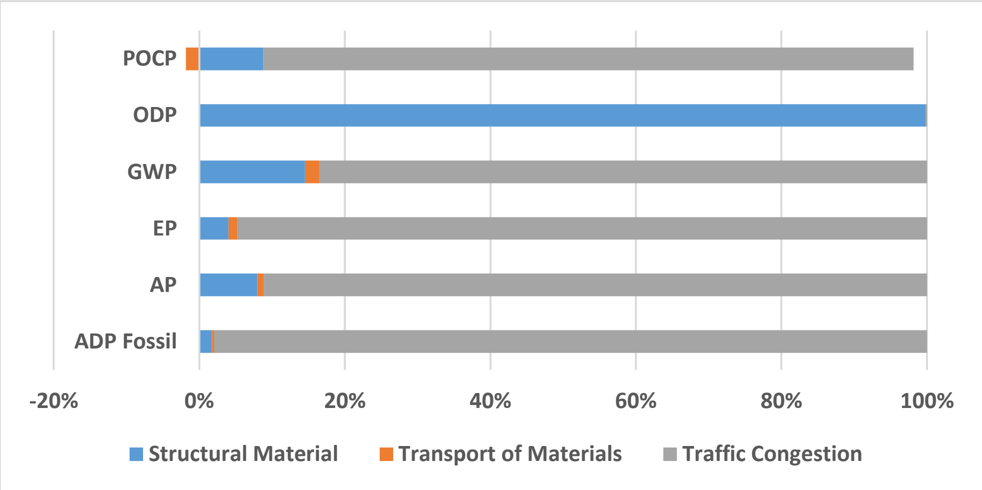
Note: However, due to restrictions in the current version of the SBRI+ Tool, all lifecycle analyses are made considering only 1 lane is closed for traffic in each direction [three lanes open for traffic in each direction] for a duration of A1=154 days, A2 = 273 days and A3 = 196 days.

- *Environmental analysis of reference case study A1*

The results of the construction stage for the reference case study A1 are presented in Table 20 and illustrated in Figure 28. Traffic congestion and operations related to the onsite production of structural materials represent the main contribution for the environmental impacts in this stage. It is observed that the contribution from traffic congestion constitutes more than 80% of the total impacts except for the ODP impact category. The impact in ODP category mainly comes from the in-situ production of materials and is small (in the order of 10^{-4} Kg R11 eq.).

Table 20: Environmental impact at the construction stage per impact category [A1]

Impact Category	Unit	Total	Structural Material	Transport of Materials	Traffic Congestion
ADP Fossil	MJ	1,17E+07	2,02E+05	3,37E+04	1,15E+07
AP	Kg SO_2 eq.	6,37E+02	5,10E+01	5,46E+00	5,81E+02
EP	Kg PO_4 eq.	1,03E+02	4,14E+00	1,30E+00	9,78E+01
GWP	Kg CO_2 eq.	1,27E+05	1,84E+04	2,45E+03	1,06E+05
ODP	Kg R11 eq.	2,50E-04	2,50E-04	8,20E-10	3,66E-07
POCP	Kg C_2H_4	8,99E+01	8,22E+00	-1,72E+00	8,34E+01



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

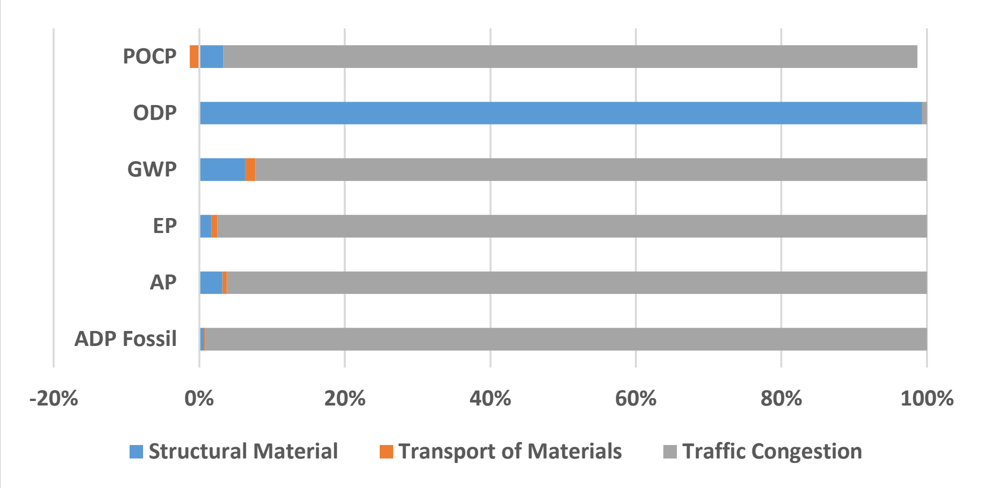
Figure 28: Contribution analysis of processes during the construction stage for case study A1

- *Environmental analysis of variant A2*

The results obtained for the variant case study A2 are presented in Table 21 and Figure 29. Table 22 indicates the variation of the results in comparison to the reference case study A1.

Table 21: Environmental impact at the construction stage per impact category [A2]

Impact Category	Unit	Total	Structural Material	Transport of Materials	Traffic Congestion
ADP Fossil	MJ	2,05E+07	1,38E+05	3,95E+04	2,03E+07
AP	Kg SO_2 eq.	1,07E+03	3,41E+01	6,40E+00	1,03E+03
EP	Kg PO_4 eq.	1,78E+02	2,88E+00	1,52E+00	1,73E+02
GWP	Kg CO_2 eq.	2,03E+05	1,28E+04	2,87E+03	1,88E+05
ODP	Kg R11 eq.	1,00E-04	9,98E-05	9,60E-10	6,48E-07
POCP	Kg C_2H_4	1,51E+02	5,10E+00	-2,02E+00	1,48E+02



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 29: Contribution analysis of processes during the construction stage for case study A2

Table 22: Environmental impacts of A2 compared to A1 at the construction stage

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	1,17E+07	2,05E+07	+75,2%
AP	Kg SO_2 eq.	6,37E+02	1,07E+03	+67,9%
EP	Kg PO_4 eq.	1,03E+02	1,78E+02	+72,2%
GWP	Kg CO_2 eq.	1,27E+05	2,03E+05	+60,4%
ODP	Kg R11 eq.	2,50E-04	1,00E-04	-59,9%
POCP	Kg C_2H_4	8,99E+01	1,51E+02	+67,9%

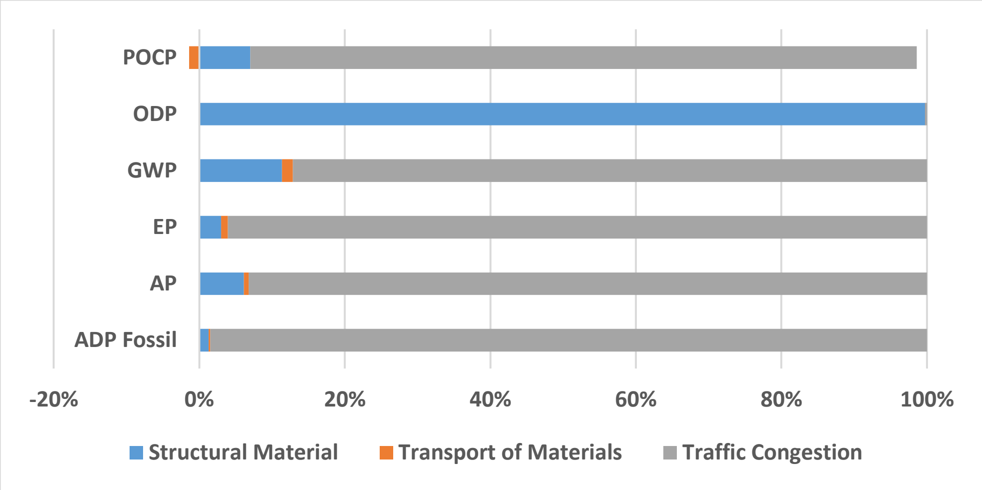
Here again, it is observed that the contribution from traffic congestion constitutes more than 90% of the total impacts except for the ODP impact category. Case A2 resulted in significantly higher impact (>60%) than case A1 at this stage except for ODP, where nearly 60% reduction in impact is calculated for case A2. Notice, however, that the absolute values of emissions are very small in magnitude for ODP albeit the variation percentage.

- *Environmental analysis of variant A3*

The results obtained for the variant case study A3 are presented in Table 23 and Figure 30. Table 24 indicates the variation of the results in comparison to the reference case study A1.

Table 23: Environmental impact at the construction stage per impact category [A3]

Impact Category	Unit	Total	Structural Material	Transport of Materials	Traffic Congestion
ADP Fossil	MJ	1,48E+07	1,92E+05	3,20E+04	1,46E+07
AP	Kg SO_2 eq.	7,93E+02	4,86E+01	5,18E+00	7,39E+02
EP	Kg PO_4 eq.	1,30E+02	3,88E+00	1,23E+00	1,25E+02
GWP	Kg CO_2 eq.	1,55E+05	1,76E+04	2,32E+03	1,35E+05
ODP	Kg R11 eq.	1,87E-04	1,87E-04	7,77E-10	4,65E-07
POCP	Kg C_2H_4	1,13E+02	8,14E+00	-1,63E+00	1,06E+02



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 30: Contribution analysis of processes during the construction stage for case study A3

Table 24: Environmental impacts of A3 compared to A1 at construction stage

Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	1,17E+07	1,48E+07	+26,6%
AP	Kg SO_2 eq.	6,37E+02	7,93E+02	+24,4%
EP	Kg PO_4 eq.	1,03E+02	1,30E+02	+25,5%
GWP	Kg CO_2 eq.	1,27E+05	1,55E+05	+22,0%
ODP	Kg R11 eq.	2,50E-04	1,87E-04	-25,2%
POCP	Kg C_2H_4	8,99E+01	1,13E+02	+25,3%

Here again, it is observed that the contribution from traffic congestion contributes to more than 85% of the total impacts except for the ODP impact category. At this stage, case A3 resulted in higher impacts, as compared to case A1, in every category with the exception of ODP. Notice, however, that the absolute values of emissions are very small in magnitude for ODP albeit the variation percentage. It is to be noted that ODP is almost completely dominated by influences coming from on-site material production as opposed to the other categories where traffic congestion plays the most role.

At this stage, it is worth to mention that the traffic congestion is the main contributor to the environmental impacts. Although the impacts due to traffic congestion were calculated with traffic obstruction to only one lane in each direction of traffic, because of limitations in the current version of the SBRI+ tool, the actual scenario is that 2 or more lanes are blocked for traffic in cases A2 and A3. (See Table 19) The increase in impacts would, clearly, be more magnified than calculated above if the actual traffic obstructions were considered for cases A2 and A3.

2.3.3 Operation stage

The maintenance scheme provided in Table A5 of Annex A indicates the traffic restraints above and under the bridge, over the years, in which maintenance activities take place also for case studies A1, A2, and A3.

- *Environmental analysis of reference case study A1*

The results of the operation stage, for the reference case study A1, are presented in Table 25 and Figure 31, for the day work plan and the standard maintenance scenario.

Table 25: Environmental impacts of A1 at the operation stage (day work)

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Traffic Congestion
ADP Fossil	MJ	7,38E+06	9,53E+05	7,76E+04	7,50E+04	6,28E+06
AP	Kg SO_2 eq.	4,17E+02	4,49E+01	1,62E+01	3,74E+01	3,19E+02
EP	Kg PO_4 eq.	6,54E+01	5,73E+00	7,87E-01	5,28E+00	5,36E+01
GWP	Kg CO_2 eq.	1,07E+05	1,93E+04	4,82E+03	2,49E+04	5,84E+04
ODP	Kg R11 eq.	3,89E-07	1,60E-08	8,99E-09	1,63E-07	2,02E-07
POCP	Kg C_2H_4	7,02E+01	1,65E+01	6,31E+00	1,64E+00	4,57E+01

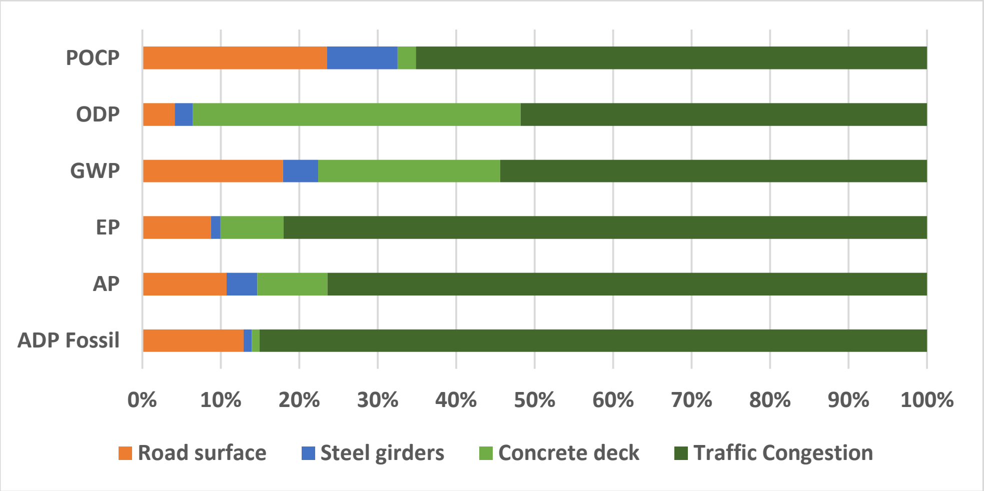


Figure 31: Contribution analysis of processes at the operation stage (A1 day work)

For the night work scenario, the results of the operation stage, for the reference case study A1, are shown in Table 26 and Figure 32. Notice that the change is only in traffic congestion.

Table 26: Environmental impacts of A1 at the operation stage (night work)

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Traffic Congestion
ADP Fossil	MJ	6,24E+06	9,53E+05	7,76E+04	7,50E+04	5,13E+06
AP	Kg SO_2 eq.	3,58E+02	4,49E+01	1,62E+01	3,74E+01	2,59E+02
EP	Kg PO_4 eq.	5,55E+01	5,73E+00	7,87E-01	5,28E+00	4,37E+01
GWP	Kg CO_2 eq.	9,60E+04	1,93E+04	4,82E+03	2,49E+04	4,71E+04
ODP	Kg R11 eq.	3,50E-07	1,60E-08	8,99E-09	1,63E-07	1,63E-07
POCP	Kg C_2H_4	6,18E+01	1,65E+01	6,31E+00	1,64E+00	3,73E+01

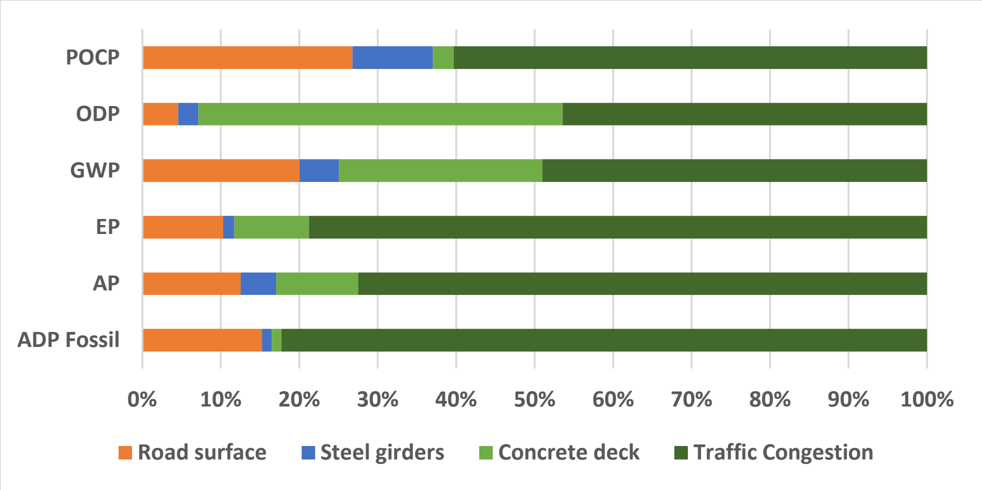


Figure 32: Contribution analysis of processes during the operation stage (A1 night work)

In both scenarios, it is observed the major contribution for all impact categories come from traffic congestion, maintenance of the concrete deck, road surface and steel girders. The contribution of the traffic congestion is lower in the night work than in the day work scenario.

- *Environmental analysis of variant A2*

The results obtained for the variant case study A2 are presented in Figure 33 and Table 27, assuming the day work scenario for all case studies. Table 28 indicates the variation of the results in relation to the reference case study A1.

Table 27: Environmental impacts of A2 at the operation stage (day work)

Impact Category	Unit	Total	Road surface	Concrete deck	Traffic Congestion
ADP Fossil	MJ	5,92E+06	9,53E+05	2,97E+05	4,67E+06
AP	Kg SO_2 eq.	4,29E+02	4,49E+01	1,48E+02	2,36E+02
EP	Kg PO_4 eq.	6,65E+01	5,73E+00	2,09E+01	3,98E+01
GWP	Kg CO_2 eq.	1,61E+05	1,93E+04	9,85E+04	4,30E+04
ODP	Kg R11 eq.	8,09E-07	1,60E-08	6,44E-07	1,49E-07
POCP	Kg C_2H_4	5,70E+01	1,65E+01	6,51E+00	3,39E+01

Table 28: Environmental impacts of A2 compared to A1 at the operation stage (day work)

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	7,38E+06	5,92E+06	-19,8%
AP	Kg SO_2 eq.	4,17E+02	4,29E+02	+2,9%
EP	Kg PO_4 eq.	6,54E+01	6,65E+01	+1,6%
GWP	Kg CO_2 eq.	1,07E+05	1,61E+05	+49,7%
ODP	Kg R11 eq.	3,89E-07	8,09E-07	+107,8%
POCP	Kg C_2H_4	7,02E+01	5,70E+01	-18,9%

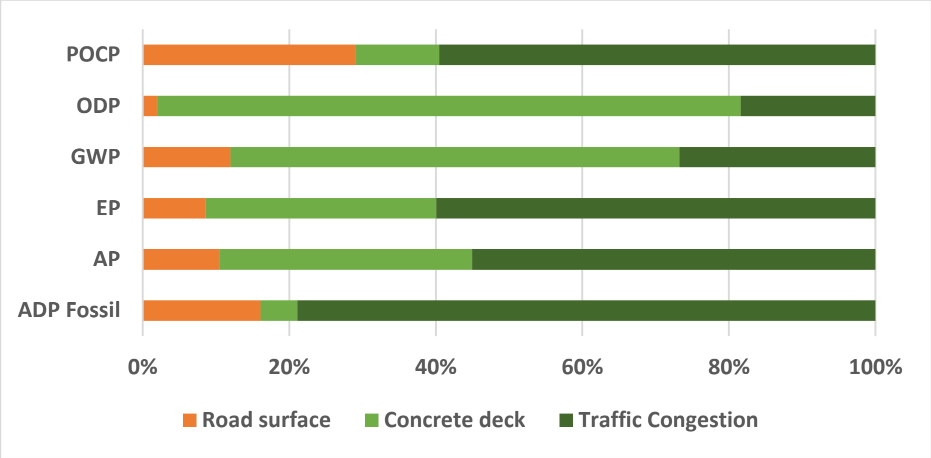


Figure 33: Contribution analysis of processes during the operation stage (A2 day work)

Considering the night work scenario, the results obtained for the variant case study A2 are presented in Table 29 and these results are compared against those from case A1 in

Table 30.

Table 29: Environmental impacts of A2 at the operation stage (night work)

Impact Category	Unit	Total	Road surface	Concrete deck	Traffic Congestion
ADP Fossil	MJ	5,23E+06	9,53E+05	2,97E+05	3,98E+06
AP	Kg SO_2 eq.	3,93E+02	4,49E+01	1,48E+02	2,01E+02
EP	Kg PO_4 eq.	6,05E+01	5,73E+00	2,09E+01	3,38E+01
GWP	Kg CO_2 eq.	1,54E+05	1,93E+04	9,85E+04	3,61E+04
ODP	Kg R11 eq.	7,85E-07	1,60E-08	6,44E-07	1,25E-07
POCP	Kg C_2H_4	5,19E+01	1,65E+01	6,51E+00	2,88E+01

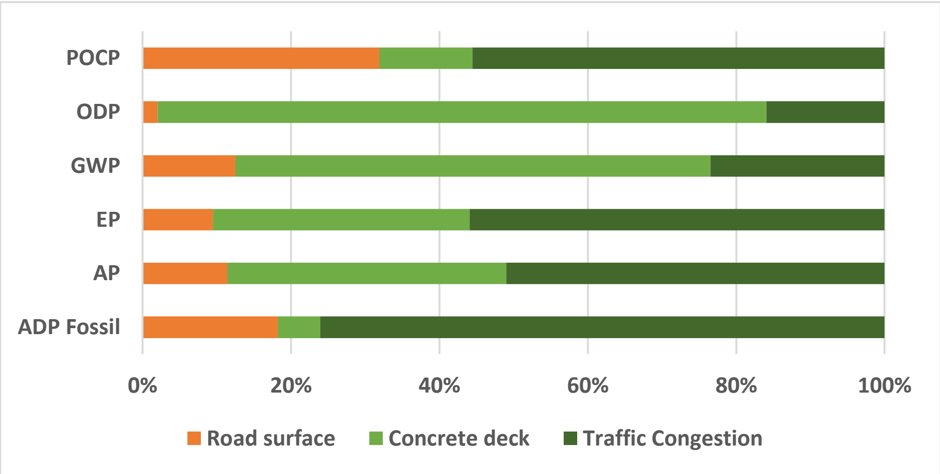


Figure 34: Contribution analysis of processes at the operation stage (A2 night work)

Table 30: Environmental impacts of A2 compared to A1 at the operation stage (night work)

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	6,24E+06	5,23E+06	-16,2%
AP	Kg SO_2 eq.	3,58E+02	3,93E+02	+9,9%
EP	Kg PO_4 eq.	5,55E+01	6,05E+01	+8,9%
GWP	Kg CO_2 eq.	9,60E+04	1,54E+05	+60,3%
ODP	Kg R11 eq.	3,50E-07	7,85E-07	+124,1%
POCP	Kg C_2H_4	6,18E+01	5,19E+01	-16,0%

As expected, the night work scenario provides the higher reduction of impacts overall.

- *Environmental analysis of variant A3*

The results obtained for the variant case study A3 are detailed in Table 31 and Figure 35. Table 32 indicates the variation of the results in relation to the reference case study A1 assuming the day work scenario for all case studies.

Table 31: Environmental impacts of A3 at the operation stage (day work)

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Traffic Congestion
ADP Fossil	MJ	7,46E+06	9,53E+05	4,98E+04	6,80E+04	6,39E+06
AP	Kg SO_2 eq.	4,13E+02	4,49E+01	1,04E+01	3,39E+01	3,24E+02
EP	Kg PO_4 eq.	6,55E+01	5,73E+00	5,06E-01	4,78E+00	5,45E+01
GWP	Kg CO_2 eq.	1,04E+05	1,93E+04	3,10E+03	2,25E+04	5,90E+04
ODP	Kg R11 eq.	3,73E-07	1,60E-08	5,78E-09	1,47E-07	2,04E-07
POCP	Kg C_2H_4	6,85E+01	1,65E+01	4,06E+00	1,49E+00	4,65E+01

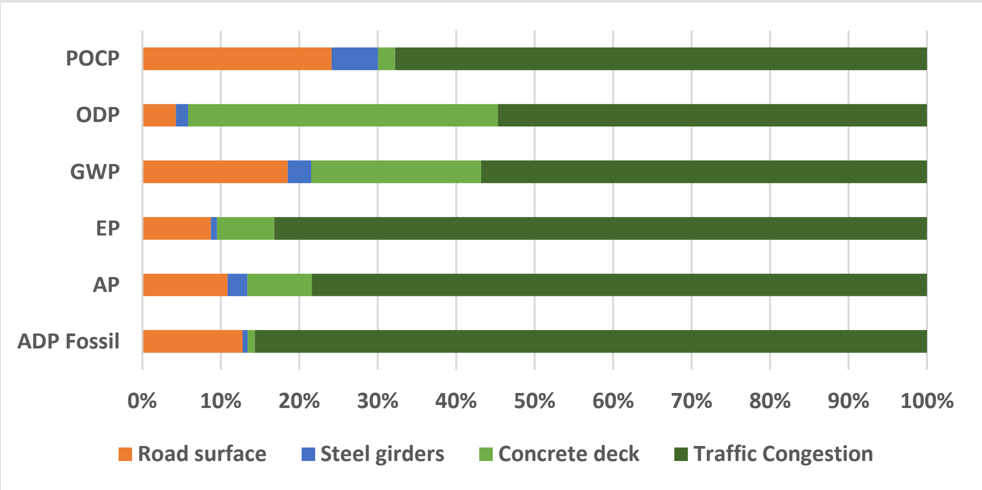


Figure 35: Contribution analysis of processes at the operation stage (A3 day work)

Table 32: Environmental impacts of A3 compared to A1 at the operation stage (day work)

Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	7,38E+06	7,46E+06	+1,0%
AP	Kg SO_2 eq.	4,17E+02	4,13E+02	-1,1%
EP	Kg PO_4 eq.	6,54E+01	6,55E+01	+0,1%
GWP	Kg CO_2 eq.	1,07E+05	1,04E+05	-3,2%
ODP	Kg R11 eq.	3,89E-07	3,73E-07	-4,1%
POCP	Kg C_2H_4	7,02E+01	6,85E+01	-2,4%

Considering the night work scenario, the results obtained for the variant case study A3 are presented in Table 33 and a comparison of these results with those from case A1 is given in Table 34.

Table 33: Environmental impacts of A3 at the operation stage (night work)

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Traffic Congestion
ADP Fossil	MJ	6,45E+06	9,53E+05	4,98E+04	6,80E+04	5,38E+06
AP	Kg SO_2 eq.	3,61E+02	4,49E+01	1,04E+01	3,39E+01	2,71E+02
EP	Kg PO_4 eq.	5,68E+01	5,73E+00	5,06E-01	4,78E+00	4,58E+01
GWP	Kg CO_2 eq.	9,39E+04	1,93E+04	3,10E+03	2,25E+04	4,90E+04
ODP	Kg R11 eq.	3,39E-07	1,60E-08	5,78E-09	1,47E-07	1,70E-07
POCP	Kg C_2H_4	6,11E+01	1,65E+01	4,06E+00	1,49E+00	3,90E+01

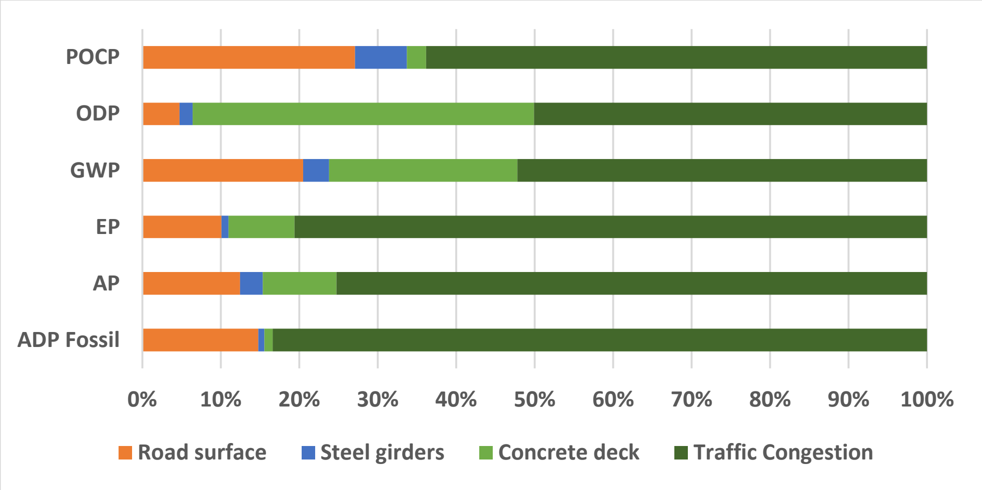


Figure 36: Contribution analysis of processes at the operation stage (A3 night work)

Table 34: Environmental impacts of A3 compared to A1 at the operation stage (night work)

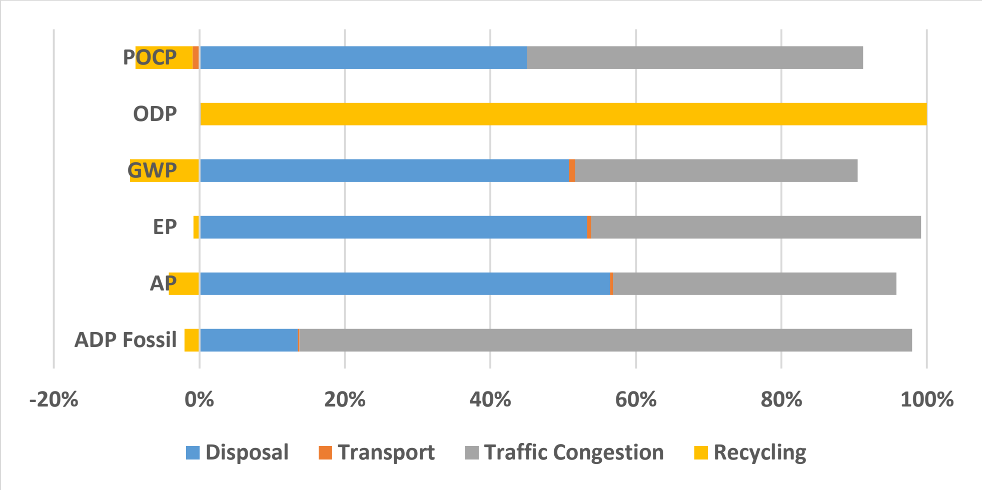
Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	6,24E+06	6,45E+06	+3,4%
AP	Kg SO_2 eq.	3,58E+02	3,61E+02	+0,7%
EP	Kg PO_4 eq.	5,55E+01	5,68E+01	+2,3%
GWP	Kg CO_2 eq.	9,60E+04	9,39E+04	-2,2%
ODP	Kg R11 eq.	3,50E-07	3,39E-07	-3,3%
POCP	Kg C_2H_4	6,18E+01	6,11E+01	-1,1%

Case A3 resulted in slightly increased impacts in some categories while resulting in slightly decreased impacts in others. Overall, it can be said both A1 and A3 have comparable impacts at this stage.

2.3.4 End-of-life stage

- *Environmental analysis of reference case study A1*

Total emissions per impact category of this stage are indicated in Figure 37, which also indicates the contribution of each process per impact category. The negative values in Figure 37 represent the credits given to the recycling processes.



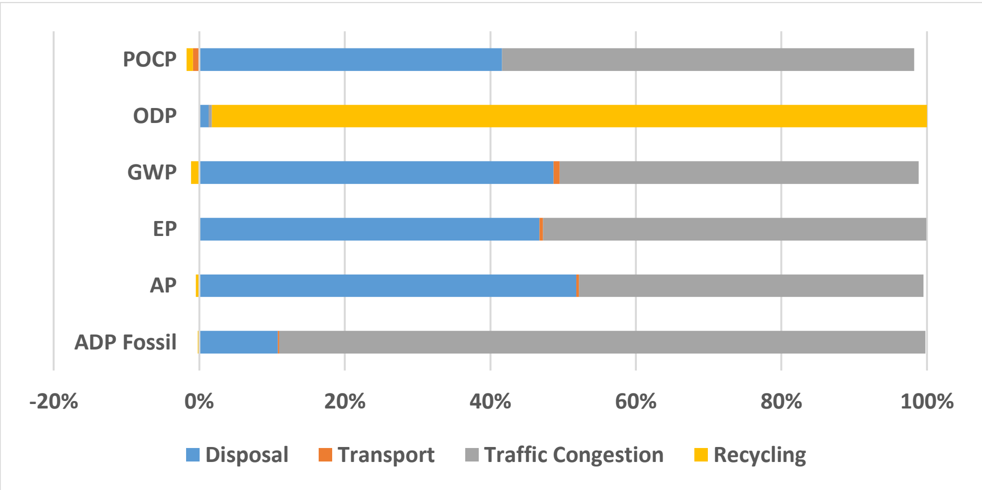
Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 37: Contribution analysis of processes during the end-of-life stage – Case A1

Disposal of concrete and bituminous materials contributes the most impact in all categories with the exception of ADP fossil fuel where the second most significant contributor, traffic congestion, dominates. The transportation of these materials caused the least impact in all impact categories. Recycling, on the other hand, benefits the environment in all impact categories except the Ozone Depletion Potential where the recycling process itself gives rise to such emissions.

- *Environmental analysis of variant A2*

As can be seen in Figure 38, disposal contributes the most in all impact categories with the exception of ADP fossil fuel. The second most significant contributor is traffic congestion. Transportation causes the least of impacts compared to the others. Recycling contributes in favor of the environment in all impact categories but ODP where the recycling process itself gives rise to such emissions.



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 38: Contribution analysis of processes during the end-of-life stage [A2]

Total emissions per impact category of this stage for the variant case study A2 are presented in Table 35. This table also indicates the variation of the results of this case study in comparison to the reference case study A1. These results are also displayed in Figure 39.

Table 35: Environmental impacts of A2 compared to A1 at the end-of-life stage

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	2,51E+07	4,39E+07	+74,5%
AP	Kg SO_2 eq.	2,65E+03	4,18E+03	+57,7%
EP	Kg PO_4 eq.	4,11E+02	6,36E+02	+54,8%
GWP	Kg CO_2 eq.	4,37E+05	7,36E+05	+68,4%
ODP	Kg R11 eq.	1,64E-03	2,80E-04	-82,9%
POCP	Kg C_2H_4	2,88E+02	4,88E+02	+69,3%

According to these results, it can be concluded that at this stage the reference example led to lower values. This is given by the advantages coming from the relatively more recycling possibilities in the reference example A1.

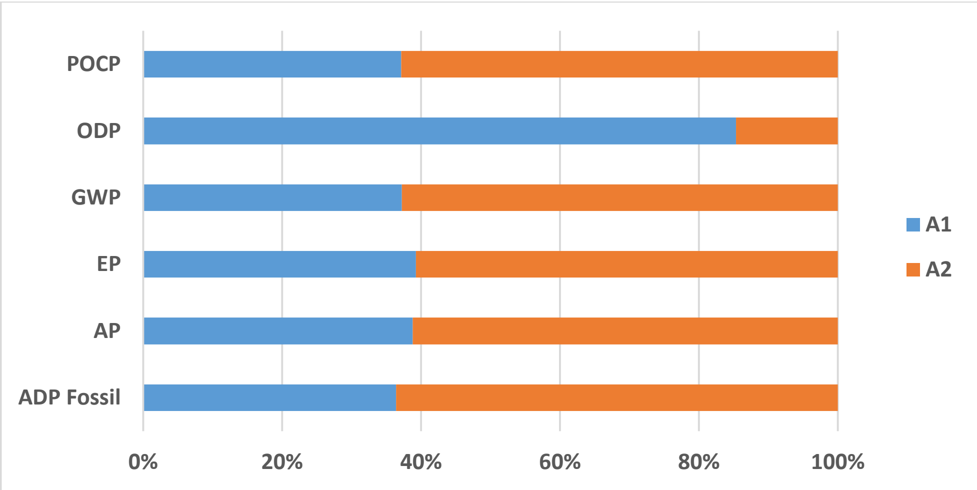
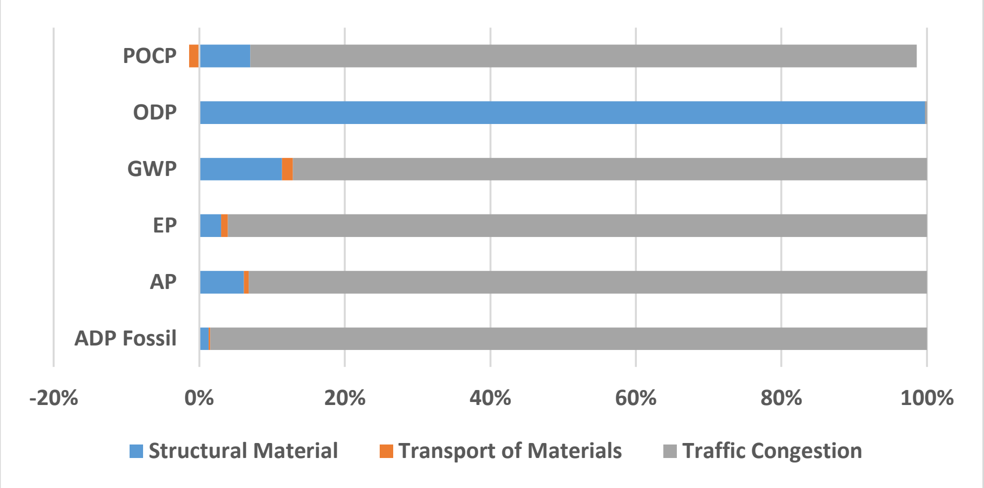


Figure 39: Relative contributions of A1 and A2 at the end-of-life stage

- *Environmental analysis of variant A3*

As can be seen in Figure 38, disposal contributes the most in all impact categories with the exception of ADP fossil fuel. The second most significant contributor is traffic congestion. Transportation causes the least of impacts compared to the others. Recycling contributes in favor of the environment in all impact categories but ODP.



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 40: Contribution analysis of processes during the end-of-life stage [A3]

Total emissions per impact category of this stage for the variant case study A3 are provided in Table 36. This table also indicates the variation of the results in comparison to the reference case study A1. These results are also illustrated in Figure 41.

Table 36: Environmental impacts of A3 compared to A1 at the end-of-life stage

Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	2,51E+07	3,08E+07	+22,6%
AP	Kg SO_2 eq.	2,65E+03	2,86E+03	+7,9%
EP	Kg PO_4 eq.	4,11E+02	4,55E+02	+10,7%
GWP	Kg CO_2 eq.	4,37E+05	4,65E+05	+6,4%
ODP	Kg R11 eq.	1,64E-03	2,31E-03	+41,2%
POCP	Kg C_2H_4	2,88E+02	3,16E+02	+9,9%

According to these results, it can be concluded that at this stage that the reference example A1 resulted in less environmental impacts in all categories.

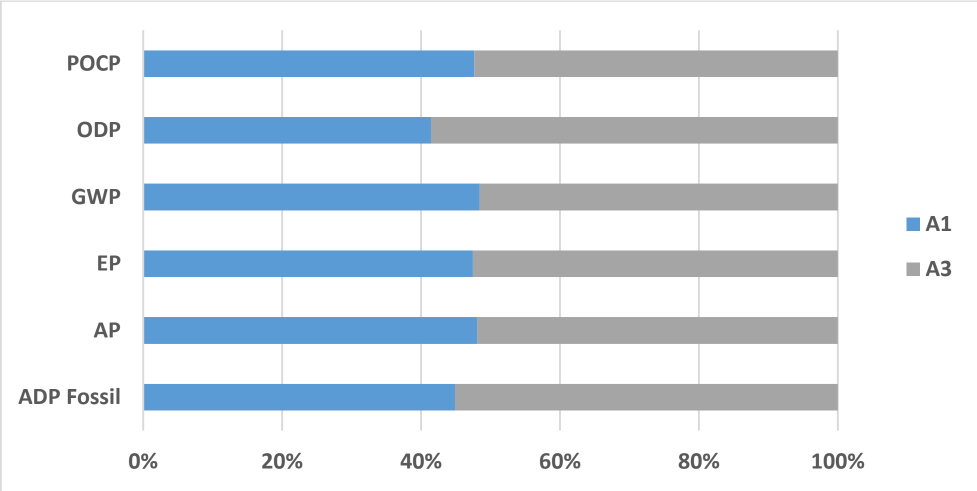


Figure 41: Relative contributions of A1 and A3 at the end-of-life stage

2.3.5 Results of the environmental lifecycle analysis

- *Aggregate lifecycle results for case study A1*

In the previous sections, the partial results per stage have been presented. In this subsection, the results of the different stages are summed up in relation to each impact category and the aggregate results are presented in Table 37, considering the day work plan and standard maintenance scenario.

Table 37: Aggregate lifecycle environmental impacts per Lifecycle stage [A1]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	4,95E+07	5,22E+06	1,17E+07	7,38E+06	2,51E+07
AP	Kg SO_2 eq.	5,25E+03	1,54E+03	6,37E+02	4,17E+02	2,65E+03
EP	Kg PO_4 eq.	7,37E+02	1,58E+02	1,03E+02	6,54E+01	4,11E+02
GWP	Kg CO_2 eq.	1,38E+06	7,04E+05	1,27E+05	1,07E+05	4,37E+05
ODP	Kg R11 eq.	7,87E-03	5,98E-03	2,50E-04	3,89E-07	1,64E-03
POCP	Kg C_2H_4	6,40E+02	1,92E+02	8,99E+01	7,02E+01	2,88E+02

To understand the contribution of each stage to the aggregated result better, these results are also presented in Figure 42.

The material production and end-of-life stages contribute the most in all the impact categories. The operation stage has the second major contribution for the impact categories. The construction stage also contributes considerably while the operation stage has a relatively low contribution for all impact categories.

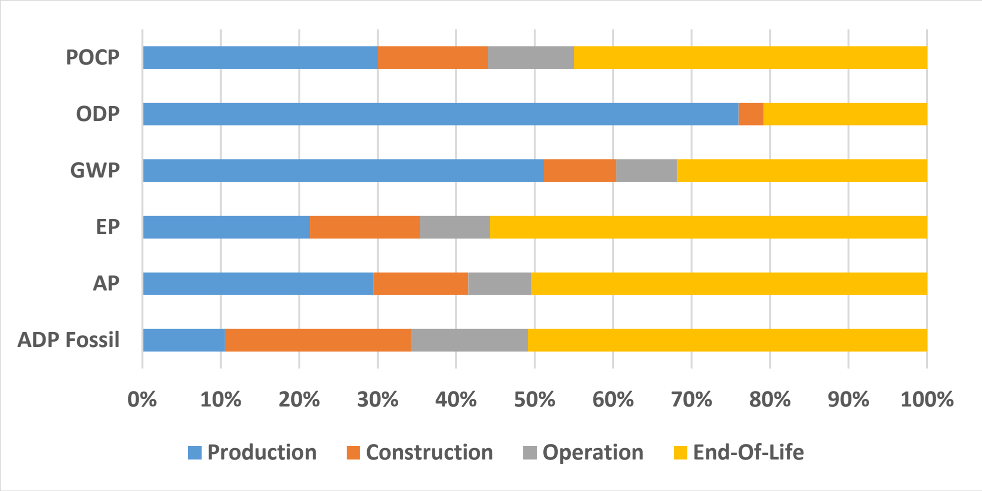


Figure 42: Contribution of each stage per impact category [A1]

- *Aggregate lifecycle results for A2*

The results obtained for the variant case studies A2 are detailed in Table 38, considering the day work scenario in all cases. This table also indicates the variation of the results this case study in relation to the reference case study A1.

Table 38: Aggregate environmental impacts of A2 compared to A1

Impact Category	Unit	Case Study A1	Case Study A2	Variation relative to A1
ADP Fossil	MJ	4,95E+07	7,45E+07	+50,6%
AP	Kg SO_2 eq.	5,25E+03	7,06E+03	+34,5%
EP	Kg PO_4 eq.	7,37E+02	1,04E+03	+40,5%
GWP	Kg CO_2 eq.	1,38E+06	1,81E+06	+31,9%
ODP	Kg R11 eq.	7,87E-03	2,42E-03	-69,3%
POCP	Kg C_2H_4	6,40E+02	8,32E+02	+29,9%

To understand the contribution of each case study to the aggregated result better, the results are also illustrated in Figure 43.

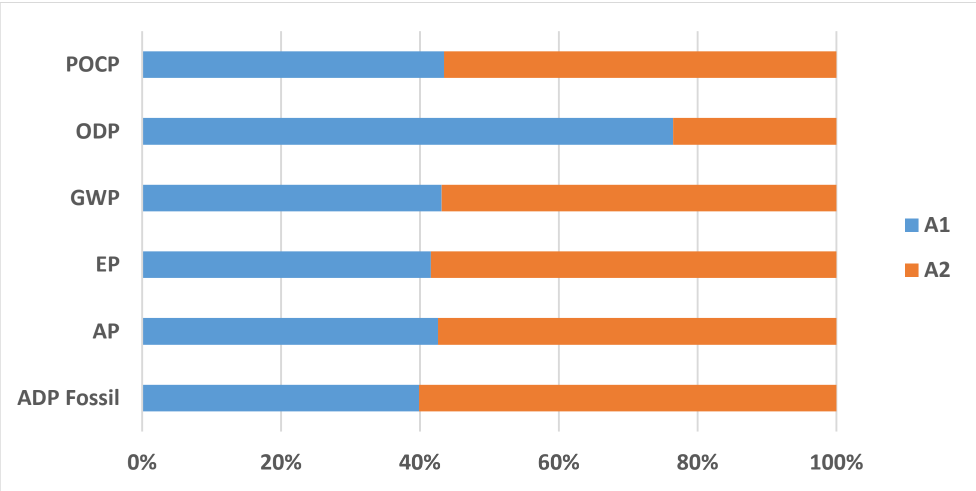


Figure 43: Relative contribution of A1 and A2 per impact category

As it can be seen from the above illustrations, the reference example A1 features comparatively favorable characteristics in all impact categories except for ozone depletion potential (OPD) where higher emissions (although in the order of 10^{-3}) are registered for the reference example as a result of the recycling process.

- *Aggregate lifecycle results for A3*

The results obtained for the variant case studies A3 are given in Table 39, considering the day work scenario in all cases. This table also indicates the variation of the results this case study in relation to the reference case study A1.

Table 39: Aggregate environmental impacts of A3 compared to A1

Impact Category	Unit	Case Study A1	Case Study A3	Variation relative to A1
ADP Fossil	MJ	4,95E+07	5,81E+07	+17,5%
AP	Kg SO_2 eq.	5,25E+03	5,56E+03	+5,8%
EP	Kg PO_4 eq.	7,37E+02	7,99E+02	+8,4%
GWP	Kg CO_2 eq.	1,38E+06	1,41E+06	+2,7%
ODP	Kg R11 eq.	7,87E-03	6,27E-03	-20,3%
POCP	Kg C_2H_4	6,40E+02	6,89E+02	+7,6%

To understand the contribution of each case study to the aggregated result better, the results are also shown in Figure 44.

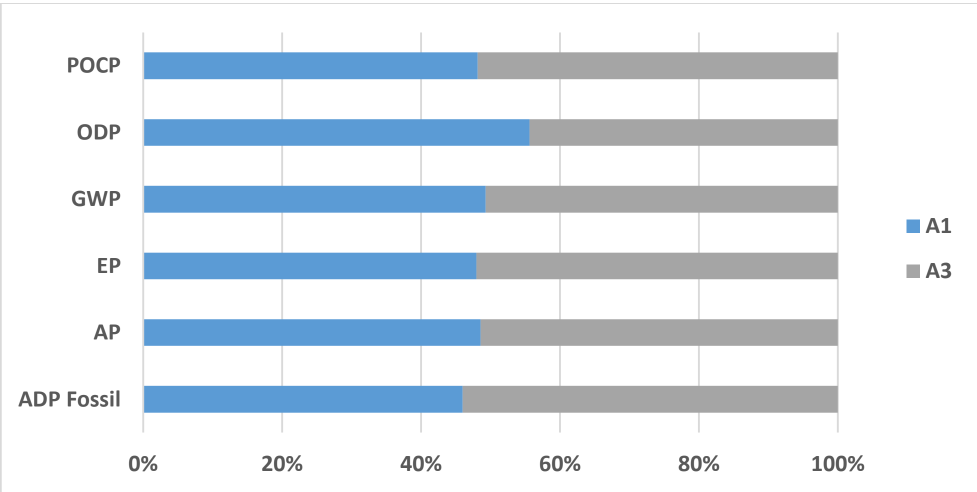


Figure 44: Relative contribution of A1 and A3 per impact category

As it can be seen from the above illustrations, the reference example A1 features comparatively favorable characteristics in all impact categories except for ozone depletion potential (OPD). The two bridges result in comparable results in terms of GWP with a difference of 2.7%.

Due to restrictions in the current version of the SBRI+ Tool, all lifecycle analyses are made considering only 1 lane closed for traffic in each direction [three lanes open for traffic in each direction] for a duration of A1=154 days, A2 = 273 days and A3 = 196 days. If we consider more lanes closed the emissions due to traffic congestion will increase respectively which will lead to higher difference between the case studies.

2.3.6 Alternative maintenance scenarios

- *Analysis of reference case study A1*

In this section, two additional alternative maintenance plans are considered. The first alternative maintenance scenario refers to the “lack of money” situation, in which the frequency of maintenance is changed to cope with budget restrictions. The second alternative maintenance scenario refers to the “prolonged life” situation, in which the service life of the bridge is extended to 130 years.

Both alternative scenarios only affect the operation stage. Hence, the results presented in this section refer only to the operation stage. The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 40 for the standard and both alternative maintenance scenarios.

Table 40: Comparison of environmental impacts at the operation stage with different maintenance scenarios [A1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	7,38E+06	3,79E+06	-48,7%	1,53E+07	+107,7%
AP	Kg SO_2 eq.	4,17E+02	2,10E+02	-49,7%	8,60E+02	+106,1%
EP	Kg PO_4 eq.	6,54E+01	3,26E+01	-50,1%	1,37E+02	+109,5%
GWP	Kg CO_2 eq.	1,07E+05	5,19E+04	-51,6%	2,13E+05	+98,1%
ODP	Kg R11 eq.	3,89E-07	1,71E-07	-56,0%	8,03E-07	+106,4%
POCP	Kg C_2H_4	7,02E+01	3,73E+01	-46,9%	1,36E+02	+94,0%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 41 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 41: Comparison of environmental impacts <u>per year</u> at the operation stage with different maintenance scenarios [A1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	7,38E+04	3,79E+04	-48,7%	1,18E+05	+59,7%
AP	Kg SO_2 eq.	4,17E+00	2,10E+00	-49,7%	6,61E+00	+58,5%
EP	Kg PO_4 eq.	6,54E-01	3,26E-01	-50,1%	1,05E+00	+61,2%
GWP	Kg CO_2 eq.	1,07E+03	5,19E+02	-51,6%	1,64E+03	+52,4%
ODP	Kg R11 eq.	3,89E-09	1,71E-09	-56,0%	6,18E-09	+58,8%
POCP	Kg C_2H_4	7,02E-01	3,73E-01	-46,9%	1,05E+00	+49,2%

From the results, it is evident that the “lack of money” scenario led to 50.5% (Avg.) reduced impacts per year in all categories, as less maintenance work is applied with this maintenance scheme. The effort to prolong the service life of the bridge with the “prolonged life” scenario led to 56.6% (Avg.) increase of impact in all environmental categories.

- *Analysis of reference case study A2*

The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 42 for the standard and both alternative maintenance scenarios.

Table 42: Comparison of environmental impacts at the operation stage with different maintenance scenarios [A2]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	5,92E+06	3,05E+06	-48,5%	1,27E+07	+114,7%
AP	Kg SO_2 eq.	4,29E+02	1,97E+02	-54,2%	9,06E+02	+111,0%
EP	Kg PO_4 eq.	6,65E+01	3,08E+01	-53,7%	1,42E+02	+113,4%
GWP	Kg CO_2 eq.	1,61E+05	6,57E+04	-59,1%	3,25E+05	+101,9%
ODP	Kg R11 eq.	8,09E-07	3,00E-07	-62,9%	1,66E-06	+104,8%
POCP	Kg C_2H_4	5,70E+01	2,90E+01	-49,2%	1,15E+02	+101,9%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 43 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 43: Comparison of environmental impacts per year at the operation stage with different maintenance scenarios [A2]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	5,92E+04	3,05E+04	-48,5%	9,78E+04	+65,1%
AP	Kg SO_2 eq.	4,29E+00	1,97E+00	-54,2%	6,97E+00	+62,3%
EP	Kg PO_4 eq.	6,65E-01	3,08E-01	-53,7%	1,09E+00	+64,2%
GWP	Kg CO_2 eq.	1,61E+03	6,57E+02	-59,1%	2,50E+03	+55,3%
ODP	Kg R11 eq.	8,09E-09	3,00E-09	-62,9%	1,27E-08	+57,5%
POCP	Kg C_2H_4	5,70E-01	2,90E-01	-49,2%	8,85E-01	+55,3%

The “lack of money” scenario led to reduced impacts in all impact categories. However, the effort to prolong the service life of the bridge with the “prolonged life” scenario led to an increased impact in all environmental categories.

- *Analysis of reference case study A3*

The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 44 for the standard and both alternative maintenance scenarios.

Table 44: Comparison of environmental impacts at the operation stage with different maintenance scenarios [A3]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	7,46E+06	4,18E+06	-44,0%	1,52E+07	+103,7%
AP	Kg SO_2 eq.	4,13E+02	2,25E+02	-45,5%	8,39E+02	+103,2%
EP	Kg PO_4 eq.	6,55E+01	3,57E+01	-45,5%	1,35E+02	+105,8%
GWP	Kg CO_2 eq.	1,04E+05	5,34E+04	-48,6%	2,04E+05	+96,4%
ODP	Kg R11 eq.	3,73E-07	1,76E-07	-52,8%	7,64E-07	+104,7%
POCP	Kg C_2H_4	6,85E+01	3,86E+01	-43,6%	1,32E+02	+92,4%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 45 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 45: Comparison of environmental impacts per year at the operation stage with different maintenance scenarios [A3]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	7,46E+04	4,18E+04	-44,0%	1,17E+05	+56,7%
AP	Kg SO_2 eq.	4,13E+00	2,25E+00	-45,5%	6,45E+00	+56,3%
EP	Kg PO_4 eq.	6,55E-01	3,57E-01	-45,5%	1,04E+00	+58,3%
GWP	Kg CO_2 eq.	1,04E+03	5,34E+02	-48,6%	1,57E+03	+51,1%
ODP	Kg R11 eq.	3,73E-09	1,76E-09	-52,8%	5,87E-09	+57,5%
POCP	Kg C_2H_4	6,85E-01	3,86E-01	-43,6%	1,01E+00	+48,0%

The “lack of money” scenario led to reduced impacts in all impact categories while the effort to prolong the service life of the bridge with the “prolonged life” scenario led to increased impacts in all environmental categories.

2.4 Lifecycle Cost Analysis

2.4.1 Initial construction costs

- *Analysis of reference case study A1*

The initial cost of the structure, including the material transport cost, is 826.145,01 €, which is about 1.553,82 €/m^2. Figure 45 shows the proportion of the costs for the substructure, superstructure and the roadway which are calculated based on the bill of materials and unit costs indicated in Table 11.

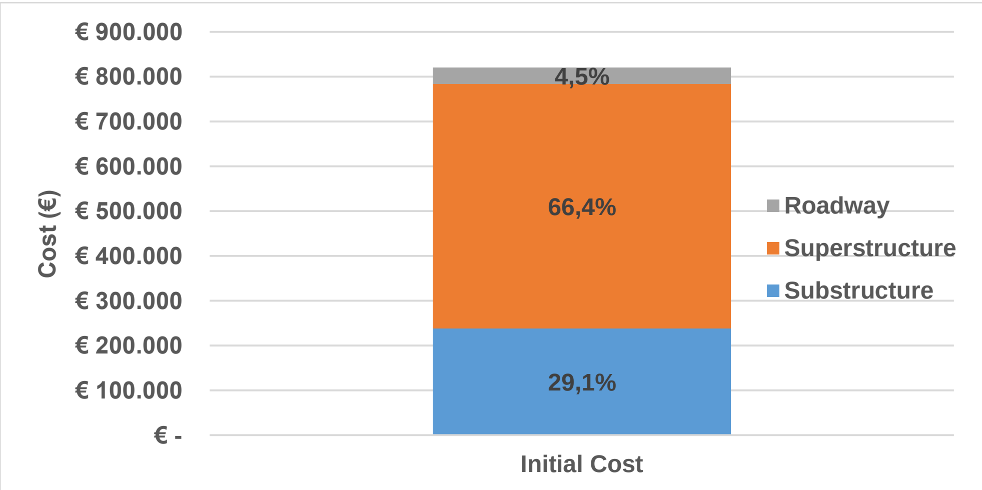


Figure 45: Initial cost of A1

- *Analysis of variant A2*

The initial cost and the proportion of the costs for the substructure, superstructure and the roadway shown in Figure 46 are calculated based on the bill of materials and unit costs indicated in Table 11. The result obtained for the variant case study A2 is an initial cost, including the material transport cost, of 850.713,82 € representing about 1.600,1 €/m^2.

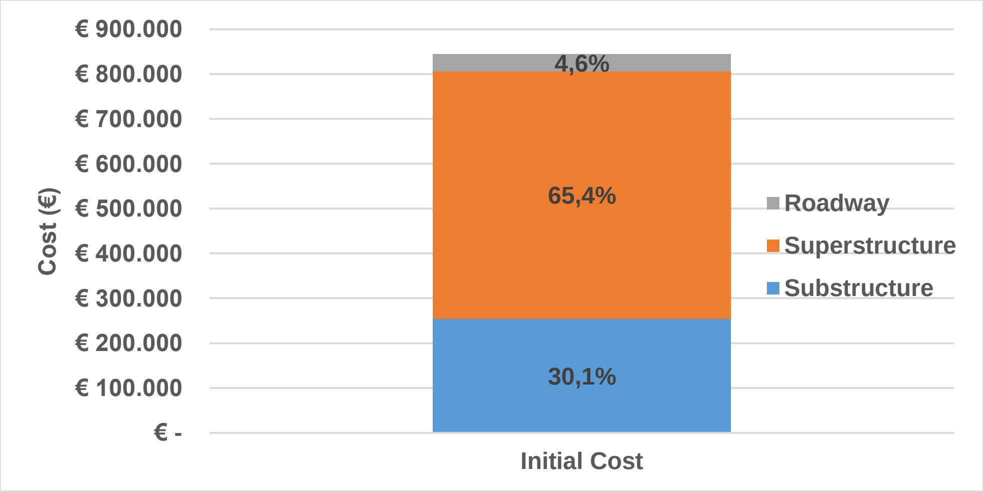


Figure 46: Initial cost of A2

- *Analysis of variant A3*

The initial cost and the proportion of the costs for the substructure, superstructure and the roadway shown in Figure 47 are calculated based on the bill of materials and unit costs indicated in Table 11. The result obtained for the variant case study A3 is an initial cost, including the material transport cost, of 779.264,42 € representing about 1.465,64 €/m^2.

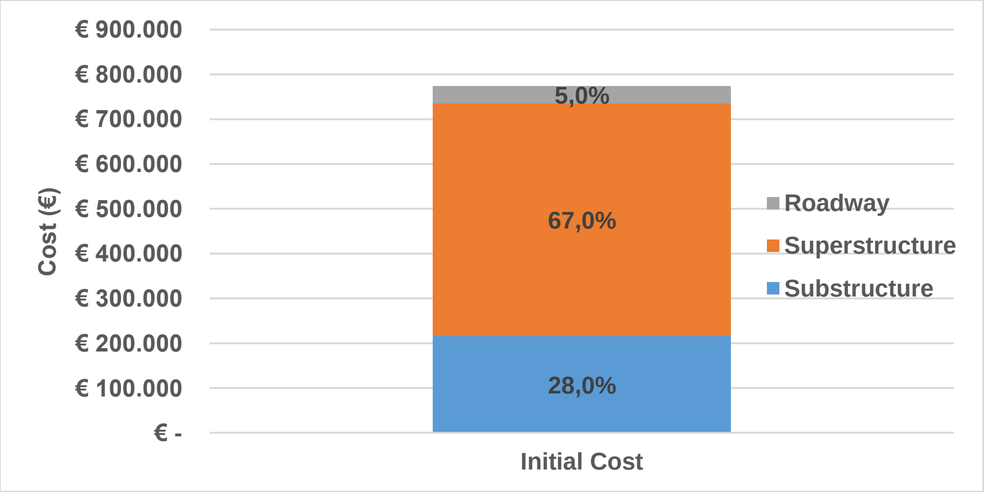


Figure 47: Initial cost of A3

2.4.2 Operation costs

Over the period of 100 years, the bridges in the examples are assumed to be maintained and rehabilitated according to the plan indicated in the Annex – Table A1, the definition of a standard Inspection scenario.

- *Analysis of reference case study A1*

The costs associated with inspection and maintenance work carried out on bridge A1 throughout its service life are calculated based on the unit costs and frequencies indicated in Tables A1 - A6 of the annex and found to be 165.236,13€. These costs are illustrated in Figure 48 along with the net present values of accumulated costs considering a discount rate of 2%.

It can be seen from the figure that the operation costs are notably higher in the years 35 and 70. This peaks in the operation costs are associated with the replacement of the corrosion protection layers.

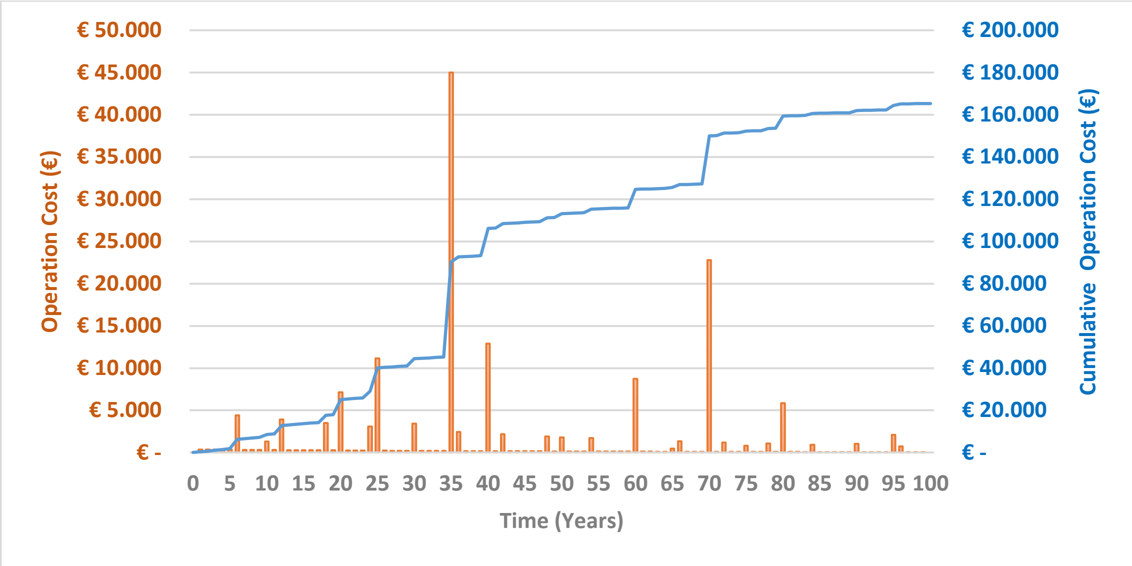


Figure 48: Operation costs of A1 over its service life

- *Analysis of reference case study A2*

The costs associated with inspection and maintenance work carried out on bridge A2 throughout its service life are calculated based on the unit costs and frequencies indicated in Table A1 and found to be 140.019,44 €. These costs are illustrated in Figure 49 along with the net present values of accumulated costs considering a discount rate of 2%. It can be seen from the figure that the operation costs are notably higher on the years 20, 35 and 40. These peaks come as a result of operation costs associated with the replacement of the road surface and the repair [years 20 and 40] or replacement of bearings [year 35].

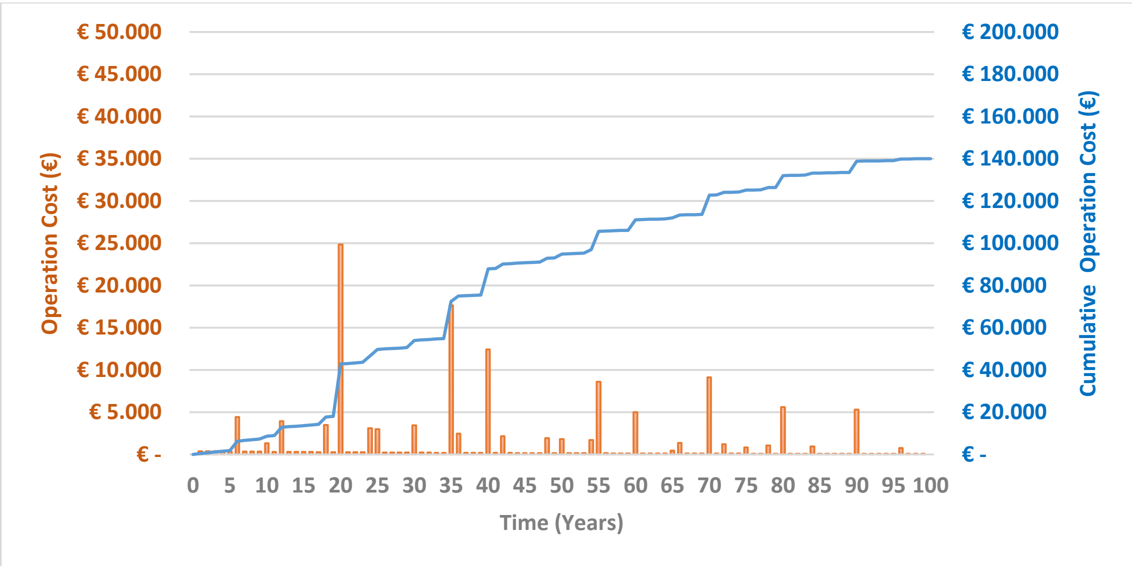


Figure 49: Operation costs of A2 over its service life

- *Analysis of reference case study A3*

The costs associated with inspection and maintenance work carried out on bridge A2 throughout its service life are calculated based on the unit costs and frequencies indicated in Table A1 and found to be 191.962,47 €. These costs are illustrated in Figure 50 along with the net present values of accumulated costs considering a discount rate of 2%. These peaks come as a result of operation costs associated with the replacement of the road surface and the repair [years 20 and 40] or replacement of bearings [year 35]. The corrosion protection layers are replaced in tears 35 and 70.

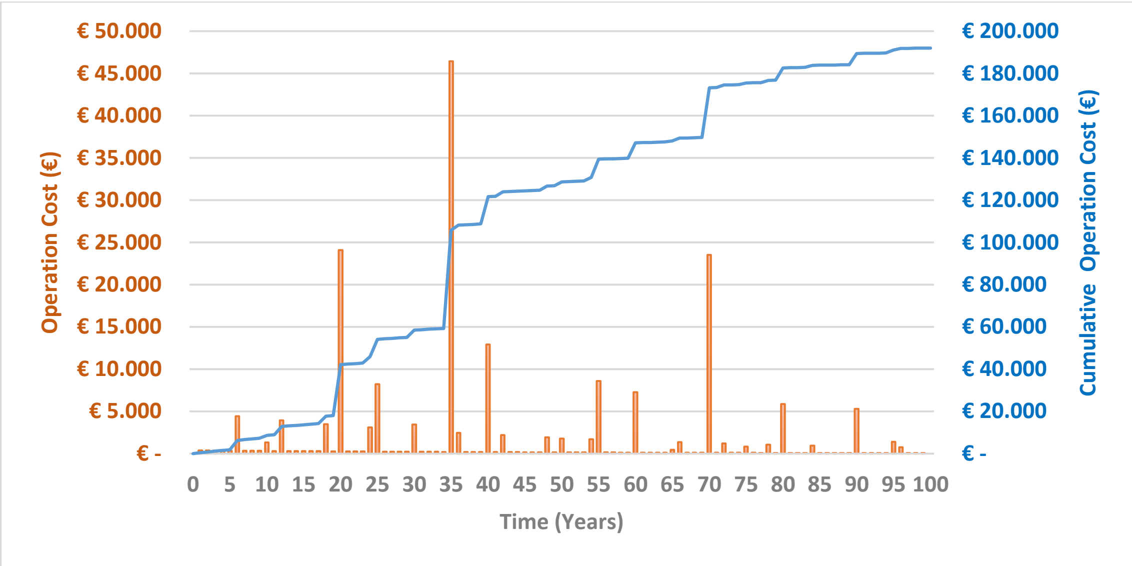


Figure 50: Operation costs of A3 over its service life

A1 takes 112 days for maintenance during the bridge's service life while A2 and A3 take 191 and 206 days, respectively. A1 has achieved reduced number of days required for maintenance since it is built without bearings. However, it can be noted from the results that the concrete solution A2 resulted in reduced operation costs as compared to the other two cases. This is due to the high cost for maintaining the corrosion protection layers in the other two bridges. Still, A1 has proven to be favorable in terms of operation cost as compared to A3.

2.4.3 End-of-life costs

End-of-life costs encompass the cost of labor work, cost of equipment, cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

The cost for demolition of a similar bridge is about 100 €/m^2 [1].This cost includes the cost of labor, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

Construction and Demolition Waste (C&DW) is sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the efficiency of the trucks and the price of fuel. In the case of the waste sent to a disposal site, the facility operator charges a fee to assume possession of the demolition waste. The cost for disposal of C&DW varies according to the type of material and the degree of contamination of the C&DW.

In the case of steel, i.e., both reinforcement steel bars and structural steel, it is assumed that the dealer pays the contractor 100 €/tonne (this price usually depends on the price of steel, according to the information from the U.S. recycling institute a price of $120/ton of steel may be considered). This figure has a negative sign since it is a revenue and not a cost for the contractor. A summary of the end-of-life costs for bridges A1, A2 and A3 are given in Table 46, 47 and 48, respectively. The integral bridge solution, A1, results in 9.5% lower end-of-life cost than the concrete bridge and 7.2% less than that of the steel composite bridge.

Table 46: End-of-life costs for A1

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	226,382	-2417,01	50	46,87
Concrete	3096,24	4273,83	50	641,07
Earthwork	13640	94138,48	10	564,83
Bitumen	55,62	383,87	20	4,61
Others		98,21		0,00
			Sub-Total (€)	97734,77
			Demolition cost (€)	7339,04
			Total Cost (€)	105073,81

Table 47: End-of-life costs for A2

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	161,7284	-1562,67	50	33,49
Concrete	4163,808	5747,43	50	862,11
Earthwork	14640	101040,13	10	606,24
Bitumen	55,62	383,87	20	4,61
	-	114,09	-	-
			Sub-Total (€)	107229,29
			Demolition cost (€)	7339,04
			Total Cost (€)	114568,33

Table 48: End-of-life costs for A3

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	199,6669	-2158,58	50	41,34
Concrete	3005,4	4148,44	50	622,27
Earthwork	14640	101040,13	10	606,24
Bitumen	55,62	383,87	20	4,61
	-	114,09	-	-
			Sub-Total (€)	104802,40
			Demolition cost (€)	7339,04
			Total Cost (€)	112141,45

(*) Considering disposal cost for concrete 10 €/tonne, for steel scrap value of 100 €/tonne and transportation cost of 0.03 €/tonne/km.

(**) The amount of steel calculated above includes both the reinforcement steel bars and structural steel sections/plates and connections. Note: The costs are given in their present value calculated according to equation 2 at a discount rate of 2%.

2.4.4 Total Lifecycle costs

Summing the costs calculated in the previous sections for case study A1 led to the total lifecycle net present cost (LCC) of 1.096.454,96 € using a discount rate of 2.0%. This represents a total cost of about 2062.22 €/m^2. On the other hand, total lifecycle net present costs (LCC) of 1.104.940,0 € and 1.083.368,0 € are calculated for case studies A2 and A3, respectively, at a discount rate of 2.0%. These represent a total cost of about 2078.2 €/m^2 for A2 and 2037,6 €/m^2 for A3. The costs of the bridge for each stage are summarized in Table 49 and illustrated in Figure 51.

Table 49: Comparison of lifecycle costs between A1, A2, and A3

	Case Study A1 (€)	Case Study A2 (€)	Variation relative to A1	Case Study A3 (€)	Variation relative to A1
Initial Cost	826145,01	850713,8	+3,0%	779264,4	-5,7%
Operation Cost	165236,13	139657,7	-15,5%	191962,5	+16,2%
End of life Cost	105073,81	114568,3	+9,0%	112141,4	+6,7%
Total Cost	1096454,96	1104940	+0,8%	1083368	-1,2%

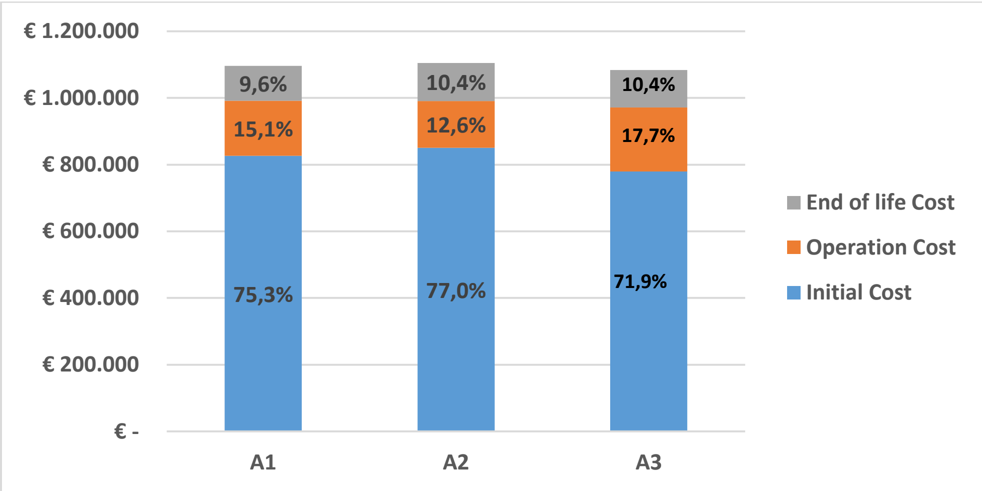


Figure 51: Total lifecycle costs of A1, A2 and A3

Figure 52 compares the total lifecycle costs (LCC) for the different case studies A1, A2, and A3. In this particular comparison, it is evident that the composite steel solution (A3) is better than both its concrete equivalent (A2) and the integral solution A1 when considering the initial costs. On the other hand, it is evident that the integral steel composite solution is the best choice in terms of minimizing the end-of-life costs. The concrete solution led to high initial costs and end-of-life costs. In summary, the conventional composite bridge solution was found to be cheaper by a margin of 1.2% as compared to the integral bridge; and the concrete bridge is 0.8% more expensive than the integral bridge.

It is noted that the end-of-life costs are much lower than operation or construction costs due to the fact that these costs occur at year 100 and are discounted with a yearly discount rate fixed at 2%.

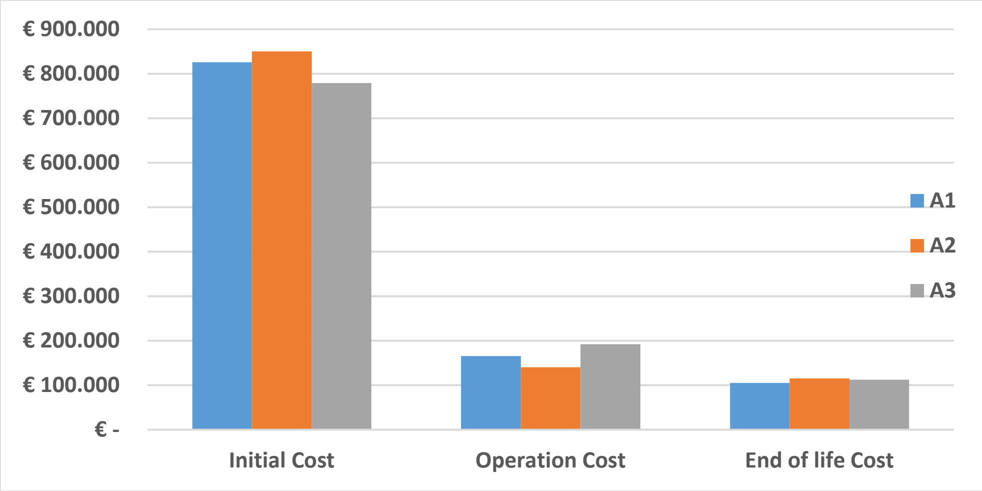


Figure 52: Total Lifecycle costs for each case study

2.4.5 Alternative maintenance scenarios

Besides the standard scenario, two alternative maintenance scenarios, namely "lack of money" and "prolonged life" scenarios have been studied. Lack of money scenario refers to the situation in which the frequency of maintenance is lowered to cope with budget restrictions. On the other hand, the prolonged life scenario considers that a decision is made at year 80 to keep the bridge in service longer than the designed service life (130 years instead of 100). Maintenance actions strategy is adapted at the end of service life to ensure an adequate level of performance of the bridges until year 130.

- *Analysis of reference case study A1*

Figure 53 shows the total lifecycle costs for case study A1 with standard, "lack of money" and "prolonged life" maintenance scenarios.

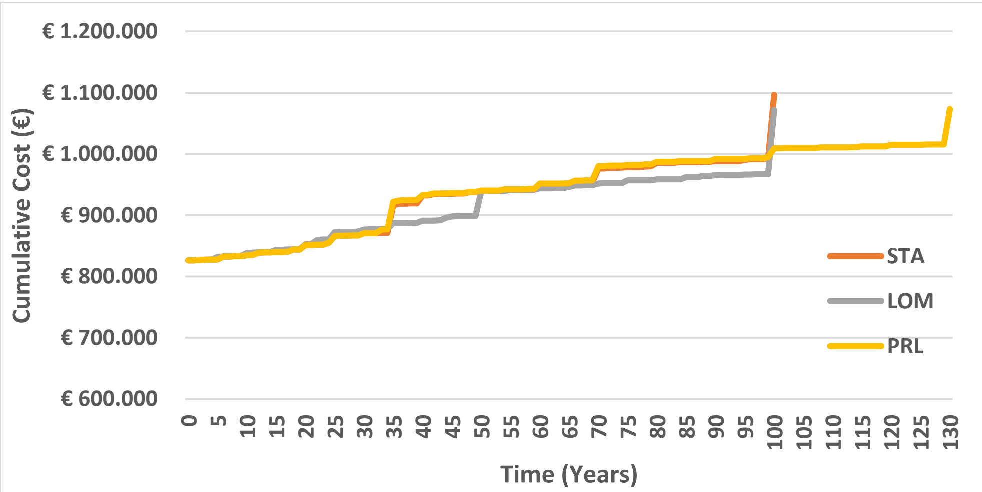


Figure 53: Lifecycle costs for A1 with the "standard", "lack of money", and "prolonged life" maintenance scenarios

It is noted that the rate of increase of lifecycle costs is lower after year 80 than that at the beginning of the service life since costs are discounted with a fixed yearly discount rate of 2%. The lack of money and prolonged life scenarios resulted in 2.2% and 4% lower LCC value, respectively, as compared to the standard scenario. The reason for the decrease in the total lifecycle cost for the prolonged life scenario is the highly taxed/discounted end-of-life cost at year 130. The net present value of end-of-life cost in the prolonged life scenario (at year 130) is computed to be 55% of that from the standard scenario (at year 100).

- *Analysis of reference case study A2*

Figure 54 shows the total lifecycle costs for case study A2 with standard, “lack of money” and “prolonged life” maintenance scenarios. With the prestressed concrete bridge solution here, slightly lower LCC value has been registered for the “prolonged life” scenario albeit the longer service life of the bridge. The reason for the decrease in the total lifecycle cost for the prolonged life scenario is the highly taxed/discounted end-of-life cost at year 130. The net present value of end-of-life cost in the prolonged life scenario (at year 130) is computed to be 55% of that from the standard scenario (at year 100).

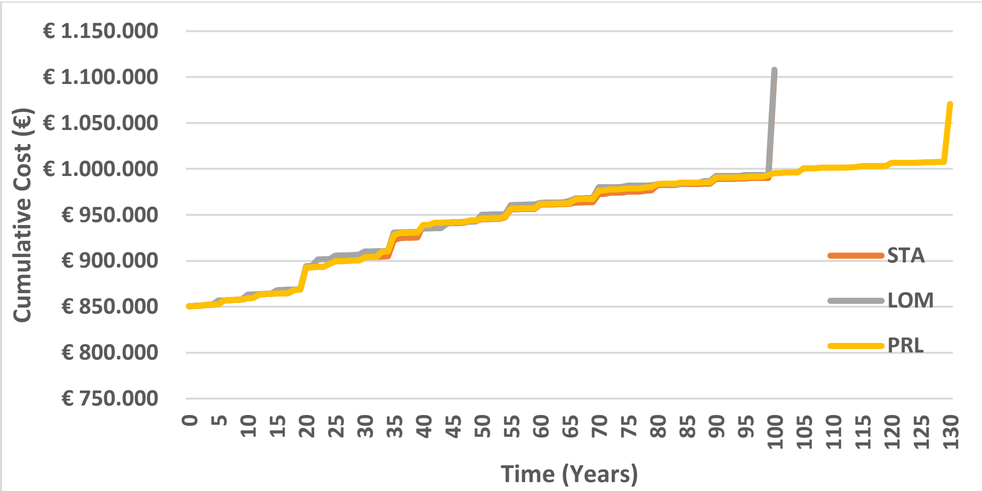


Figure 54: Lifecycle costs for A2 with the “standard”, “lack of money”, and “prolonged life” maintenance scenarios

- *Analysis of reference case study A3*

Figure 55 shows the total lifecycle costs for case study A3 with standard, “lack of money” and “prolonged life” maintenance scenarios. Slightly higher LCC value has been registered for the “lack of money” and “prolonged life” scenarios, albeit the longer service life of the latter scenario. The reason for the decrease in the total lifecycle cost for the prolonged life scenario is the highly taxed/discounted end-of-life cost at year 130. The net present value of end-of-life cost in the prolonged life scenario (at year 130) is computed to be 55% of that from the standard scenario (at year 100).

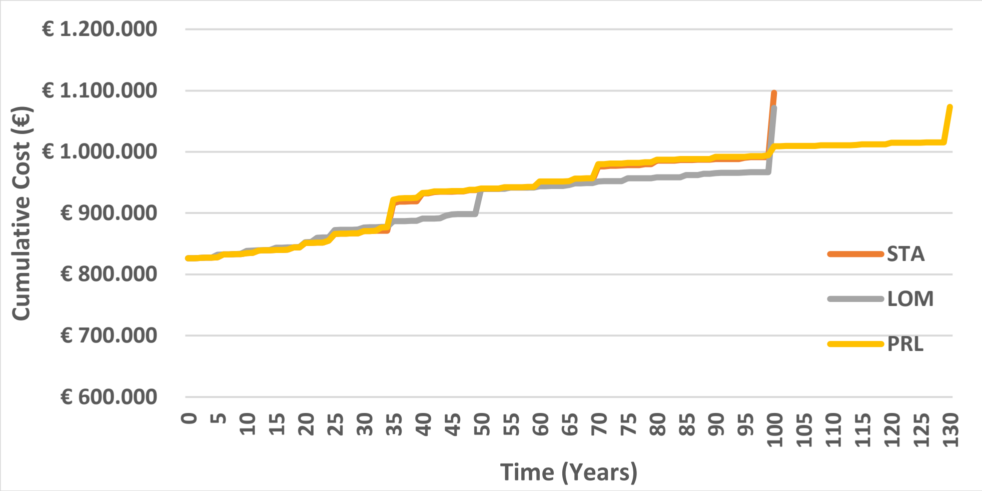


Figure 55: Lifecycle costs for A3 with the "standard", "lack of money", and "prolonged life" maintenance scenarios

2.5 Lifecycle Social Analysis

Two maintenance scenarios have been studied for user costs' calculation: (i) a "day" scenario where most actions are carried out during the day (from 6:00 AM to 10:00 PM) and the bridge has one lane closed for major maintenance actions (road surface/waterproofing layer replacement); (ii) "night" scenario, similar to the "day" scenario except that most of the maintenance actions are carried out during the night (from 10:00 PM to 6:00 AM).

Figure 56 details the user costs for case studies A1 with "day" and "night" scenario. It is noted that the user inconvenience is reduced if work is carried out during the night since there is less traffic than during the day.

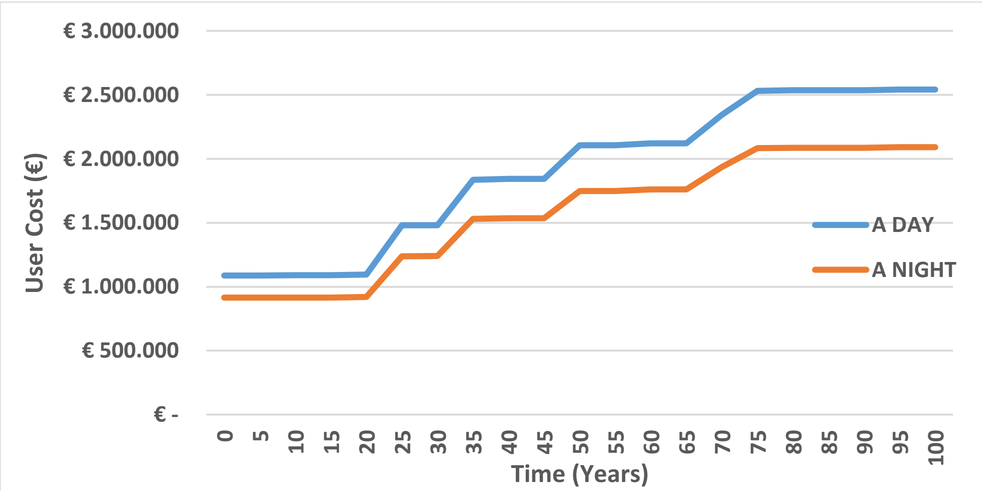
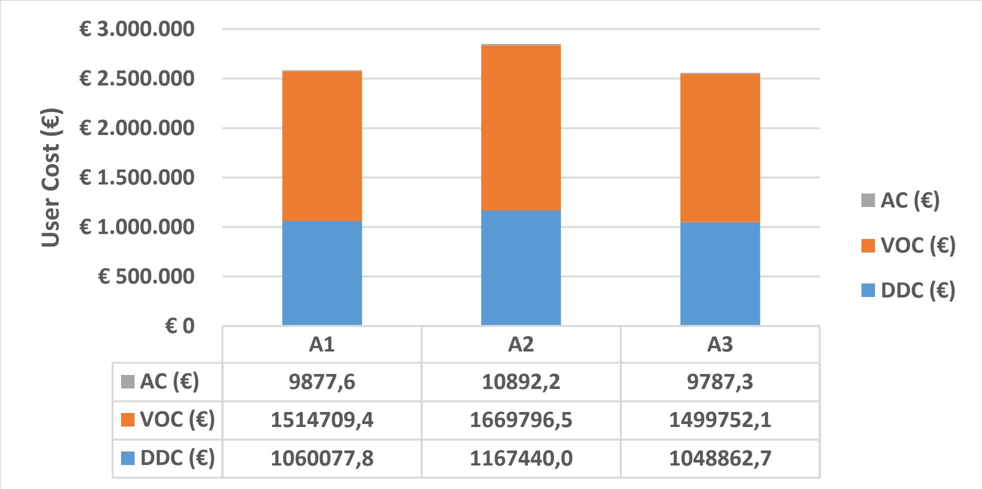


Figure 56: User costs for case studies A1 with "day" and "night" scenarios.

A1 and A3 resulted in comparable difference in user costs of 1%. It is also observed in Figure 57, that the user costs associated with case A1 were found to be lower than those for case A1 by 10.2%. This difference can be explained by the need longer days of maintenance in the last two bridges as a result of the bearings involved [that don't exist in A1] and the additional work required for the middle pier in bridge A2 and A3.



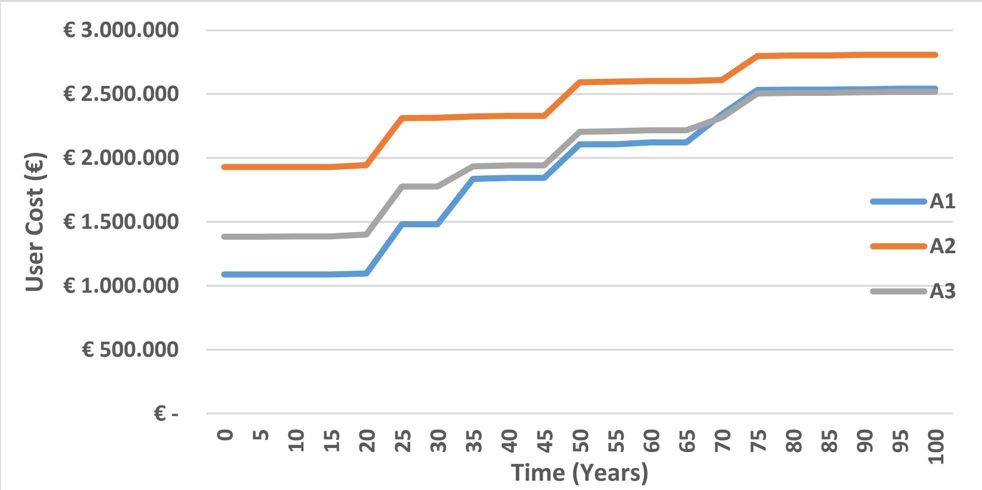


Figure 57: User costs for case studies A1, A2 and A3 with the standard scenario and day work plan.

Now, with the user costs computed, an overall user cost comparison of the three bridges is presented in Table 50 . One can understand from the figures/numbers that the user cost constitutes a large portion of the lifecycle cost for bridges crossing motorways that are operational at the time of construction of the bridge. The integral bridge is 10.2% cheaper than its concrete equivalent (A2) and 1.0% more expensive than the conventional composite bridge (A3) with a pier at mid-span.

Table 50: Comparison of user cost between Cases A1, A2, and A3

	Case Study A1 (€)	Case Study A2 (€)	Variation relative to A1	Case Study A3 (€)	Variation relative to A1
User cost	2584664,83	2848129	+10,2%	2558402	-1,0%

Note once again, due to restrictions in the current version of the SBRI+ Tool, all lifecycle analyses are made considering only 1 lane closed for traffic in each direction [three lanes open for traffic in each direction] for a duration of A1=154 days, A2 = 273 days and A3 = 196 days. If we had considered more lanes closed, which is the reality, the costs due to traffic congestion (user costs) will lead to higher differences between the case studies; and the integral bridge would be the best choice as it causes less obstruction to traffic.

2.5.1 Alternative maintenance scenarios

As was the case for LCA and LCC, for the user's costs, the alternative maintenance scenarios: "lack of money" and "prolonged life" have been studied and compared with the standard maintenance scenario.

- *Analysis of reference case study A1*

Figure 58 shows the user costs for case study A1 with standard, "lack of money" and "prolonged life" maintenance scenarios.

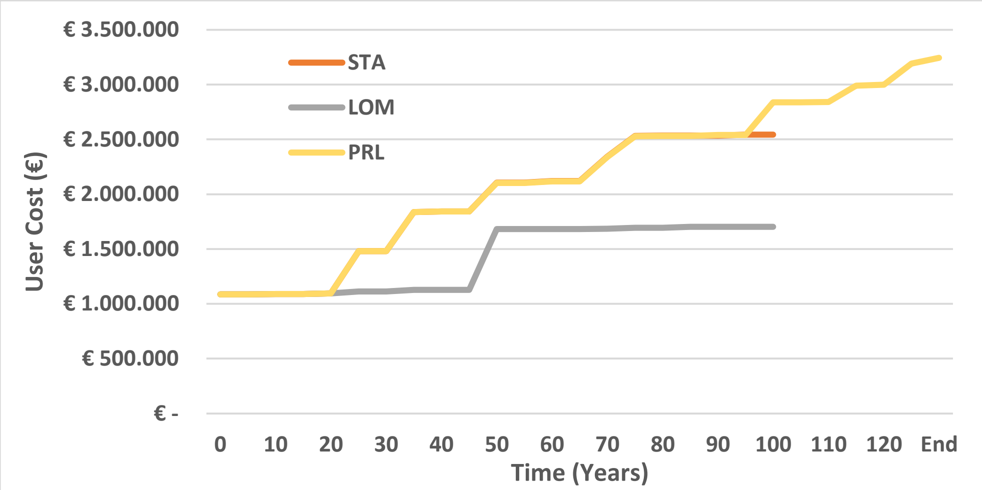


Figure 58: User costs for A1 with "standard", "lack of money", and "prolonged life" maintenance scenarios

- *Analysis of reference case study A2*

Figure 59 shows the total lifecycle costs for case study A2 with standard, "lack of money" and "prolonged life" maintenance scenarios.

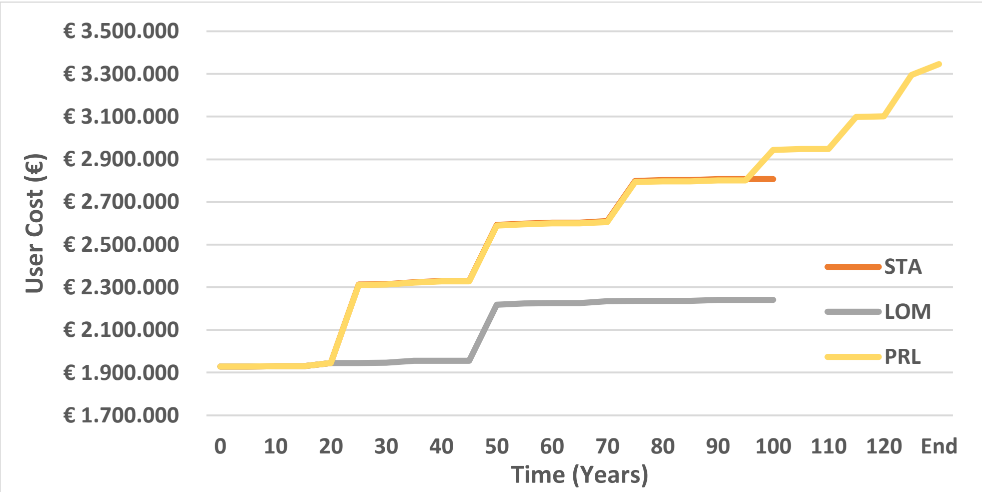


Figure 59: User costs for A2 with "standard", "lack of money", and "prolonged life" maintenance scenarios

- *Analysis of reference case study A3*

Figure 60 shows the total lifecycle costs for case study A2 with standard, “lack of money” and “prolonged life” maintenance scenarios.

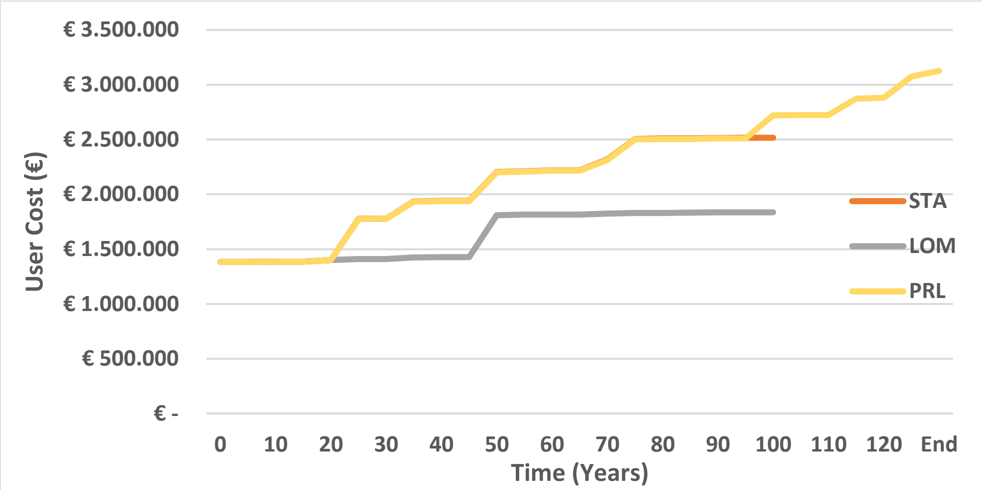


Figure 60: User costs for A3 with “standard”, “lack of money”, and “prolonged life” maintenance scenarios

In all three cases A1, A2, and A3, the “lack of money” scenario resulted in lower user costs than the standard scenario while the “prolonged life” scenario resulted in higher user costs as maintenances that are more frequent are made to the bridge to prolong its service life, which consequently leads to traffic obstructions thereby user costs.

2.6 Discussion of the Results for case A

It can be observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories. The production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage, the impacts are mainly caused by traffic congestion. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides a reduction of impacts owing to the fact that traffic count is lesser at night.

In terms of Lifecycle costs, it is evident from the case studies that the integral and conventional steel composite bridges exhibited preferable characteristics. The Initial cost was found higher for the in situ concrete bridge (A2) in comparison to the other two composite variants, namely the integral (A1) and the conventional (A3) steel composite solutions. However, the operation and demolition costs are lower in case A1, due to the lack of bearings and the corresponding maintenance operations. The operation costs are lower owing to its nature. It avoids the need for the maintenance of bearings, as it has none. The application of the different scenarios to these case studies reveals the lack of money scenario has the lower LCC value. Interestingly, the prolonged life scenario too leads to lower LCC (not considering the social costs). The reason for the decrease in the total lifecycle cost for the prolonged life scenario is the highly taxed/discounted end-of-life cost at year 130. The net present value of end-of-life cost in the prolonged life scenario (at year 130) is computed to be 55% of that from the standard scenario (at year 100).

Once more, the social aspects of the LCA prove that the night shift is favorable in reducing the impacts on user cost. The user costs associated with the in situ concrete solution corresponding to the case A2 were 10.2% higher than those for the integral composite bridge case A1. The integral and conventional composite bridges caused comparable user costs with the latter gaining 1% preference. The comparison between the different scenarios reveals that the “lack of money” scenario has lower user costs than the standard scenario while the “prolonged life” scenario has the higher user costs. However, it should be noted that this comes at the expense of degradation of the bridge which may ultimately lead to a decision to replace the bridge altogether – resulting in substantially higher costs.

3 CASE STUDY – BRIDGE TYPE B

3.1 Description of the Case Study B1

3.1.1 Definition of bridge systems, geometry, and parameters

The Case B1 describes a three-span highway bridge, with theoretical length equal to 44.00+77.50+44.00=165.60 m and deck width equal to 11.50 m, Figure 61. The steel-concrete composite deck consists of 3 welded I-shaped steel girders (S355 N), 2.40 m high, with a center to center spacing equal to 4.00 m, placed on-site by launching. The superstructure is supported and seismically isolated by anchored (though replaceable) normal damping rubber bearings. Each reinforced concrete (C30/37) pier consists of two circular columns Φ160 with a center-to-center spacing equal to 5.40 m, which are connected transversally with a rectangular pier head. The substructure (piers and r/c abutments) are deeply founded by 8-pile groups.

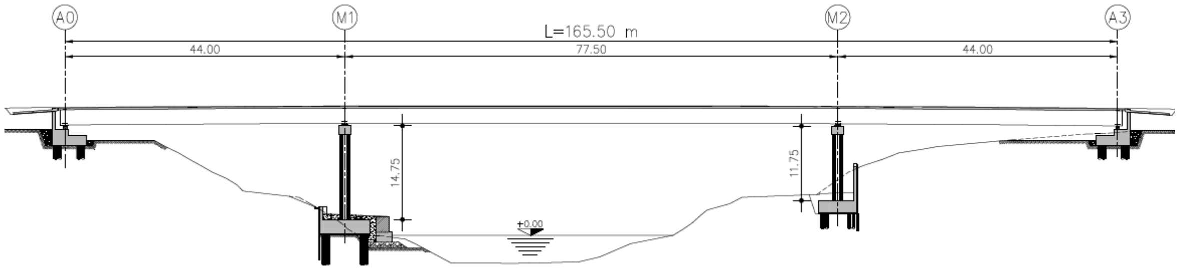


Figure 61: Case B1 Longitudinal view

The road cross-section consists of two traffic lanes 3.75 m and 3.50 m, two shoulders 0.75 m and 0.50 m and a sidewalk 1.50 m wide. The roadway, as well as the sidewalk, are bordered by safety barriers and railing, respectively, Figure 62.

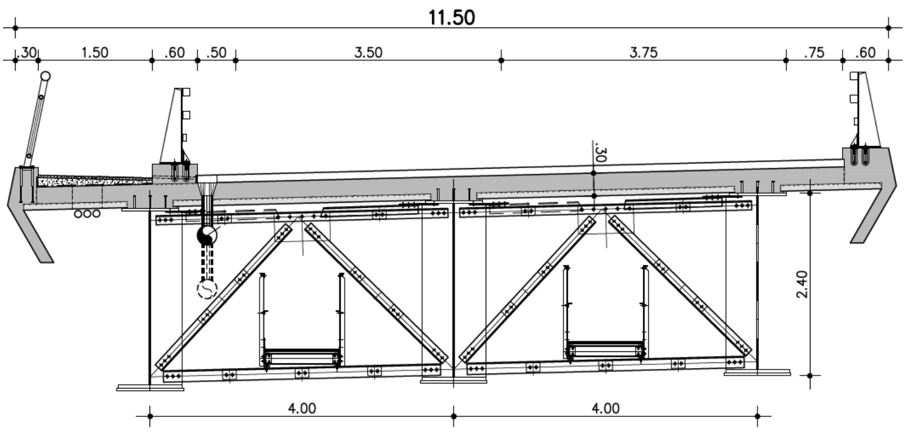


Figure 62: Case B1 Typical cross section

The steel-concrete composite deck consists of 3 welded I-shaped steel girders (S355 N), 2.40 m high, with a center to center spacing equal to 4.00 m, placed on-site by launching. The upper flange is variable from 750 mm to 880 m wide, and the lower one 880 mm. The deck slab (C30/37) consists of a 0.20 m layer cast in-situ on precast slabs 0.10 m thick. The three steel girders are connected transversally every 8.80 m by a K-shaped diaphragm, which is formed with L-type steel cross-sections. At each supporting cross-section, a plated steel diaphragm is formed.

The superstructure is supported and seismically isolated by anchored (though replaceable) normal damping rubber bearings (type C according to EN1337). Bearings are placed below each main girder in its supporting plane. At the abutments 2x3 NDRB 400x500x241mm (t_{el}=121mm), and at the piers 2x3 NDRB 700x800x235mm (t_{el}=120mm) are used.

The reinforced concrete (C25/30) abutments are 12.60 m wide and their total height is 5.90 m. The deep foundation of each abutment consists of a pile head 1.50 m thick and 5.40 m long, and 8 Φ120 piles 38 m long. Each reinforced concrete (C30/37) pier consists of two circular columns Φ160 with a center-to-center spacing equal to 5.40 m, which are connected transversally with a rectangular pier head 1.30 m high and 1.80 m wide. The deep foundation of each pier consists of a pile head 7.80x12.60x1.50 m and 8 Φ120 piles 38 m long. LCA, LCC, and LCS analyses are performed on this bridge in the following sections. This example is only meant to show the LCA assessment in long span bridges and no comparison is made to the results obtained from the analyses.

3.1.2 Design considerations

The most significant quantities for case B are presented in the following table:

Table 51: Quantities of Case B provided to perform LCA and LCC analysis

Description	Unit	Case B	Unit	Unit cost* (Greece 2015)
Substructure				
Excavations	[m³]	1900	[€/m³]	1,50
Backfilling	[m³]	510	[€/m³]	5,00
Abutments' concrete C25/30	[m³]	405	[€/m³]	95,00
Abutments' reinforcement B500C	[kg]	38600	[€/kg]	0,80
Piers' concrete C30/37	[m³]	505	[€/m³]	150,00
Piers' reinforcement B500C	[kg]	87300	[€/kg]	0,80
Piles' concrete C20/25	[m³]	1345	[€/m³]	130,00
Piles' reinforcement B500C	[kg]	215960	[€/kg]	0,80
Superstructure				
Structural steel S355N	[kg]	725000	[€/kg]	2,50
Corrosion protection	[m²]	7600	[€/m²]	9,00
Deck's concrete C30/37	[m³]	685	[€/m³]	110,00
Deck's reinforcement B500C	[kg]	117100	[€/kg]	0,80
Bearings	[pcs]	12		
	[lt]	1080	[€/lt]	45,00
Roadway				
Pavement's asphalt layers (2x5cm)	[m²]	2x1675	[€/m²]	6,00
Pavement's waterproofing membrane	[m²]	2090	[€/m²]	11,40
Gullies	[kg]	3297	[€/kg]	4,90
Gutters PVC Φ200	[m]	200	[€/m]	8,60
Expansion joint T200	[m]	23	[€/m]	2900,00
Safety barriers	[kg]	21775	[€/kg]	1,70
Railings	[kg]	4190	[€/kg]	1,90

(*) The provided unit costs refer to the direct construction costs. In order to take the general expenses and profit of the Contractor into account, these costs were increased by 30%. Note also that these values are for the bridge in one traffic direction. The same bridge exists in the other direction of traffic. For this reason, LCA, LCC, and LCS effects have been doubled in the calculations that follow.

3.2 Traffic analysis

For the base year of the study, an estimated Average Daily Traffic (ADT) of 12000 vehicles/day was used in the calculations. It was considered that the percentages of light-weight vehicles and heavy-weight vehicles are 88% and 12% of the ADT, respectively. A distribution of hourly traffic was assumed for the motorway as shown in Figure 63. It is assumed that the traffic growth over time follows equation (3) (See item 5.3 of Part A) where a growth rate of 0.5% is considered.

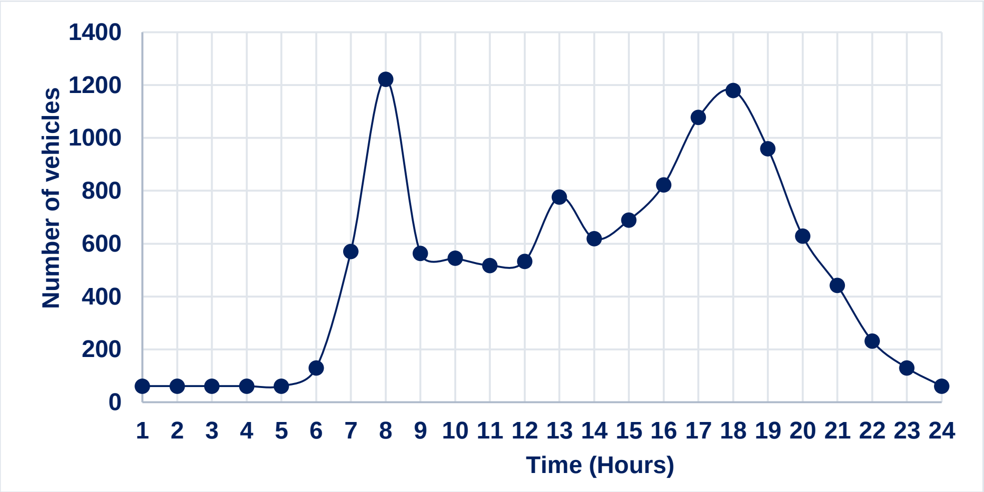


Figure 63: Hourly traffic distribution for B1

3.3 Lifecycle Environmental Analysis

3.3.1 Material production stage

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 64.

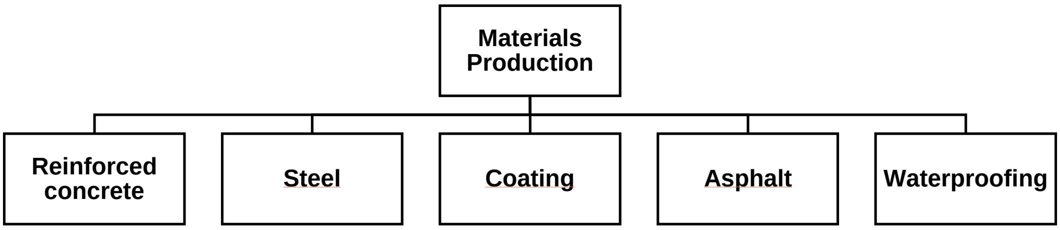


Figure 64: Material production stage

- *Environmental analysis*

The results obtained for the construction stage are presented in Table 52. It is concluded that the production of structural steel and reinforced concrete are the main processes contributing to global impacts in the material production stage. The same results are plotted in Figure 65.

Table 52: Environmental impacts at the material production stage per impact category [B1]

Impact Category	Unit	Total	Reinforced Concrete	Steel	Coating	Asphalt	Waterproof layer
ADP Fossil	MJ	5,19E+07	1,88E+07	2,86E+07	5,06E+05	2,74E+06	1,27E+06
AP	Kg SO_2 eq.	1,36E+04	5,90E+03	7,30E+03	1,06E+02	1,28E+02	1,33E+02
EP	Kg PO_4 eq.	1,24E+03	6,16E+02	5,68E+02	5,14E+00	1,61E+01	3,93E+01
GWP	Kg CO_2 eq.	5,40E+06	2,75E+06	2,53E+06	3,15E+04	5,48E+04	3,07E+04
ODP	Kg R11 eq.	8,14E-02	1,13E-02	5,73E-02	5,87E-08	4,60E-08	1,28E-02
POCP	Kg C_2H_4	2,03E+03	6,45E+02	1,28E+03	4,12E+01	4,85E+01	1,24E+01

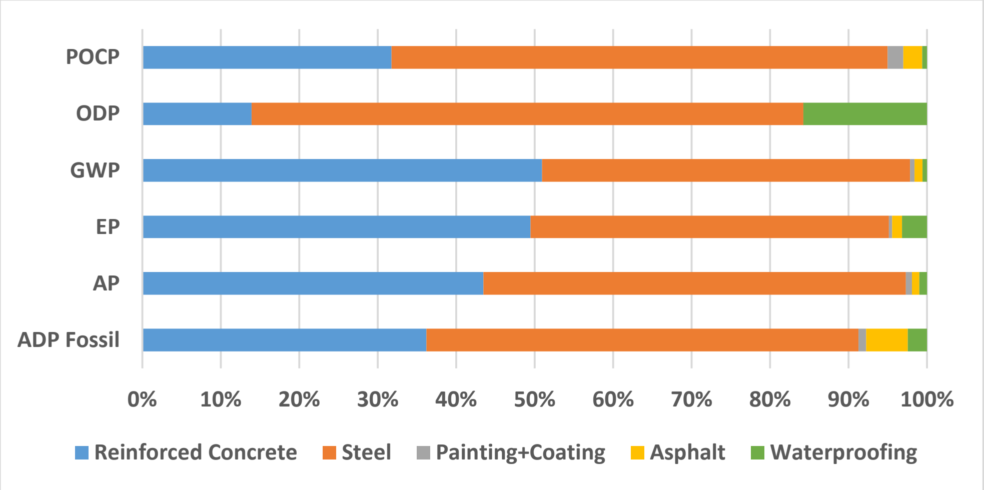


Figure 65: Contribution analysis of construction elements at the material production stage [B1]

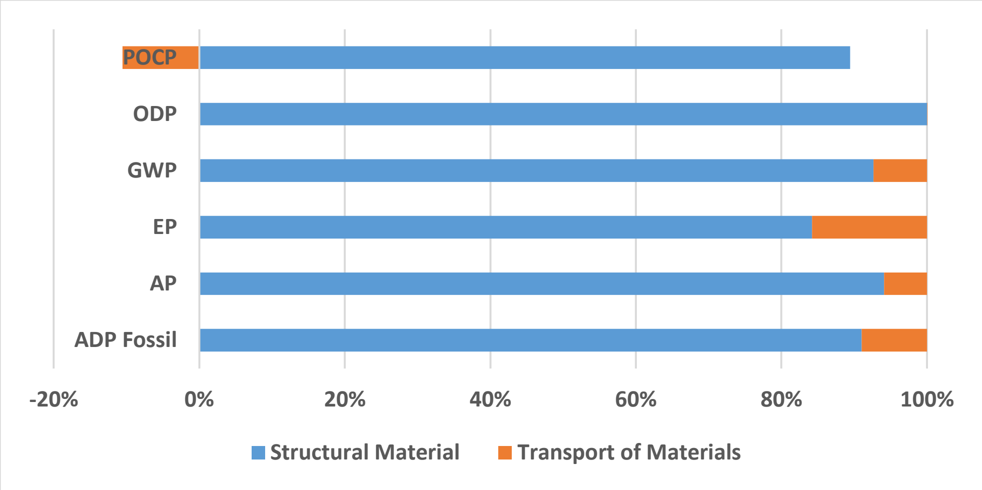
3.3.2 Construction stage

- *Environmental analysis*

The results of the construction stage of case study B1 are presented in Table 53 and illustrated in Figure 66. The operations related to the structural materials represent the main contribution to the environmental impacts.

Table 53: Environmental at the construction stage [B1]

Impact Category	Unit	Total	Structural Material	Transport of Materials
ADP Fossil	MJ	2,39E+06	2,18E+06	2,14E+05
AP	Kg SO_2 eq.	5,88E+02	5,53E+02	3,47E+01
EP	Kg PO_4 eq.	5,22E+01	4,39E+01	8,24E+00
GWP	Kg CO_2 eq.	2,11E+05	1,96E+05	1,55E+04
ODP	Kg R11 eq.	3,43E-03	3,43E-03	5,21E-09
POCP	Kg C_2H_4	8,18E+01	9,27E+01	-1,09E+01



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 66: Contribution analysis of processes at the construction stage [B1]

3.3.3 Operation stage

The maintenance scheme provided in Table A4 - Annex A indicates the traffic restraints above the bridge, over the years, in which maintenance activities take place.

- *Environmental analysis*

The results of the operation stage for case B1 are presented in Figure 67, for the day work scenario.

Table 54: Environmental impacts at the operation stage [B1 day work]

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Waterproofing layer	Traffic Congestion
ADP Fossil	MJ	8,25E+07	1,38E+07	1,32E+06	7,13E+05	2,55E+06	6,42E+07
AP	Kg SO_2 eq.	4,81E+03	6,49E+02	2,75E+02	3,55E+02	2,66E+02	3,26E+03
EP	Kg PO_4 eq.	7,73E+02	8,28E+01	1,34E+01	5,01E+01	7,86E+01	5,48E+02
GWP	Kg CO_2 eq.	1,26E+06	2,78E+05	8,18E+04	2,36E+05	6,15E+04	5,98E+05
ODP	Kg R11 eq.	2,56E-02	2,31E-07	1,53E-07	1,54E-06	2,56E-02	2,06E-06
POCP	Kg C_2H_4	8,54E+02	2,39E+02	1,07E+02	1,56E+01	2,48E+01	4,68E+02

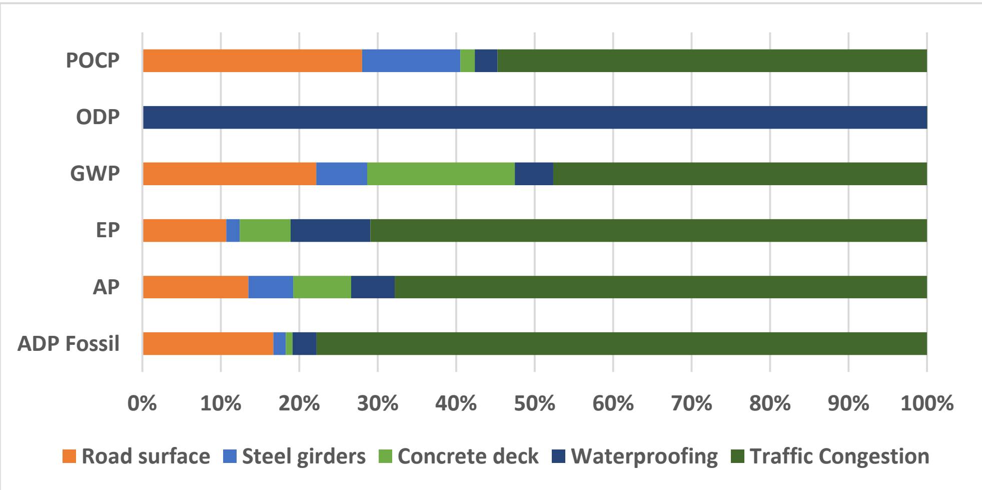


Figure 67: Contribution analysis of processes during the operation stage [B1 day work]

The results of the operation stage for the night work scenario of case B1 are presented in Figure 68.

Table 55: Environmental impacts at the operation stage [B1 night work]

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Waterproofing layer	Traffic Congestion
ADP Fossil	MJ	5,61E+07	1,38E+07	1,32E+06	7,13E+05	2,55E+06	3,77E+07
AP	Kg SO_2 eq.	3,45E+03	6,49E+02	2,75E+02	3,55E+02	2,66E+02	1,90E+03
EP	Kg PO_4 eq.	5,46E+02	8,28E+01	1,34E+01	5,01E+01	7,86E+01	3,21E+02
GWP	Kg CO_2 eq.	1,00E+06	2,78E+05	8,18E+04	2,36E+05	6,15E+04	3,44E+05
ODP	Kg R11 eq.	2,56E-02	2,31E-07	1,53E-07	1,54E-06	2,56E-02	1,19E-06
POCP	Kg C_2H_4	6,60E+02	2,39E+02	1,07E+02	1,56E+01	2,48E+01	2,74E+02

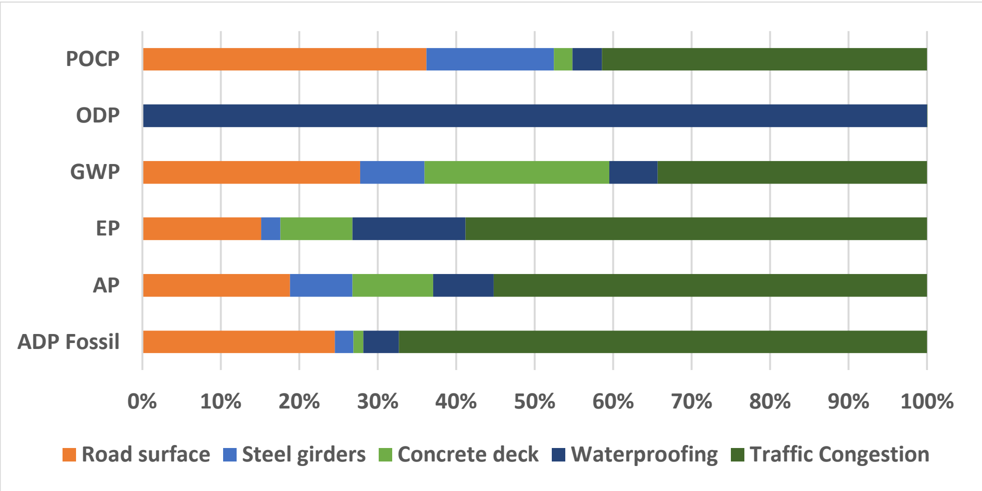


Figure 68: Contribution analysis of processes during the operation stage [B1 night work]

As can be seen in Table 56, the major contribution for all impact categories come from the road surface, steel girders, waterproofing layer and traffic congestion in both scenarios. Although for the “night scenario”, the contribution from the traffic congestion is slightly lower than in the day work scenario with reductions up to 32% in some impact categories.

Table 56: Comparison of environmental impacts between day and night work at the operation stage [B1]

Impact Category	Unit	Case B1 Day	Case B1 Night	Variation relative to B1 Day
ADP Fossil	MJ	8,25E+07	5,61E+07	-32,0%
AP	Kg SO_2 eq.	4,81E+03	3,45E+03	-28,2%
EP	Kg PO_4 eq.	7,73E+02	5,46E+02	-29,4%
GWP	Kg CO_2 eq.	1,26E+06	1,00E+06	-20,2%
ODP	Kg R11 eq.	2,56E-02	2,56E-02	-0,0%
POCP	Kg C_2H_4	8,54E+02	6,60E+02	-22,7%

3.3.4 End-of-life stage

- *Environmental analysis*

Total emissions per impact category of this stage are indicated in Figure 69, which also indicates the contribution of each process per impact category. The negative values in Figure 69 represent the credits given to the recycling processes.

Table 57: Environmental impacts per process at the end-of-life stage [B1]

Impact Category	Unit	Total	Disposal	Transport	Recycling
ADP Fossil	MJ	8,87E+06	1,68E+07	3,27E+05	-8,28E+06
AP	Kg SO_2 eq.	5,93E+03	7,75E+03	5,29E+01	-1,87E+03
EP	Kg PO_4 eq.	1,02E+03	1,05E+03	1,26E+01	-5,17E+01
GWP	Kg CO_2 eq.	5,33E+05	1,30E+06	2,37E+04	-7,91E+05
ODP	Kg R11 eq.	2,51E-02	1,27E-05	7,93E-09	2,51E-02
POCP	Kg C_2H_4	3,10E+02	7,45E+02	-1,67E+01	-4,19E+02

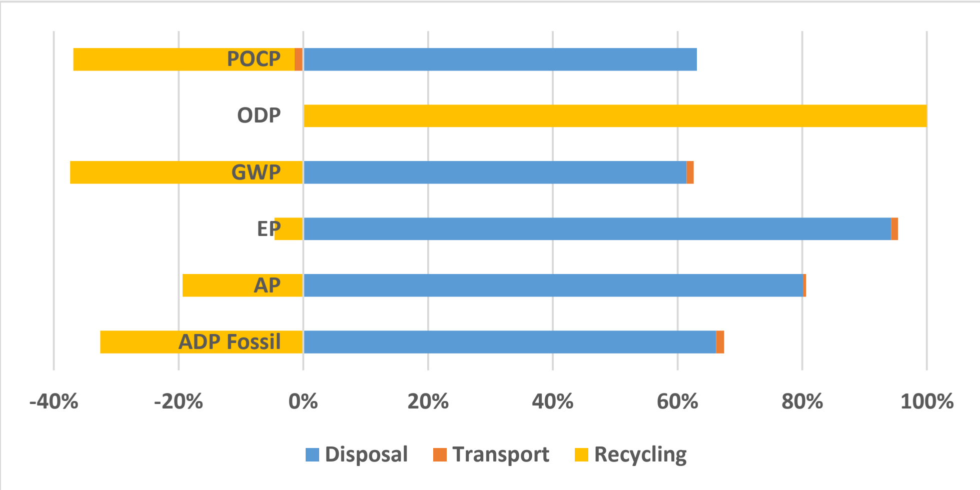


Figure 69: Contribution analysis of processes at the end-of-life stage [B1]

The disposal process bears the highest contribution while transportation imparts little impact on the different categories. It can also be noted that the recycling process contributes gains the environment in all impact categories except ODP.

3.3.5 Results of the lifecycle environmental analysis

- *Aggregate lifecycle results for case B1*

In the previous sections, the partial results per stage have been presented. In this subsection, the results of the different stages are summed up in relation to each impact category and the aggregate results are presented in Table 58, considering the day work plan in the standard maintenance scenario.

Table 58: Aggregate lifecycle environmental impacts per lifecycle stage [B1]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	1,46E+08	5,19E+07	2,39E+06	8,25E+07	8,87E+06
AP	Kg SO_2 eq.	2,49E+04	1,36E+04	5,88E+02	4,81E+03	5,93E+03
EP	Kg PO_4 eq.	3,09E+03	1,24E+03	5,22E+01	7,73E+02	1,02E+03
GWP	Kg CO_2 eq.	7,40E+06	5,40E+06	2,11E+05	1,26E+06	5,33E+05
ODP	Kg R11 eq.	1,36E-01	8,14E-02	3,43E-03	2,56E-02	2,51E-02
POCP	Kg C_2H_4	3,28E+03	2,03E+03	8,18E+01	8,54E+02	3,10E+02

To understand the contribution of each stage to the aggregated result better, these results are also shown in Figure 70.

The material production stage is the stage that most contributes to all the impact categories, except for the ADP Fossil. The operation stage has the second major contribution for the impact categories while the end-of-life stage contributes the third highest contributions. Stage of construction has a negligible contribution for all impact categories.

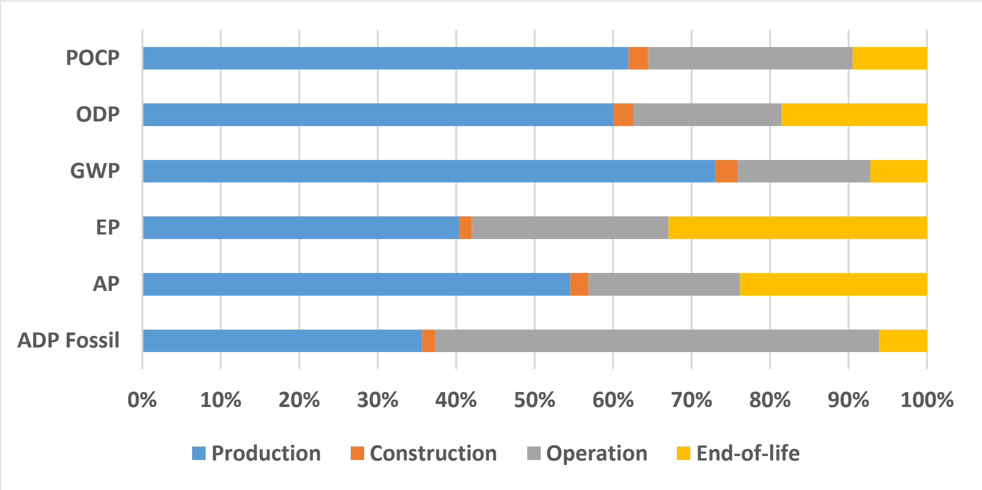


Figure 70: Contribution of each stage per impact category [B1]

3.3.6 Alternative maintenance scenarios

In this section, two additional alternative maintenance plans are considered. The first alternative maintenance scenario refers to the “lack of money” situation, in which the frequency of maintenance is changed to cope with budget restrictions. The second alternative maintenance scenario refers to the “prolonged life” situation, in which the service life of the bridge is extended to 130 years.

Both alternative scenarios only affect the operation stage. Hence, the results presented in this section refer only to the operation stage. The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 59 for the standard and both alternative maintenance scenarios.

Table 59: Comparison of environmental impacts at the operation stage with different maintenance scenarios [B1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	8,25E+07	5,16E+07	-37,4%	1,57E+08	+90,0%
AP	Kg SO_2 eq.	4,81E+03	2,91E+03	-39,4%	9,00E+03	+87,3%
EP	Kg PO_4 eq.	7,73E+02	4,66E+02	-39,7%	1,44E+03	+86,3%
GWP	Kg CO_2 eq.	1,26E+06	7,07E+05	-43,7%	2,29E+06	+82,7%
ODP	Kg R11 eq.	2,56E-02	1,28E-02	-50,0%	2,56E-02	+0,0%
POCP	Kg C_2H_4	8,54E+02	5,28E+02	-38,2%	1,52E+03	+77,4%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 60 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 60: Comparison of environmental impacts per year at the operation stage with different maintenance scenarios [B1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	8,25E+05	5,16E+05	-37,4%	1,21E+06	+46,1%
AP	Kg SO_2 eq.	4,81E+01	2,91E+01	-39,4%	6,92E+01	+44,1%
EP	Kg PO_4 eq.	7,73E+00	4,66E+00	-39,7%	1,11E+01	+43,3%
GWP	Kg CO_2 eq.	1,26E+04	7,07E+03	-43,7%	1,76E+04	+40,5%
ODP	Kg R11 eq.	2,56E-04	1,28E-04	-50,0%	1,97E-04	-23,1%
POCP	Kg C_2H_4	8,54E+00	5,28E+00	-38,2%	1,17E+01	+36,4%

From the results, it is evident that the “lack of money” scenario reduces the impacts by an average of 41.4%. The effort to prolong the service life of the bridge with the “prolonged life” scenario led to 31.2% increased impacts in all environmental categories except ODP.

3.4 Lifecycle Cost Analysis

3.4.1 Initial construction costs

The initial cost of the structure, including the material transport cost, is 8.735.404,67 €, which is about 2.293,48 €/m^2. Figure 71 shows the proportion of the costs for the substructure, superstructure and the roadway, which are calculated based on the bill of materials and unit costs indicated in Table 51.

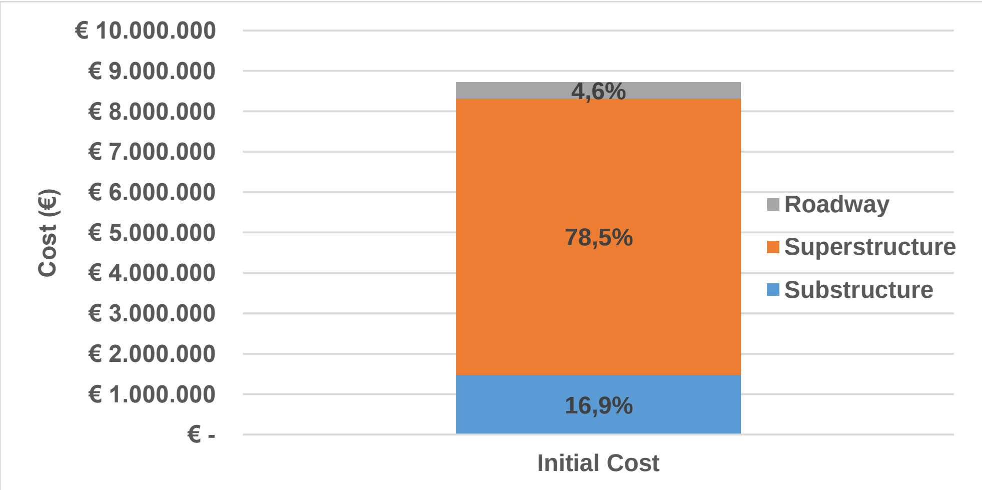


Figure 71: Initial cost of B1

3.4.2 Operation costs

Over the period of 100 years, the bridges examples are assumed to be maintained and rehabilitated according to the plan indicated in the Annex – Table A1, the definition of a standard Inspection scenario. The costs per year are based on the unit costs and frequencies indicated in Table A6. These costs are illustrated in Figure 72.

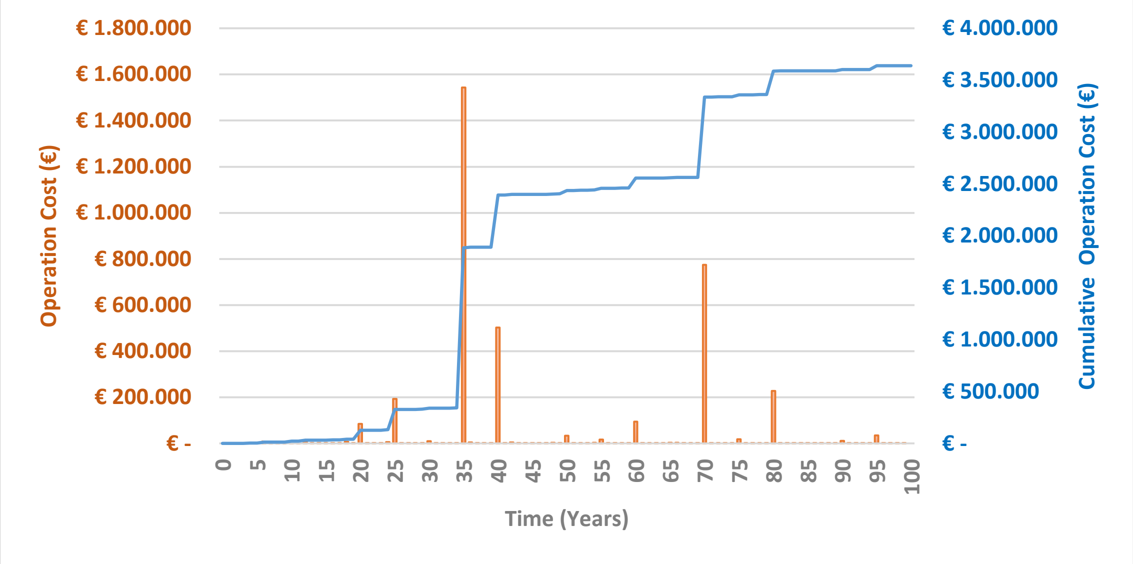


Figure 72: Operation costs of the bridge B1 over its service life

3.4.3 End-of-life costs

A summary of the end-of-life costs is given in Table 61.

Table 61: End-of-life costs for B1

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	2367,92	-26882,53	50	490,28
Concrete	14112	19479,21	50	2921,88
Earthwork	9640	66531,89	10	399,19
Bitumen	804	5548,93	20	66,59
Others	-	403,91	-	-
			Sub-Total (€)	68959,35
			Demolition cost (€)	52574,00
			Total Cost (€)	121533,35

(*) Considering disposal cost for concrete 10 €/tonne, for steel scrap value of 100 €/tonne and transportation cost of 0.03 €/tonne/km.

(**) The amount of steel calculated above includes both the reinforcement steel bars and structural steel sections/plates and connections. Note: The costs are given in their present value calculated according to equation 2 at a discount rate of 2%.

3.4.4 Total Lifecycle costs

The compilation of the costs calculated in the previous sections leads to the total lifecycle net present cost (LCC) of 11.488.362,07 €, using a discount rate of 2% and the first end-of-life scenario. This represents a total cost of about 3.016,27 €/m^2. The costs of the bridge for each stage are illustrated in Figure 73.

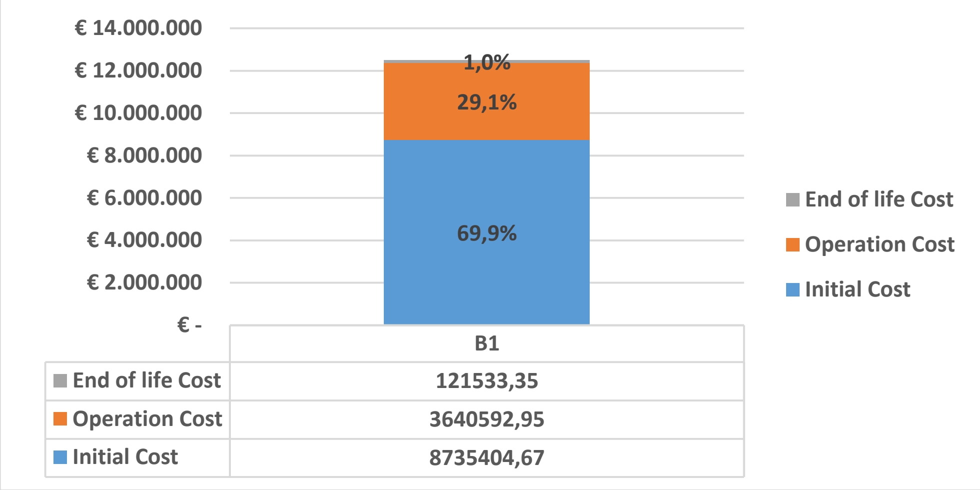


Figure 73: Lifecycle costs of B1

3.4.5 Alternative maintenance scenarios

Besides the standard scenario, two alternative maintenance scenarios, namely “lack of money” and “prolonged life” scenarios have been studied. Lack of money scenario refers to the situation in which the frequency of maintenance is lowered to cope with budget restrictions. On the other hand, the prolonged life scenario considers that a decision is made at year 80 to keep the bridge in service longer than the designed service life (130 years instead of 100). Maintenance actions strategy is adopted at the end of service life to ensure an adequate level of performance of the bridges until year 130.

Figure 74 shows the total lifecycle costs for case study B1 with the “standard”, “lack of money” and “prolonged life” maintenance scenarios.

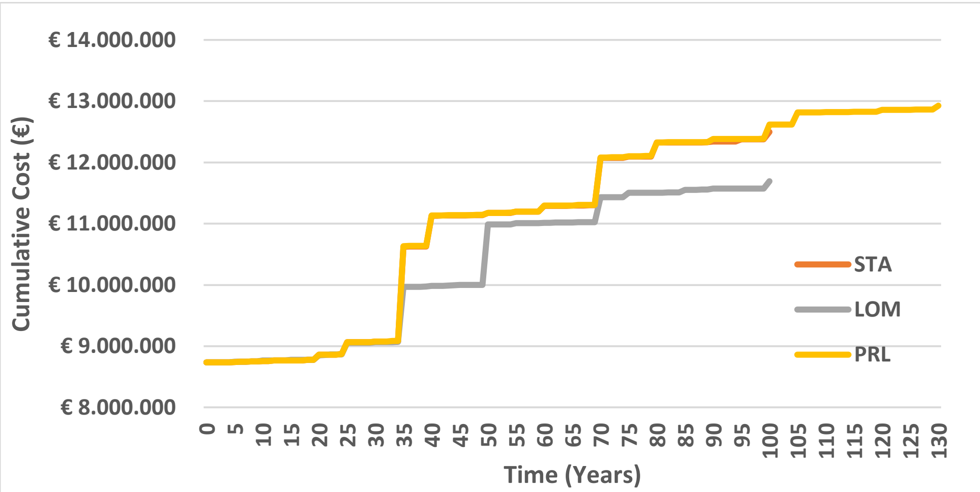


Figure 74: Lifecycle costs for B1 with “standard”, “lack of money”, and “prolonged life” maintenance scenarios

The prolonged life maintenance scenario costs 3% more than the standard scenario since frequent maintenance activities take place in this scenario in order to keep the bridge in service for prolonged time. This result is contrary to the previous examples in that the end-of-life cost is much smaller compared to the cost of maintenance operations carried out on the bridge after year 100. The lack of money scenario resulted in reduced costs than the standard scenario.

3.5 Lifecycle Social Analysis

Two maintenance scenarios have been studied for user costs' calculation: (i) a "day" scenario where most actions are carried out during the day (from 6:00 AM to 10:00 PM) and the bridge has one lane closed for major maintenance actions (road surface/waterproofing layer replacement); (ii) "night" scenario, similar to the "day" scenario except that most of the maintenance actions are carried out during the night (from 10:00 PM to 6:00 AM).

Figure 75 details the user costs for case study B1 with "day" and "night" scenario. It is noted that the user inconvenience is reduced if work is carried out during the night since there is less traffic than during the day. The peak increase at year 80 is due to increased costs on users during the maintenance of the road surface and waterproofing layers.

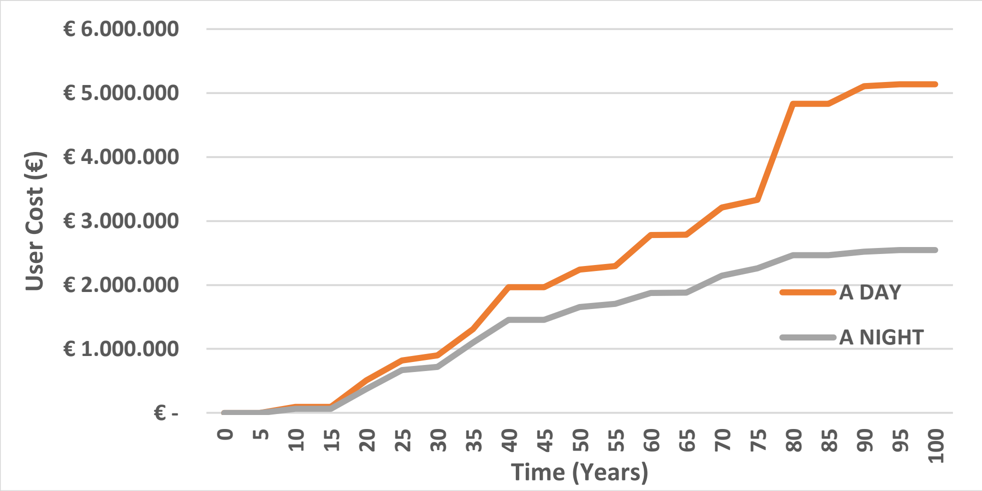


Figure 75: User costs for case studies B1 with "day" and "night" scenarios.

3.5.1 Alternative maintenance scenarios

As was the case for LCA and LCC, for the user's costs, the alternative maintenance scenarios: "Lack of Money" and "Prolonged Life" have been studied and compared with the standard maintenance scenario.

Figure 76 shows the user costs for case study B1 with standard, "lack of money" and "prolonged life" maintenance scenarios.

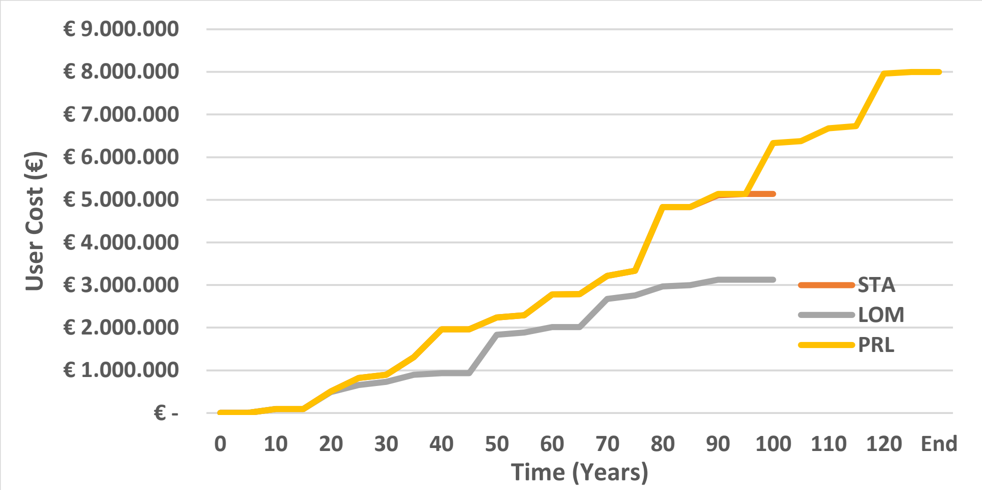


Figure 76: User costs for B1 with "standard", "lack of money", and "prolonged life" maintenance scenarios

The "lack of money" scenario resulted in a slightly lower user costs at the end than the standard scenario while the "prolonged life" scenario resulted in higher user costs as the service life of the bridge is prolonged.

3.6 Discussion of the Results for the case B

In this case study for long span motorway bridges, it can be observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories. The production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage, the impacts are mainly caused by traffic congestion. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides a reduction of impacts owing to the fact that traffic count is lesser at night.

Once more, the social aspects of the LCA prove that the night shift is considered favorable in reducing the impacts on user cost. The user costs calculated for the two different working shifts on the same bridge resulted in a difference of almost 1.5 million €. The application of the different scenarios to this case study reveals that the "lack of money" scenario has lower user costs at the end than the standard scenario while the "prolonged life" scenario has the higher user costs. However, it should be noted that the lower costs for "lack of money" scenario come at the expense of degradation of the bridge which may ultimately lead to a decision to replace the bridge altogether – resulting in substantially higher costs.

4 CASE STUDIES – BRIDGE TYPE C

Four cases are studied for this bridge type: two bridges with steel-concrete composite deck (C1.1 and C2.1), as well as their equivalents with precast prestressed concrete beams (C1.2 and C2.2, respectively).

4.1 Case C1 – Multi-span motorway bridges

4.1.1 Description of the Case Studies

4.1.1.1 Case C1.1: Definition of bridge systems, geometry, and parameters

This bridge, named Viaduto São Sebastião, is located in Portugal on highway A10. The bridge was opened for traffic in 2006. The structural typology of the bridge is a continuous beam with a total length of 308 m distributed over nine spans of 28 m+7x36 m+28 m. The plan layout is a circular curve with a 700 m radius and a constant super-elevation of 7%, Figure 77.

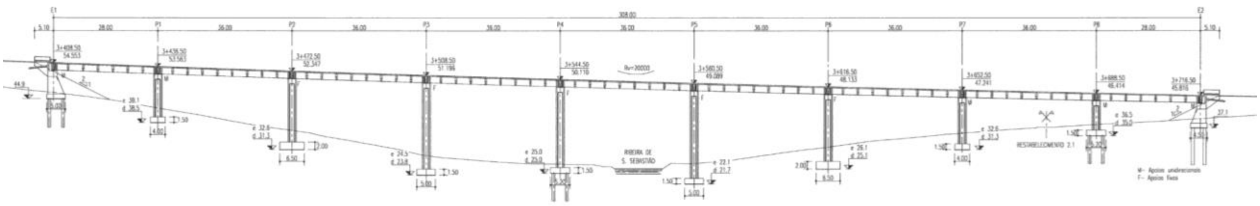


Figure 77: Case C1.1 Longitudinal section

The cross-section of the motorway has a total width of 36.40 m with the following composition as shown in Figure 78.

- 2 x 3 lanes of 3.50 m: 21 m
- 2 right shoulders of 4.50 m: 9 m
- 2 left shoulders of 1.00 m: 2 m
- Central reserve: 2 m
- 2 sidewalks with 1.20 m: 2.40 m

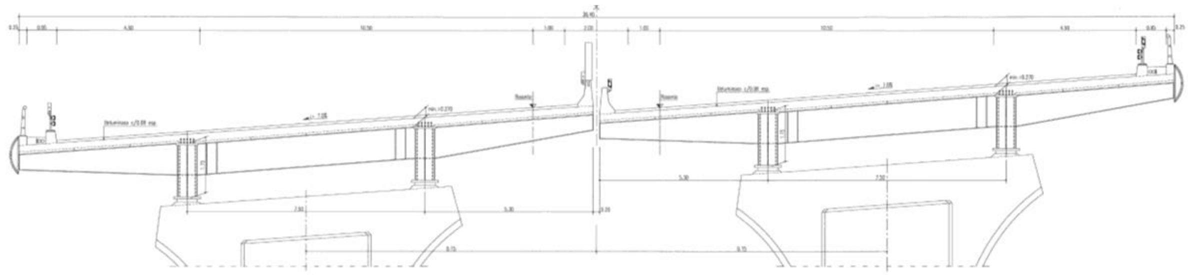


Figure 78: Case C1.1 Typical cross-section

Given the width of the platform, it was decided to design two independent structures, one for each direction of traffic.

Each deck consists of a composite section made up of a reinforced concrete slab supported by two "I-shape" steel plate girders of 1750 mm high. Upper and bottom flanges have constant widths of 700 mm and 850 mm, respectively. Web and flange thicknesses are variable over the length of each span. The maximum plate thickness is 70 mm. Cross-girders, placed every 4m, provide additional support to the concrete slab allowing it to span in two directions. In these alignments, cantilever cross-girders were used for the same purpose. Every support is provided with load bearing stiffener arrangements on both sides of the webs. The construction of the reinforced concrete slab is carried out with precast concrete planks used as lost formwork.

Intermediate supports are single-column bents with hollow sections of reinforced concrete. At the top of the columns, the box section width increases to support both girders of each deck. The higher columns are 26 m high. Columns P2 to P6 support the deck through fixed pot-bearings, therefore, all longitudinal braking forces, temperature, and seismic effects will be absorbed by biaxial bending of this elements. All the other connections between deck and columns are also bearing support but without any longitudinal restraint.

Both end supports are open (spill-through) abutments consisting of buried columns with rectangular cross section of variable height and capped by a cill beam to carry the deck through pot bearings. The deck was constructed by incremental launching. All cross-section except the cast-in-place concrete was launched entirely from on end until its final position. Once the launching process has been completed, provisional bearings were replaced by permanent ones.

4.1.1.2 Case C1.1: Design considerations

The most significant quantities for case C1.1 are presented in the following table:

Table 62: Quantities for case C1.1 provided to perform LCA and LCC analysis

Description	Unit	Case C1.1 (Plate girder composite bridge)	Unit	Unit cost* (Portugal 2006)
Substructure				
Excavation	[m^3]	3310	[€/m^3]	25,33
Backfilling	[m^3]	1810	[€/m^3]	9,68
Formwork - for abutments and columns	[m^2]	8395	[€/m^2]	30,89
Reinforcement steel - except concrete deck	[kg]	897600	[€/kg]	0,93
Concrete - C16/20	[m^3]	89	[€/m^3]	84,66
Concrete - C30/37	[m^3]	3386	[€/m^3]	95,15
Superstructure				
Structural steel S355*	[kg]	1521000	[€/kg]	2,42
Formwork	[m^2]	1325	[€/m^2]	28,64
Reinforcement steel - concrete deck	[kg]	371400	[€/kg]	0,93
Concrete - light weight	[m^3]	96	[€/m^3]	82,31
Concrete C 40/50	[m^3]	3095	[€/m^3]	107,59
Steel connectors including Implementation and quality control	[kg]	31655	[€/kg]	5,66
Left-in-place formwork planks C40/50 with reinforcement steel A500NR	[m^2]	9850	[€/m^2]	42,88

Concrete or steel cornice	[m]	620	[€/m]	203,52
Pot-bearings and elastomeric reinforced bearings	[pcs]	40	[€/pcs]	2682,85
Lamelle (roadway slats steel/ plastic and similar)	[pcs]	108	[€/pcs]	15,97
Roadway				
Surface levelling with concrete bituminous & single bituminous surfacing	[m^2]	22360	[€/m^2]	7,04
Protective device - guardrail	[m]	637	[€/m]	48,22
Protective equipment - railings	[m]	637	[€/m]	100,87
Expansion joint	[m]	72	[€/m]	1167,43
Other work and/or equipment	[gv]	1	[€/gv]	29753,88
Deck launching & deck scaffolding	[gv]	1	[€/gv]	274652,79

(*) Supply, transport and assembling of the plate steel structure, S355 steel plates according to EN10025, including weldings, protective coatings, and all the works needed according to detailed design

4.1.1.3 Case C1.2: Definition of bridge systems, geometry, and parameters

This bridge, named Viaduto Cerro da Barreira, is located in Portugal on highway A2. The bridge was opened for traffic in 2002. The structural typology of the bridge is similar to the previous one. It is also a continuous beam with a total length of 308 m distributed for nine spans of 28 m + 7x36 m +28 m. The plan layout is a horizontal transition curve (A=500) followed by a circular curve with a 1000 m radius, Figure 79.

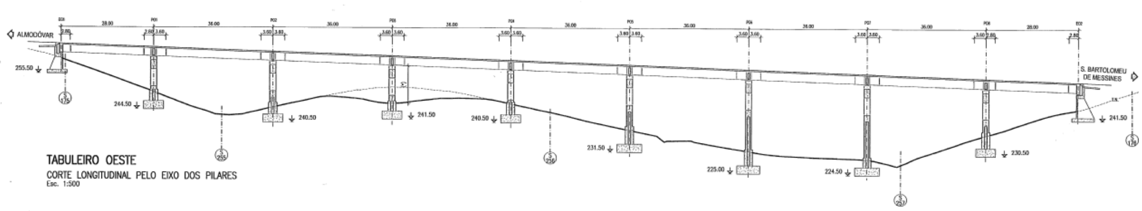


Figure 79: Case C1.2 Longitudinal section

The cross-section of the motorway has a total width of 37.12 m with the following composition:

- 2 x 3 lanes of 3.75 m: 22.5 m
- 2 right shoulders of 3 m: 6 m
- 2 left shoulders of 1.00 m: 2 m
- Central reserve: 4 m
- 2 sidewalks with 1.31 m: 2.62 m

Given the width of the platform and the uneven topography, it was decided to design two independent unaligned structures, one for each direction of traffic.

Each deck consists of a classical post-tensioned reinforced concrete section. The deck slab between girders has a variable thickness of 0.45 m to 0.30 m. The cantilever slabs also have a variable thickness of 0.45 m to 0.20 m. All girders have constant height of 2.70 m.

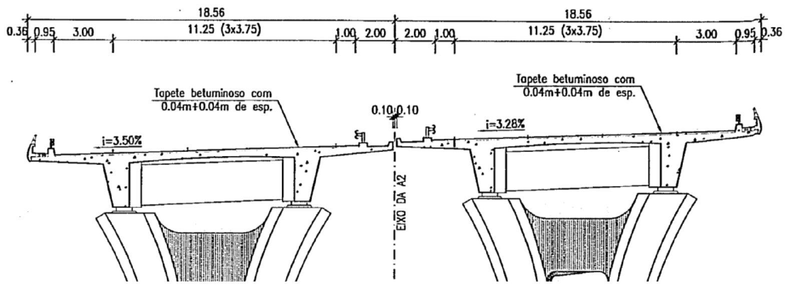


Figure 80: Case C1.2 Typical cross-section

Intermediate supports are single-column bents in reinforced concrete. At the top of the columns, the section width increases to support both girders of each deck. The higher columns have 22 m. Columns P5 to P7 support the deck through elastomeric bearings with rigid restraints in both longitudinal and transverse directions. All the other connections between deck and columns are also bearing support but with elastic restraint in the longitudinal direction and rigid restraint on transverse direction.

Both end supports are open (spill-through) abutments consisting of buried columns with rectangular cross section of variable height and capped by a cill beam to carry the deck through pot bearings. The deck was constructed with a launching girder.

4.1.1.4 Case C1.2: Design considerations

The most significant quantities of case C1.2 are presented in the following table:

Table 63: Quantities for Case C1.2 provided to perform LCA and LCC analysis

Description	Unit	Case C1.2 (Reinforced Concrete bridge)	Unit	Unit cost (Portugal 2002)
Substructure				
Excavation	[m^3]	11077	[€/m^3]	14,60
Backfilling	[m^3]	2846	[€/m^3]	5,10
Formwork - for abutments and columns	[m^2]	12387	[€/m^2]	43,73
Reinforcement steel - except concrete deck	[kg]	1210090,30	[€/kg]	1,17
Concrete - C12/15	[m^3]	191	[€/m^3]	125,98
Concrete - C30/37	[m^3]	7893	[€/m^3]	147,83
Superstructure				
Formwork	[m^2]	18161	[€/m^2]	53,07
Reinforcement steel - concrete deck	[kg]	511481,70	[€/kg]	1,17
Prestressing steel - deck	[kg]	170107,03	[€/kg]	3,88
Concrete - C35/45	[m^3]	7049	[€/m^3]	161,82
Concrete - light weight	[m^3]	45	[€/m^3]	142,88
Concrete or steel cornice	[m]	691	[€/m]	122,47
Elastomeric locking device	[pcs]	24		311,44
Pot-bearings and elastomeric reinforced bearings	[pcs]	44	[€/pcs]	6040,21
Lamelle (roadway slats steel/ plastic and similar)	[pcs]	112	[€/pcs]	27,35
Roadway				

Surface levelling with concrete bituminous & single bituminous surfacing	[m^2]	19036	[€/m^2]	7,72
Covering of buried elements	[m^2]	5847		6,13
Protective device - guardrail	[m]	1323	[€/m]	54,29
Protective equipment - railings	[m]	691	[€/m]	147,98
Expansion joint	[m]	74	[€/m]	4694,63
Other work and/or equipment	[gv]	1	[€/gv]	74910,82
Deck launching & deck scaffolding	[gv]	1	[€/gv]	817444,67

4.1.2 Traffic analysis

For cases studies in C1, it is assumed that the motorway accommodates an Average Daily Traffic (ADT) of 11575 vehicles/day in the base year of the study. It is also considered that the percentages of light-weight vehicles and heavy-weight vehicles are 88% and 12% of the ADT, respectively. The hourly traffic distribution presented in Figure 81 was assumed for the motorway.

It is important to note that the traffic growth over time follows equation (2) (See item 5.3 of Part A) where a growth rate of 0.5% is considered.

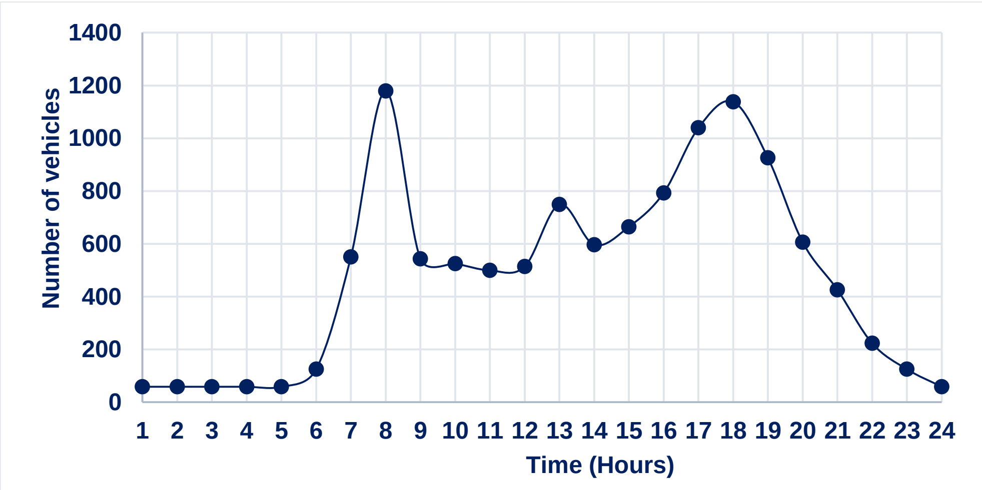


Figure 81: Hourly traffic distribution for case studies C2.1 and C2.2

4.1.3 Lifecycle Environmental Analysis

4.1.3.1 Material production stage

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 82. The data sources are as indicated in Table 8.

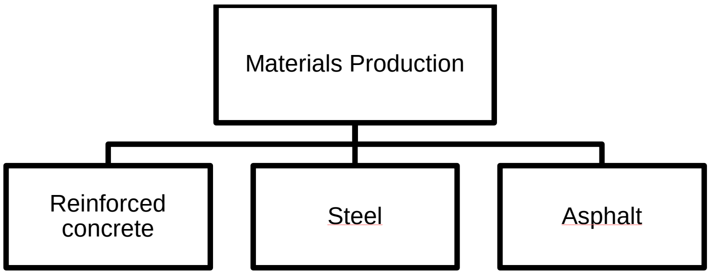


Figure 82: Material production stage

The coating and waterproofing layers are not present in C1.1 and C1.2.

- *Environmental analysis of reference case study C1.1*

The results obtained for the construction stage are detailed in Table 64. It is concluded that the production of structural steel and reinforced concrete are the main processes contributing to global impacts in the material production stage. The same results are plotted in Figure 83.

Table 64: Environmental impacts at the material production stage [C1.1]

Impact Category	Unit	Total	Reinforced Concrete	Structural Steel	Asphalt	Others
ADP Fossil	MJ	6,33E+07	2,50E+07	3,09E+07	7,32E+06	7,49E+04
AP	Kg SO_2 eq.	1,62E+04	7,94E+03	7,90E+03	3,41E+02	3,17E+01
EP	Kg PO_4 eq.	1,47E+03	8,05E+02	6,13E+02	4,29E+01	4,77E+00
GWP	Kg CO_2 eq.	6,65E+06	3,75E+06	2,74E+06	1,46E+05	1,98E+04
ODP	Kg R11 eq.	7,57E-02	1,57E-02	6,01E-02	1,23E-07	1,24E-07
POCP	Kg C_2H_4	2,45E+03	9,23E+02	1,39E+03	1,29E+02	3,89E+00

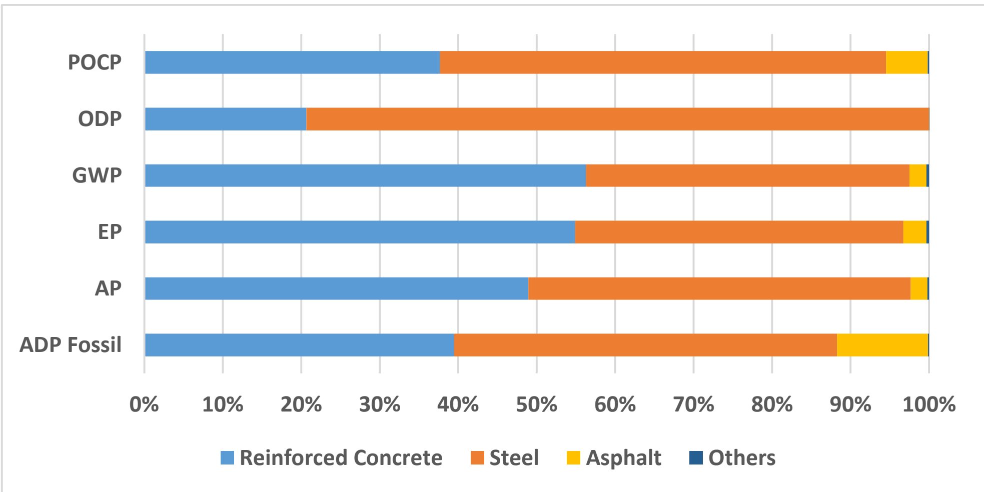


Figure 83: LCA contribution analysis for material groups at the material production stage [C1.1]

- *Environmental analysis of variant C1.2*

The results obtained for the variant case study C1.2 are provided in Table 65 and illustrated in Figure 84.

Table 65: Environmental impacts at the material production stage [C1.2]

Impact Category	Unit	Total	Reinforced Concrete	Steel (Prestressing)	Asphalt	Others
ADP Fossil	MJ	4,76E+07	3,87E+07	2,57E+06	6,23E+06	3,51E+04
AP	Kg SO_2 eq.	1,42E+04	1,32E+04	6,69E+02	2,91E+02	1,49E+01
EP	Kg PO_4 eq.	1,54E+03	1,44E+03	5,30E+01	3,65E+01	2,23E+00
GWP	Kg CO_2 eq.	7,06E+06	6,69E+06	2,36E+05	1,24E+05	9,29E+03
ODP	Kg R11 eq.	2,34E-02	2,13E-02	2,10E-03	1,05E-07	5,80E-08
POCP	Kg C_2H_4	1,57E+03	1,36E+03	1,04E+02	1,10E+02	1,82E+00

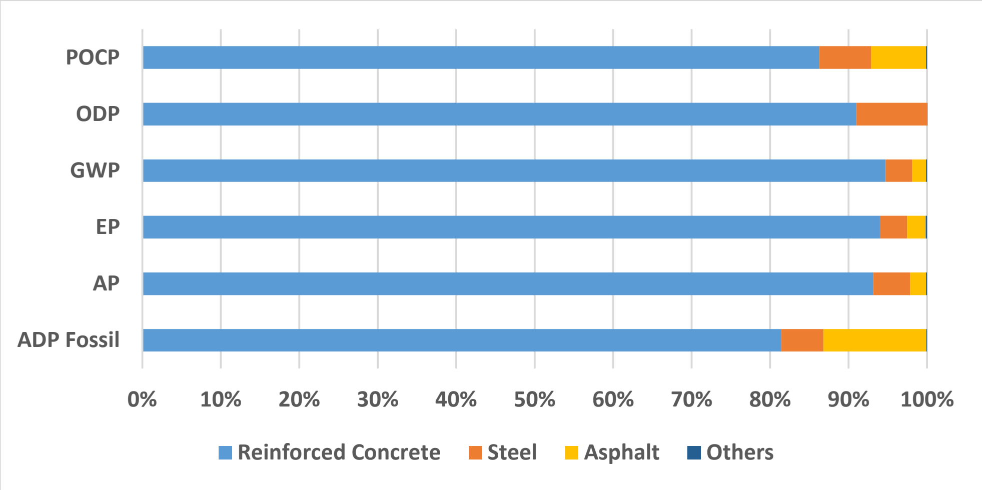


Figure 84: LCA contribution analysis for material groups at the material production stage [C1.2]

Table 66 indicates the variation of the results in comparison to the reference case study C1.1.

Table 66: Variation of the environmental impacts at the material production stage relative to C1.1

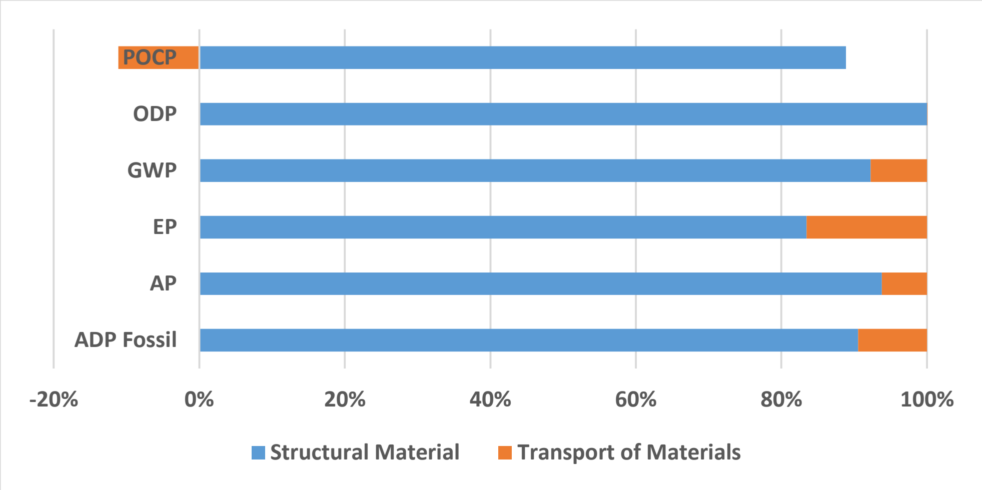
Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	6,33E+07	4,76E+07	-24,8%
AP	Kg SO_2 eq.	1,62E+04	1,42E+04	-12,4%
EP	Kg PO_4 eq.	1,47E+03	1,54E+03	+4,8%
GWP	Kg CO_2 eq.	6,65E+06	7,06E+06	+6,2%
ODP	Kg R11 eq.	7,57E-02	2,34E-02	-69,2%
POCP	Kg C_2H_4	2,45E+03	1,57E+03	-35,9%

It can be observed that solution C1.1 causes 21.9% (Avg.) higher impact on the environment than solution C1.2 in the material production stage.

4.1.3.2 Construction stage

- *Environmental analysis of reference case study C1.1*

The results of the construction stage for the reference case study C1.1 are illustrated in Figure 85. The operations related to on-site structural material productions represent the main contribution to the environmental impacts.

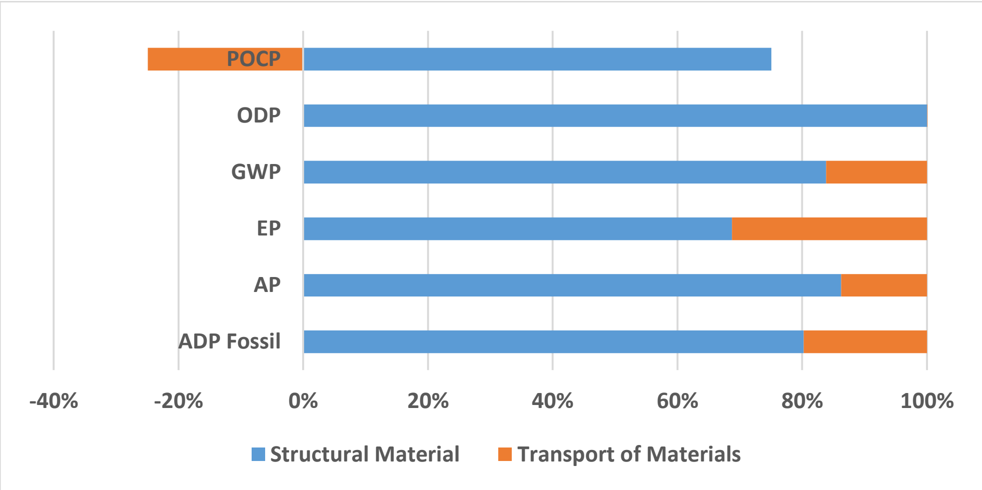


Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 85: Contribution analysis of processes at the construction stage for C1.1

- *Environmental analysis of variant C1.2*

The results obtained for the variant case study C1.2 are shown in Figure 86.



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 86: Contribution analysis of processes at the construction stage for C1.2

Table 67 indicates the variation of the results for case C1.2 relative to the reference case study C1.1.

Table 67: Environmental impacts of C1.2 at the construction stage relative to C1.1

Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	2,83E+06	1,95E+06	-31,1%
AP	Kg SO_2 eq.	6,96E+02	4,54E+02	-34,8%
EP	Kg PO_4 eq.	6,21E+01	4,74E+01	-23,6%
GWP	Kg CO_2 eq.	2,51E+05	1,73E+05	-31,0%
ODP	Kg R11 eq.	3,79E-03	1,17E-03	-69,2%

POCP	Kg C_2H_4	9,54E+01	3,95E+01	-58,6%

Case C1.2 proved to be a better alternative causing reduced environmental impact in the construction stage as compared to case C1.1.

4.1.3.3 Operation stage

The maintenance scheme provided in Table A4 indicates the traffic restraints above the bridge, over the years, in which maintenance activities take place for case studies in C1.

- *Environmental analysis of reference case study C1.1*

The results of the operation stage, for the reference case study C1.1, are given in Figure 87, for the day work scenario.

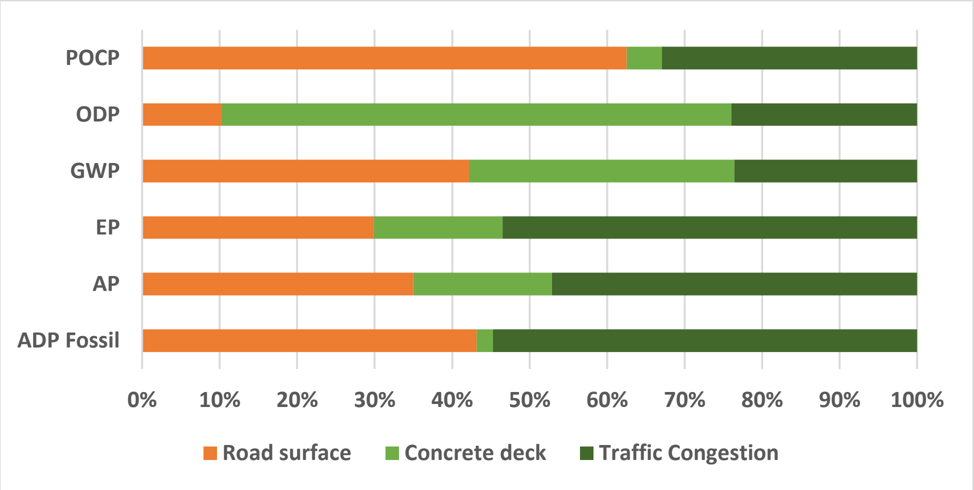


Figure 87: Contribution analysis of processes at the operation stage [C1.1 day work]

For the night work scenario, the results of the operation stage, for the reference case study C1.1, are shown in Figure 88.

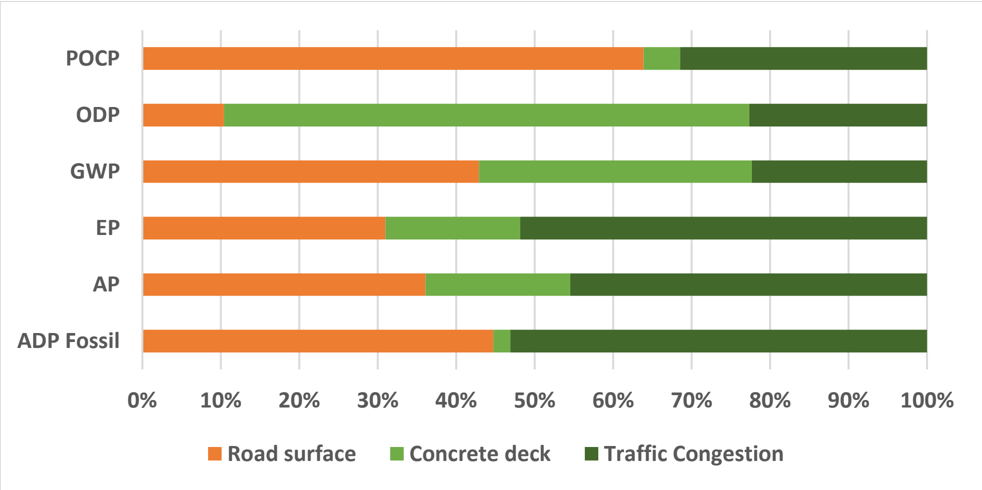


Figure 88: Contribution analysis of processes at the operation stage [C1.1 night work]

In both scenarios, it is observed that the major contribution for all impact categories comes from the road surface, steel girders and traffic congestion; although for the “night scenario” the contribution of the traffic congestion is only slightly (1-4%) lower than in the day work scenario.

- *Environmental analysis of variant C1.2*

The results obtained for the variant case study C1.2 are presented in Table 68, assuming the day work scenario for all case studies. This table also indicates the variation of the results in relation to the reference case study C1.1.

Table 68: Environmental impacts of C1.2 at the operation stage relative to C1.1 [day work]

Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	8,43E+07	8,34E+07	-1,1%
AP	Kg SO_2 eq.	4,91E+03	5,73E+03	+16,6%
EP	Kg PO_4 eq.	7,32E+02	8,57E+02	+17,1%
GWP	Kg CO_2 eq.	1,75E+06	2,28E+06	+30,0%
ODP	Kg R11 eq.	6,00E-06	9,97E-06	+66,1%
POCP	Kg C_2H_4	1,02E+03	9,73E+02	-4,1%

Considering the night work scenario, the results obtained for the variant case study C1.2 are presented in Table 69.

Table 69: Environmental impacts of C1.2 at the operation stage relative to C1.1 [night work]

Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	8,13E+07	8,03E+07	-1,3%
AP	Kg SO_2 eq.	4,76E+03	5,57E+03	+17,0%
EP	Kg PO_4 eq.	7,06E+02	8,30E+02	+17,6%
GWP	Kg CO_2 eq.	1,72E+06	2,25E+06	+30,4%
ODP	Kg R11 eq.	5,90E-06	9,87E-06	+67,2%
POCP	Kg C_2H_4	9,94E+02	9,51E+02	-4,3%

The results show that case C1.2, the concrete solution, causes higher environmental impacts compared to the composite solution, case C1.1, in the operation stage. These variations come as a result of increased maintenance works on the road surface, bearings, expansion joints, and protective devices in case C1.2. Although the concrete solution results in slightly reduced impacts (≤ 4%) in the ADP and POCP impact categories on the environment at this stage, it causes considerably higher impacts on the environment in the other majority of the impact categories. It can be said at this stage that case C1.1 is more friendly to the environment than its concrete equivalent, case C1.2. It could also be noted that the variations between cases C1.1 and C1.2 for day work and night work scenario are similar.

4.1.3.4 End-of-life stage

- *Environmental analysis of reference case study C1.1*

Total emissions per impact category of this stage are indicated in Table 70. Figure 89 shows the contribution of each process per impact category. The negative values in the figure represent the credits given to the recycling process.

Table 70: Environmental impacts at the end-of-life stage per process [C1.1]

Impact Category	Unit	Total	Disposal	Transport	Recycling
ADP Fossil	MJ	1,15E+07	2,04E+07	3,82E+05	-9,34E+06
AP	Kg SO_2 eq.	7,37E+03	9,43E+03	6,19E+01	-2,12E+03
EP	Kg PO_4 eq.	1,24E+03	1,28E+03	1,47E+01	-5,84E+01
GWP	Kg CO_2 eq.	7,15E+05	1,58E+06	2,77E+04	-8,93E+05
ODP	Kg R11 eq.	2,83E-02	1,55E-05	9,28E-09	2,83E-02
POCP	Kg C_2H_4	4,14E+02	9,06E+02	-1,95E+01	-4,73E+02

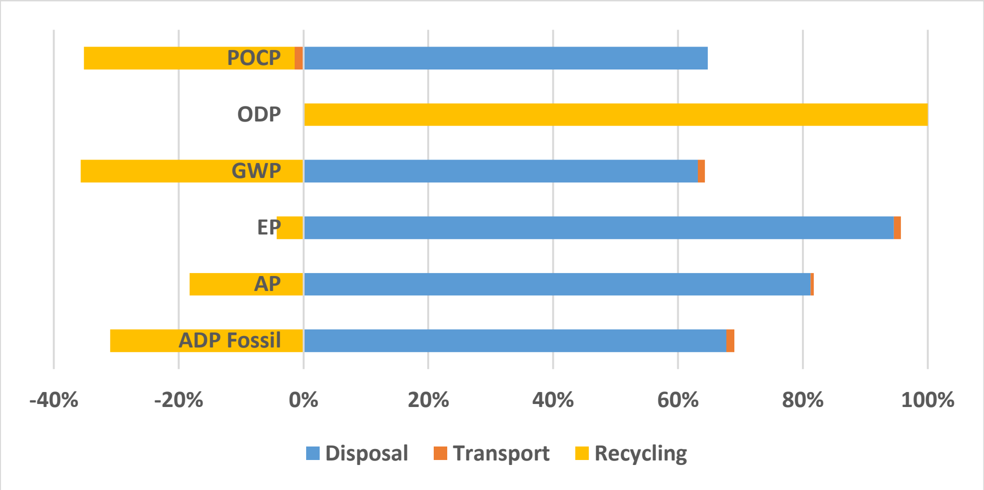


Figure 89: Contribution analysis of processes during the end-of-life stage [C1.1]

- *Environmental analysis of variant C1.2*

Total emissions per impact category of this stage for the variant case study C1.2 are detailed in Table 71 and Figure 90.

Table 71: Environmental impacts at the end-of-life stage per process [C1.2]

Impact Category	Unit	Total	Disposal	Transport	Recycling
ADP Fossil	MJ	4,27E+07	4,30E+07	7,59E+05	-1,06E+06
AP	Kg SO_2 eq.	1,97E+04	1,98E+04	1,23E+02	-2,41E+02
EP	Kg PO_4 eq.	2,72E+03	2,70E+03	2,92E+01	-6,65E+00
GWP	Kg CO_2 eq.	3,28E+06	3,33E+06	5,51E+04	-1,02E+05
ODP	Kg R11 eq.	3,26E-03	3,26E-05	1,84E-08	3,22E-03
POCP	Kg C_2H_4	1,81E+03	1,91E+03	-3,88E+01	-5,38E+01

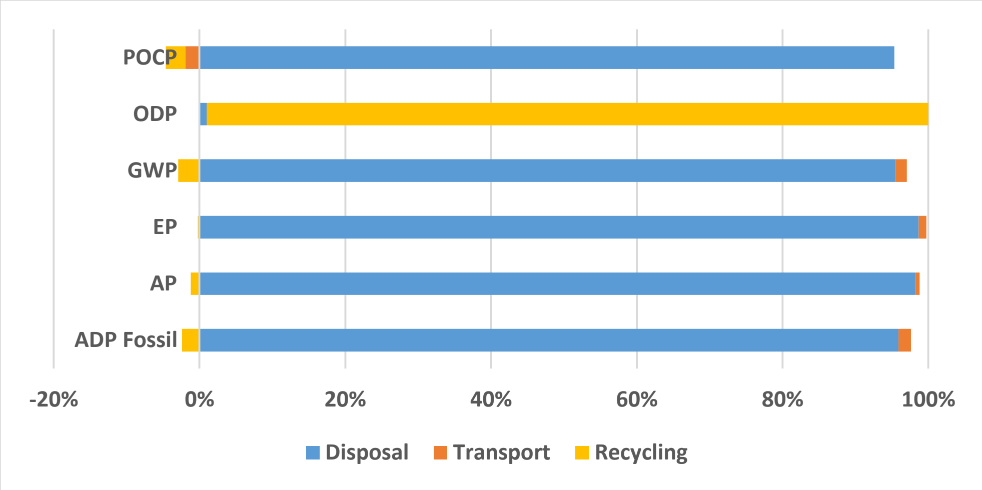


Figure 90: Contribution analysis of processes during the end-of-life stage [C1.2]

In both cases, disposal of concrete and bituminous materials caused the most burden on the environment while the transportation of these materials caused the least impact, relatively. Recycling, on the other hand, benefits the environment in all impact categories except the Ozone Depletion Potential where the recycling process itself gives rise to such emissions. Table 72 indicates the variation of the results of this case study in comparison to the reference case study C1.1. These results are further illustrated in Figure 91.

Table 72: Environmental impacts of C1.2 at the end-of-life stage relative to C1.1

Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	1,15E+07	4,27E+07	+271,9%
AP	Kg SO_2 eq.	7,37E+03	1,97E+04	+167,5%
EP	Kg PO_4 eq.	1,24E+03	2,72E+03	+119,7%
GWP	Kg CO_2 eq.	7,15E+05	3,28E+06	+358,3%
ODP	Kg R11 eq.	2,83E-02	3,26E-03	-88,5%
POCP	Kg C_2H_4	4,14E+02	1,81E+03	+338,4%

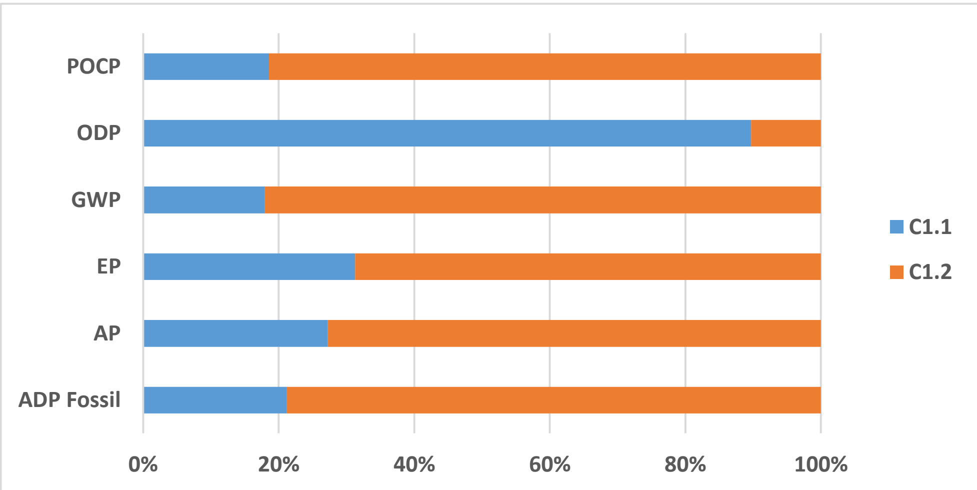


Figure 91: Comparison of C1.1 to C1.2 at end-of-life stage

According to these results, it can be concluded that at this stage the composite bridge solution, case C1.1, led to substantially lower values at the end-of-life stage as a result of the recycling possible with the use of steel as a construction material. However, higher impacts are registered for case C1.1 in the ODP category as a result of the recycling process itself that gives rise to such emissions. Notice, however, that these impacts are generally small in magnitude (in the order of 10^{-2} or lower).

4.1.3.5 Results of the lifecycle environmental analysis

- *Aggregate lifecycle results for case study C1.1*

In the previous sections, the partial results per stage have been presented. In this subsection, the results of the different stages are summed up in per each impact category and the aggregate results are presented in Table 73, considering the day work and standard maintenance scenario.

Table 73: Lifecycle environmental impacts per lifecycle stage [C1.1]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	1,62E+08	6,33E+07	2,83E+06	8,43E+07	1,15E+07
AP	Kg SO_2 eq.	2,92E+04	1,62E+04	6,96E+02	4,91E+03	7,37E+03
EP	Kg PO_4 eq.	3,50E+03	1,47E+03	6,21E+01	7,32E+02	1,24E+03
GWP	Kg CO_2 eq.	9,37E+06	6,65E+06	2,51E+05	1,75E+06	7,15E+05
ODP	Kg R11 eq.	1,08E-01	7,57E-02	3,79E-03	6,00E-06	2,83E-02
POCP	Kg C_2H_4	3,97E+03	2,45E+03	9,54E+01	1,02E+03	4,14E+02

To understand the contribution of each stage to the aggregated result better, these results are also illustrated in Figure 92.

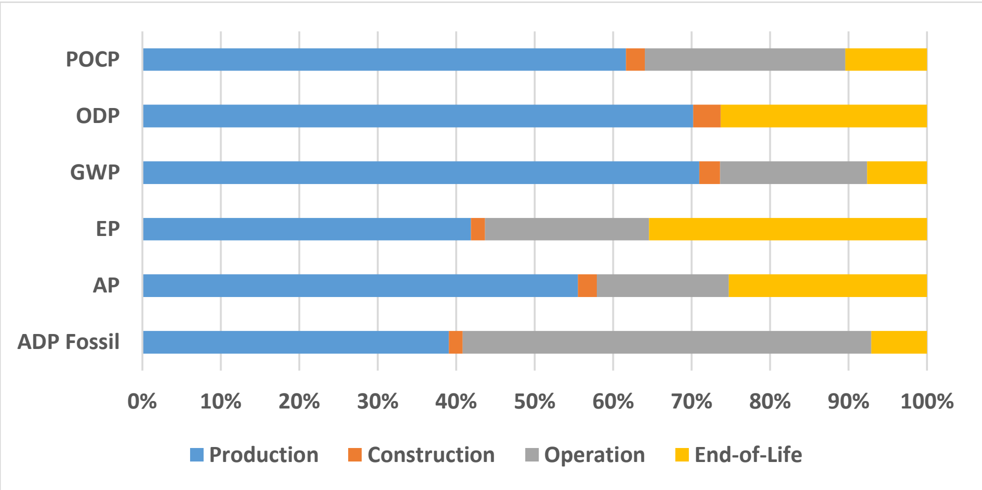


Figure 92: Contribution of each stage per impact category (day work scenario), Case C1.1

The material production stage is the stage that contributes most (56.5% average). The operation stage has the second most contribution with 24.5% average impact followed by the end-of-life stage with 18.6% contribution to the total impacts. The construction stage results in the least impact of 2.4% (Avg.).

- *Aggregate lifecycle results for C1.2*

The results obtained for the variant case studies C1.2 are detailed in Table 74 and Figure 93 considering the day work scenario.

Table 74: Lifecycle environmental impacts per lifecycle stage [C1.2]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	1,76E+08	4,76E+07	1,95E+06	8,34E+07	4,27E+07
AP	Kg SO_2 eq.	4,01E+04	1,42E+04	4,54E+02	5,73E+03	1,97E+04
EP	Kg PO_4 eq.	5,16E+03	1,54E+03	4,74E+01	8,57E+02	2,72E+03
GWP	Kg CO_2 eq.	1,28E+07	7,06E+06	1,73E+05	2,28E+06	3,28E+06
ODP	Kg R11 eq.	2,78E-02	2,34E-02	1,17E-03	9,97E-06	3,26E-03
POCP	Kg C_2H_4	4,40E+03	1,57E+03	3,95E+01	9,73E+02	1,81E+03

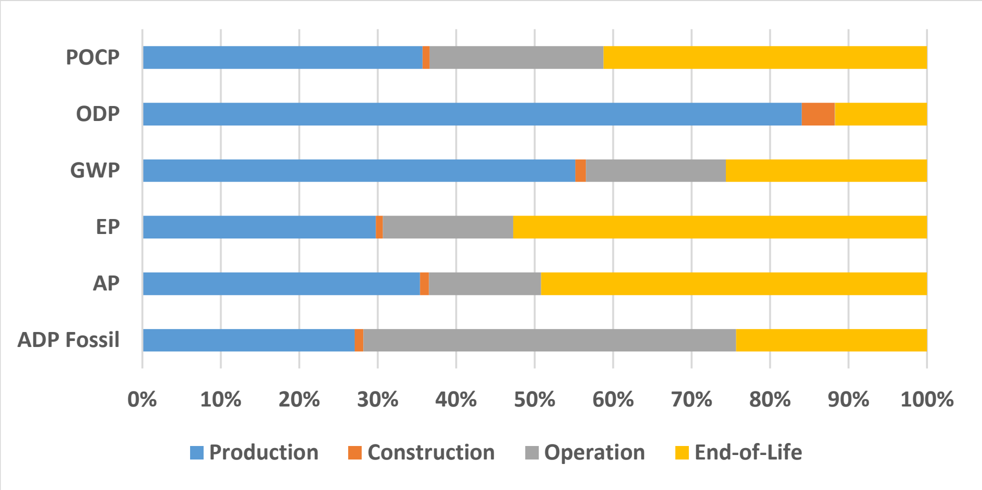


Figure 93: Contribution of each stage per impact category [C1.2]

As illustrated in Figure 93, the material production stage is the foremost contributor to the impacts (44.5% Avg.), followed by the end-of-life stage, operation stage and the construction stage with average relative contributions of 34%, 19.9%, and 1.6% respectively.

Table 75 indicates the variation of the results this case study in relation to the reference case study C1.1.

Table 75: Aggregate environmental impacts of C1.2 relative to C1.1

Impact Category	Unit	Case Study C1.1	Case Study C1.2	Variation relative to C1.1
ADP Fossil	MJ	1,62E+08	1,76E+08	+8,5%
AP	Kg SO_2 eq.	2,92E+04	4,01E+04	+37,4%
EP	Kg PO_4 eq.	3,50E+03	5,16E+03	+47,5%
GWP	Kg CO_2 eq.	9,37E+06	1,28E+07	+36,5%
ODP	Kg R11 eq.	1,08E-01	2,78E-02	-74,2%
POCP	Kg C_2H_4	3,97E+03	4,40E+03	+10,6%

To understand the contribution of each case study to the aggregated result better, the results are also displayed in Figure 94.

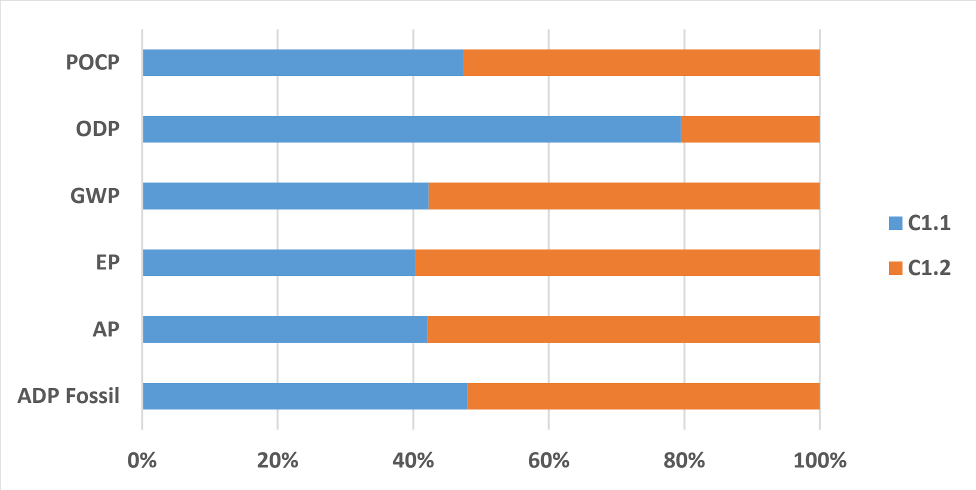


Figure 94: Relative contribution of each case study per impact category (day work scenario)

As can be seen from the above illustrations, the reference example C1.1 features comparatively favorable characteristics in all impact categories except for ozone depletion potential (OPD).

4.1.3.6 Alternative maintenance scenarios

- *Analysis of reference case study C1.1*

In this section, two additional alternative maintenance plans are considered. The first alternative maintenance scenario refers to the “lack of money” situation, in which the frequency of maintenance is changed to cope with budget restrictions. The second alternative maintenance scenario refers to the “prolonged life” situation, in which the service life of the bridge is extended to 130 years.

Both alternative scenarios only affect the operation stage. Hence, the results presented in this section refer only to the operation stage. The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 76 for the standard and both alternative maintenance scenarios.

Table 76: Comparison of environmental impacts at the operation stage for different maintenance scenarios [C1.1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	Δ(LOM, STA)	Prolonged Life Scenario (PRL)	Δ(PRL, STA)
ADP Fossil	MJ	8,43E+07	4,97E+07	-41,0%	1,38E+08	+63,7%
AP	Kg SO_2 eq.	4,91E+03	2,70E+03	-45,1%	8,36E+03	+70,1%
EP	Kg PO_4 eq.	7,32E+02	4,06E+02	-44,4%	1,25E+03	+71,5%
GWP	Kg CO_2 eq.	1,75E+06	8,71E+05	-50,3%	3,00E+06	+71,3%
ODP	Kg R11 eq.	6,00E-06	2,55E-06	-57,5%	1,14E-05	+89,2%
POCP	Kg C_2H_4	1,02E+03	5,79E+02	-43,0%	1,60E+03	+57,7%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 77 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 77: Comparison of environmental impacts at the operation stage for different maintenance scenarios per year [C1.1]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	8,43E+05	4,97E+05	-41,0%	1,06E+06	+25,9%
AP	Kg SO_2 eq.	4,91E+01	2,70E+01	-45,1%	6,43E+01	+30,8%
EP	Kg PO_4 eq.	7,32E+00	4,06E+00	-44,4%	9,65E+00	+31,9%
GWP	Kg CO_2 eq.	1,75E+04	8,71E+03	-50,3%	2,31E+04	+31,8%
ODP	Kg R11 eq.	6,00E-08	2,55E-08	-57,5%	8,74E-08	+45,5%
POCP	Kg C_2H_4	1,02E+01	5,79E+00	-43,0%	1,23E+01	+21,3%

From the results, it is evident that the “lack of money” scenario reduced the impacts in all categories by an average of 46.9%(Avg.) per year compared to the standard scenario. On the other hand, the effort to prolong the service life of the bridge with the “prolonged life” scenario led to 31.2%(Avg.) increased impacts in all environmental categories per year.

- *Analysis of reference case study C1.2*

The results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 78 for the standard and both alternative maintenance scenarios.

Table 78: Comparison of environmental impacts at the operation stage for different maintenance scenarios [C1.2]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	8,34E+07	4,92E+07	-41,0%	1,38E+08	+65,5%
AP	Kg SO_2 eq.	5,73E+03	2,96E+03	-48,3%	1,01E+04	+75,8%
EP	Kg PO_4 eq.	8,57E+02	4,50E+02	-47,5%	1,51E+03	+76,6%
GWP	Kg CO_2 eq.	2,28E+06	1,03E+06	-54,8%	4,11E+06	+80,2%
ODP	Kg R11 eq.	9,97E-06	3,89E-06	-61,0%	1,93E-05	+93,6%
POCP	Kg C_2H_4	9,73E+02	5,51E+02	-43,4%	1,56E+03	+60,4%

As the two alternative maintenance scenarios refer to two different time spans, the results of the environmental analysis for the operation stage, considering the "day work" scenario, are provided in Table 79 per year. A time span of 100 years and 130 years were considered for the "lack of money" scenario and the "prolonged life" scenarios, respectively.

Table 79: Comparison of environmental impacts at the operation stage for different maintenance scenarios per year [C1.2]

Impact Category	Unit	Standard Scenario (STA)	Lack of Money Scenario (LOM)	∆(LOM, STA)	Prolonged Life Scenario (PRL)	∆(PRL, STA)
ADP Fossil	MJ	8,34E+05	4,92E+05	-41,0%	1,06E+06	+27,3%
AP	Kg SO_2 eq.	5,73E+01	2,96E+01	-48,3%	7,75E+01	+35,2%
EP	Kg PO_4 eq.	8,57E+00	4,50E+00	-47,5%	1,16E+01	+35,9%
GWP	Kg CO_2 eq.	2,28E+04	1,03E+04	-54,8%	3,16E+04	+38,6%
ODP	Kg R11 eq.	9,97E-08	3,89E-08	-61,0%	1,49E-07	+48,9%
POCP	Kg C_2H_4	9,73E+00	5,51E+00	-43,4%	1,20E+01	+23,4%

In case C1.2, the “lack of money” scenario led to 49.3%(Avg.) reduced impacts in all impact categories in comparison with the standard scenario. While the effort to prolong the service life of the bridge with the “prolonged life” scenario led to a 34.9% average increase in impacts in all environmental categories.

4.1.4 Lifecycle Cost Analysis

4.1.4.1 Initial construction costs

- *Analysis of reference case study C1.1*

The initial cost of the bridge, including the material transport cost, is 7.421.217,1 €, which is about 665,60 €/m^2. Figure 95 shows the proportion of the costs for the substructure, superstructure and the roadway which are calculated based on the bill of materials and unit costs indicated in Table 62.

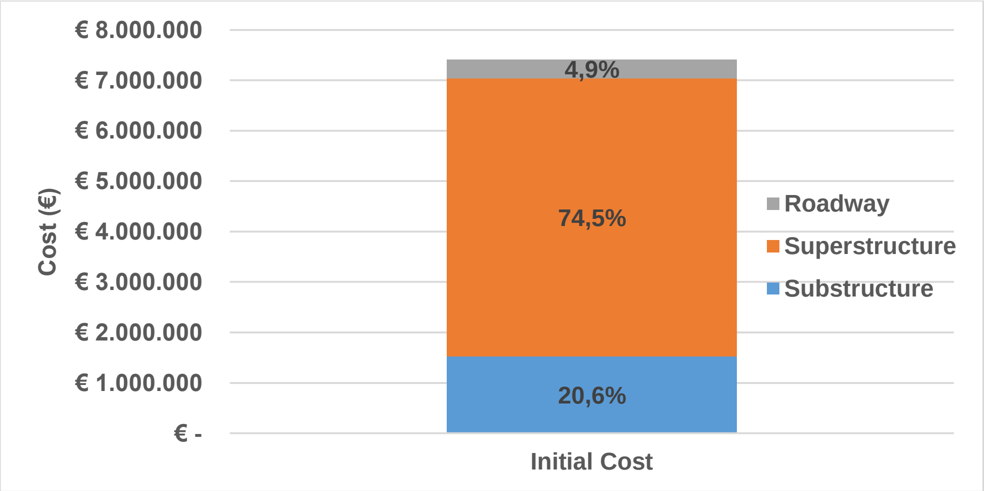


Figure 95: Initial cost of case C1.1

- *Analysis of variant C1.2*

The initial cost, including the material transport costs, calculated for the variant case study C1.2 amounts 8.684.092,5 € which corresponds to 759,56 €/m^2. Figure 96 shows the proportion of the costs for the substructure, superstructure and the roadway which are calculated based on the bill of materials and unit costs indicated in Table 63.

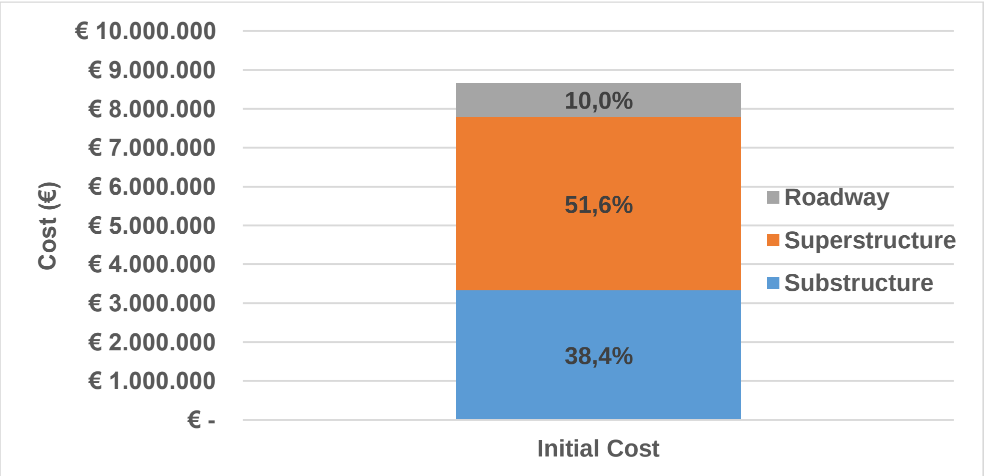


Figure 96: Initial cost of case C1.2

The initial costs presented above are calculated on the basis of the actual unit costs of the bridges. However, for comparative purposes, the two solutions need to be evaluated based on the same unit costs – ensuring a common ground. For this reason, it is assumed that the two bridges are built at the same location, at the same time and with the same unit costs where relevant. The unit costs indicated in Table 80 were equally used for both cases, instead of the actual unit costs of each bridge, for comparative purposes.

Table 80: Common unit costs used for comparative purposes

Description	Unit	Common unit cost
Substructure		
Excavation	[€/m^3]	19,97
Backfilling	[€/m^3]	7,39
Formwork - for abutments and columns	[€/m^2]	37,31
Reinforcement steel - except concrete deck	[€/kg]	1,05
Concrete - C30/37	[€/m^3]	121,49
Superstructure		
Reinforcement steel - concrete deck	[€/kg]	1,05
Concrete - light weight	[€/m^3]	112,60
Concrete or steel cornice	[€/m]	163,00
Lamelle (roadway slats steel/ plastic and similar)	[€/pcs]	21,66
Roadway		
Surface levelling with concrete bituminous & single bituminous surfacing	[€/m^2]	7,38
Protective device - guardrail	[€/m]	51,26
Protective equipment - railings	[€/m]	124,43

The use of the unit costs indicated above lead to an initial cost of 7.713.831,8 € and 8.301.478,8 € for cases C1.1 and C1.2, respectively. These represent initial cost per unit area of 691,84 €/m^2 and 726,10 €/m^2, respectively.

4.1.4.2 Operation costs

Over the period of 100 years, the bridges in the examples are assumed to be maintained and rehabilitated according to the plan indicated in the Annex – Table A1, the definition of a standard Inspection scenario.

- *Analysis of reference case study C1.1*

The costs associated with inspection and maintenance work carried out on bridge C1.1 throughout its service life are calculated based on the unit costs and frequencies indicated in Tables A1 - A6 of the annex and found to be 947.233,99 €. These costs are illustrated in Figure 97 along with the net present values of accumulated costs considering a discount rate of 2%.

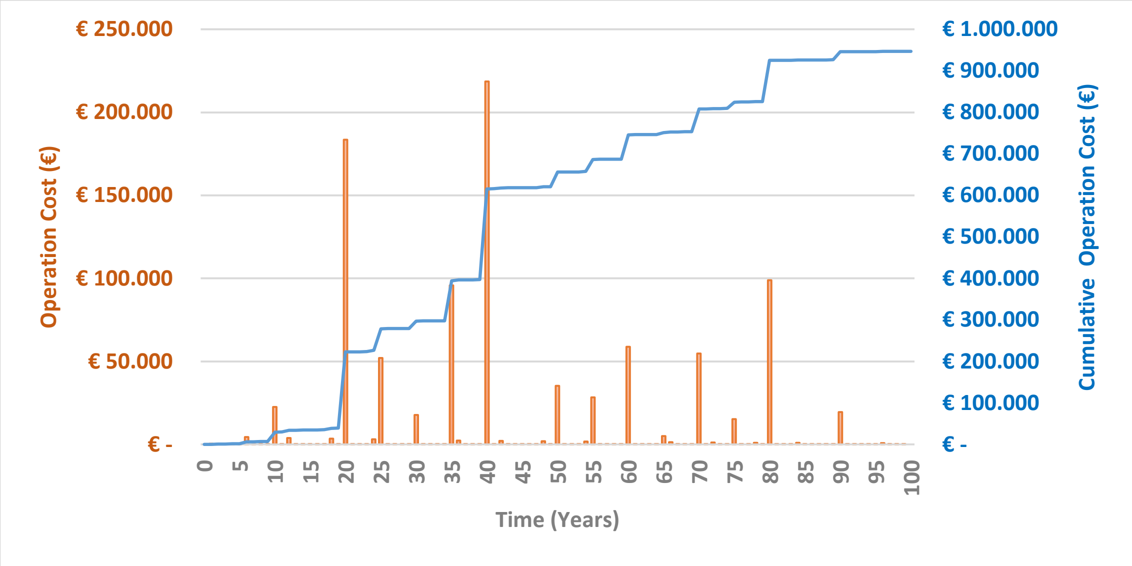


Figure 97: Operation costs of the bridge C1.1 over its service life

- *Analysis of reference case study C1.2*

The operation cost calculated for case study C1.2 is 1.183.807,66 €. The yearly and accumulated operation costs are illustrated in Figure 98.

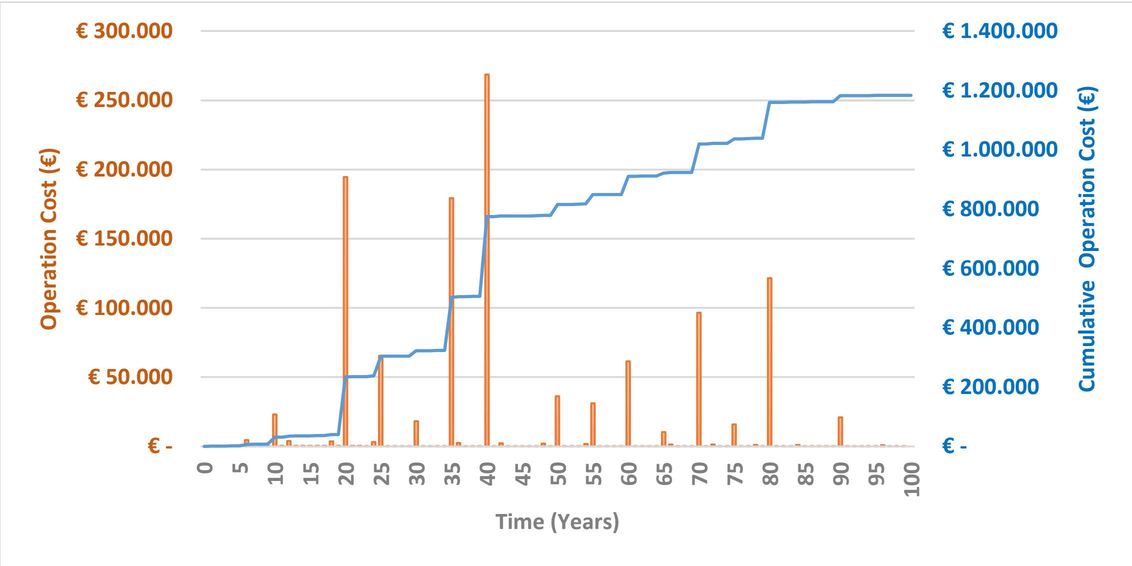


Figure 98: Operation costs of the bridge C1.2 over its service life

It can be seen from the previous two figures that the operation costs are notably higher in the years 20 and 40. These peaks in the operation cost are associated with the replacement of the road surface, which relatively covers a large area (> 11000 m²). The operation cost for the composite solution, case C1.1, is found to be 25% lower than that required by the concrete solution.

4.1.4.3 End-of-life cost

End-of-life costs encompass the cost of labor work, cost of equipment, and cost of road warning signage, cost of transportation and cost for deposition of materials and/or revenue due to recycling of materials.

The cost for demolition of a similar bridge is about 100 €/m^2 [1].This cost includes the cost of labor, the cost of equipment and fuel, the cost of ancillary material, the cost of sorting the materials, the cost of all the necessary measures to ensure the safety of the work zone and the cost for cleaning the zone.

Construction and Demolition Waste (C&DW) is sent for recycling or deposit in a landfill. The cost of transportation requires the estimation of the distances from the demolition place to the disposal/recycling place, the efficiency of the trucks and the price of fuel. In the case of the waste sent to a disposal site, the facility operator charges a fee to assume possession of the demolition waste. The cost for disposal of C&DW varies according to the type of material and the degree of contamination of the C&DW.

In the case of steel, i.e., both reinforcement steel bars and structural steel, it is assumed that the dealer pays the contractor 100 €/tonne (this price usually depends on the price of steel, according to the information from the U.S. recycling institute a price of $120/ton of steel may be considered). This figure has a negative sign since it is a revenue and not a cost for the contractor. A summary of the end-of-life costs for bridges C1.1 and C1.2 are given in Tables 81 and 82, respectively. The concrete solution, C1.2, results in 72.3% higher end-of-life cost than the steel composite bridge, C1.1.

Table 81: End-of-life cost for C1.1

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	2821,655	-31550,05	50	584,22
Concrete	15979,2	22056,56	50	3308,48
Earthwork	10240	70672,88	10	424,04
Bitumen	2146,56	14814,80	20	177,78
			Sub-Total (€)	80488,72
			Demolition cost (€)	153901,24
			Total Cost (€)	234389,95

Table 82: End-of-life cost for C1.2

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	1891,679	-18277,98	50	391,67
Concrete	36418,2	50269,12	50	7540,37
Earthwork	27846	192183,30	10	1153,10
Bitumen	1827,456	12612,46	20	151,35
			Sub-Total (€)	246023,38
			Demolition cost (€)	157812,54
			Total Cost (€)	403835,92

(*) Considering disposal cost for concrete 10 €/tonne, for steel scrap value of 100 €/tonne and transportation cost of 0.03 €/tonne/km.

(**) The amount of steel calculated above includes both the reinforcement steel bars and structural steel sections/plates and connections. Note: The costs are given in their present value calculated according to equation 2 at a discount rate of 2%.

4.1.4.4 Total Lifecycle costs

Summing the costs calculated in the previous sections for case study C1.1 led to the total lifecycle net present cost (LCC) of 8.895.455,74 € using a discount rate of 2.0%. This represents a total cost of about 797,83 €/m^2. For case study C1.2, on the other hand, a total lifecycle net present cost (LCC) of 9.889.122,39 € is calculated at a discount rate of 2.0%. This represents a total cost of about 864.96 €/m^2. The costs of the bridge for each stage are summarized in Table 83 and illustrated in Figures 99 and 100.

Table 83: Comparison of lifecycle cost between C1.1 and C1.2

	Case Study C1.1 (€)	Case Study C1.2 (€)	Variation relative to C1.1
Initial Cost	7713831,80	8301478,80	+7,6%
Operation Cost	947233,99	1183807,66	+25,0%
End of life Cost	234389,95	403835,92	+72,3%
Total Cost	8895455,74	9889122,39	+11,2%

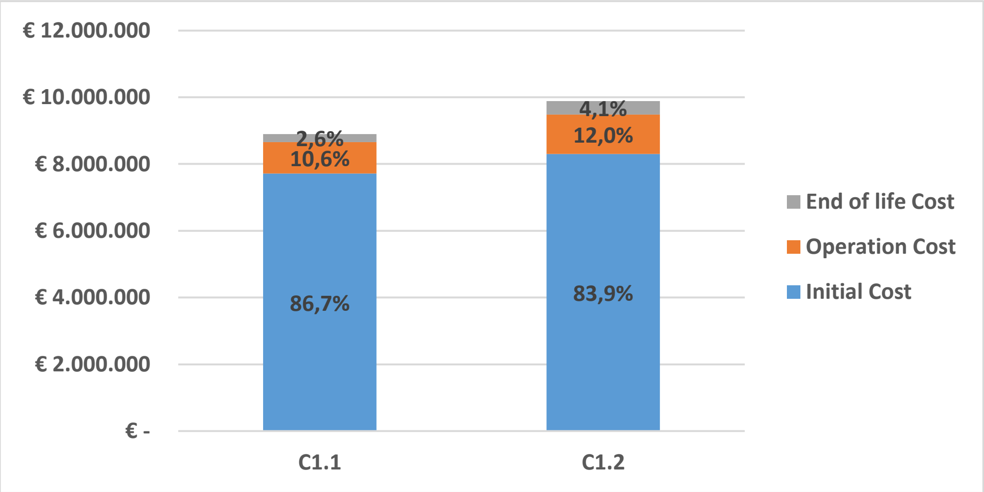


Figure 99: Total lifecycle costs of C1.1 and C1.2

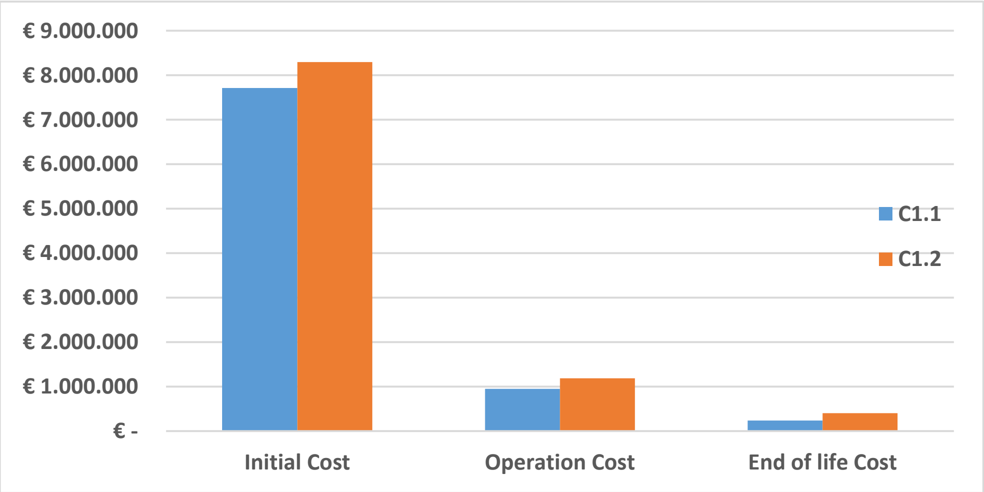


Figure 100: Comparison of lifecycle costs C1.1 and C1.2

It is commonly perceived that steel and composite bridge solutions may be more expensive in terms of the initial cost, i.e., production and construction stage, but can be more attractive when considering other stages, operation, and end-of-life. However, in this particular comparison, it is evident that the composite steel solution (case study C1.1) is better than its concrete equivalent (C1.2) and has a 11,2% lower total LCC. The differences in substructure costs can be explained by the significantly heavier deck of C1.2, implicitly associated to higher inertial forces and, therefore, higher seismic stresses in columns and foundations.

It can be noted that the end-of-life costs are much lower than operation or construction costs due to the fact that these costs occur at year 100 and are discounted with a yearly discount rate of 2%. All the above calculations were made assuming the “standard” maintenance scenario and day work conditions.

4.1.4.5 Alternative maintenance scenarios

Besides the standard scenario, two alternative maintenance scenarios, namely “lack of money” and “prolonged life” scenarios have been studied. Lack of money scenario refers to the situation in which the frequency of maintenance is lowered to cope with budget restrictions. On the other hand, the prolonged life scenario considers that a decision is made at year 80 to keep the bridge in service longer than the designed service life (130 years instead of 100). Maintenance actions strategy is adapted at the end of service life to ensure an adequate level of performance of the bridges until year 130.

- *Analysis of reference case study C1.1*

Figure 101 shows the total lifecycle costs for case study C1.1 with standard [STA], “lack of money” [LOM] and “prolonged life” [PRL] maintenance scenarios. It is noted that the rate of increase of lifecycle costs is lower after year 80 than that at the beginning of the service life since costs are discounted with a fixed yearly discount rate of 2%. The lack of money scenario resulted in 3% lower costs as expected. The total cost with the prolonged life scenario is also 1.3% less than the standard scenario. The reason for the decrease in the total lifecycle cost for the prolonged life scenario is the highly taxed/discounted end-of-life cost at year 130. The net present value of end-of-life cost in the prolonged life scenario (at year 130) is computed to be 55% of that from the standard scenario (at year 100).

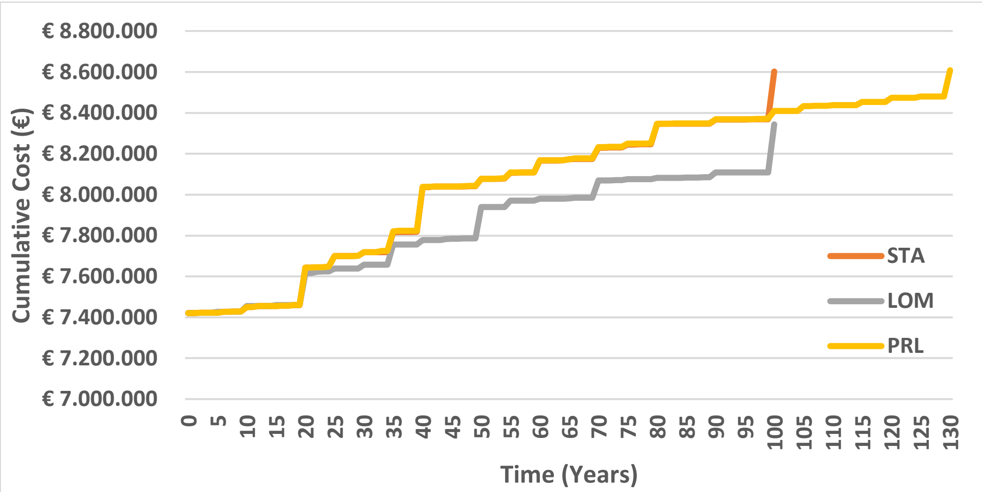


Figure 101: Lifecycle costs of C1.1 with “standard”, “lack of money” and “prolonged life” maintenance scenarios

- *Analysis of reference case study C1.2*

Figure 102 shows the total lifecycle costs for case study C1.2 with standard, “lack of money” and “prolonged life” maintenance scenarios. With the post-tensioned reinforced concrete bridge solution here, 2.8% lower LCC value has been registered for the “lack of money” scenario albeit the longer service life of the bridge. It is also noted that the “prolonged life” scenario resulted in 1.7% lower costs than the standard scenario. The reason for the decrease in the total cost is the highly taxed/discounted end-of-life cost at year 130. The same activities at the end-of-life cost the same amount of money for all scenarios. However, the costs are multiplied by different factors when converting to present value; and the end-of-life cost in the Prolonged life scenario is computed to be 55% of those from the standard scenario in the net present value.

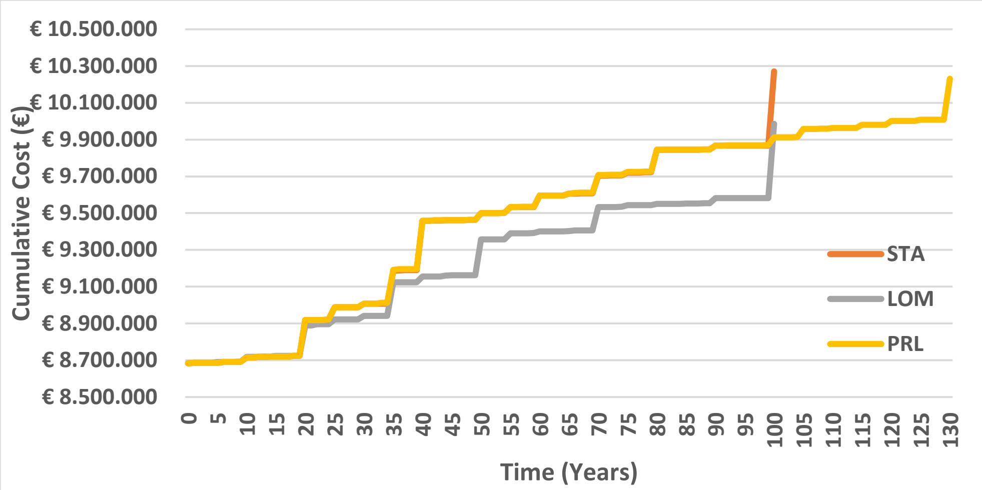


Figure 102: Lifecycle costs of C1.2 with "standard", "lack of money" and "prolonged life" maintenance scenarios

4.1.5 Lifecycle Social Analysis

Considering the standard maintenance scenario, two work plans have been studied for user costs' calculation. (i) a day work scenario where most actions are carried out during the day (from 6 AM to 10 PM) and the bridge has one lane closed for major maintenance actions (road surface); (ii) night work scenario, similar to the "day" scenario except that most of the maintenance actions are carried out during the night (from 10 PM to 6 AM).

Figure 103 details the user costs for case studies C1.1 with "day" and "night" work plans in the standard maintenance scenario. It is noted that the user inconvenience is reduced if work is carried out during the night since there is less traffic than during the day. However, the magnitude of the difference between the two scenarios is not huge as a relatively small ADT is accommodated by the bridge and since there is no traffic underneath the bridge.

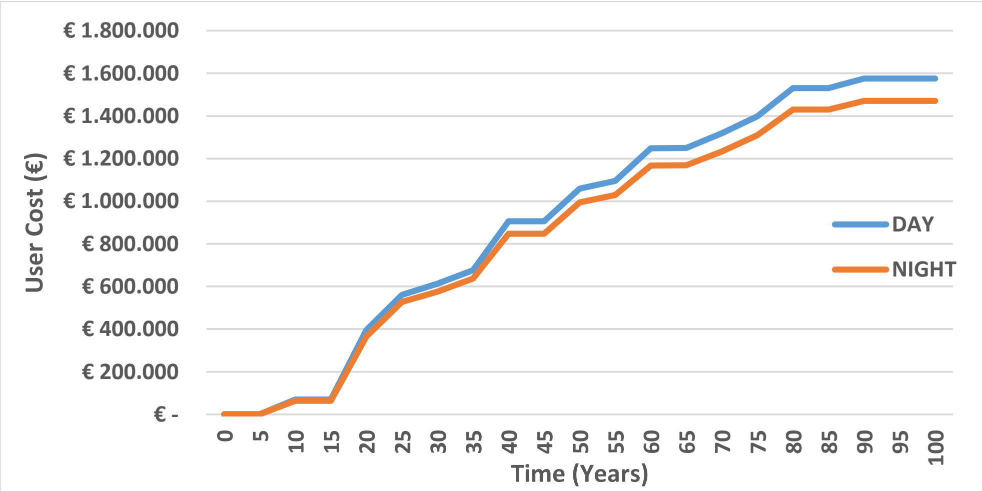


Figure 103: User costs for C1.1 with the "day" and "night" work plans

It is also observed in Figure 104, that user costs for case studies C1.1 are lower than those for and C1.2 by 6.4%) because the maintenance of concrete bridge takes more time.

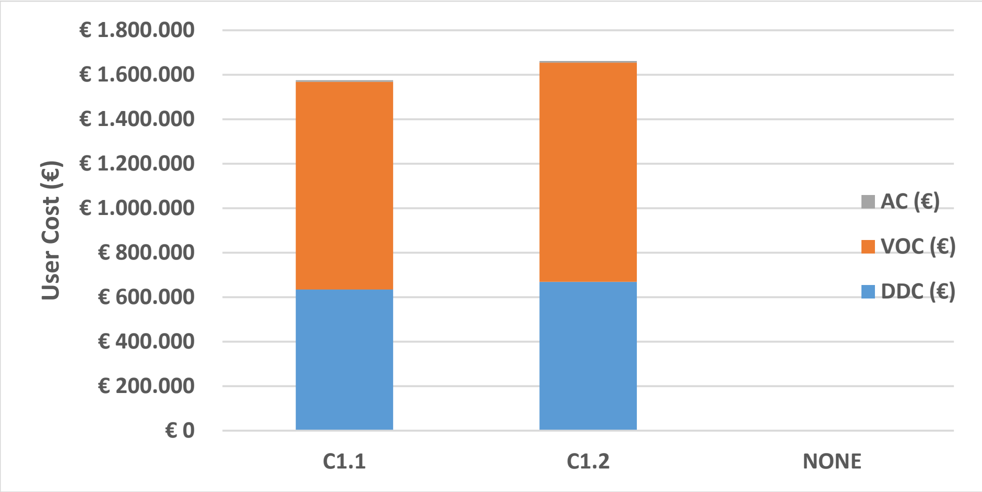


Figure 104: Comparison of user costs for C1.1 and C1.2 with standard day work scenario.

4.1.5.1 Alternative maintenance scenarios

As was the case for LCA and LCC, for the user's costs, the alternative maintenance scenarios: "lack of money" and "prolonged life" have been studied and compared with the standard maintenance scenario.

- *Analysis of reference case study C1.1*

Figure 105 shows the user costs for case study C1.1 with standard, "lack of money" and "prolonged life" maintenance scenarios.

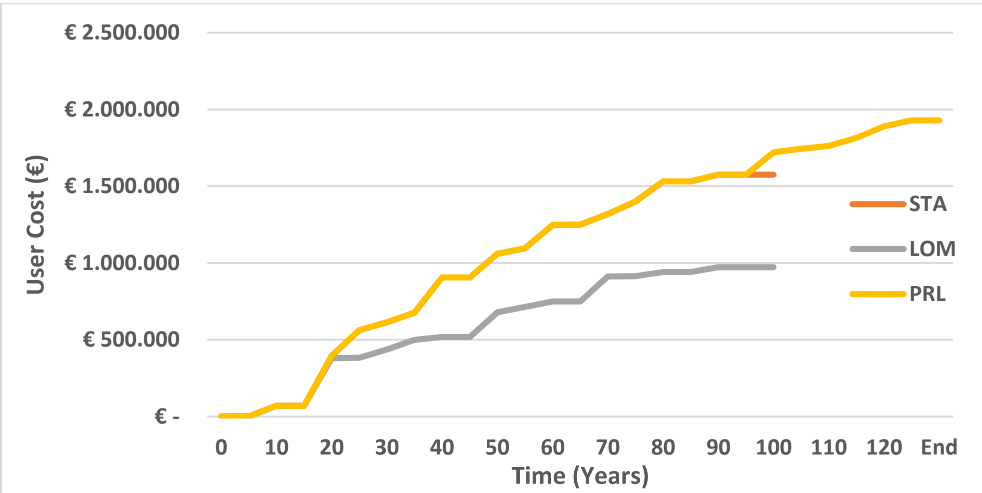


Figure 105: User costs for C1.1 with the "standard", "lack of money", and "prolonged life" maintenance scenarios

- *Analysis of reference case study C1.2*

Figure 106 shows the total lifecycle costs for case study C1.2 with standard, "lack of money" and "prolonged life" maintenance scenarios.

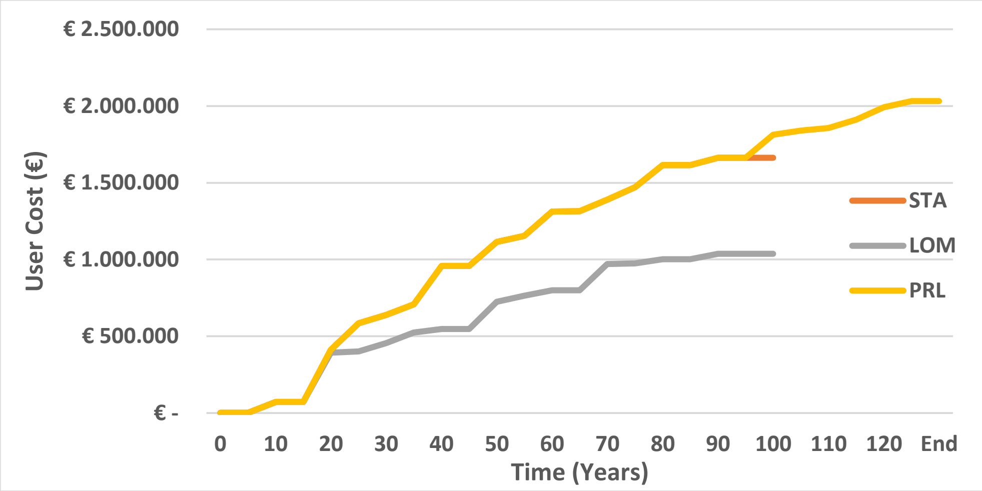


Figure 106: User costs for C1.2 with the "standard", "lack of money", and "prolonged life" maintenance scenarios

In both cases, C1.1 and C1.2, the "lack of money" scenario resulted in lower user costs than the standard scenario while the "prolonged life" scenario resulted in higher user costs as the service life of the bridge is prolonged. The user costs associated with case C1.2 were found to be higher than those for case C1.1.

4.1.6 Discussion of the Results for case C1

As is the case in case C2, it can be observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories in this case study too. The production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage, the impacts are mainly caused by traffic congestion. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides a reduction of impacts owing to the fact that traffic count is lesser at night. The reference example C1.1 features comparatively favorable characteristics in all impact categories except for ozone depletion potential (OPD). However, the impacts calculated for ODP are very low (in the order of 10^{-3}).

In terms of Lifecycle costs, it is evident from the case studies that the steel composite bridge exhibited preferable characteristics. Although the two bridges had different unit costs for the same items, the two solutions were evaluated based on the same unit costs where relevant – ensuring a common ground for the purpose of comparison. The Initial cost and operation costs for the steel composite bridge were found to be less than its concrete counterpart. The steel composite bridge gained favorability in the end-of-life stage, as well, owing to the abundant recycling possibilities with steel as a construction material.

Once more, the social aspects of the LCA prove that the night shift is favorable in reducing the impacts on user cost. The user costs for case C1.1 are lower than those for case C1.2 by 5.5% due to the relatively lower time required to perform the maintenance activities in the former. In both C1.1 and C1.2, the application of "lack of money" maintenance scenario led to lower user costs while the "prolonged life" scenario led to increased user costs. However, it should be noted that the lower costs for "lack of money" scenario come at the expense of degradation of the bridge which may ultimately lead to a decision to replace the bridge altogether – resulting in substantially higher costs.

4.2 Case C2 – Single span motorway bridges

Case C2 describes a single span motorway bridge with theoretical length equal to 34.80 m and deck width of 12.14 m. The composite deck solution consists of two welded I-shaped girders S355-N, with 1.85 m high, with a center-to-center spacing equal to 7.00 m, placed on-site by light cranes. This bridge is located in South Albania.

In contrast to all other previous case studies, in this case, in order to compare the composite bridge with an equivalent concrete solution, a variant fictive case was designed (not built), which consists of 4 precast prestressed I-shaped girders (C30/37), 2.20 m high, with a center-to-center spacing equal to 3.50 m, placed on-site also by cranes.

Both superstructures are supported and seismically isolated by anchored (though replaceable) normal damping rubber bearings. Their substructure is a typical reinforced concrete (C25/30) abutment with spread foundation.

4.2.1 Description of the Case Study

4.2.1.1 Definition of bridge systems, geometry, and parameters

The composite deck solution (Case C2.1, Figure 107) consists of two welded I-shaped girders S355-N, with 1.85 m high, with a center-to-center spacing equal to 7.00 m, placed on-site by light cranes. The upper flange is 700 mm wide and the lower one is 900 mm. The deck slab made of concrete (C30/37) consists of a 0.20 m layer cast in-situ on precast slabs 0.10 m thick. Transverse beams HEA500 (between the main girders) and HEA340 (at the cantilevers) are placed every 2.90 m. At each supporting cross-section, a reinforced concrete crossbeam, 420 mm thick, is formed, Figure 108.

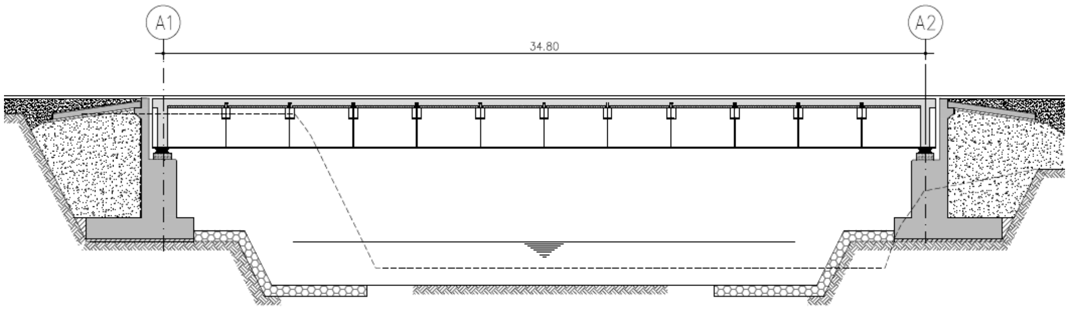


Figure 107: Case C2.1 Longitudinal section

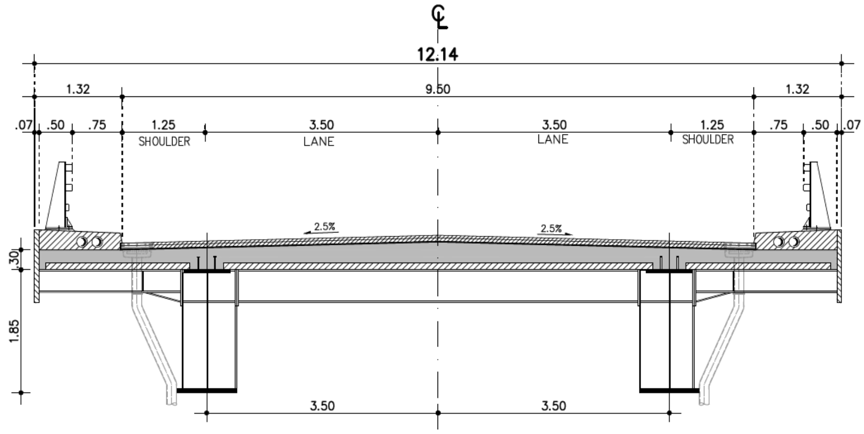


Figure 108: Case C2.1 Typical cross section

The equivalent prestressed concrete bridge (Case C2.2, Figure 109) consists of 4 precast prestressed I-shaped girders (C30/37), 2.20 m high, with a center-to-center spacing equal to 3.50 m, placed on-site by cranes. The upper flange is 1400 mm wide and the lower one 750 mm. The deck slab (C30/37) consists of a 0.20 m layer cast in-situ on precast slabs 0.10 m thick, same as in Case C2.1. No transverse beams are foreseen within the span; at each supporting cross-section, a reinforced concrete crossbeam, 500 mm thick, is formed, Figure 110.

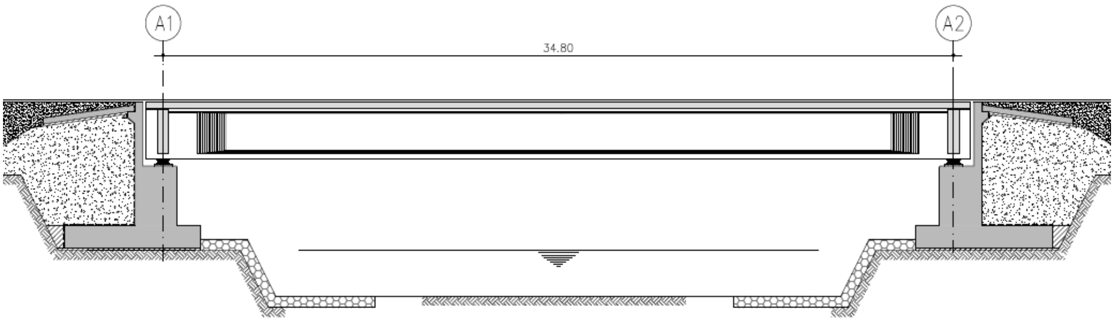


Figure 109: Case C2.2 Longitudinal section

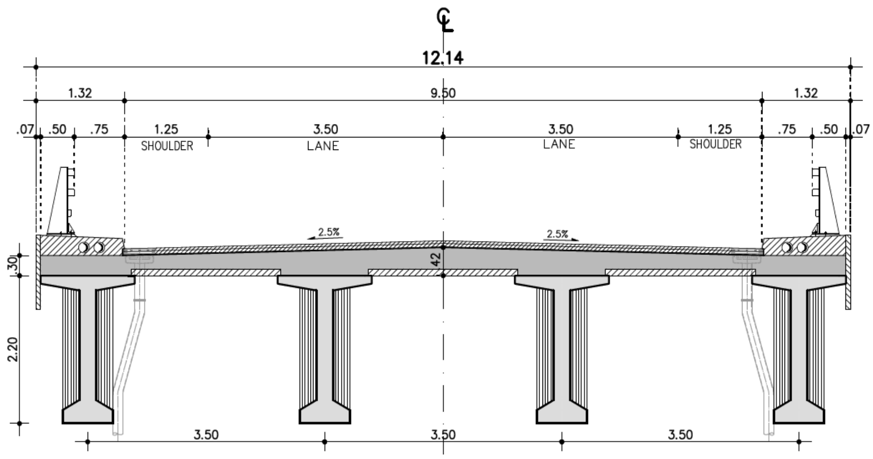


Figure 110: Case C2.2 Typical cross-section

Both superstructures are supported and seismically isolated by anchored (though replaceable) normal damping rubber bearings (type C according to EN1337). Bearings are placed below each main girder. For the case C2.1, 2x2 NDRB 350x450x166 mm (t_{el}=66 mm), and for the case C2.2, 2x4 NDRB 300x400x145 mm (t_{el}= 64 mm) are used.

Case C2.1's substructure is a typical reinforced concrete (C25/30) abutment with spread foundation (soil type A: Flyschy layers of sandstone and siltstone). The abutment is 12.14 m wide and its total height is 6.35 m. The footing slab is 1.00 m thick and 4.90 m long.

For comparison reasons with the Case C2.2, a similar abutment was designed, keeping the same height and width. The width of the abutment's web thickness was increased to accommodate properly the precast beams. Also, the length of the footing slab was increased to 6.0 m in order to adjust the soil stresses due to the increased dead load of this variant.

It is noted that Case C2.2 being a fictive bridge (not built) but only designed for the sake of comparison, it will not exhibit the same level of utilization ratio, as can be easily seen by the identical quantities of concrete in both bridges. Therefore, it does not necessary reflect a "fair" comparison, whereby both solutions are optimised to the same level.

4.2.1.2 Design Considerations

The most significant quantities of Cases C2.1 and C2.2 are presented in the following table (per deck and for one direction of the traffic):

Table 84: Quantities for Cases C2.1 and C2.2 provided to perform LCA and LCC analysis

Description	**Unit**	**Case C2.1 (composite beams)**	**Case C2.2 (precast concrete beams)**	**Unit**	**Unit cost* (Greece 2015)**
Substructure					
Excavations	[m^3]	2200	2400	[€/m^3]	1,50
Backfilling	[m^3]	530	600	[€/m^3]	5,00
Abutments' concrete C25/30	[m^3]	300	350	[€/m^3]	95,00
Abutments' reinforcement S500C	[kg]	22530	26180	[€/kg]	0,80
Superstructure					
Structural steel S355 N	[kg]	94000	-	[€/kg]	1,80
Corrosion protection	[m^2]	720	-	[€/m^2]	9,00
Concrete precast beams C30/37	[m^3]	-	148	[€/m^3]	160,00
Concrete slab C30/37	[m^3]	210	212	[€/m^3]	110,00
Reinforcement S500C	[kg]	37350	41790	[€/kg]	0,80
Prestressing steel 1570/1770	[kg]	-	8460	[€/kg]	3,10
Bearings	[pcs]	4	8		
	[lt]	105	139	[€/lt]	45,00
Crane on-site deck placement cost	[GV]	20000	70000	[€]	1
Roadway					
Pavement's asphalt layers (2x5cm)	[m^2]	2x340	2x345	[€/m^2]	6,00
Pavement's waterproofing member.	[m^2]	418	422	[€/m^2]	11,40
Gullies	[kg]	1256	1256	[€/kg]	4,90
Gutters PVC Φ200	[m]	45,80	49,00	[€/m]	8,60

Expansion joint T80	[m]	24,30	24,30	[€/m]	800,00
Safety barriers	[kg]	4650	4720	[€/kg]	1,90

(*) The provided unit costs refer to the direct construction costs. In order to incorporate the general expenses and the profit of the contractor, these costs should be increased by 30%

4.2.2 Traffic analysis

For cases studies in C2, it is assumed that the motorway accommodates an Average Daily Traffic (ADT) of 8000 vehicles/day in the base year of the study. It is also considered that the percentages of light-weight vehicles and heavy-weight vehicles are 88% and 12% of the ADT, respectively. The hourly traffic distribution presented in Figure 111 was assumed for the motorway.

It is important to note that the traffic growth over time follows equation (3) (See item 5.3 of Part A) where a growth rate of 0.5% is considered.

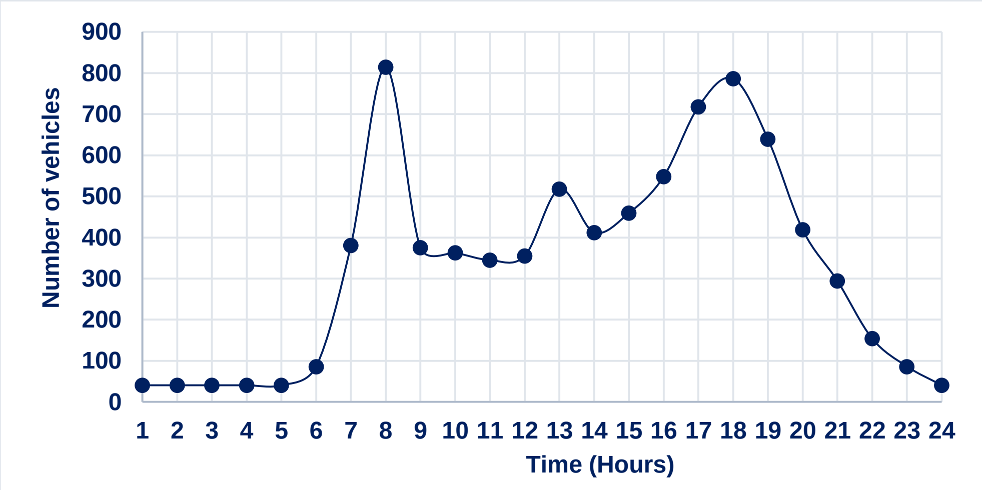


Figure 111: Hourly traffic distribution for cases C2.1 and C2.2

4.2.3 Lifecycle Environmental Analysis

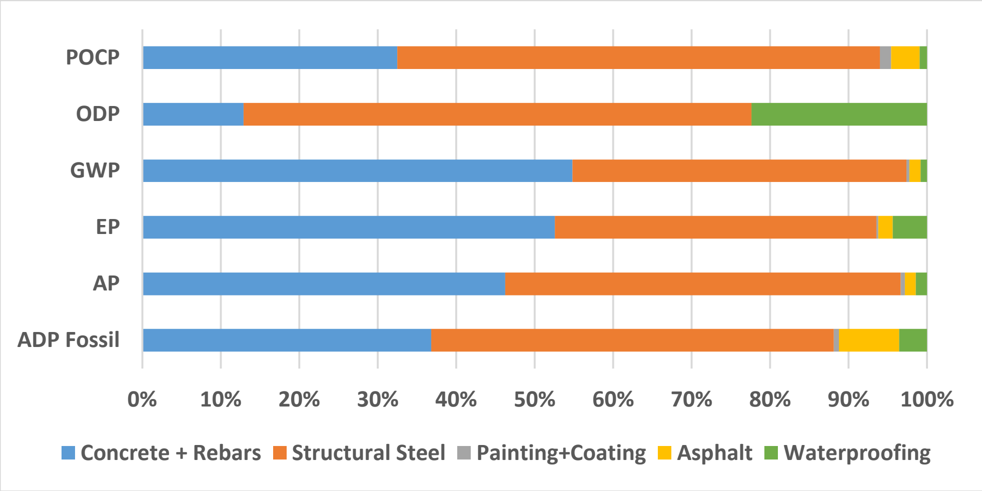
4.2.3.1 Material production stage

- *Environmental analysis of reference case study C2.1*

The results obtained for the construction stage are detailed in Table 85. Note that the quantities presented in Table 84 were used in the calculations and the results doubled to represent the existence of the same bridge in the opposite traffic direction. It can be concluded from the results that the production of structural steel and reinforced concrete are the main processes contributing to global impacts in the material production stage. The same results are plotted in Figure 112.

Table 85: Environmental impacts at the material production stage per impact category [C2.1]

Impact Category	Unit	Total	Concrete + Rebars	Structural Steel	Coating + Painting	Asphalt	Waterproof layer
ADP Fossil	MJ	7,23E+06	2,66E+06	3,71E+06	4,80E+04	5,57E+05	2,55E+05
AP	Kg SO_2 eq.	1,88E+03	8,69E+02	9,47E+02	1,00E+01	2,59E+01	2,66E+01
EP	Kg PO_4 eq.	1,80E+02	9,46E+01	7,37E+01	4,87E-01	3,26E+00	7,86E+00
GWP	Kg CO_2 eq.	7,72E+05	4,23E+05	3,28E+05	2,98E+03	1,11E+04	6,15E+03
ODP	Kg R11 eq.	1,15E-02	1,48E-03	7,42E-03	5,56E-09	9,34E-09	2,56E-03
POCP	Kg C_2H_4	2,70E+02	8,78E+01	1,66E+02	3,90E+00	9,84E+00	2,48E+00



Note: Results for painting and coating include the environmental impacts coming from painting applied to non-structural elements such as protective equipment.

Figure 112: Contribution analysis of processes during the material production stage [C2.1]

- *Environmental analysis of variant C2.2*

The results obtained for the variant case study C2.2 are presented in Table 86 and the same has been illustrated in Figure 113.

Table 86: Environmental impacts at the material production stage per impact category [C2.2]

Impact Category	Unit	Total	Concrete + Rebars	Prestressing Steel	Asphalt	Waterproof layer
ADP Fossil	MJ	4,35E+06	3,27E+06	2,56E+05	5,65E+05	2,57E+05
AP	Kg SO_2 eq.	1,23E+03	1,11E+03	6,65E+01	2,63E+01	2,69E+01
EP	Kg PO_4 eq.	1,41E+02	1,25E+02	5,27E+00	3,31E+00	7,94E+00
GWP	Kg CO_2 eq.	6,06E+05	5,65E+05	2,35E+04	1,13E+04	6,21E+03
ODP	Kg R11 eq.	4,47E-03	1,68E-03	2,09E-04	9,47E-09	2,59E-03
POCP	Kg C_2H_4	1,29E+02	1,07E+02	1,03E+01	9,99E+00	2,50E+00

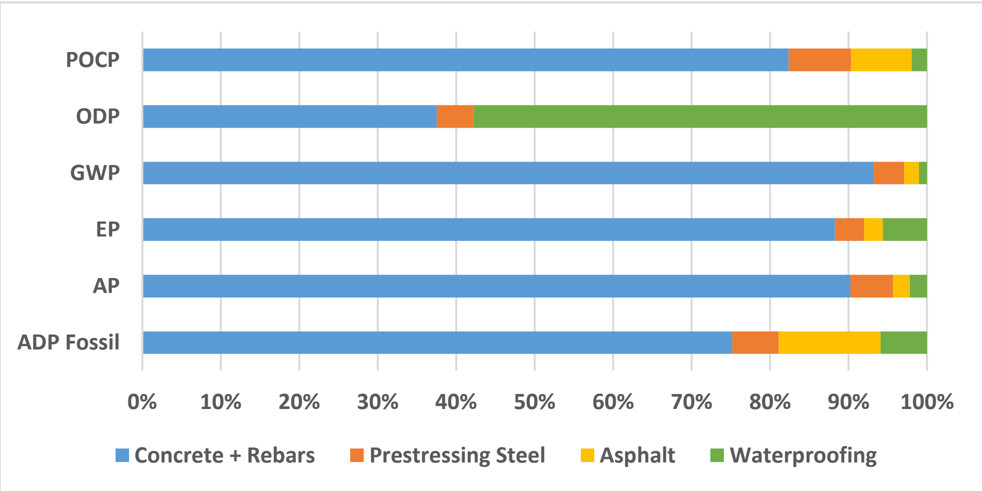


Figure 113: Contribution analysis of processes during the material production stage [C2.2]

Table 87 indicates the variation of the results for C2.2 relative to the reference case study C2.1.

Table 87: Environmental impacts at the material production stage relative to case C2.1

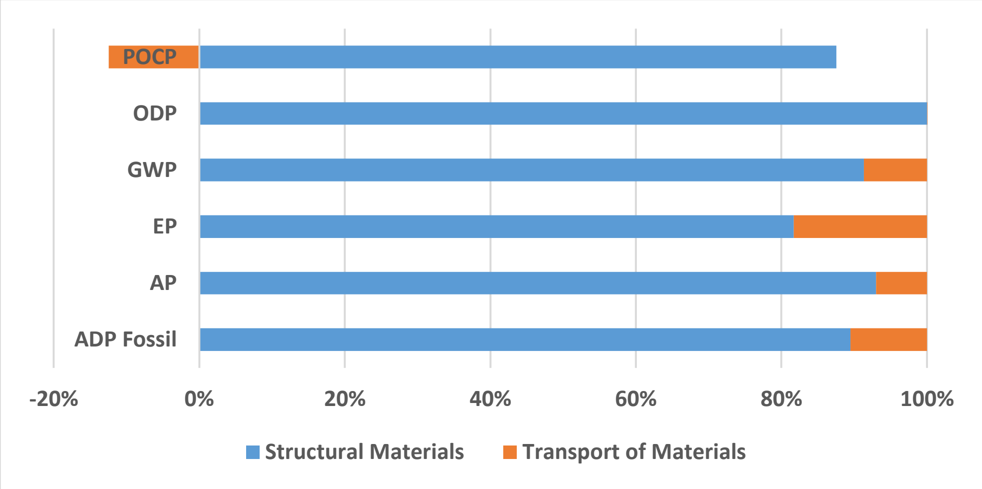
Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	7,23E+06	4,35E+06	-39,9%
AP	Kg SO_2 eq.	1,88E+03	1,23E+03	-34,5%
EP	Kg PO_4 eq.	1,80E+02	1,41E+02	-21,6%
GWP	Kg CO_2 eq.	7,72E+05	6,06E+05	-21,5%
ODP	Kg R11 eq.	1,15E-02	4,47E-03	-61,0%
POCP	Kg C_2H_4	2,70E+02	1,29E+02	-52,2%

According to these results, case study C2.2 has a major advantage relative to C2.1 in all impact categories at the material production stage.

4.2.3.2 Construction stage

- *Environmental analysis of reference case study C2.1*

The results of the environmental analysis for the construction stage for the reference case study C2.1 are presented in Figure 114. The operations related to on-site structural material productions represent the main contribution to the environmental impacts.

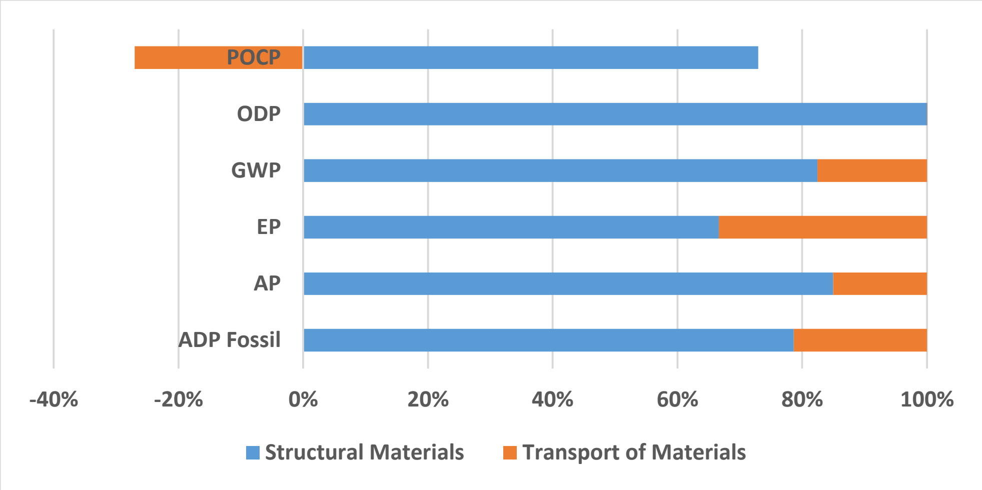


Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 114: Contribution analysis of processes during the construction stage [C2.1]

- *Environmental analysis of variant C2.2*

Environmental analysis of case C2.2 for the construction stage resulted in the values presented in Figure 115.



Note: The reason for a negative value in POPC is due to Nitric Oxide (NO) emissions from transport by truck, which have a counter effect on the environmental category of POCP [21]. See section 1.2.6.

Figure 115: Contribution analysis of processes during the construction stage [C2.2]

The results obtained for the variant case study C2.2 are summarized and compared with the reference case study C2.1 in Table 87.

Table 88: Environmental impacts at the construction stage relative to C2.1

Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	3,19E+05	1,63E+05	-48,7%
AP	Kg SO_2 eq.	7,77E+01	3,76E+01	-51,6%
EP	Kg PO_4 eq.	7,05E+00	4,02E+00	-43,0%
GWP	Kg CO_2 eq.	2,81E+04	1,44E+04	-48,6%
ODP	Kg R11 eq.	4,45E-04	9,43E-05	-78,8%
POCP	Kg C_2H_4	1,04E+01	3,01E+00	-70,9%

According to these results, the case study C2.2 has a major advantage (> 40% reduction) as compared to C2.1 in all impact categories at the construction stage.

4.2.3.3 Operation Stage

- *Environmental analysis of reference case study C2.1*

The results obtained for the day work scenario in the operation stage of the reference case study C2.1 are shown in Table 88 and Figure 116.

Table 89: Environmental impacts at the operation stage per maintenance process [C2.1 day work]

Impact Category	Unit	Total	Road surface	Steel girders	Concrete deck	Waterproofing layer	Traffic Congestion
ADP Fossil	MJ	1,07E+07	2,80E+06	1,25E+05	2,18E+05	5,09E+05	7,03E+06
AP	Kg SO_2 eq.	6,75E+02	1,32E+02	2,61E+01	1,09E+02	5,33E+01	3,55E+02
EP	Kg PO_4 eq.	1,09E+02	1,68E+01	1,27E+00	1,54E+01	1,57E+01	5,99E+01
GWP	Kg CO_2 eq.	2,13E+05	5,65E+04	7,75E+03	7,24E+04	1,23E+04	6,43E+04
ODP	Kg R11 eq.	5,12E-03	4,70E-08	1,45E-08	4,74E-07	5,12E-03	2,23E-07
POCP	Kg C_2H_4	1,19E+02	4,86E+01	1,01E+01	4,79E+00	4,96E+00	5,10E+01

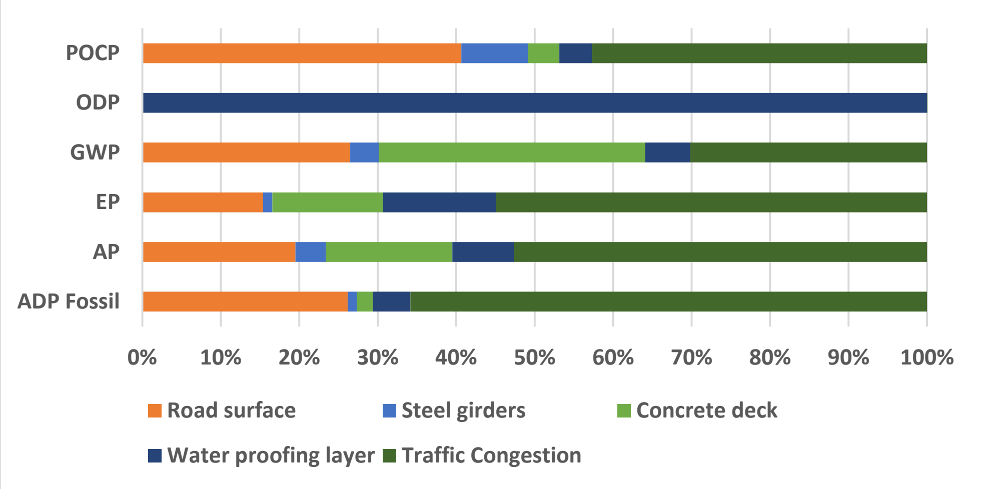


Figure 116: Contribution analysis of processes during the operation stage [C2.1 day work]

Ozone Depletion Potential (ODP) is dominated by the impact coming from the waterproofing layer. The replacement of the waterproofing layer in years 40 and 80 make up for the most contribution as compared to the rest maintenance processes, although generally of very low magnitude (in the order of 10^{-7} or less). The rest of the impact categories are dominated by the impacts arising from traffic congestion, maintenance to the concrete deck and road surface. It is seen that the contribution from the maintenance of the steel girders, namely the application of a corrosion protection layer, is minimal as compared to the others. As will be seen in the following paragraph, the explanation above holds for the night work scenario too.

The results obtained for the night work scenario in the operation stage of the reference case study C2.1 are shown in Figure 117.

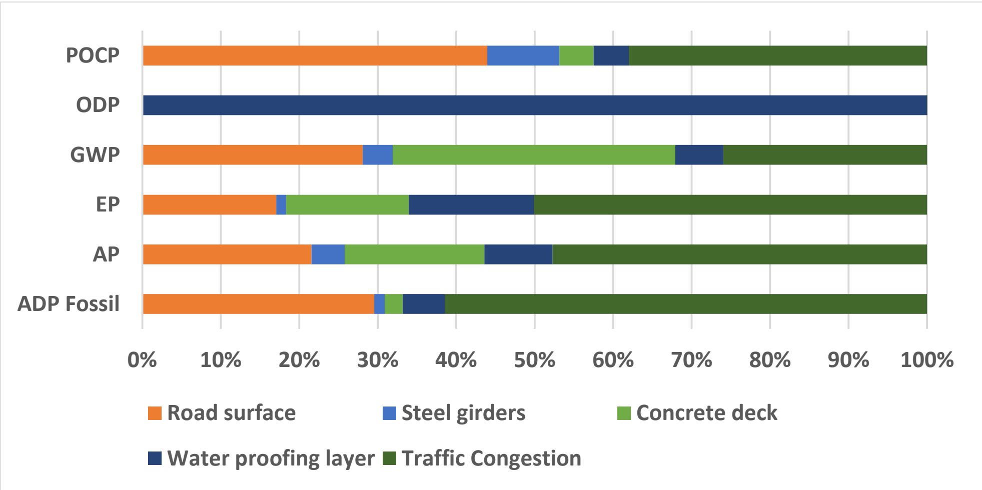


Figure 117: Contribution analysis of processes during the operation stage [C2.1 night work]

It is observed in both day and night work scenarios that maintenance of the road surface, steel girders, and traffic congestion contribute the most in almost all impact categories. It could be noted from Table 90 that lower impact was calculated with the night work scenario than the day work. All the parameters except the traffic are kept constant in both analyses. Thus, this reduction can only be attributed to the lower traffic congestion during the night work. Table 91 compares the results for both work plans with emphasis given to the traffic congestion alone. An average reduction of 17~19% is calculated with the night work plan.

Table 90: Variation of environmental impacts at the operation stage considering night work relative to day work [C2.1]

Impact Category	Unit	Case Study C2.1 Day	Case Study C2.1 Night	Variation relative to C2.1 Day
ADP Fossil	MJ	1,07E+07	9,45E+06	-11,5%
AP	Kg SO_2 eq.	6,75E+02	6,12E+02	-9,4%
EP	Kg PO_4 eq.	1,09E+02	9,85E+01	-9,7%
GWP	Kg CO_2 eq.	2,13E+05	2,01E+05	-5,7%
ODP	Kg R11 eq.	5,12E-03	5,12E-03	0,0%
POCP	Kg C_2H_4	1,19E+02	1,10E+02	-7,6%

Table 91: Impact variation in day and night work considering the traffic congestion alone [C2.1]

Impact Category	Unit	Case Study C2.1 Day	Case Study C2.1 Night	Variation relative to C2.1 Day
ADP Fossil	MJ	7,03E+06	5,80E+06	-17,4%
AP	Kg SO_2 eq.	3,55E+02	2,92E+02	-17,9%
EP	Kg PO_4 eq.	5,99E+01	4,93E+01	-17,7%
GWP	Kg CO_2 eq.	6,43E+04	5,22E+04	-18,9%
ODP	Kg R11 eq.	2,23E-07	1,81E-07	-18,6%
POCP	Kg C_2H_4	5,10E+01	4,19E+01	-17,8%

- *Environmental analysis of variant C2.2*

The environmental impacts made in the operation stage, for the day work scenario and night work scenario, of the variant case study C2.2 are presented in Table 92.

Table 92: Environmental impacts at the operation stage considering night work relative to day work [C2.2]

Impact Category	Unit	Case Study C2.2 DAY	Case Study C2.2 NIGHT	Variation relative to C2.2 DAY
ADP Fossil	MJ	1,11E+07	9,85E+06	-11,3%
AP	Kg SO_2 eq.	6,78E+02	6,13E+02	-9,6%
EP	Kg PO_4 eq.	1,13E+02	1,02E+02	-9,6%
GWP	Kg CO_2 eq.	2,12E+05	1,99E+05	-5,9%
ODP	Kg R11 eq.	5,17E-03	5,17E-03	0,0%
POCP	Kg C_2H_4	1,14E+02	1,04E+02	-8,1%

As expected, the night work scenario results in a reduction of impacts. However, the reduction (7.3%) is not so big due to the relatively small ADT for these bridges. Case C2.2 is compared to the reference case C2.1 in the operation stage with day and night work plans in Tables 93 and 94, respectively.

Table 93: Environmental impacts at the operation stage in C2.2 relative to C2.1 day work

Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	1,07E+07	1,11E+07	+4,0%
AP	Kg SO_2 eq.	6,75E+02	6,78E+02	+0,4%
EP	Kg PO_4 eq.	1,09E+02	1,13E+02	+3,2%
GWP	Kg CO_2 eq.	2,13E+05	2,12E+05	-0,8%
ODP	Kg R11 eq.	5,12E-03	5,17E-03	+1,0%
POCP	Kg C_2H_4	1,19E+02	1,14E+02	-4,8%

Table 94: Environmental impacts at the operation stage in C2.2 relative to C2.1 night work

Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	9,45E+06	9,85E+06	+4,2%
AP	Kg SO_2 eq.	6,12E+02	6,13E+02	+0,2%
EP	Kg PO_4 eq.	9,85E+01	1,02E+02	+3,3%
GWP	Kg CO_2 eq.	2,01E+05	1,99E+05	-0,9%

ODP	Kg R11 eq.	5,12E-03	5,17E-03	+1,0%
POCP	Kg C_2H_4	1,10E+02	1,04E+02	-5,4%

The variant case C2.2 led to higher impacts in most categories as compared to the reference case C2.1 at the operation stage.

4.2.3.4 End-of-life stage

- *Environmental analysis of reference case study C2.1*

The contribution of each process at the end-of-life stage as well as the total emissions per impact category are indicated in Table 95. The same has been illustrated in Figure 118. Disposal of concrete and bituminous materials cause the most burden on the environment while their transportation causes the least relative impact. The negative values in the figure represent the credits gained due to the recycling processes.

Table 95: Environmental impacts per process at the end-of-life stage [C2.1]

Impact Category	Unit	Total	Disposal	Transport	Recycling
ADP Fossil	MJ	1,92E+06	2,94E+06	5,48E+04	-1,07E+06
AP	Kg SO_2 eq.	1,12E+03	1,36E+03	8,88E+00	-2,43E+02
EP	Kg PO_4 eq.	1,80E+02	1,84E+02	2,11E+00	-6,71E+00
GWP	Kg CO_2 eq.	1,29E+05	2,27E+05	3,98E+03	-1,03E+05
ODP	Kg R11 eq.	3,25E-03	2,23E-06	1,33E-09	3,25E-03
POCP	Kg C_2H_4	7,32E+01	1,30E+02	-2,80E+00	-5,43E+01

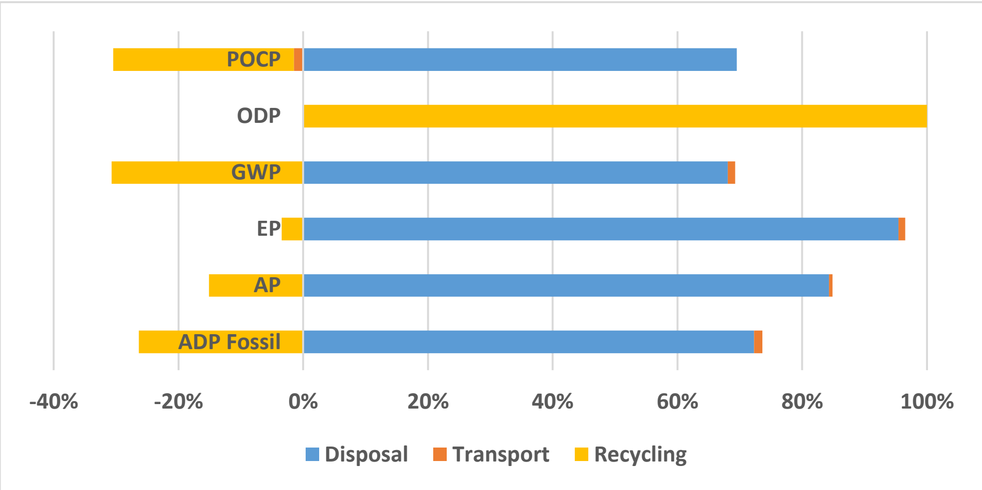


Figure 118: Contribution analysis of processes at the end-of-life stage [C2.1]

- *Environmental analysis of variant C2.2*

The contribution of each process at the end-of-life stage as well as the total emissions per impact category are presented in Table 96. The same has been presented in Figure 119 for better illustration. Disposal of concrete and bituminous materials cause the most burden on the environment while their transportation causes the least impact, relatively. The negative values in the figure represent the credits gained due to the recycling processes.

Table 96: Environmental impacts per process at the end-of-life stage [C2.2]

Impact Category	Unit	Total	Disposal	Transport	Recycling

ADP Fossil	MJ	4,00E+06	4,02E+06	7,05E+04	-8,60E+04
AP	Kg SO_2 eq.	1,84E+03	1,85E+03	1,14E+01	-1,95E+01
EP	Kg PO_4 eq.	2,54E+02	2,52E+02	2,71E+00	-5,37E-01
GWP	Kg CO_2 eq.	3,08E+05	3,11E+05	5,12E+03	-8,22E+03
ODP	Kg R11 eq.	2,64E-04	3,04E-06	1,71E-09	2,60E-04
POCP	Kg C_2H_4	1,70E+02	1,78E+02	-3,60E+00	-4,35E+00

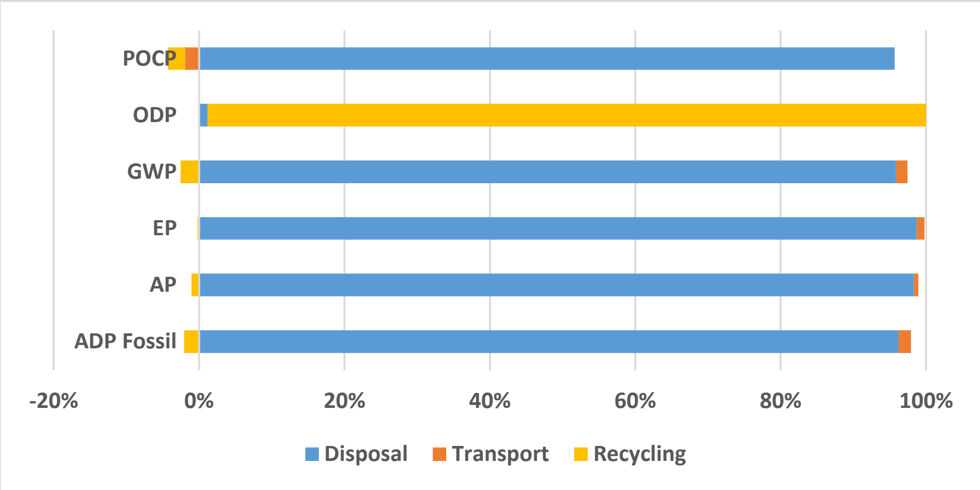


Figure 119: Contribution analysis of processes at the end-of-life stage [C2.2]

The results for the two cases are summarized and compared in Table 97 and illustrated in Figure 120.

Table 97: Environmental impacts in C2.2 at the end-of-life stage relative to C2.1

Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	1,92E+06	4,00E+06	+108,3%
AP	Kg SO_2 eq.	1,12E+03	1,84E+03	+64,5%
EP	Kg PO_4 eq.	1,80E+02	2,54E+02	+41,4%
GWP	Kg CO_2 eq.	1,29E+05	3,08E+05	+138,9%
ODP	Kg R11 eq.	3,25E-03	2,64E-04	-91,9%
POCP	Kg C_2H_4	7,32E+01	1,70E+02	+132,4%

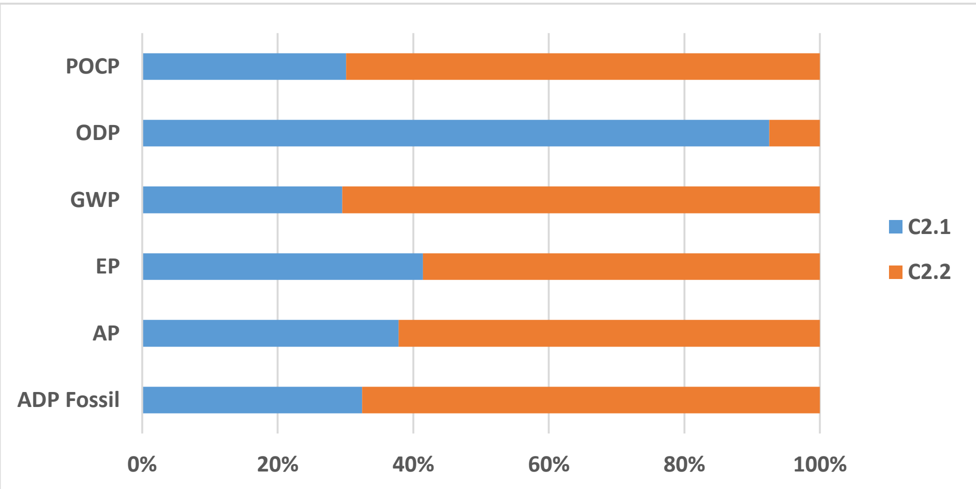


Figure 120: Contribution analysis of each bridge during the end-of-life stage [case C2.1 & C2.2]

It can be concluded from the previous two illustrations that the reference example led to lower values at this stage. This is given by the recycling processes in the reference example C2.1. Higher impacts are registered for case C2.1 in the ODP category as a result of the recycling process itself that gives rise to such emissions. Notice, however, that these impacts are generally small in magnitude (in the order of 10^{-3} or lower).

4.2.3.5 Results of the lifecycle environmental analysis

- *Aggregate lifecycle results for case study C2.1*

The previous sections presented the partial results per stage/phase in the bridge life. In this subsection, the results for each impact category of the different stages are summed up and the aggregate results are presented in Table 98, considering the day work scenario.

Table 98: Lifecycle environmental impacts per lifecycle stage [C2.1]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	2,01E+07	7,23E+06	3,19E+05	1,07E+07	1,92E+06
AP	Kg SO_2 eq.	3,75E+03	1,88E+03	7,77E+01	6,75E+02	1,12E+03
EP	Kg PO_4 eq.	4,76E+02	1,80E+02	7,05E+00	1,09E+02	1,80E+02
GWP	Kg CO_2 eq.	1,14E+06	7,72E+05	2,81E+04	2,13E+05	1,29E+05
ODP	Kg R11 eq.	2,03E-02	1,15E-02	4,45E-04	5,12E-03	3,25E-03
POCP	Kg C_2H_4	4,73E+02	2,70E+02	1,04E+01	1,19E+02	7,32E+01

For a better understanding of the contribution of each stage to the aggregated result, these results are also illustrated in Figure 121.

The production stage is the stage that most contributes to all the impact categories, with an average percentage of 50.8%. The operation stage has the second major contribution for the impact categories (27.2% Avg.). The end-of-life stage has a relatively smaller (20% Avg.) but considerable contribution while the construction stage has a negligible contribution (2% Avg.) for all impact categories.

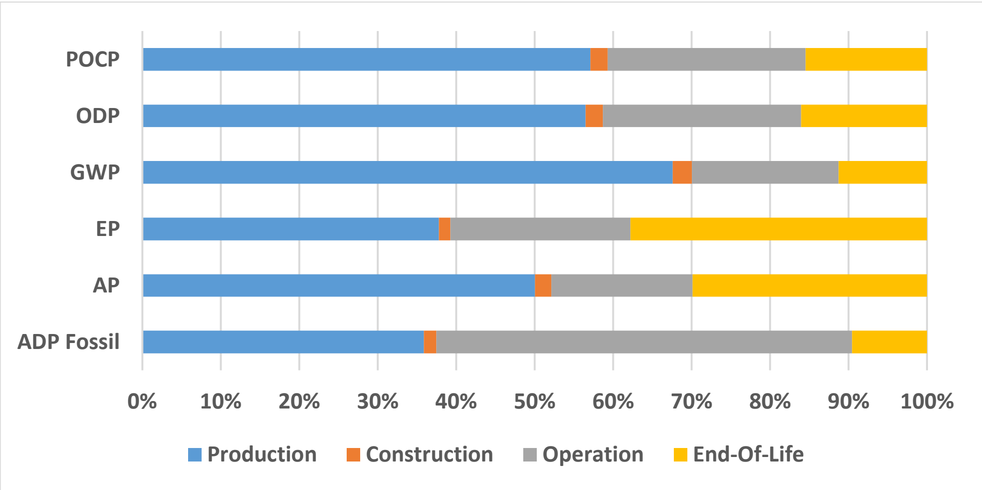


Figure 121: Contribution of each stage per impact category [C2.1]

- *Aggregate lifecycle results for C2.2*

The results for each impact category of the different stages presented in the previous sections were summed up and the aggregate results are shown in Table 99, considering the day work scenario for case study C2.2.

Table 99: Lifecycle environmental impacts per Lifecycle stage [C2.2]

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	1,96E+07	4,35E+06	1,63E+05	1,11E+07	4,00E+06
AP	Kg SO_2 eq.	3,79E+03	1,23E+03	3,76E+01	6,78E+02	1,84E+03
EP	Kg PO_4 eq.	5,12E+02	1,41E+02	4,02E+00	1,13E+02	2,54E+02
GWP	Kg CO_2 eq.	1,14E+06	6,06E+05	1,44E+04	2,12E+05	3,08E+05
ODP	Kg R11 eq.	1,00E-02	4,47E-03	9,43E-05	5,17E-03	2,64E-04
POCP	Kg C_2H_4	4,16E+02	1,29E+02	3,01E+00	1,14E+02	1,70E+02

As illustrated in Figure 122, the material production stage is the foremost contributor to the impacts (35.3% Avg.), followed by the end-of-life stage, operation stage and the construction stage with average relative contributions of 31.6%, 32.1%, and 1% respectively. Comparing values obtained in Table 98 and Table 99 one can see that the concrete solution results in significantly higher impacts in the operation and end-of-life stage.

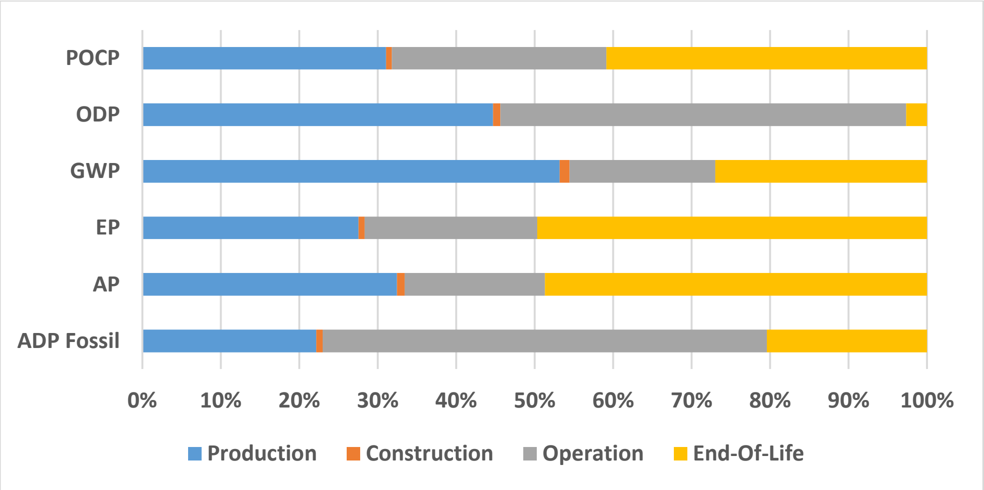


Figure 122: Contribution of each stage per impact category [C2.2]

The results obtained for the case C2.2 are compared to the reference case C2.1 in Table 100, considering the day work scenario for both cases.

Table 100: Variation of the aggregate environmental impacts in C2.2 relative to C2.1

Impact Category	Unit	Case Study C2.1	Case Study C2.2	Variation relative to C2.1
ADP Fossil	MJ	2,01E+07	1,96E+07	-2,7%
AP	Kg SO_2 eq.	3,75E+03	3,79E+03	+1,0%
EP	Kg PO_4 eq.	4,76E+02	5,12E+02	+7,6%
GWP	Kg CO_2 eq.	1,14E+06	1,14E+06	-0,2%
ODP	Kg R11 eq.	2,03E-02	1,00E-02	-50,7%
POCP	Kg C_2H_4	4,73E+02	4,16E+02	-12,1%

To understand the contribution of each case study to the aggregated result better, the results are illustrated in Figure 123.

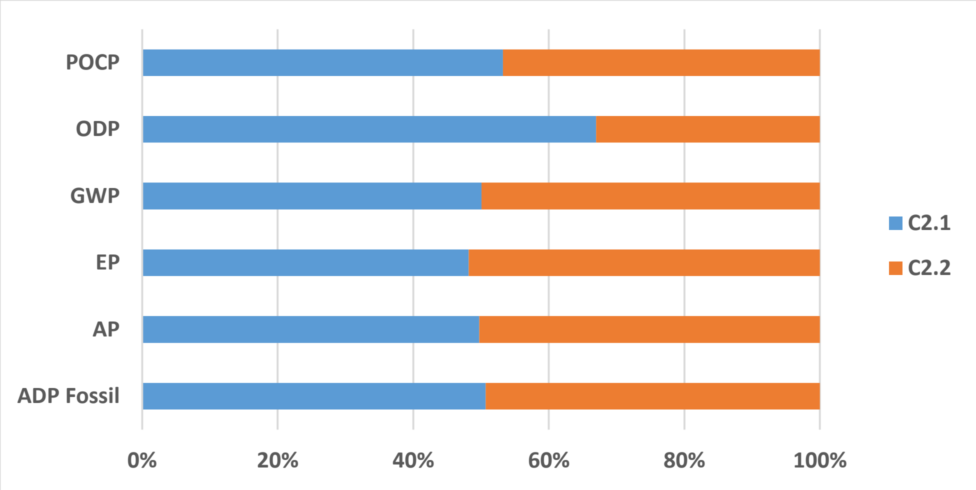


Figure 123: Relative impacts of C2.2 compared to C2.1 per impact category

The reference example C2.1 gained preference over C2.2 in terms of acidification, eutrophication, adiabatic depletion (fossil fuel) and global warming potentials. However, C2.2 is found to be preferable in terms of ozone depletion and photochemical oxidants creation potentials. The greatest difference appears in the ozone depletion potential impact category. Higher impacts are registered for case C2.1 in the ODP category because of emissions in the production, construction, and recycling stages. Notice, however, that these impacts are generally small in magnitude (in the order of 10^{-2} or lower).

4.2.4 Lifecycle Costs Analysis

4.2.4.1 Initial construction costs

- *Analysis of the reference case study C2.1*

The initial cost of the bridge structure, including the material transport costs, is 928.779,30 €. For the 2 × 422.85m^2 area of the two bridges, this translates to a cost of about 1098,2 €/m^2. Figure 124 shows the proportion of the costs for the substructure, superstructure and the roadway which are calculated based on the bill of materials and unit costs indicated in Table 84.

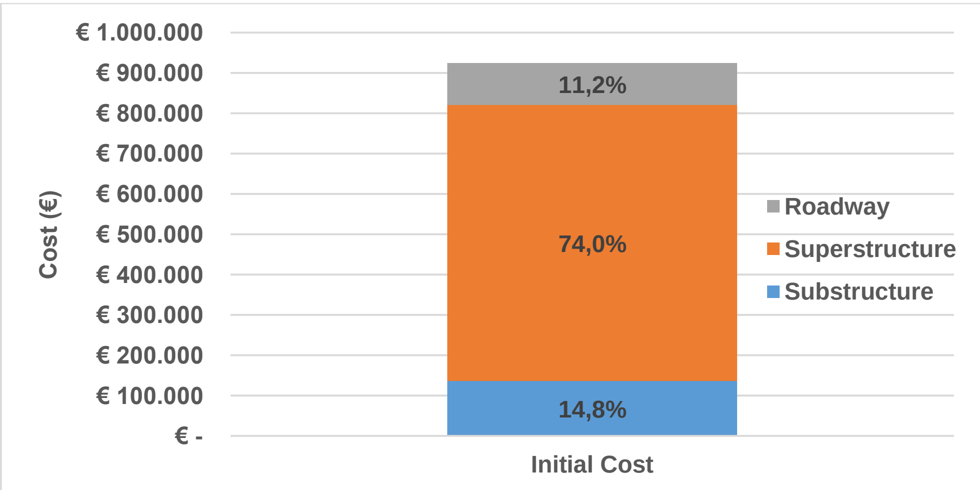


Figure 124: Initial cost of C2.1

- *Analysis of the variant C2.2*

The initial cost, including the material transport costs, calculated for the variant case study C2.2 is 826.410,9 €. For the 2 × 422.45m^2 area of the two bridges, this translates to a cost of about 978,1 €/m^2. Figure 125 shows the proportion of the costs for the substructure, superstructure and the roadway which are calculated based on the bill of materials and unit costs indicated in Table 84.

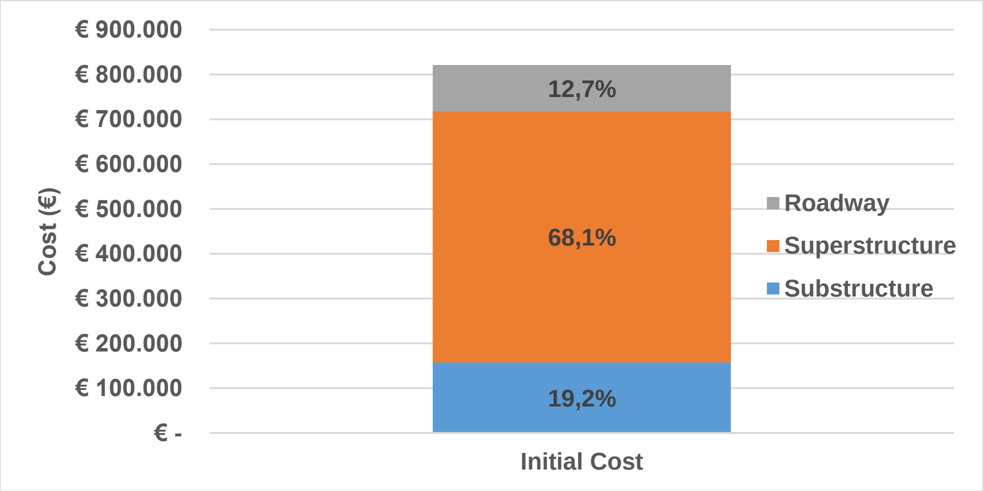


Figure 125: Initial cost of C2.2

4.2.4.2 Operation costs

Over the period of 100 years, the bridge case studies are assumed to be maintained and rehabilitated according to the plan indicated in the Annex – Table A1, which contains the definition of a standard Inspection scenario. In addition to the maintenance cost, the following charts also include costs associated with inspection works.

- *Analysis of reference case study C2.1*

The operation costs per year are based on the unit costs and frequencies of the maintenance events indicated in Table A1. These costs are illustrated in Figure 126 along with the cumulative operation costs at their net present value considering a discount rate of 2%. The high value of operation cost at year 40 comes as a result of replacement work on the road surface and expansion joints. The unit cost associated with the replacement of expansion joints is high and thus the higher operation cost. The replacement of the expansion joints is repeated in year 80. However, this peak is not noticeable in the figure since the devaluation of money increases as time increases in converting these costs to the net present value. In the same years mentioned above, the concrete deck is also maintained. The peaks in the years 35 and 70, on the other hand, relate to costs incurred during maintenance work on both the bearings and the corrosion protection layers of the steel girders.

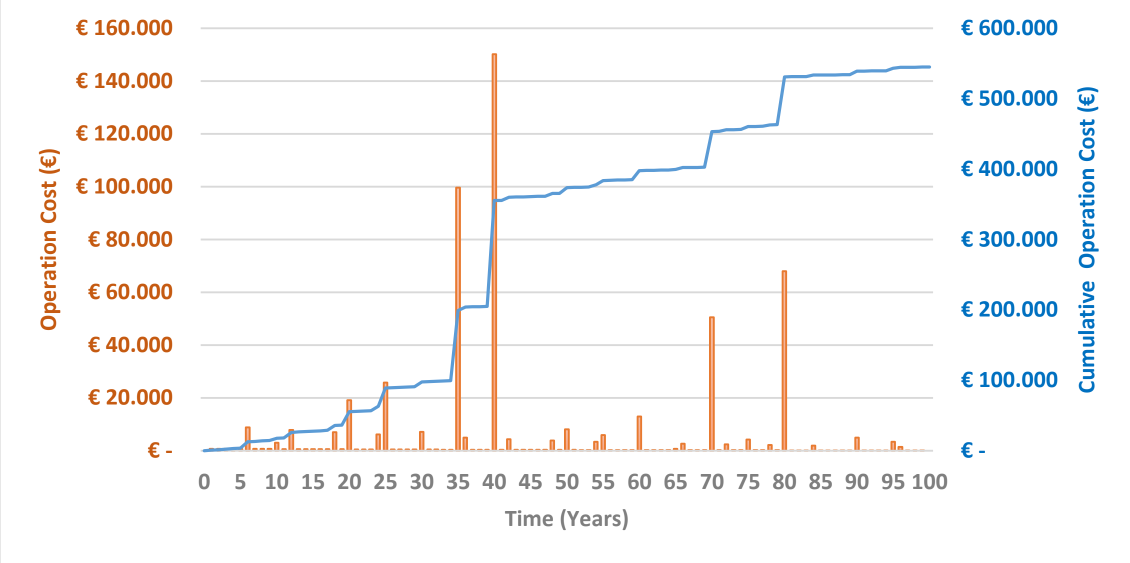


Figure 126: Operation costs of bridge C2.1 over its service life

- *Analysis of reference case study C2.2*

The operation costs per year are based on the unit costs and frequencies of the maintenance events indicated in Table A1. These costs are illustrated in Figure 127 along with the cumulative operation costs in their net present value considering a discount rate of 2%. The high value of operation cost at year 40 comes as a result of replacement work on the expansion joints. The unit cost associated with the replacement of these devices is high and thus the higher operation cost.

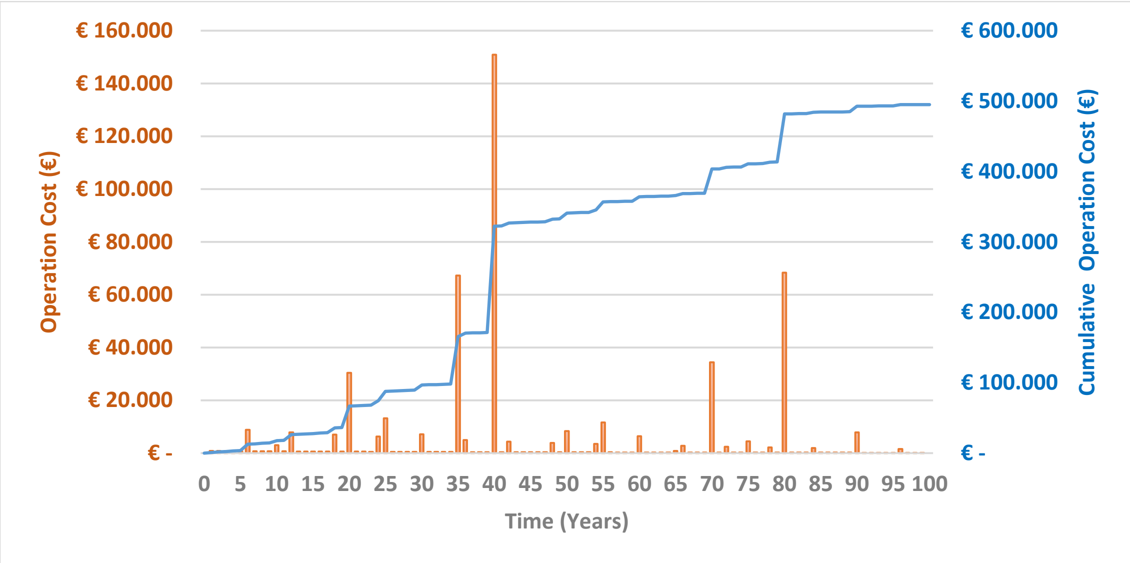


Figure 127: Operation costs of bridge C2.2 over its service life

There are variations between the operation costs for the two bridges at different times in their service lives. For instance, the peaks in operation cost for C2.2 at years 35 and 70 relate to costs incurred during maintenance work on the bearings. C2.2 requires maintenance of eight bearings as opposed to the four bearings that require maintenance in C2.1.

4.2.4.3 End-of-life cost

A summary of the end-of-life costs for bridges C2.1 and C2.2 are given in Tables 101 and 102, respectively. The concrete solution, C2.2, results in 12.3% higher end-of-life cost than the steel composite bridge.

Table 101: End-of-life cost for C2.1

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	307,76	-3492,68	50	63,72
Concrete	2448	3379,05	50	506,86
Earthwork	10920	75366,00	10	452,20
Bitumen	163,2	1126,35	20	13,52
Other		81,52		0,00
			Sub-Total (€)	77496,53
			Demolition cost (€)	11663,01
			Total Cost (€)	89159,55

Table 102: End-of-life cost for C2.2

Material	Mass (tonnes)	Disposal cost or Scrap Value (€)*	Distance (km)	Transport Cost (€)*
Steel**	152,86	-1476,98	50	31,65
Concrete	3408	4704,16	50	705,62
Earthwork	12000	82819,78	10	496,92
Bitumen	155,25	1071,48	20	12,86
Other		82,49		0,00
			Sub-Total (€)	88447,98
			Demolition cost (€)	11663,01
			Total Cost (€)	100111,00

(*) Considering disposal cost for concrete 10 €/tonne, for steel scrap value of 100 €/tonne and transportation cost of 0.03 €/tonne/km.

(**) The amount of steel calculated above includes both the reinforcement steel bars and structural steel sections/plates and connections. Note: The costs are given in their present value calculated according to equation 2 at a discount rate of 2%.

4.2.4.4 Total Lifecycle cost

Summing the costs calculated in the previous sections for case study C2.1 led to the total lifecycle net present cost (LCC) of 1.562.781,9 € using a discount rate of 2.0%. This represents a total cost of about 1847,92 €/m^2. For case study C2.2, on the other hand, a total lifecycle net present cost (LCC) of 1.421.637,6 € is calculated at a discount rate of 2.0%. This represents a total cost of about 1682,61 €/m^2. The costs of the bridge for each stage are summarized in Table 103 and illustrated in Figures 128 and 129.

Table 103: Comparison of lifecycle costs between C2.1 and C2.2

	Case Study C2.1 (€)	Case Study C2.2 (€)	Variation relative to C2.1
Initial Cost	928779,3	826410,9	-11,0%
Operation Cost	544843,0	495043,4	-9,1%
End of life Cost	89159,5	100183,3	+12,4%
Total Cost	1562781,9	1421637,6	-9,0%

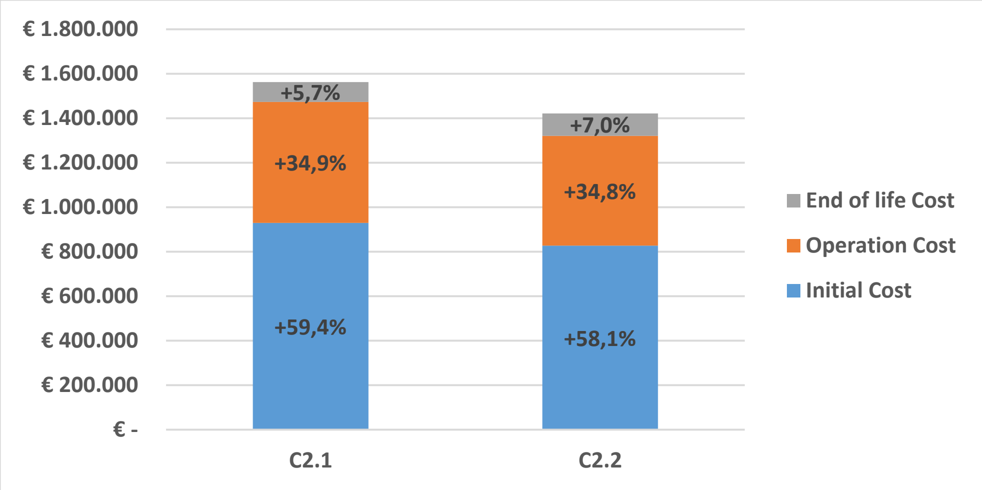


Figure 128: Total lifecycle costs of C2.1 and C2.2 (without user costs)

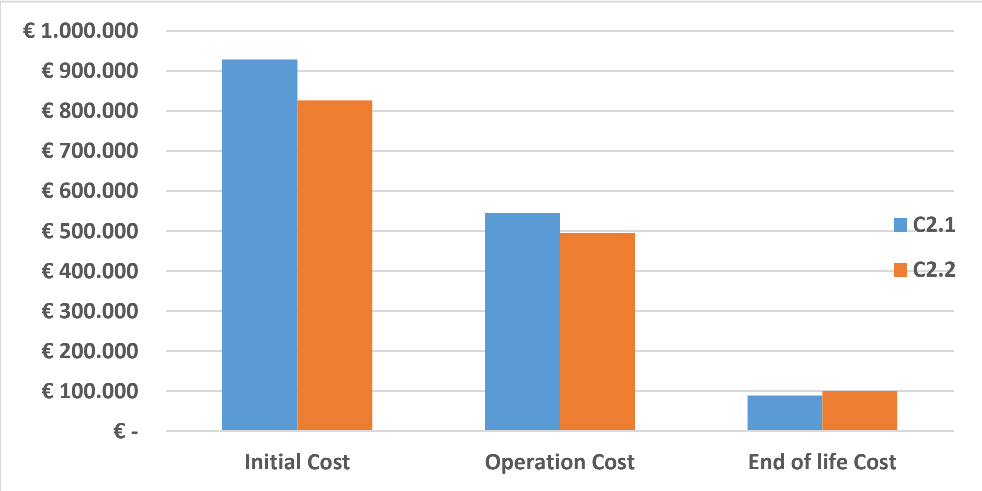


Figure 129: Lifecycle costs of C2.1 compared to C2.2

The composite solution appears to be more expensive at the construction and operation stage but more attractive when considering the end-of-life stage. Nonetheless, the solution C2.2 has 17.9% lower total LCC when compared to case study C2.1. It is noted that the end-of-life costs are much lower than operation or construction costs due to the fact that these costs occur at year 100 and are discounted with a yearly discount rate fixed at 2%.

4.2.5 Lifecycle Social Analysis

Two maintenance scenarios have been studied for user costs calculation: (i) a day work scenario where maintenance actions are carried out during the day (from 6:00 AM to 10:00 PM) and the bridge has one lane closed for major maintenance actions (road surface/waterproofing layer replacement); (ii) night work scenario, different from the day work scenario in that maintenance actions are carried out during the night (from 10:00 PM to 6:00 AM).

Figure 130 details the user costs for case studies C2.1 with day work and night work scenarios. It is noted that the user inconvenience is reduced if work is carried out during the night since there is less traffic than during the day. An 17.3% reduction in user costs was calculated with the night work.

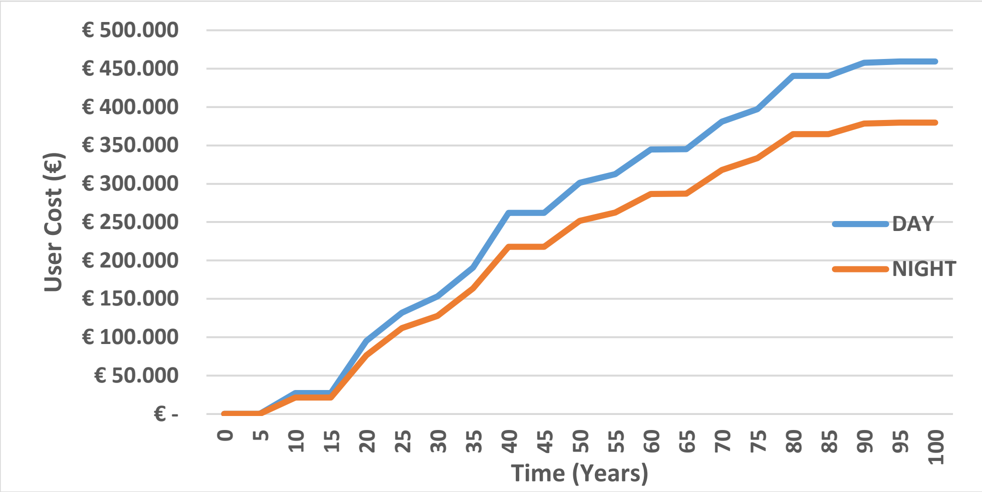


Figure 130: User costs for C2.1 with “day” and “night” work scenarios

It is also observed in Figure 131, that user costs for case studies C2.1 are 7.4% lower than those for and C2.2 because the maintenance of concrete bridge takes more time. There is a need for maintenance of the steel girders for the composite bridge, which is not required for the concrete bridge. However, there are eight bearings in the concrete bridge, double the amount of bearings in the composite bridge, which require longer durations for maintenance. This change resulted in a significant difference that the composite bridge took 194 days for maintenance during the whole lifespan of the bridge while the concrete bridge took 211 days. The longer the duration of maintenance activities the higher the user costs.

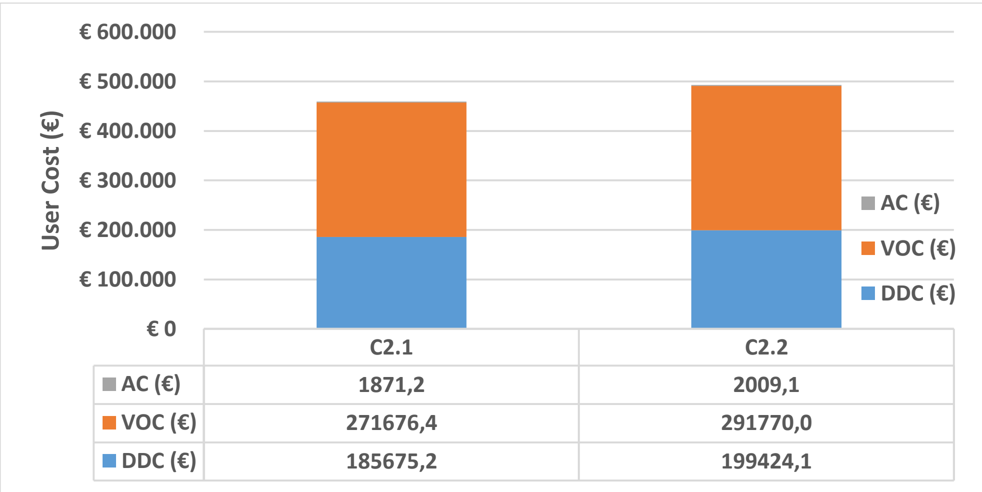


Figure 131: User costs for C2.1 and C2.2 with the day work scenario

4.2.6 Discussion of the Results for case C2

In this case study for small motorway bridges, it can be observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories. The production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. In the operation stage, the impacts are mainly caused by traffic congestion. It has been seen that the overall results are improved when carrying out maintenance work at night. Night shift work provides a reduction of impacts owing to the fact that traffic count is lower at night.

The reference example C2.1 gained preference over C2.2 in terms of acidification, eutrophication, adiabatic depletion (fossil fuel) and global warming potentials. However, C2.2 is found to be preferable in terms of ozone depletion and photochemical oxidants creation potentials. The greatest difference appears in the ozone depletion potential impact category. Higher impacts are registered for case C2.1 in the ODP category because of emissions in the production, construction, and recycling stages. However, that these impacts are generally small in magnitude (in the order of 10^{-2} or lower). Overall it can be said that both examples have comparable environmental impacts.

In terms of Lifecycle costs, it is evident that the initial cost for the steel composite bridge is higher (11.2%) due to material and construction costs. The operation costs were also computed to be 9.1% higher in the composite bridge. However, the steel composite bridge gains favorability in the end-of-life stage as compared to its concrete counterpart by 12.4%. The favorability comes as a result of the abundant recycling possibilities with steel at the end-of-life stage.

The higher values of LCC for case C2.1 is due to the fact that the initial cost is around 59.4% of the total cost of the bridge. The operation and end-of-life costs make up for 64.9% and 5.7% of the total cost, respectively. On the other hand, case C2.2 requires 9.1% more operation cost as a result of the longer maintenance/operation durations it requires. The same conclusion can also be drawn for the user costs.

Once more, the social aspects of the lifecycle analysis prove that the night shift is favorable in reducing the impacts on user cost. The user costs calculated for the composite bridge is found to be less than that calculated for the concrete bridge. The difference in user costs between the two bridges would have increased even more significantly if the average daily traffic volume was higher or if there had been traffic underneath the bridges. This implies that with for a higher average daily traffic (ADT), the steel solution would gain more preference in terms of LCS and LCC too.

5 SUMMARY AND CONCLUSIONS

In this project European partners from universities, research centers, road administrations, design offices and steel producers brought together their knowledge and experiences on steel-composite bridges. These bridges were not as commonly regarded only under the aspect of an efficient initial state and construction cost performance but over the entire lifecycle. On the one hand, during this long lifecycle bridges are designed for, degradation processes such as fatigue, corrosion and carbonation were regarded. On the other side, inspection and maintenance were closely looked at in worder to keep the bridges in good conditions. The functional quality was combined with the environmental and economic quality. By this holistic approach (LCA, LCC, and LCS) an assessment of the lifecycle was reached.

Typical for the application range of concrete and steel-composite bridges in Europe three bridge types were identified according to the span length and their functionality. Small single span motorway bridges spanning nearly 35 meters using either composite girders or precast concrete girders were considered as bridges of type C2. Multi-span motorway bridges having a structural typology of continuous beam with a total length of 308 m distributed over nine spans were studied as bridges of type B1. Bridges of type A consisted of crossings of motorways spanning 40 – 50 m and allowed for comparisons between different abutment types (integral and seated bridges) and span distributions (single and two-span bridges). Span lengths up to 166 meters were reached by big motorway bridges and were assigned to type C1 with plate girder composite sections.

As given in Table 7 an extensive number of case studies was selected, assigned to the bridge types and studied in detail. The base of the analyses was the extensive data collection performed and compared for the different European countries involved. The detailed data compilation was integrated into a database. Bridges are designed for more than 100 years and the operation stage plays a central role. Special focus was given by compiling and comparing inspection and maintenance strategies. Standard scenarios were elaborated including frequencies, costs, traffic restrictions during the actions, equipment etc. For the maintenance scenarios average service lives of bridge elements were defined and necessary actions described. In addition, two specific scenarios were elaborated and studied: a) the lack of money scenario and b) the prolonged life scenario. For both of these scenarios further assumptions were made and an adapted frequency of maintenance actions assumed.

The case studies were designed following the requirements of codes and rules. The material quantities determined were further used in lifecycle costs and lifecycle environmental analyses. Bridges immediately start to deteriorate after entering into service. In order to keep the bridges above a required condition, inspection, maintenance and rehabilitation actions are necessary. With each intervention environmental and economic impacts are caused and need to be taken into account. Hence, the structural performance must be known as environmental and economic analysis directly depend on it.

For the lifecycle environmental analysis, a system boundary was set, including all stages over the complete lifecycle of the bridges, from raw material extraction to the end-of-life, considering also the recycling. Seven indicators of environmental performance were regarded and the inputs determined.

Lifecycle costs were regarded from design to the end-of-life of the bridges. In order to compare past and future cash-flows with those of today several methods were compared. A yearly discount rate was set to 2% in the LCC for the 100-year service life in the standard and lack of money maintenance scenarios and for 130-year service life in the prolonged life maintenance scenario. Lifecycle social analysis was regarded considering user costs apart from direct measurable costs. These user costs are costs caused by maintenance operations leading to traffic congestion or disruption of the normal traffic flow. User costs were divided into traffic delay costs and vehicle operating costs.

The established database, the analysis of lifecycle performance, the lifecycle environmental and economic analyses were all together integrated in the holistic approach to the aforementioned and selected case studies.

The following conclusions can be provided for each bridge type:

- ***Case A - Crossings of motorways***

For crossings of motorways the environmental impacts of the material production and the operation stage dominate by far the lifecycle. In general, a reduction of these impacts is achieved for the integral bridge solution. For crossings of a motorway a big benefit was registered for the integral as the maintenance of bearings and expansion joints is avoided and therewith traffic congestion reduced.

In terms of LCC, the integral steel composite solution (A1) is costly in terms of initial investments relative to the concrete counterpart. It was deduced that the composite steel solution (case study A3) is better than both its concrete equivalent (A2) and the integral solution A1 when considering the initial costs. On the other hand, the integral bridge gave reduced operating costs as it avoids the need for maintenance actions concerning expansion joints. The integral bridge requires less maintenance and therefore leads to less traffic disruption and reduced user costs. However, the traditional steel composite bridge gains slight favorability in the overall analysis.

LCA considering alternative maintenance scenarios showed that the lack of money scenario resulted in reduced emissions in all impact categories for the concrete bridge whereas the integral and traditional composite bridges had some increments as well as decrements in the different impact categories. The prolonged life scenario resulted in higher environmental impacts in all three cases.

LCC considering the alternative maintenance scenarios resulted in a more or less similar economic implications in the concrete bridge (A2); while for the integral bridge and the traditional composite bridge, both the lack of money and prolonged life scenario incurred additional costs as compared to the standard scenario.

The social analysis (LCS) proved that the integral and the composite bridge share similar characteristics for the alternative maintenance scenarios. In both bridge types, the lack of money scenario lead to reduced user costs and the prolonged life scenario caused an increase in the user costs. However, for the concrete bridge (A2), both alternative scenarios, standard and prolonged life, resulted in a comparatively higher user cost as compared to the lack of money scenario.

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

- ***Case B - Big motorway bridges***

Similar conclusions on the lifecycle environmental analysis can be drawn for the big motorway bridges. As before, the material production and the operation stage dominate the lifecycle, here again. Once more, the social aspects of the LCA prove that the night shift is considered favorable in reducing the impacts on user cost. The user costs calculated for the two different working shifts on the same bridge resulted in a difference of almost 1.5 million €. The application of the different scenarios to this case study reveals that the “lack of money” scenario has lower user costs at the end than the standard scenario while the “prolonged life” scenario has the higher user costs.

- ***Case C1 - Multi-span motorway bridges:***

It was observed from the lifecycle environmental analysis that the stages of material production and operation dominate all impact categories. In terms of processes, the production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage the impacts are mainly caused by traffic congestion.

In terms of Lifecycle costs, it is evident from the case studies that the steel composite bridge exhibited preferable characteristics. The Initial cost and operation costs for the steel composite bridge were found to be less than its concrete counterpart. The steel composite bridge gained favorability in the end-of-life stage, as well, due to the abundant recycling possibilities with steel. Once more, the social aspects of the LCA prove that the night shift is favourable in reducing the impacts on user cost.

Assessing alternative maintenance scenarios, it was found that the lack of money scenario led to lower impacts on the environment in both the steel composite bridge and the concrete bridge. Moreover, it was concluded from both the LCC and LCS analyses that lower operation and user costs, respectively, are achieved with the “lack of money” compared to the standard maintenance scenario for both bridge types. The effort made to prolong the service life of the bridge with the “prolonged life” scenario lead to an increase of impact in all environmental categories. The operation costs and user costs were also increased as the service life is prolonged except that lower LCC value were obtained for the post-tensioned reinforced concrete bridge in the “prolonged life” scenario albeit the longer service life of the bridge.

- ***Case C2 - Small single-span motorway bridges:***

In this case study for small motorway bridges, it was observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories. In terms of processes, the production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage, the impacts are mainly caused by traffic congestion.

In terms of Lifecycle costs, it was evident that the initial cost for the steel composite bridge is higher due to material and construction costs. Moreover, the operation costs are more or less similar for the two bridge types namely, steel composite bridge and its concrete counterpart. However, the steel composite bridge gains slight favorability at the end-of-life stage owing to its abundant recycling possibilities.

The social aspects of the lifecycle prove that the night shift is favourable in reducing the impacts on user cost. It has been seen that the overall results are improved when carrying out maintenance work at night. Night shift work provides reduction of impacts owing to the fact that traffic count is lesser at night. The user costs calculated for the two bridge types are comparable for the given traffic volume.

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ANNEX A:

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	demolition / replacement																			x
Corrosion (small points/small areas)	partial surface corrosion protection (1)				x							x							x	
Corrosion (complete renewal)	complete renewal corrosion protection(1)						x							x						
Concrete																				
concrete slab - used up	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)	total replacement							x								x				
broken concrete header (repair)	total/partial replacement	x		x		x		x		x		x		x		x		x		
tightening of bolts	total/partial replacement	x		x		x		x		x		x		x		x		x		
Cleaning		x		x		x		x		x		x		x		x		x		
Bearings																				
Elastomeric bearing - used up	total replacement						x							x						
Elastomeric bearing (repair)	partial replacement			x							x							x		
Calote bearing - used up	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		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				
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

(1): classification according to the duration of protection EN ISSO 12944-2 (L= 2-5 years;M=5-15 years; H>15 years)

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 protection(1)									x										
Concrete																				
concrete slab - used up	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)	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	total replacement						x							x						
Elastomeric bearing (repair)	partial replacement			x							x							x		
Calote bearing - used up	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																				
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																			

(1): classification according to the duration of protection EN ISSO 12944-2 (L= 2-5 years;M=5-15 years; H>15 years)

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	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)	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	total replacement						x							x							x					
Elastomeric bearing (repair)	partial replacement			x							x							x						x		
Calotte bearing - used up	total replacement																									
Calotte bearing - maintenance	total/partial replacement																									
Corrosion of metallic elements (Sa2/St3)	painting of metallic 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 metallic elements			x								x								x			x			
damage caused by corrosion	partial replacement																						x			
Gutters																										
replacement dewatering	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																									

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

Table A4: Traffic restriction for Cases B and C

Damage	Maintenance Actions	Traffic Restrictions	
		Over the bridge	Under the bridge
Steels			
Steel girder - used up	demolition / replacement	Road Closed	-
Corrosion (small points/small areas)	partial surface corrosion protection	No restrictions	-
Corrosion (complete renewal)	complete renewal corrosion protection	No restrictions	-
Concrete			
concrete slab - used up	demolition / replacement	Road Closed	-
Corrosion of the reinforcement deck plate	partial renewal	1 lane closed per day	-
Concrete edge beam	total surface treatment	Speed reduction	-
Concrete edge beam	partial renewal of surface treatment	Speed reduction	-
Concrete edge beam	total replacement	Speed reduction	-
Concrete edge beam repairs	partial renewal	Speed reduction	-
Expansion joints			
broken modules (considering a modular joint)	total replacement	1 lane closed per day	-
broken concrete header (repair)	total/partial replacement	1 lane closed per day	-
tightening of bolts/ partial module replacement	total/partial replacement	1 lane closed per day	-
Cleaning		1 lane closed per day	-
Bearings			
Elastomeric bearing - used up	total replacement	Speed reduction	-
Elastomeric bearing (repair)	partial replacement	Speed reduction	-
Calote bearing - used up	total replacement	Speed reduction	-
Calote bearing - maintenance	total/partial replacement	Speed reduction	-
Corrosion of metalic elements (Sa2/St3)	painting of metalic elements	Speed reduction	-
Road surface			
cracks, ruts, excavation	total replacement	1 lane closed per day	-
cracks, ruts, excavation	total survival road surface layer *	1 lane closed per day	-
cracks, ruts, excavation	minor repairs	1 lane closed per day	-
Water proofing layer			
cracks, ruts, excavation	total replacement	1 lane closed per day	-
Railings			
used up	total replacement of railings	No restrictions / speed reduction	-
painting	painting of metalic elements	No restrictions / speed reduction	-
damage caused by corrosion	partial replacement	No restrictions / speed reduction	-
Gutters			
replacement dewatewring	total replacement	No restrictions / speed reduction	-
Safety barrier			
used up	total replacement of safety barrier	1 lane closed per day	-
safety barriers - minor repairs due to corrosion	total/partial replacement	1 lane closed per day	-
damage caused by accident (steel)	partial replacement	1 lane closed per day	-

* scarse layer of asphalt containing a large amount of betumen that is placed on top of the existing damaged surface layer (and waterproofing layer)

Table A5: Traffic restriction for Case A

Damage	Maintenance Actions	Traffic Restrictions – Over the bridge	Traffic Restrictions – Under the bridge
Steels			
Steel girder - used up	demolition / replacement	**Road Closed**	-
Corrosion (small points/small areas)	partial surface corrosion protection	No restrictions	No restrictions
Corrosion (complete renewal)	complete renewal corrosion protection	No restrictions	1 lane closed per day
Concrete			
concrete slab - used up	demolition / replacement	Road Closed	1 lane closed per day
Corrosion of the reinforcement deck plate	partial renewal	1 lane closed per day	1 lane closed per day
Concrete edge beam	total surface treatment	Speed reduction	1 lane closed per day
Concrete edge beam	partial renewal of surface treatment	Speed reduction	1 lane closed per day
Concrete edge beam	total replacement	Speed reduction	1 lane closed per day
Concrete edge beam repairs	partial renewal	Speed reduction	1 lane closed per day
Expansion joints			
broken modules (considering a modular joint)	total replacement	1 lane closed per day	No restrictions
broken concrete header (repair)	total/partial replacement	1 lane closed per day	No restrictions
tightening of bolts/ partial module replacement	total/partial replacement	1 lane closed per day	No restrictions
Cleaning		1 lane closed per day	No restrictions
Bearings			
Elastomeric bearing - used up	total replacement	Speed reduction	No restrictions
Elastomeric bearing (repair)	partial replacement	Speed reduction	No restrictions
Calote bearing - used up	total replacement	Speed reduction	No restrictions
Calote bearing - maintenance	total/partial replacement	Speed reduction	No restrictions
Corrosion of metalic elements (Sa2/St3)	painting of metalic elements	Speed reduction	No restrictions
Road surface			
cracks, ruts, excavation	total replacement	1 lane closed per day	No restrictions
cracks, ruts, excavation	total survival road surface layer *	1 lane closed per day	No restrictions
cracks, ruts, excavation	minor repairs	1 lane closed per day	No restrictions
Water proofing layer			
cracks, ruts, excavation	total replacement	1 lane closed per day	No restrictions
Railings			
used up	total replacement of railings	No restrictions / speed reduction	No restrictions
painting	painting of metalic elements	No restrictions / speed reduction	No restrictions
damage caused by corrosion	partial replacement	No restrictions / speed reduction	No restrictions
Gutters			
replacement dewatewring	total replacement	No restrictions / speed reduction	No restrictions
Safety barrier			
used up	total replacement of safety barrier	1 lane closed per day	No restrictions
safety barriers - minor repairs due to corrosion	total/partial replacement	1 lane closed per day	No restrictions
damage caused by accident (steel)	partial replacement	1 lane closed per day	No restrictions

* scarse layer of asphalt containing a large amount of betumen that is placed on top of the existing damaged surface layer (and waterproofing layer)

Table A6: Operation types, rates of work and maintenance unit cost

Maintenance		Rate of work	Unit cost
To	Type		
Bearings	Repair	1,5 day/un	2100 €/un
Bearings	Replacement	2 day/un	(2100 + cost of new bearing) €/un
Concrete deck	Refurbishment	0,08 days/m²	30 €/m²
Concrete edge beams	Replacement	0,225 days/m	70 €/m
Edge beams	Refurbishment	0,225 days/m	70 €/m
Expansion joints	Repair	0,75 m/h	10 €/m
Expansion joints	Maintenance	40 m/day	10 €/m
Expansion joints	Replacement	3,5 m/day	2500 €/m
Gutters	Replacement	0,1 days/m	140 €/m
Railings	Refurbishment	4 m²/h	90 €/m
Railings	Replacement	1,75 m/h	115 €/m
Road surface	Repair	0,02 days/m²	11,4 €/m²
Road surface	Replacement	0,02 days/m²	11,5 €/m²
Safety barriers	Replacement	1,3 m²/h	140 €/m
Steel girders	Refurbishment	0,02 days/m²	75 €/m²
Steel girders	Repair	0,02 days/m²	100 €/m²
Water proofing layer	Replacement	0,02 days/m²	202 €/m²