SBRI+ Design Manual II

Advanced Applications

1st Edition, 2018

Institute of Structural Design (USTUTT), Germany

Universidade de Coimbra, Portugal

Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, (IFSTTAR), France

ArcelorMittal (AMBD), Luxembourg

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SBRI+: Valorisation of Knowledge for Sustainable Steel-Composite Bridges in Built Environment – Design Manual II

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PREFACE

1st Edition

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

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- Nuno Martins (Brisa Engenharia e Gestão SA)
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Contents

1 INTRODUCTION

1.1 Holistic Approach

In the research project SBRI, only standard situations of deck bridges were analyzed and investigated. The approach introduced during the SBRI project is now to be tested and extended in this report to further bridge types and innovative solutions. The sustainable design of advanced bridges is carried out based on built example bridges existing in the diverse countries of the project partners. Advanced innovative solutions are compared with more common designs of the same bridge type in this manual. The case bridge types under analysis are indicated in Table 1.

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Table 1: Bridge case studies in Manual II

	Number of cases	Cases
Case D	3	D1 Hot-dip galvanization
		D2 Traditional coating
		D3 Hot-dip galvanization + traditional coating
Case E	2	E1 PRECOBEAM
		E2 Steel–concrete composite girders

Holistic Analysis

The investigations are carried out under a holistic analysis in order to grasp relationships and to identify the potential for optimization. It examines ecological (Lifecycle Environmental Assessment), economic (Lifecycle Cost) and socio-functional aspects (Lifecycle Social Analysis) for which the analytical approaches presented below are selected.

Lifecycle Assessment

Life cycle assessment is an established method for evaluating environmental impacts. Products can have a negative impact on the environment during their entire life cycle, from design, raw material production, construction and use to recycling or disposal. Lifecycle Assessment (LCA) is therefore used to examine the flow of substances and energy and the associated environmental effects over the entire lifecycle. Here, the existing model is expanded and adapted from SBRI to innovative design bridges.

Lifecycle Cost

The life cycle cost calculation (LCC) encompasses all costs incurred during the life cycle that are directly attributable to the structure. One challenge of the life cycle cost calculation is to determine the approach for the various maintenance activities in the lifecycle, which are depicted as a scenario. The life cycle costs are calculated on the basis of the theoretical lifetime of the individual bridge components.

Lifecycle Social Analysis

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 travelling through the roads, beneath and above the bridge.

Analysis Procedure

First, all necessary input data are collected, as it can be seen in the bridges in the worked examples. The exact quantities and all construction processes are particularly important for life cycle assessment and lifecycle calculation to obtain the respective results.

1.2 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.

Three types of inspection and maintenance scenarios were considered in Design Manual I:

Standard – for a 100-year service life, where it is considered that there will always be enough money to undergo necessary inspections and maintenance/ rehabilitation actions.

Lack of money – for a 100 year service life, but there is not enough money to undergo necessary inspection actions and consequent maintenance/repair actions. When these actions take place, it was considered that the bridge will be severely deteriorated in the end of the service life and near this year inspection actions will have to be increased for the knowledge of the real bridge condition. Maintenance and repair actions will also be increased near year 100.

Prolonged Life – in year 80 of the bridge service life, decision that the bridge will be maintained in service for an extra 30 years, until year 130, is taken. After year 80, inspection and maintenance/rehabilitation actions are adapted to accomplish this service life extension.

In Design Manual II, only the standard scenario will be considered.

1.2.1 Standard scenario

In the standard scenario, the inspection types and frequencies discussed below are considered as necessary to maintain a knowledge of the bridge condition and average service life of bridge elements. Well defined frequency for maintenance/repair actions is considered essential to maintain 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 and some elements do not have maintenance actions, when the element reaches the end of the service life, replacement takes place.

For the operation phase the necessary inspection actions are taken with the following maintenance/rehabilitation actions:

- Routine inspection – visual observation of all components of the bridge taken every year. The aim is detection of small damage that can be promptly repaired;

- Principal inspection – detailed visual inspection performed with specific means of access. The aim is an evaluation of the bridge condition to evaluate the bridge condition evolution. Eventual repair and rehabilitation actions are defined;

- Special inspection - detailed visual inspection performed with specific means of access when there is a need for a specific repair plan for the complete or partial rehabilitation of a bridge. During this inspection tests together with laboratory analysis of bridge materials are used to evaluate real bridge condition and allow recommendations for damage repair.

The frequency assumed for each type of inspection for the standard scenario is shown in Table 2.

Table 2: Standard scenario - types of Inspection, inspection frequency and average occurrence Loss of zinc relative to the corrosion load (DIN EN ISO 12944-2, 1998)

Types of inspection	Inspection frequency	Average occurence during bridge service life (100 years)
Routine	annualy	100
Principal	every 6 years	17
Special	2 in 100 years	2

Table 3 shows the average service life assumed for the bridge elements.

Table 3: Average service life for bridge elements for the standard maintenance scenario

Bridge elements	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
Calote Bearing	100
Railing	40

For the elements of the bridge, the following maintenance/repair actions and frequency were assumed necessary to maintain a good condition rating for the bridge,Table 4.

Table 4: Standard scenario - average maintenance/repair actions frequency

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

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

1.3 Presentation of advanced bridge types

1.3.1 Case Bridge Type D

The first case bridge analyzed is an innovative integral bridge started to be built in mid-2014 with hot-dip galvanized girders spanning over a motorway. The bridge shown in Figures 1 to 3 is the first road bridge being built with hot-dip galvanized girders over a motorway in Germany. Therefore, the analysis of this bridge is promising to show extended results and conclusions with the sustainable analysis according to SBRI. The data of this bridge have been collected and the innovative corrosion protection with hot-dip galvanized steel-girders analyzed under the perspective of sustainable bridge design. The advantages and disadvantages are worked out and the conclusions are drawn for this innovative bridge solution.

Figure 1: Hot-dip galvanized bridge in Germany - side view

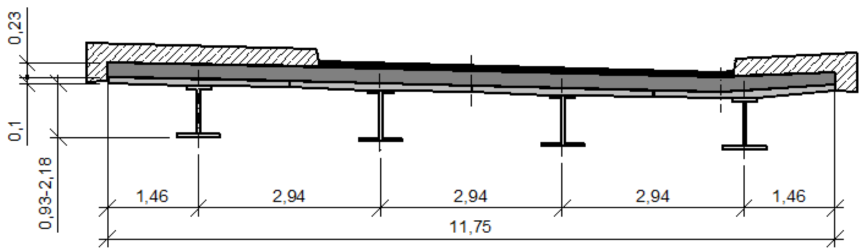


Figure 2: Hot-dip galvanized bridge in Germany – cross section

Figure 3: Hot-dip galvanized bridge in Germany in the fabrication

1.3.2 Case Bridge Type E

In the design and construction of bridges, questions of sustainability, maintenance and durability become more and more important for European road administrations in addition to safety and serviceability issues.

Since 1998, bridges have been created in a composite pre-fabrication (VFT® = Verbund-Fertigteil-Träger = prefabricated composite beam) method of construction. The system established with over 300 erected structures principally in Germany as well as in Poland and Austria. It is a cost-effective construction for composite bridges of small and medium spans with site-prepared traffic deck.

The PRECOBEAM system – VFT girder with rolled girders in concrete – represents a further development of this method of construction. The new system provides a rolled beam section that is cut in the web centre in such a way to result in 2 T-sections, whereas the cutting form provides the shear connector, Figure 4. This special cut of steel web allows a perfect connection to the upper concrete part. The cutting guide selected for the manufacture of the concrete dowels enables the manufacture of tall sections without waste. With the separation technology used it is possible to achieve a high quality for the separating faces with minimum local notch effects.

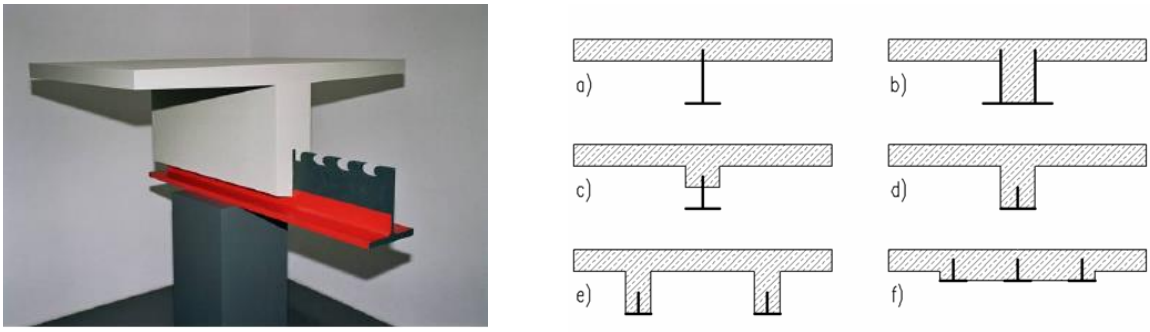


Figure 4 : Precobeam girder. Configuration variants of PRECO girders for bridge construction

The PRECO principle combines the advantages of the VFT girder with the robustness of the traditional “filler beam plate”. The steel components consist of profiles with no upper chord as shown in the schematic representations in Figure 4. The in-site concrete deck that is later completed is coupled by means of connecting reinforcement with the concrete chord of the pre-fabricated girder.

This economic technology has developed fast: by the end of 2016, at least 34 bridges using composite dowels had been constructed in Europe (13 in Germany, 11 in Poland, 4 in Czech Republic, 4 in Austria, 2 in Romania).

Bridges with VFT method have been built in Poland since the year 2000, Figure 5. Many diverse solutions and structures were developed, each adapting to the different conditions and requirements. The experience gained in time and the well behavior of the VFT bridges, allowed for the solution to be appreciated.

Figure 5 : Precobeam in Poland Cross-section

The experiences gained by the design of 6 Precobeam bridges and by further analyses including Lifecycle Assessment and Lifecycle Costs during this projects makes this innovative solution promising for bridges in Poland nowadays.

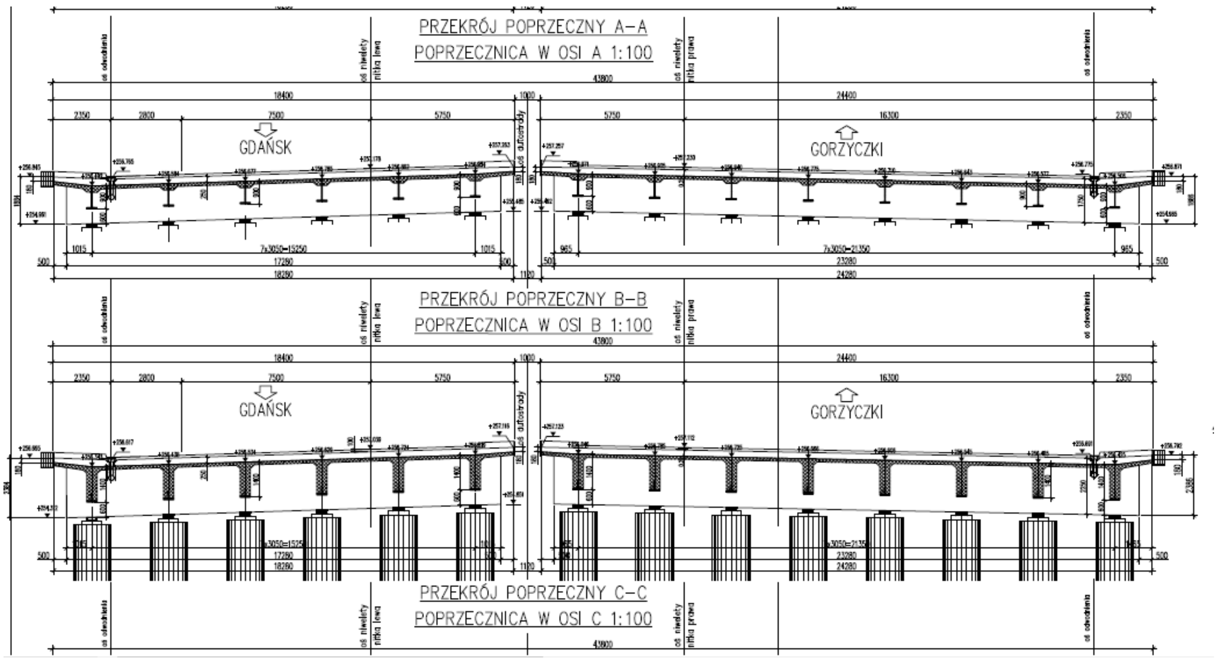


Figure 6: Cross Section alternative of Precobeam designed by SSF Inginierue, Munich

The above mentioned bridges built across Europe are analyzed in detail for their entire lifecycle considering the environmental and social analyses with associated inspection and maintenance procedures in mind. The lifecycle cost was not assessed for this case due to lack of data. The holistic approach from the SBRI project is applied.

1.4 Scenarios and assumptions for Lifecycle Environmental Analysis

1.4.1 Material Production stage

This stage takes into consideration the production of all the materials needed to build the bridge, according to Figure 7. The data sources are as indicated in Table 5.

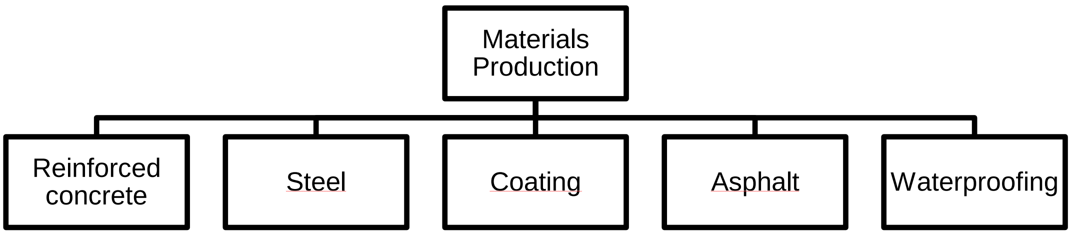


Figure 7: Material production stage

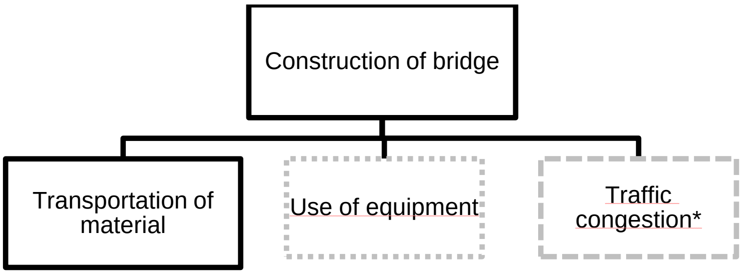
Table 5: Sources of data for materials and transportation

Material/Process	Source
Concrete (several grades)	GaBi [1]
Structural steel	Supplied to GaBi [1] by World Steel
Hot-dip galvanized Steel	EPD-BFS-20130173-IBG1-DE [2]

Reinforcement steel	GaBi [1]
Coating and Painting	GaBi [1]
Asphalt	GaBi [1]
Waterproof layer	GaBi [1]

1.4.2 Construction Stage

The construction stage covers all the processes needed for and affected by the construction of the bridge. Hence, as shown in Figure 8, 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 8: 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 6. The consumption of diesel is also calculated based on the travel distances displayed in this table.

Table 6: 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.

1.4.3 Operation Stage

It is hereby assumed that no major damage or failure of the bridge will occur over the bridge's service life taking into account the standard maintenance and rehabilitation plans defined in Part A, section 2.4 of Manual I, [2]. 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 the standard maintenance scenario are presented in Table D1 of Annex A. The maintenance plans are based on the estimated service life of different components of the bridge.

- *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.

1.4.4 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 9 illustrates the general unit processes included in this stage.

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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.

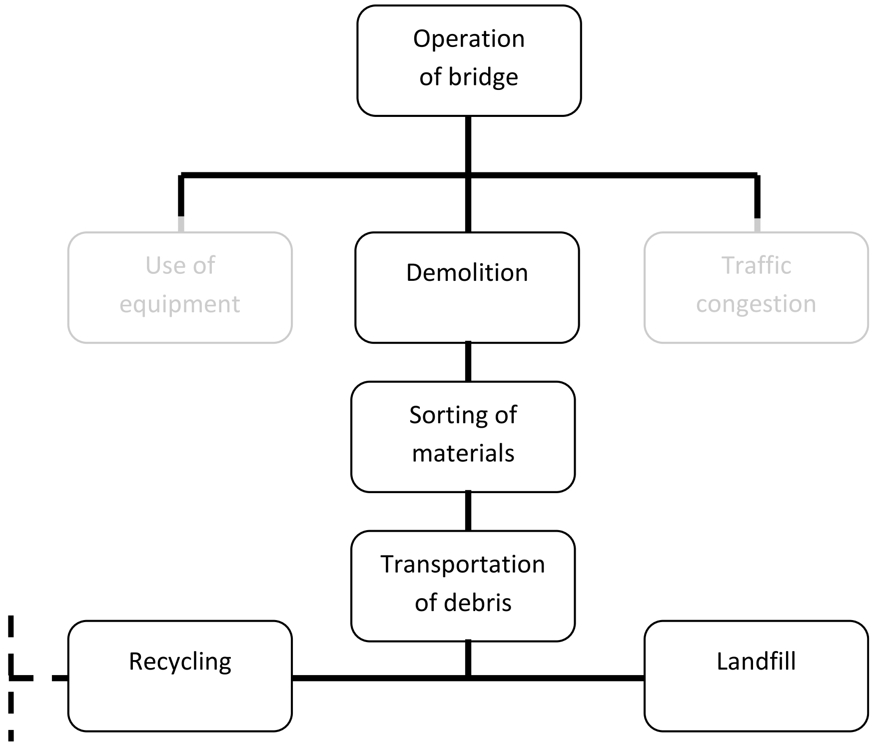


Figure 9: Processes included in the end-of-life stage

- *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 7.

Table 7: 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.

1.4.5 Environmental category of $ADP_{Elements}$

The environmental categories adopted in the methodology (as indicated in Part A of Manual I [2]) are calculated according to the CML methodology [3]. 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 [4]. 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.

1.4.6 Environmental category of POCP (Transport by truck)

According to the CML methodology [3], 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.

1.4.7 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.).

1.5 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 [5]. 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 WORKED EXAMPLES- BRIDGE TYPE D

2.1 GENERAL DESCRIPTION

2.1.1 Motivation

Since steel bridges are in the range of large-bridge construction and composite bridges are to be found throughout the entire span range, their traffic-related importance is generally very high. Any restrictions on use should be minimized in order to reduce the environmental impacts and traffic congestion. During the long life cycle of a computational 100 years, road safety, stability and durability must be ensured for bridge structures. Due to environmental and traffic influences, various effects on the bridge structure and its details, such as corrosion, carbonation, fatigue, etc., have to be considered. Corrosion protection is an important aspect especially for steel and composite bridges. In order to counter the increasing need for maintenance of steel surfaces, the choice of sustainable corrosion protection measures must be taken into account at an early stage in the planning of new construction projects so effective bridge solutions can be achieved. A comparison of corrosion protection systems is used herein to illustrate the effects on the holistic view of a reference structure over the entire life cycle. It is crucial from an economical point of view to optimize bridge solutions taking into account the overall service life and to evaluate them holistically, considering all the effects.

Since a large number of repairs are to be carried out during the long life cycle, the time and size of the measures play an important role. For the maintenance of the corrosion protection, the hot-dip galvanizing of bridge structures is a promising measure compared to the organic coating. The appropriate zinc coating can be expected not to require any intermediate renovation, maintenance actions can be avoided, and consequently there is no traffic restriction. It is assumed that, according to the condition-determining maintenance strategy [6] an organic coating has to be subjected twice to a complete renewal during the life cycle of bridges.

Hot galvanizing is investigated here as corrosion protection for steel girders in bridge construction according to aspects of sustainability. The process of hot-dip galvanizing is analyzed in a bridge project under a holistic approach in order to quantify costs as well as emissions and traffic restrictions over the entire life cycle.

In Germany, only footbridge bridges have been constructed with hot-dip galvanizing. Open questions on the fatigue safety of hot-dip galvanized bridges were answered in a project led by the Chair for Steel Construction at the TU Dortmund [7]. In a pilot plant, hot-dip galvanizing is now also to be used in road bridge construction for the first time. With the study of this case bridge under holistic aspects, it is examined whether the hot-dip galvanizing is a competitive solution.

2.1.2 Objectives

The aim with this case is to elaborate and provide guidance for the design of steel composite bridges with a lifetime-oriented corrosion protection.

The comparison of the corrosion protection is made here by using an integral highway composite bridge. The span is 45 meters. For the steel beams, an organic corrosion protection coating is compared with a hot galvanizing system and a duplex system produced during the utilization phase. The composite bridge is considered throughout the entire lifecycle, from manufacturing, through the whole use until demolition.

2.1.3 Corrosion protection in bridges

The durability of steel and composite bridge constructions is strongly influenced by environmental stress. Effective protection against corrosion is indispensable in bridge construction. For this purpose, a life of 100 years is to be expected, which requires a long retention of the protection duration. In Germany, more than 1,200 steel and composite bridges have to be protected in the road network, which have a steel area of more than 15 million square meters. As a corrosion protection, multilayer corrosion protection systems made of organic coatings are used as standard. In German bridge construction, hot-dip galvanizing is only used for traffic bridges signs as well as non-load-bearing components such as railings, passive protective devices, bearings, road junctions and noise barriers. In addition, hot-dip galvanizing is used as a corrosion protection for footbridges. The first hot-dip galvanized steel bridge approved for motorways in Germany was built in the Sauerland over the Lenne River in 1987 and restricted to a maximum permissible total weight of 12 tonnes [8]. A further corrosion protection process is the combination of galvanizing and a coating system for the so-called duplex system. The life of a duplex system is longer in the regel than the sum of the individual protection lives: hot-dip galvanizing and coating, since mutual protective mechanisms enhance their performance [9].

In addition to passive corrosion protection, the constructional corrosion protection should be considered as an integral part of the planning, by avoiding water accumulations or the attack of corrosive media on the structure. The active corrosion protection by the use of corrosion-resistant materials is taken into account in bridge construction by the use of weather-resistant steel, which forms a protective layer by an additional metal alloy.

The passive corrosion protection methods of steel structures under analysis are listed and explained in detail below.

A) Organic traditional coating

B) Application of metallic coating by the melt dip process, such as hot-dip galvanizing.

C) Duplex systems as a combination of coating processes and metallic coatings.

A. Organic traditional coating

Usually, a coating system consists of a base layer, (one or more) intermediate layers, and a cover layer. The basic coating ensures the adhesion of the other coatings on the surface. The intermediate coating is usually provided with corrosion-inhibiting pigments (epoxy resin or polyurethan) in order to achieve the corrosion protection effect. The top coat is responsible for the weather resistance and has also a decorative function. The selection of these coating layers should be done in such a way that the layers match to ensure protection of the steel against corrosion stresses as normatively regulated in DIN EN ISO 12944-2 [10]. In addition, ZTV-ING (Zusätzliche Technische Ver-tragsbedingungen und Richtlinien für Ingenieur-bauten ZTV-Ing) provides regulations for corrosion protection in part 4, section 3 [11].

Steel girders are generally provided with multi-layer anti-corrosive coatings, which have to be renewed every 25 to 35 years. These renovations of the corrosion protection not only entail costs for the construction process itself, but often also lead to a restriction of use and, in addition, to environmental emissions.

B. Hot-dip galvanizing

Hot-dip galvanizing is the most widely used corrosion protection method in metal construction. The design cannot be carried out on the construction site, but under controlled production conditions in a hot galvanizing plant according to DIN EN ISO 1461 [12]. After surface preparation and chemical cleaning to remove rust and mill scale, the steel parts are dried and coated with zinc in a dipping bath with molten zinc at a temperature of 450 °C (see Figure 10).The steel reacts with the liquid zinc and at the steel surface, iron-zinc alloy layers are formed. These have a higher hardness than steel and thus have high abrasion and resistance. Mechanical damage during transport and assembly is therefore rarely to be expected. In the critical corners and edges (thinner coating thickness) where the coating can be more difficult to perform, a thicker zinc coating is recommended to improve the corrosion protection.

Another aspect to consider, that is at the same time crucial for the life cycle cost analysis is the size of the girders, currently the length of the girder that can receive the treatment cannot be longer than 18m. In the case of bridges with span longer than 18 m it will be necessary to design intermediate joints, so that; for a bridge of 40 m two joints will be defined in the section of null moment.

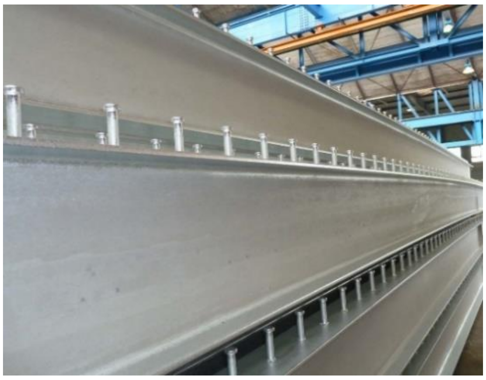


Figure 10 : Hot-dip galvanizing of steel components (a) Removal from the boiler (b) Hot-dip galvanized carriers

Figure 11: Definition of joints in Hot-dip galvanized girders

Figure 12: Zinc corrosion map of the Environment Agency

Zinc forms cover layers due to atmospheric weathering, which take over the protection of the steel surface. These top layers are removed by wind and weather, but are constantly being replaced by the zinc below. Along the structure life, zinc coatings are becoming ever thinner, due to the annual expected abrasion by the atmosphere, which has a strong influence. There is a continuous zinc removal. The expected duration of the corrosion protection effect depends directly on the zinc coating thickness, which is defined accordingly to the corrosion stresses on the building site. In DIN EN ISO 12944-2 [10] a subdivision into corrosion categories is made for atmospheric ambient conditions and the corresponding annual loss of zinc. The zinc corrosion map of the Environmental Bureau in Figure 12 shows the expected annual zinc removal. A comparison of Table 8: Loss of zinc relative to the corrosion load (DIN EN ISO 12944-2, 1998) with the map of Germany from Figure 12: Zinc corrosion map of the Environment Agency shows that the corrosion categories C2 and C3 are present in Germany, with the exception of the coastal areas. For Germany, therefore, an annual zinc removal of 0.5 and 1.7 micrometers per year, with the exception of a few coastal areas, is to be assumed [13]. For the zinc coating of 85 micrometers, which is an average in the building construction, a protection period of at least 50 years is thus ensured. For bridges, the lifetime of the corrosion protection could be the same as the bridge lifetime, 100 years, if the initial coating thickness is thick enough. In addition to the macroclimate, the microclimate and the boundary conditions of the structure should be also considered. The spray mist area must be taken into account when determining the necessary zinc thickness, especially for motorway bridges and motorway crossings.

Table 8: Loss of zinc relative to the corrosion load (DIN EN ISO 12944-2, 1998)

Corrosion category	Loss of thickness of zinc [µm/a]
C1 insignificant	≤ 0.1
C2 low	> 0.1 - 0.7
C3 moderately	> 0.7 - 2.1
C4 strong	> 2.1-4.2
C5 very high	>4.2 - 8.4

For steel structures subjected to atmospheric stress, hot-dip galvanizing has proven its worth as corrosion protection. The key is to find a corrosion protection that last many decades without maintenance. In many hot-dip galvanized buildings the same durability and useful life have been achieved. As an innovative solution for steel bridge construction, hot-dip galvanizing is an economic corrosion protection in terms of sustainability considering the whole life span of the structure. This applies in particular if the steel construction is not accessible for maintenance operations, or the maintenance measures limit the use of the bridge and the traffic below. The duration of the protection depends on the quality of the steel (Si-soothed, Al-soothed, etc.), the quality of the hot-dip galvanizing, the execution of the assembly and the actual atmospheric conditions.

C. Double system

Duplex systems are made of galvanizing (mainly hot-dip galvanizing) in combination with one (or more) coatings according to DIN EN ISO 12944-5 [14]. The essential advantage of the duplex system is a significant increase in the corrosion protection time in comparison with the sum of the protection durations of the individual systems: hot-dip galvanizing and coating. There is a synergy effect, which can be between 1.2 and 2.5 depending on the system [15] based on mutual protection. On the one hand, the zinc coating is protected from atmospheric and chemical influences by the overlying coating and thus against abrasion. On the other hand, there is no corrosion of the coating due to the zinc coating and, despite damage to the coating, the high resistance and abrasion resistance of the zinc coating below guarantee the protection of the steel from corrosion. Mutual protection of the two systems is particularly important at corners and edges, where the zinc coating is thicker and thus compensates for weaknesses in the coating due to its occurrence.

A sensible extension of the protection duration can be achieved by a subsequent coating of a hot-dip galvanizing. If this repair is carried out at a time when the initial system is still effective as a residual coating, the above-mentioned advantages of the duplex systems can be achieved.

The aim is to guarantee by means of the three mentioned corrosion protection types a useful life of the bridge of 100 years. Maintenance of the corrosion protection layers should be carried out as soon as possible, where necessary, in order to avoid further damage. In order to carry out an analysis over the entire life cycle, error-free installation must be assumed and measures taken during the utilization phase in the form of a maintenance strategy.

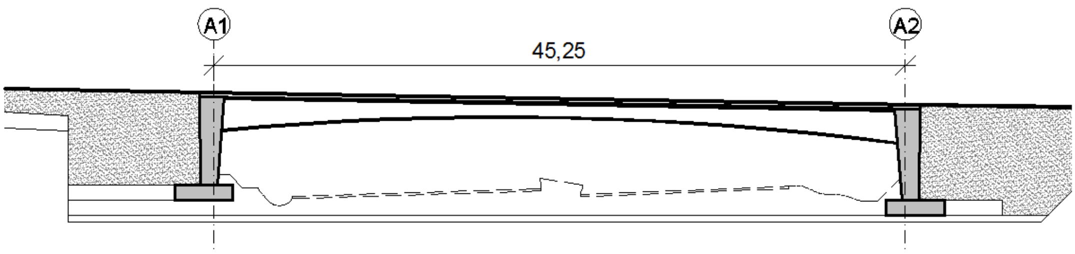
2.1.4 Analysis of further criteria

A sustainability analysis for bridge structures includes a variety of assessment criteria. Depending on the evaluation objective and system limits, it may be necessary to add individual criteria or not to take into account the analyses.

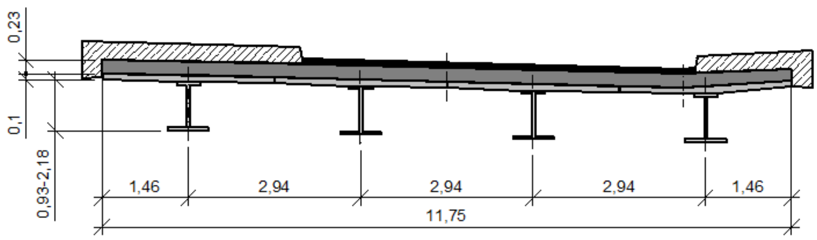
The aspects that are analogous to all bridges, so does not change with the corrosion protection, receive the same evaluation in all the cases. For instance, regarding the social aspects, the comfort of the use of bridges, the dynamic behavior, noise, accident costs and user safety are the same for all variants.

2.1.5 Definition of case studies

The bridge studied herein corresponds with the case A1 from Manual I [2]. It is motorway crossing bridge of two traffic lanes with dimensions 45.25 m length and 11.75 m width. It is an integral composite bridge with integral abutments and there is not support in the middle of the highway. The deck consists of four composite girders, Figure 13, which are made of plated steel S355 J2 G3 with variable height, from 0.93 m in mid-span to 2.18 m 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 0.1-0.12 m thick.



a)

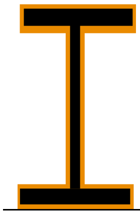
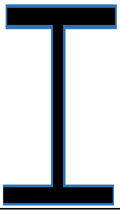


b)

Figure 13: Case D. Integral composite bridge: a) Longitudinal view; b) Cross section with girders of variable height

The three case studies corresponding with the design variants of the corrosion protection are summarized in Table 9 where the measures to be taken for maintenance over the entire life cycle of the bridge are indicated.

Table 9: Cases Bridge Type D

Corrosion protection		Maintenance
	**Case D1** Hot-dip galvanization (thickness 300 µm)	No renovation during the whole life cycle
	**Case D2** Organic protection coating	Complete renovation of the corrosion protection in year 33 and 66 of the life cycle
	**Case D3** Hot-dip galvanization (thickness 200 µm) and organic protection	Application of an organic corrosion coating only in the year 66 to the residual coating of hot-dip galvanizing

The most significant quantities of case study D are presented in Table 10:

Table 10: Quantities of Cases D1, D2 and D3

Description	Case D1	Case D2	Case D3	Unit	Unit cost (Germany 2008)
Substructure					
Excavations	4500	4500	4500	[€/m³]	5.88
Backfilling	2320	2320	2320	[€/m³]	7.60
Foundations' concrete C25/30	254	254	254	[€/m³]	77.67
Abutments' + piles concrete C30/37	746.20	746.20	746.20	[€/m³]	84.47
Reinforcement S500	90600	90600	90600	[€/kg]	0.99
Superstructure					
Structural steel S355 J2 G3	81800	81800	81800	[€/kg]	2.49
Structural steel S355 J2 G3 in HL1000A	-	-	-	[€/kg]	2.49
Concrete precast C30/37	58	58	58	[€/m³]	588.73
Concrete C35/45	144.20	144.20	144.20	[€/m³]	84.47
Concrete Prestressed girder C45/55	-	-	-	[€/m³]	588.73
Reinforcement S500	44600	44600	44600	[€/kg]	0.99
Steel connectors	1382	1382	1382	[€/u]	2.31
Bearings Elastomeric	-	-	-	[€/u]	812
Bearing Lamelle	-	-	-	[€/u]	750
Roadway					
Pavement's asphalt layers	309	309	309	[€/m²]	6
Pavement's waterproofing member.	309	309	309	[€/m²]	11.40
Safety barriers	7429.20	7429.20	7429.20	[€/m³]	1.9
Corrosion protection					
Organic Coating	-	896	896	[€/m²]	25
Hot-dip galvanization (300µm thickness)	896	-	-	[€/m²]	22
Hot-dip galvanization (200µm thickness)	-	-	896	[€/m²]	21
Joints	8	-	8	[€/u]	1750

2.2 Scenarios and assumptions for lifecycle environmental analysis

2.2.1 Traffic analysis

In case study 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 in this stage. Later at the end of life stage also, it was considered that the traffic would be diverted to an alternative route; therefore, no traffic on the bridge. The bridge roadway consists of one traffic lane for each direction and the whole bridge is bordered by safety barriers.

However, during the time 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 light-weight vehicles and heavy-weight vehicles are 88% and 12% of the ADT, respectively. The hourly traffic distribution presented in Figure 14 was assumed for the motorway.

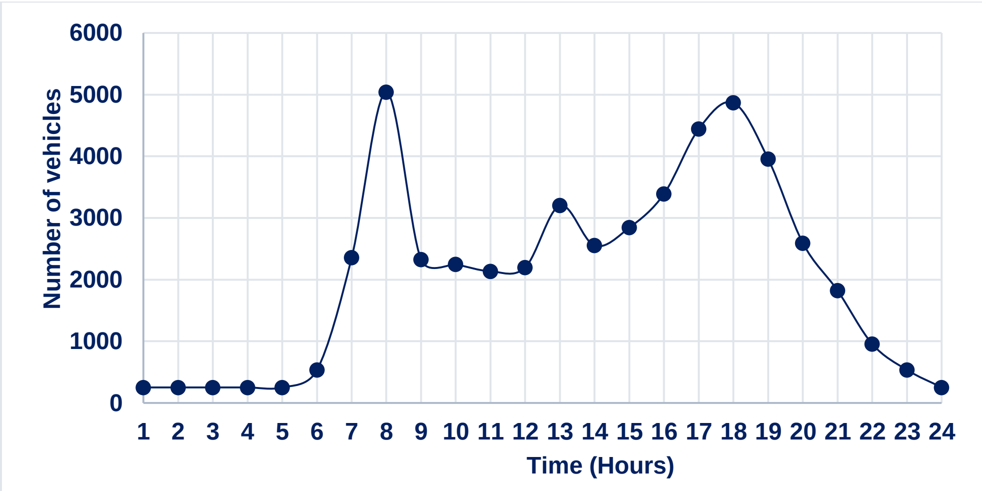


Figure 14: Distribution of hourly traffic for case studies D1, D2 and D3.

It is important to note that the traffic growth over time follows Equation (3) (See section 5.3 of Part A, Manual I [2]) where a growth rate of 0.5% is considered. Hence the traffic growth over a period of 100 years is presented in Table 11.

Table 11: 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 8000 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 12.

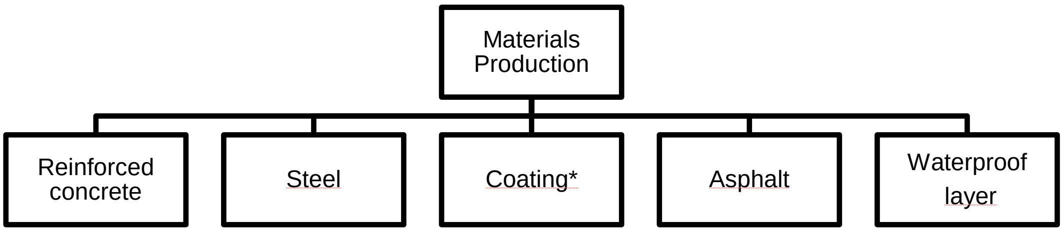
Table 12: Estimated Average Daily Traffic (ADT) over the bridge

	Base year	Base year + 50 years	Base year + 100 years
ADT(Vehicles/day)	8000	12500	16000

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 15. Data were collected from the sources indicated in Table 5.



(*) Coating is applied only in cases D2 (Ordinary steel coating) and D3 (Duplex system: Hot-dip galvanized + coating applied at year 66).

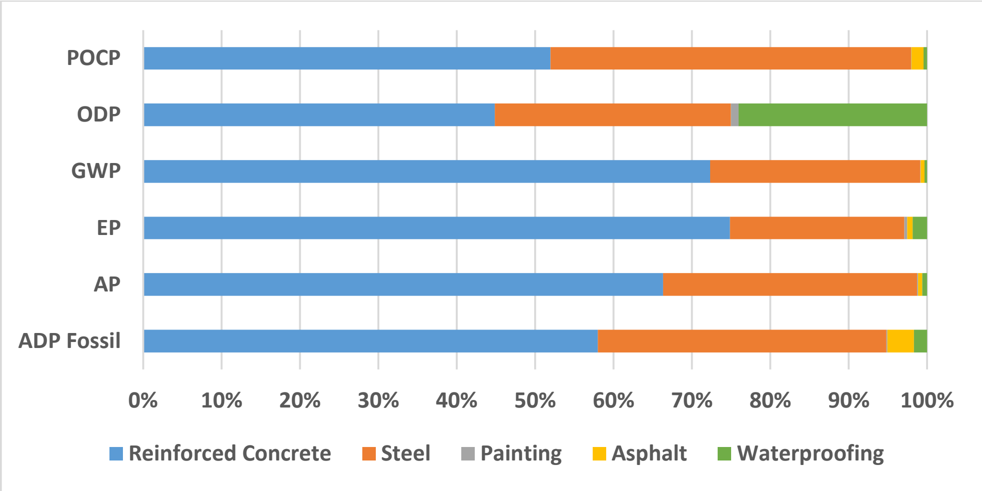
Figure 15: Material production stage

- *Environmental analysis of reference case D1, and D3*

The results obtained for the construction stage are presented in Table 13. 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 16.

Table 13: Environmental impacts at the material production stage per impact category [D1 & D3]

Impact Category	Unit	Total	Reinforced Concrete	Steel	Paint	Asphalt	Waterproof
ADP Fossil	MJ	5,60E+06	3,25E+06	2,06E+06	4,99E+03	1,90E+05	9,41E+04
AP	Kg SO2 eq	1,65E+03	1,10E+03	5,36E+02	1,73E+00	8,84E+00	9,84E+00
EP	Kg PO4 eq	1,60E+02	1,20E+02	3,57E+01	6,18E-01	1,11E+00	2,91E+00
GWP	Kg CO2 eq	7,60E+05	5,50E+05	2,04E+05	2,85E+02	3,79E+03	2,27E+03
ODP	Kg R11 eq	3,94E-03	1,77E-03	1,19E-03	3,90E-05	3,18E-09	9,46E-04
POCP	Kg C2H4	2,14E+02	1,11E+02	9,83E+01	8,05E-02	3,35E+00	9,17E-01



(*) Results for painting came from the paints applied to the protective equipment (railings) not from the structural elements

Figure 16: Contribution analysis of elements at the material production stage [D1 & D3]

- *Environmental analysis of variant D2*

The results obtained for the variant case study D2 are presented in Figure 17 and Table 14. Table 15 indicates the variation of the results in comparison to the reference case study D1. The contribution coming from the variation in steel type is highlighted in Table 16.

Table 14: Environmental impacts at the material production stage per impact category [D2]

Impact Category	Unit	Total	Reinforced Concrete	Steel	Paint	Asphalt	Waterproof
ADP Fossil	MJ	5,22E+06	3,25E+06	1,65E+06	3,48E+04	1,90E+05	9,41E+04
AP	Kg SO2 eq	1,54E+03	1,10E+03	4,22E+02	7,97E+00	8,84E+00	9,84E+00
EP	Kg PO4 eq	1,58E+02	1,20E+02	3,28E+01	9,21E-01	1,11E+00	2,91E+00
GWP	Kg CO2 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 C2H4	1,92E+02	1,11E+02	7,45E+01	2,51E+00	3,35E+00	9,17E-01

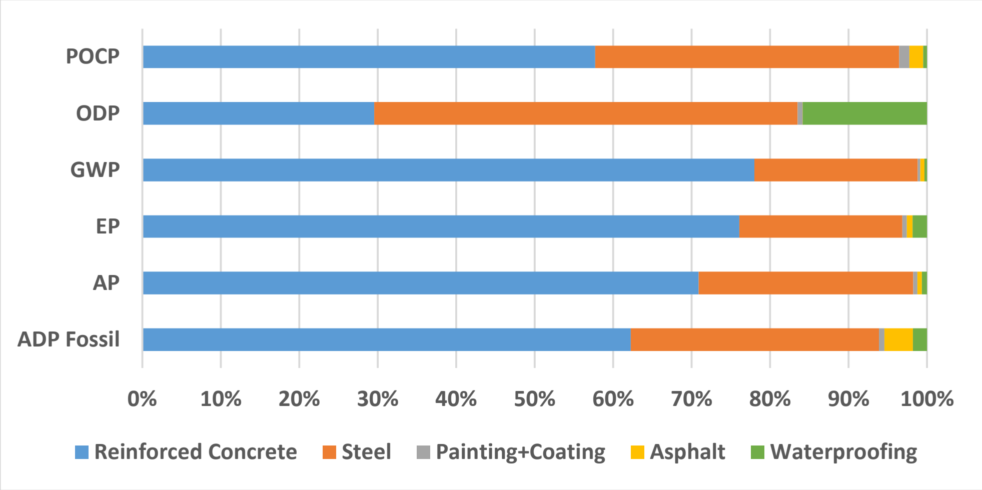


Figure 17: Contribution analysis of elements at the material production stage [D2]

Table 15: Environmental impacts of D2 at the material production stage relative to D1

Impact Category	Unit	Case Study D1	Case Study D2	Variation relative to D1
ADP Fossil	MJ	5,60E+06	5,22E+06	-6,8%
AP	Kg SO2 eq	1,65E+03	1,54E+03	-6,5%
EP	Kg PO4 eq	1,60E+02	1,58E+02	-1,6%
GWP	Kg CO2 eq	7,60E+05	7,04E+05	-7,3%
ODP	Kg R11 eq	3,94E-03	5,98E-03	+51,8%
POCP	Kg C2H4	2,14E+02	1,92E+02	-10,0%

Table 16: Environmental impacts of D2 at the material production stage relative to D1 [Steel alone]

Impact Category	Unit	Case Study D1	Case Study D2	Variation relative to D1
ADP Fossil	MJ	2,06E+06	1,65E+06	-19,9%
AP	Kg SO2 eq	5,36E+02	4,22E+02	-21,1%
EP	Kg PO4 eq	3,57E+01	3,28E+01	-8,1%
GWP	Kg CO2 eq	2,04E+05	1,47E+05	-28,1%
ODP	Kg R11 eq	1,19E-03	3,23E-03	+171,9%
POCP	Kg C2H4	9,83E+01	7,45E+01	-24,2%

Reinforced concrete and steel are the main contributor for emissions (> 80% in total) for all impact categories at the material production stage for case D2. When compared with D1, reduced impacts were calculated in D2 every category with the exception of ODP. This is evident from the fact that the production of hot-dip galvanized steel involves an extra step of dipping the manufactured steel in zinc bath which resulted in the increments shown in the table.

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 presented in Figure 18, it includes also the transportation of materials to the construction site (according to the distances indicated in Table 6).

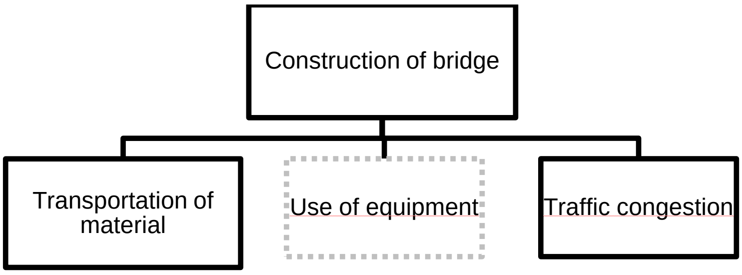


Figure 18: Construction stage

However, due to the lack of data, the use and transport of construction equipment was not considered in the analysis. In this sub-section, only the traffic congestion due to the construction activity is analysed. The 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 [17]. 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 [16]. 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*

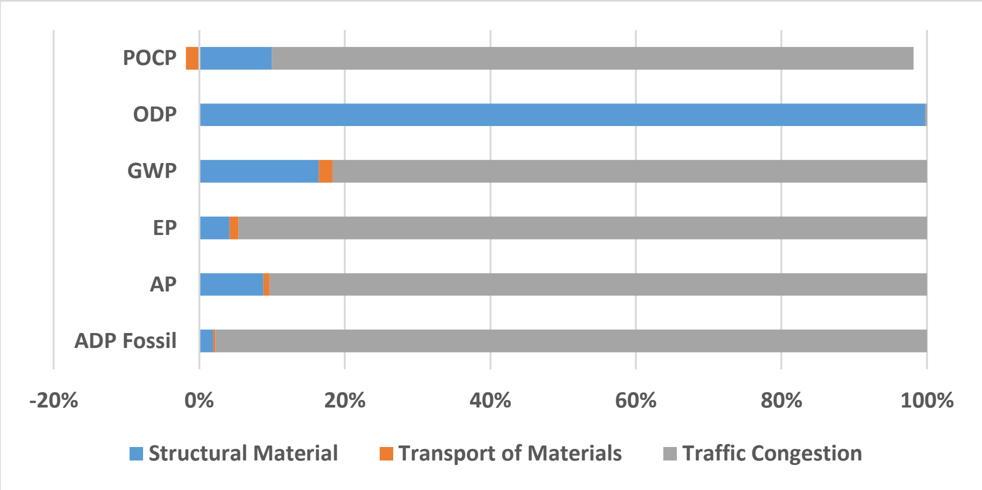
As already referred, all the bridges in this case study are new. Therefore, there is no traffic over the bridge during the construction phase and thus no emissions are considered at this stage. However, the traffic on the motorway under the bridge is affected either due to restrictions in the traffic 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 2.2.1. The duration of construction is the same for all the three bridges. The construction process takes 154 days, considering parallel building activities. There will be one lane obstructed to traffic underneath the bridge throughout the construction process.

- *Environmental analysis of D1, D2, and D3*

As the same bridge is being analysed with varying corrosion protection, there is no difference in environmental impact between the three variants. The results of the construction stage for all case studies are presented in Table 17 and illustrated in Figure 19. The operations related with the structural materials and traffic congestion 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.

Table 17: Environmental analysis of reference case studies D1-D3

Impact Category	Unit	Total	Structural Material	Transport of Materials	Traffic Congestion
ADP Fossil	MJ	1,17E+07	2,23E+05	3,37E+04	1,15E+07
AP	Kg SO2 eq	6,43E+02	5,66E+01	5,46E+00	5,81E+02
EP	Kg PO4 eq	1,03E+02	4,28E+00	1,30E+00	9,78E+01
GWP	Kg CO2 eq	1,30E+05	2,13E+04	2,45E+03	1,06E+05
ODP	Kg R11 eq	1,48E-04	1,48E-04	8,20E-10	3,66E-07
POCP	Kg C2H4	9,11E+01	9,41E+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 [3]. See section 1.4.6.

Figure 19: Contribution analysis of processes at the construction stage for D1, D2, and D3

2.3.3 Operation stage

The different case studies covered in this section are particularly different from one another only in terms of the corrosion protection methodology. Hence, the standard maintenance scenario has been adopted for all with three different maintenance schemes for the corrosion protection layers as shown in Table 9. The environmental impact coming from the other materials is the same for all three cases and is presented in Table 18**Erro! A origem da referência não foi encontrada.**.

Table 18: Environmental impacts of materials other than steel at the operation stage

Impact Category	Unit	Total	Road surface	Concrete deck	Waterproof layer	Traffic Congestion
ADP Fossil	MJ	5,27E+06	9,53E+05	7,50E+04	1,88E+05	4,06E+06
AP	Kg SO_2 eq.	3,08E+02	4,49E+01	3,74E+01	1,97E+01	2,06E+02
EP	Kg PO_4 eq.	5,15E+01	5,73E+00	5,28E+00	5,81E+00	3,46E+01
GWP	Kg CO_2 eq.	8,63E+04	1,93E+04	2,49E+04	4,54E+03	3,76E+04
ODP	Kg R11 eq.	1,89E-03	1,60E-08	1,63E-07	1,89E-03	1,30E-07
POCP	Kg C_2H_4	4,96E+01	1,65E+01	1,64E+00	1,83E+00	2,95E+01

The variation of the impacts with the different steel corrosion protection systems is studied with emphasis in Table 19. And Table 20 presents a comparison of the total environmental impacts during the operation stage.

Table 19: Environmental impacts related to corrosion protection of the steel at the operation stage

Impact Category	Unit	Case D1	Case D2	Case D3
ADP Fossil	MJ	-	5,97E+04	2,98E+04
AP	Kg SO_2 eq	-	1,25E+01	6,24E+00
EP	Kg PO_4 eq	-	6,06E-01	3,03E-01
GWP	Kg CO_2 eq	-	3,71E+03	1,85E+03
ODP	Kg R11 eq	-	6,92E-09	3,46E-09
POCP	Kg C_2H_4	-	4,86E+00	2,43E+00

Table 20: Comparison of environmental impacts of D1, D2 & D3 at the operation stage

Impact Category	Unit	Case D1	Case D2	Δ(D1,D2)	Case D3	Δ(D1,D3)
ADP Fossil	MJ	5,27E+06	7,36E+06	+39,6%	6,40E+06	+21,4%
AP	Kg SO2 eq	3,08E+02	4,23E+02	+37,5%	3,70E+02	+20,2%
EP	Kg PO4 eq	5,15E+01	6,94E+01	+34,9%	6,12E+01	+18,9%
GWP	Kg CO2 eq	8,63E+04	1,09E+05	+26,2%	9,84E+04	+14,1%
ODP	Kg R11 eq	1,89E-03	1,89E-03	+0,0%	1,89E-03	+0,0%
POCP	Kg C2H4	4,96E+01	6,92E+01	+39,6%	6,00E+01	+21,1%

No maintenance of the corrosion protection layer is required for the reference case D1. As a result, zero emissions were calculated. Noting that for case D2, the steel girders undergo maintenance actions during the operation phase (two full refurbishment of the corrosion protection layers by organic coating on years 33 and 66), 30% higher impacts were calculated as compared to Case D1. Case D3 involves one application of organic coating on year 66 resulted in 16% increased impacts (Avg.) as compared to the reference case, D1. A comparison between two full replacements of corrosion protection layer in D2 and a single replacement of the layers in D3 showed that 10.1% reduction of impacts was possible with the latter solution, D3.

2.3.4 End-of-life stage

- *Environmental analysis of reference case D1 and D3*

As case D1 and D3 use the same material, hot-dip galvanized steel, except for the coating applied in the operation stage for D3, the end-of-life results are the same for the two case studies. Total emissions per impact category of this stage are indicated in Figure 20, which also indicates the contribution of each process per impact category. The negative values in the figure represent the credits given to the recycling processes.

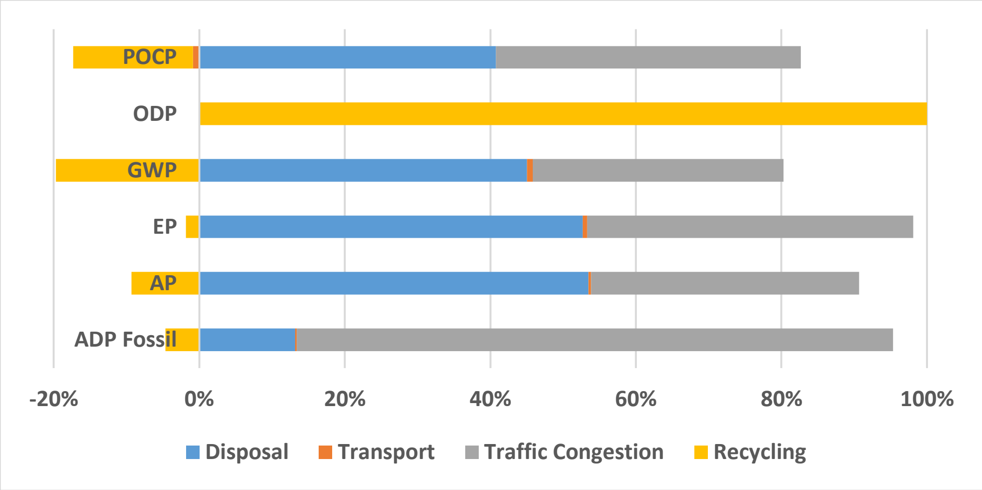


Figure 20: Contribution analysis of processes at the end-of-life stage – Case D1

Disposal contributes the most impact in all categories with the exception of ADP fossil fuel where the second most significant contributor, traffic congestion, dominates. Recycling contributes in favour of the environment in all impact categories but ODP where it lays a small impact with magnitude in the order of 10^{-3}.

- *Environmental analysis of variant D2*

As can be seen in Figure 21, disposal contributes for the most impact in all 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 favour of the environment in all impact categories but ODP.

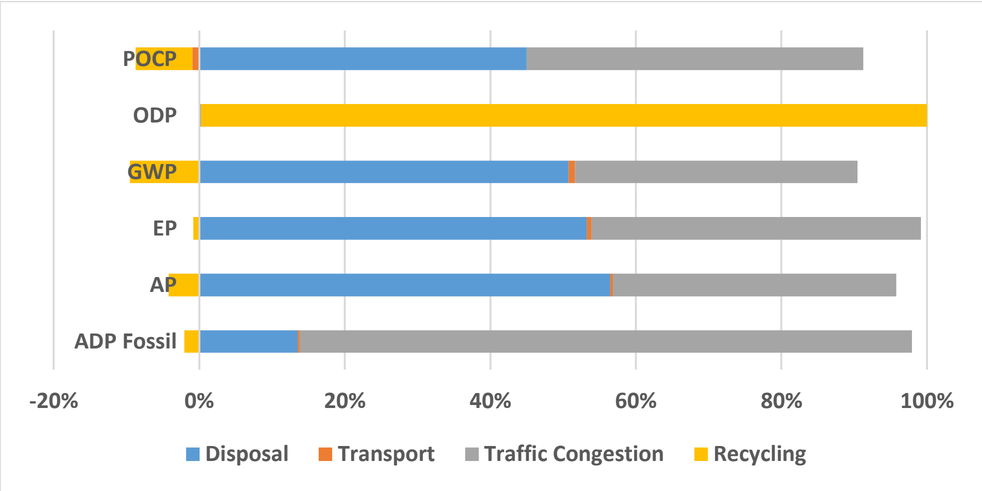


Figure 21: Contribution analysis of processes at the end-of-life stage – Case D2

Total emissions per impact category of this stage for the variant case study D2 are presented in Table 21. This table also indicates the variation of the results for this case study in comparison to the reference case study D1. These results are illustrated in Figure 22.

Eliminad
Eliminad

Table 21: Variation of the results for the end-of-life stage relative to case study D1

Impact Category	Unit	Case D1	Case D2	Variation relative to D1
ADP Fossil	MJ	2,44E+07	2,51E+07	+2,9%
AP	Kg SO2 eq	2,49E+03	2,65E+03	+6,5%
EP	Kg PO4 eq	4,06E+02	4,11E+02	+1,1%
GWP	Kg CO2 eq	3,68E+05	4,37E+05	+18,6%
ODP	Kg R11 eq	3,81E-03	1,64E-03	-57,0%
POCP	Kg C2H4	2,52E+02	2,88E+02	+14,4%

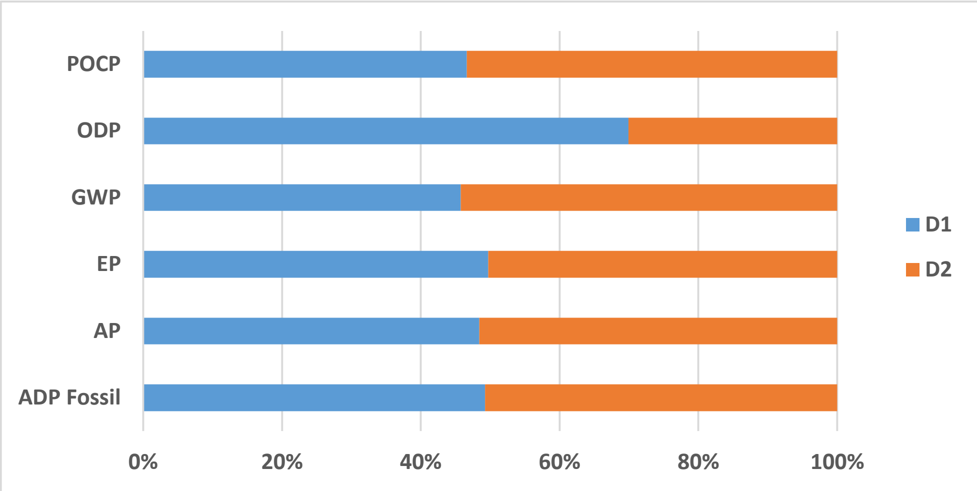


Figure 22: Relative contributions of D1 and D2 at the end-of-life stage

D2 resulted in increased impacts in all categories except ODP at the end-of-life stage as compared to both D1 and D3. This result comes as a result of the different impacts the galvanized steel has at the end-of-life stage as compared to the ordinary steel according to data gathered from the EPD mentioned in section 1.4.1.

2.3.5 Results of the environmental lifecycle analysis

- *Aggregate lifecycle results for case D1*

In the previous sections, the partial results per stage have been presented. In this sub-section the results of the different stages are summed up relative to each impact category and the aggregate results are presented in Table 22, considering the "day work" plan and standard maintenance scenario.

Table 22: Lifecycle results per life cycle stage

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	4,70E+07	5,60E+06	1,17E+07	5,27E+06	2,44E+07
AP	Kg SO_2 eq	5,09E+03	1,65E+03	6,43E+02	3,08E+02	2,49E+03
EP	Kg PO_4 eq	7,22E+02	1,60E+02	1,03E+02	5,15E+01	4,06E+02
GWP	Kg CO_2 eq	1,34E+06	7,60E+05	1,30E+05	8,63E+04	3,68E+05
ODP	Kg R11 eq	9,79E-03	3,94E-03	1,48E-04	1,89E-03	3,81E-03
POCP	Kg C_2H_4	6,06E+02	2,14E+02	9,11E+01	4,96E+01	2,52E+02

To better understand the contribution of each stage to the aggregated result, these results are also presented in Figure 23.

The material production (33.1%) and end of life stages (44.2%) contribute the most in all the impact categories. The operation stage has the least impact of 9.7% while the construction stage contributes 13% to the total environmental impact.

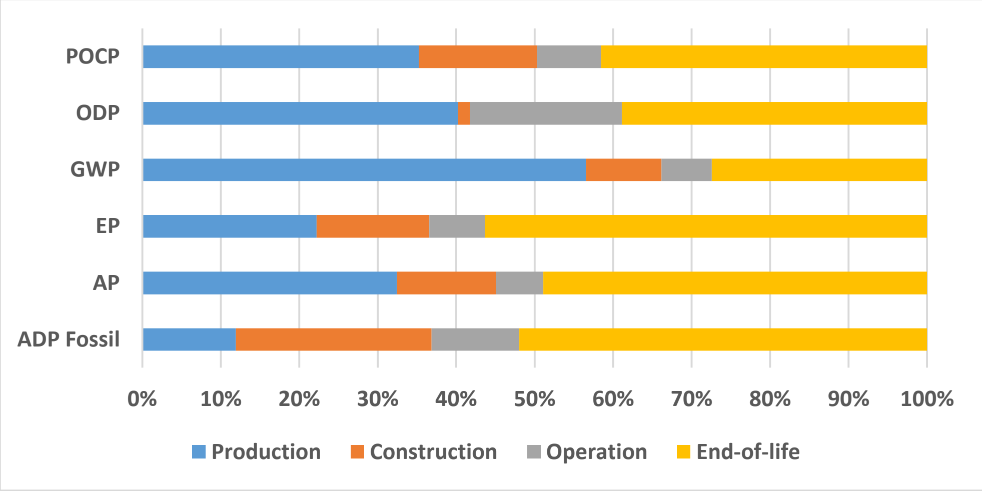


Figure 23: Contribution of each stage per impact category [D1]

- *Comparison of aggregate lifecycle environmental impacts*

The results obtained for the variant case studies D2 and D3 are presented in Table 23, considering the “day work” scenario for all cases. This table also indicates the variation of the impacts relative to the reference case study D1.

Table 23: Aggregate environmental impacts of D2 and D3 compared to D1

Impact Category	Unit	Case D1	Case D2	Δ(D1,D2)	Case D3	Δ(D1,D3)
ADP Fossil	MJ	4,70E+07	4,94E+07	+5,1%	4,82E+07	+2,4%
AP	Kg SO_2 eq	5,09E+03	5,26E+03	+3,2%	5,15E+03	+1,2%
EP	Kg PO_4 eq	7,22E+02	7,41E+02	+2,7%	7,31E+02	+1,3%
GWP	Kg CO_2 eq	1,34E+06	1,38E+06	+2,4%	1,36E+06	+0,9%
ODP	Kg R11 eq	9,79E-03	9,76E-03	-0,3%	9,79E-03	0,0%
POCP	Kg C_2H_4	6,06E+02	6,39E+02	+5,5%	6,17E+02	+1,7%

As it can be seen from the above table, the reference example D1 features better characteristics that are in favour of the environment. 3.1% and 1.3% higher impacts were calculated for the case D2 and D3, respectively.

2.4 Lifecycle Cost Analysis

2.4.1 Initial construction costs

The initial cost of the bridges in this case study are all identical except for the cost of corrosion protection as indicated in Table 10. The initial cost, including transportation costs, for each bridge is shown in Table 24. The general proportion between costs in this case study is presented in Figure 24. This proportion between the costs is approximately the same for cases D2 and D3.

Table 24: Summary and comparison of initial cost for D2 and D3 relative to D1

	D1	D2	Δ(D1,D2)	D3	Δ(D1,D3)
Initial Cost (€)	847071,09	835759,1	-1,3%	846175,1	-0,1%
Cost per area (€/m^2)	1593,2	1571,9		1591,5	

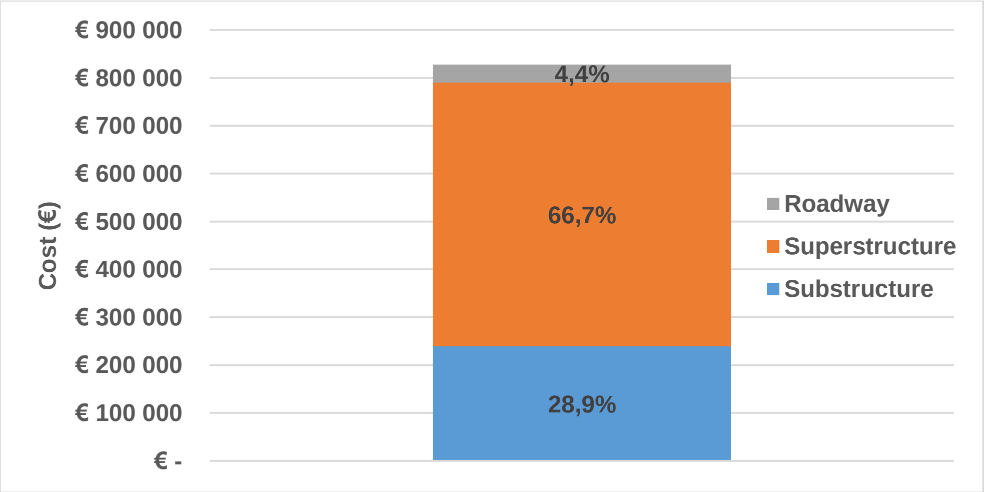


Figure 24: Initial cost of D1

2.4.2 Operation costs

The operation costs for the three bridges are presented in Figures 25 to 28, expressed as costs in present values with a discount rate of 2%.

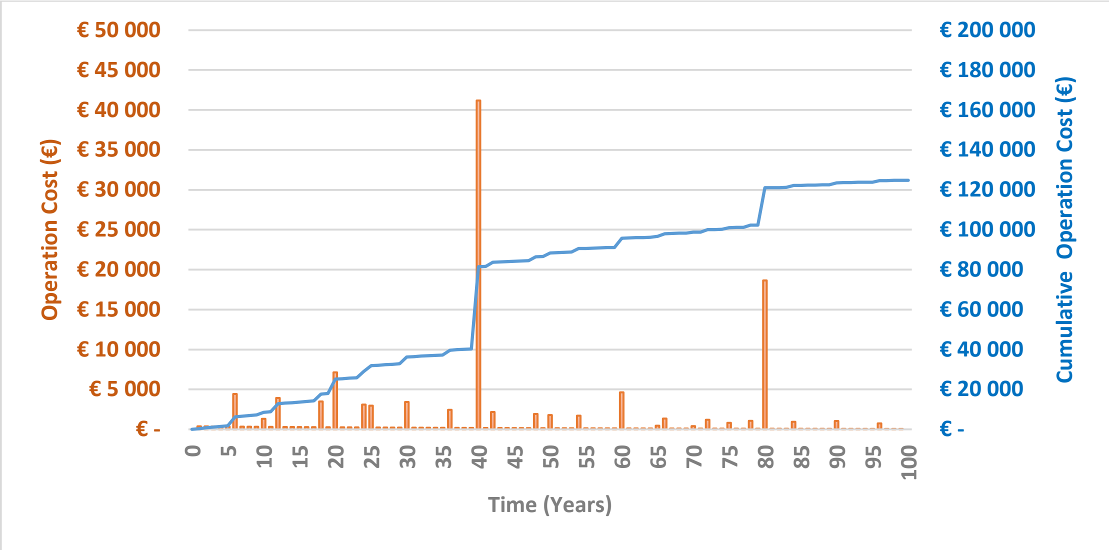


Figure 25: Operation costs of D1 over its service life

Over the period of 100 years, the bridges in the examples are assumed to be maintained and rehabilitated according to the plan indicated in Table A1 of the annex, the definition of a standard Inspection scenario. Case D1 employs Hotdip galvanized steel girders that won't need maintenance throughout the lifespan of the bridge. In case D2, on the other hand, two complete replacements of the corrosion protection layers are made in years 33 and 66. The duplex coating system used in case D3, allows for a one time maintenance of the corrosion protection layer in year 66.

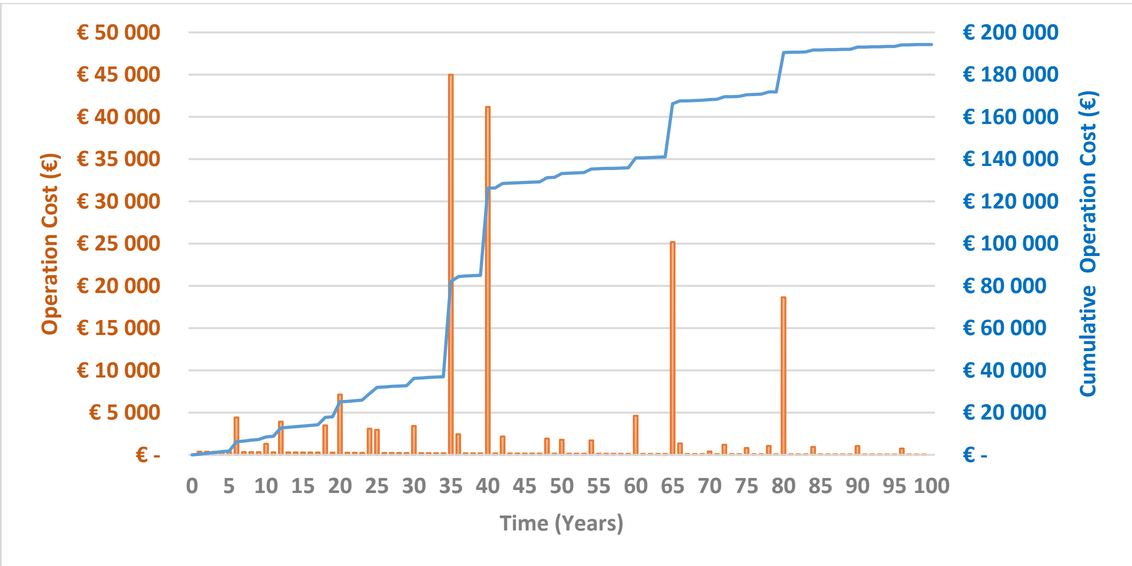


Figure 26: Operation costs of D2 over its service life

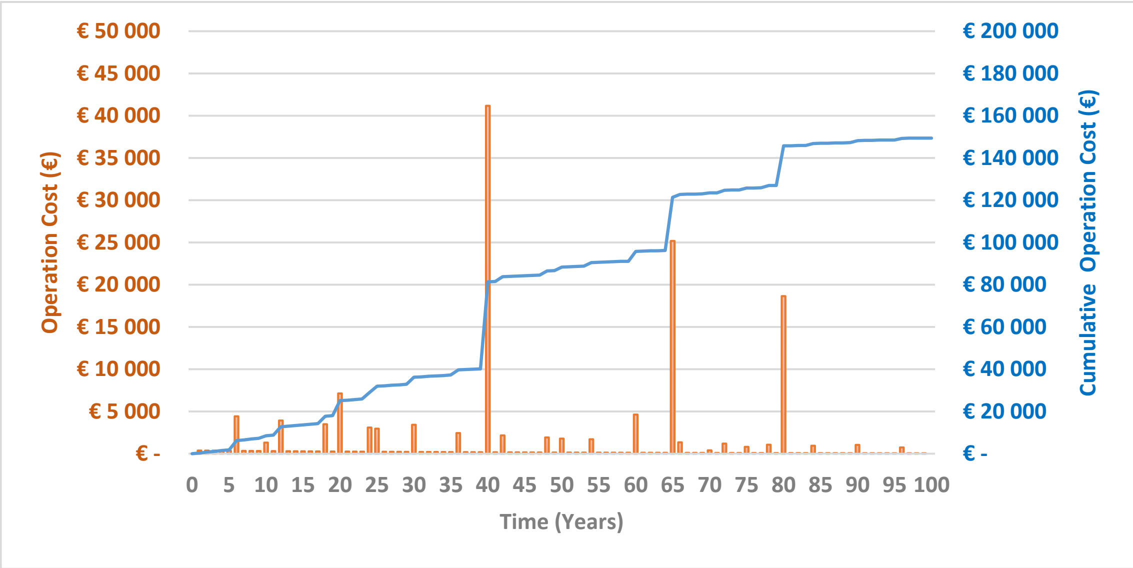


Figure 27: Operation costs of D3 over its service life

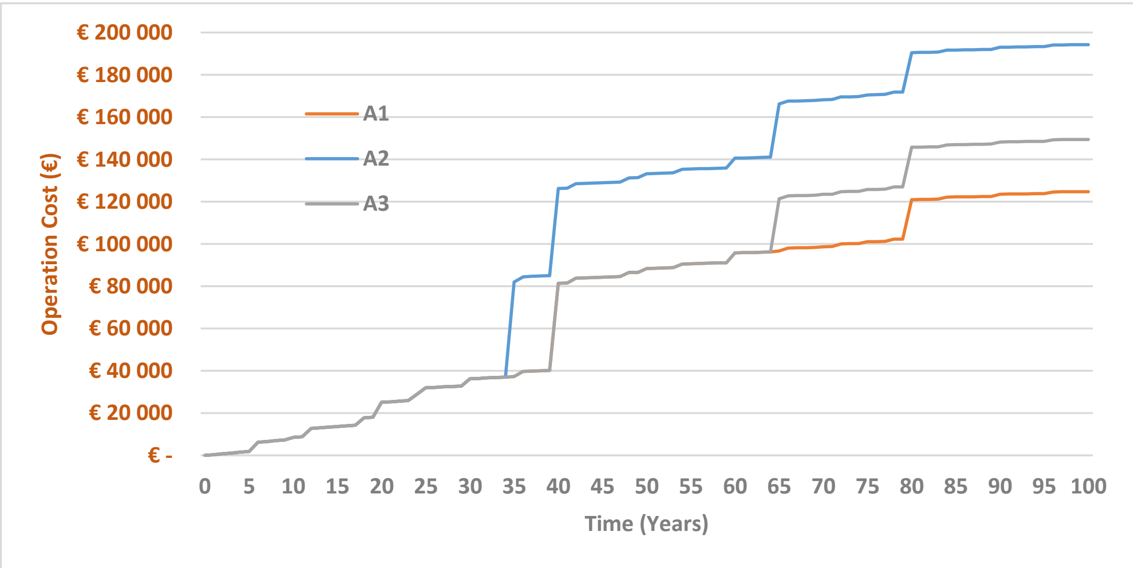


Figure 28: Comparison of operation costs between D1, D2 and D3

It can be noted from the results that the hotdip galvanized solution case D1 resulted in substantially reduced operation costs as compared to the other two cases. The duplex coating applied in D3 is in turn better than the least favourable option D2 which employed organic coatings that need maintenance twice in the lifespan of the bridge.

2.4.3 End-of-life costs

- *Analysis of all case studies (D1, D2 and D3)*

The end of life cost is the same for all the three bridges as the only difference between them was the corrosion protection mechanism. A summary of the end-of-life costs for bridges D1, D2 and D3 are given in Table 25.

Table 25: End-of-life cost for D1, D2 and D3

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
Other		98,21		0,00
			Sub-Total (€)	97734,77
			Demolition cost (€)	7339,04
			Total Cost (€)	105073,81

(*) 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 life cycle costs

The compilation of the costs calculated in the previous sections leads to the total lifecycle net present cost (LCC) using a discount rate of 2,0%. These values are summarized and presented in Table 26 and illustrated in Figure 29.

Table 26: Total lifecycle costs for D1, D2 and D3

	D1	D2	Δ(D1,D2)	D3	Δ(D1,D3)
Initial Cost (€)	847071,09	835759,1	-1,3%	846175,1	-0,1%
Operation Cost (€)	124765,74	194302,4	+55,7%	149499,9	+19,8%
End of life Cost (€)	105073,81	105073,8	0%	105073,8	0%
Total Cost without user cost (€)	1076910,64	1135135	+5,4%	1100749	+2,2%

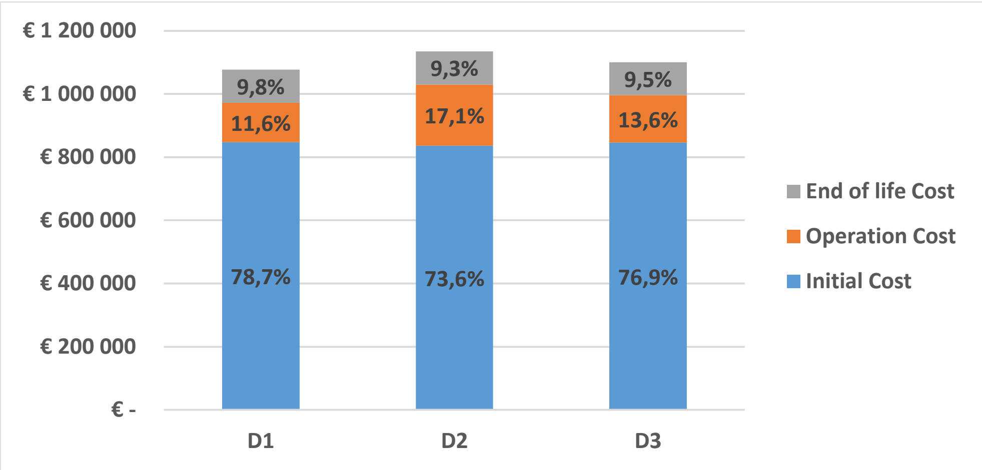


Figure 29: Lifecycle costs of D1, D2 and D3

In terms of the initial cost, i.e., production and construction costs, the three alternatives of corrosion protection lead to a relatively similar cost with slight favourablility to the ordinary steel coating. And the end of life costs are the same for all the three alternatives. However, the first alternative, 300mm hot-dip galvanized steel, showed significant reduction in cost in the operation stage. The second alternative, which required two full renovations - via organic coating - of the corrosion protection layers, resulted in higher operation costs. The third alternative, where by duplex coating scheme was adopted, is less costly than the second but is still more expensive than the first alternative. In conclusion, it can be said that the hot-dip galvanization presents itself as the best alternative in terms of overall lifecycle cost.

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 maintenance actions are carried out during the night (from 10:00 PM to 6:00 AM).

Illustrations from Figure 30 to 32 detail the user costs for design options D1, D2 and D3 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 same applies for design options D2 and D3. The hot-dip galvanized bridge case takes 101 days of maintenance while the second alternative with organic coating requires 119 days. The third variant with duplex coating takes 110 days of maintenance during the whole lifespan of the bridge. Figure 33 shows how the first alternative is the best solution in terms of reducing the user costs as compared to the other two.

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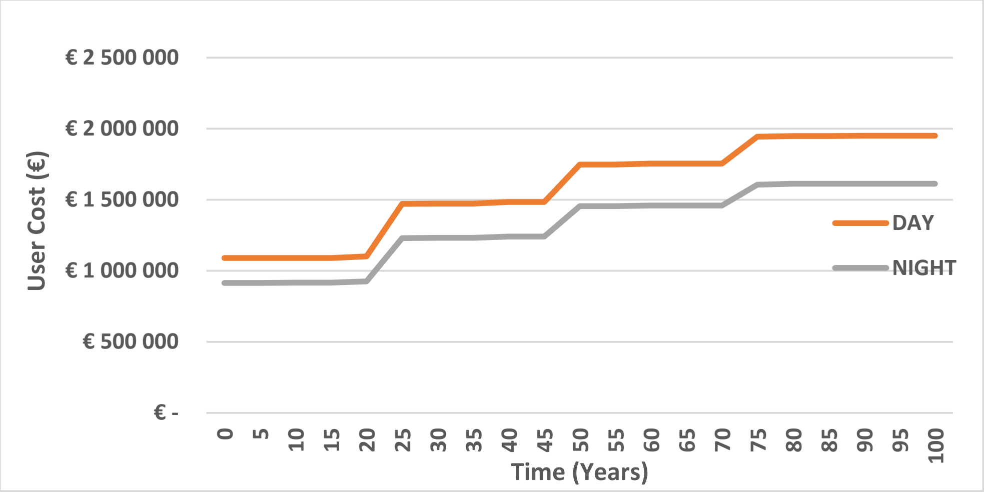

Figure 30: User costs for D1 with “day” and “night” scenarios.

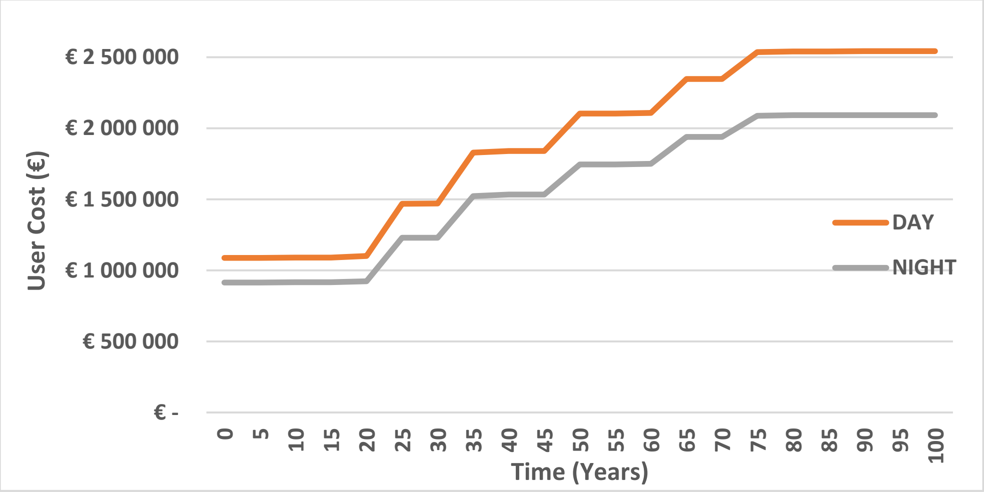

Figure 31: User costs for D2 with “day” and “night” scenarios.

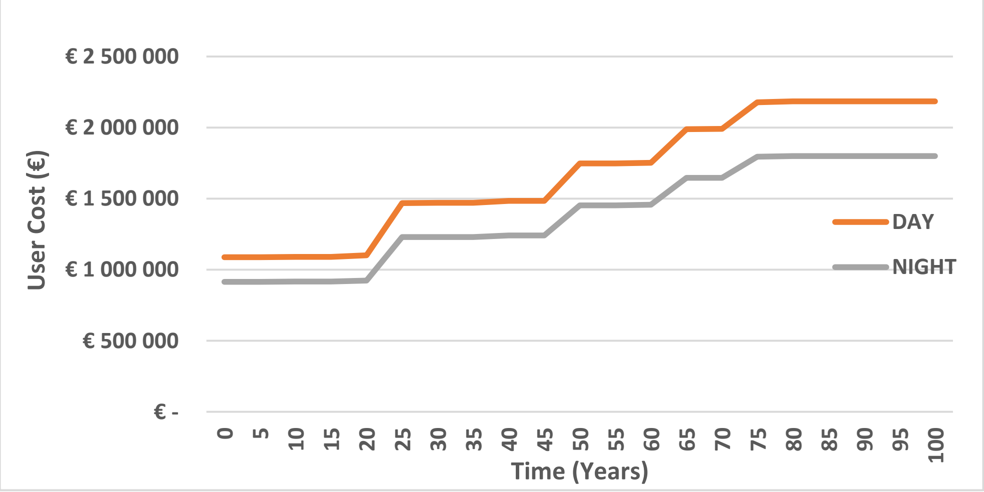

Figure 32: User costs for D3 with “day” and “night” scenarios.

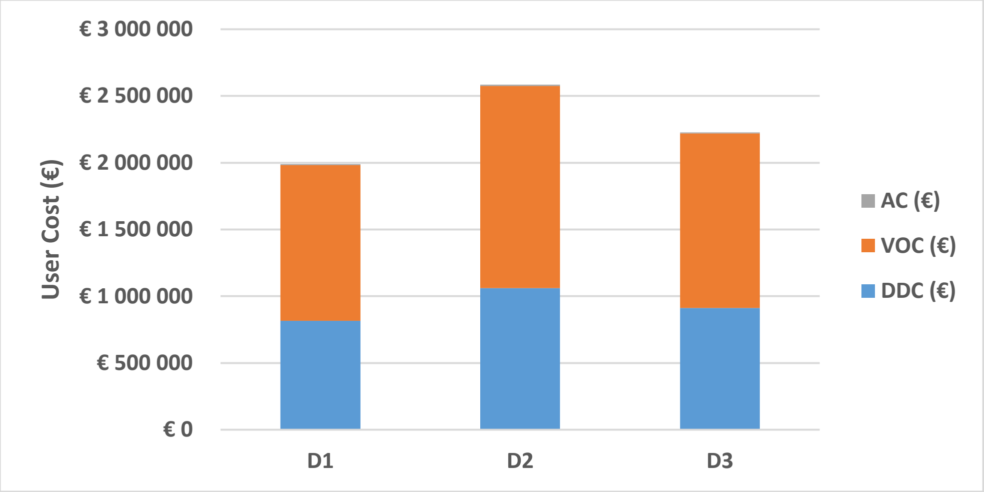

Figure 33: User costs for design options D1, D2 and D3 with the standard scenario and "day work" plan.

As shown in Table 27, it is observed that the user costs associated with case D1 were found to be 29.8% and 11.9% lower than those for cases D2 and D3, respectively.

Table 27: User costs for D1, D2 and D3

	D1	D2	Δ(D1,D2)	D3	Δ(D1,D3)
User costs (€)	1990440,9	2584124,20	+29,8%	2227287	+11,9%

2.6 Discussion of the Results for case D

It was observed from the lifecycle environmental analysis that the stages of material production and end of life dominate all impact categories. The alternative that used conventional coating resulted in higher impacts on the environment and users due to repeated maintenance operations on the steel girder’s corrosion protection layers. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides reduction of impacts owing to the fact that traffic count is lesser at night.

In terms of the initial cost, i.e., production and construction costs, the three alternatives of corrosion protection lead to a relatively similar cost with slight favourablility to the ordinary steel coating. And the end of life costs are the same for all the three alternatives. However, the first alternative, 300 mm hot-dip galvanized steel, showed significant reduction in cost in the operation stage as there is no need for maintenance throughout the lifespan of the bridge. The second alternative, which required two full renovations - via organic coating - of the corrosion protection layers, resulted in higher operation costs. The third alternative, where by duplex coating scheme was adopted, is less costly than the second but still more expensive than the first alternative. In conclusion, it can be said that the hot-dip galvanization presents itself as the best alternative in terms of lifecycle cost.

Once more, the social aspects of the lifecycle analysis prove that the night shift is favourable in reducing the impacts on user cost. The user costs associated with D1 were found to be 29.8% and 11.9% lower than those for cases D2 and D3, respectively. It was also noted that the user costs make up for more than 65% of the total lifecycle costs.

3 WORKED EXAMPLES- BRIDGE TYPE E - PRECOBEAM GIRDER

3.1 GENERAL DESCRIPTION

The Precobeam (prefabricated composite beam) solution is a new bridge construction method invented in the beginning of the new millennium. It is an example for economic bridge solutions with rolled beams and a high degree of prefabrication. This method is based on a rolled steel beam, oxycut longitudinally in two T-sections with a special shape. This shape works as a continuous shear connector which allows for the shear connection between profile and slab without the use of studs, and thus without any welding.

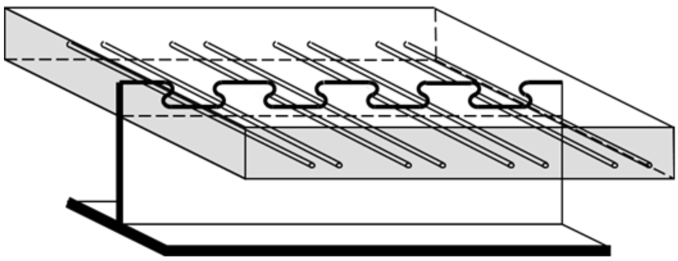

Figure 34 : Cross Section alternative of the Precobeam designed by SSF Ingenieure, Munich

The method is a very flexible solution offering various cross section possibilities according to the design requirements. As a result, the Precobeam, with the use of state-of-the-art continuous shear connectors and integrating the advantages of prefabricated element bridges, meet the following targets for competitive and sustainable construction:

- high safety standard for vehicle impact, especially for bridges with only two girders (shock),
- reduction of coating surface,
- elementary steel construction nearly without any welding,
- sparse maintenance and easy monitoring.

After cutting, corrosion protection is placed on the profiles on the parts exposed to the atmosphere in the final stage. In the next step reinforcement bars are placed through the cutting shape and a concrete top chord is concreted in the shop to produce a prefabricated bridge element. Subsequently the prefabricated bridge elements are transported to the site, placed on the abutments and, finally, the residual concrete chord is added on-site.

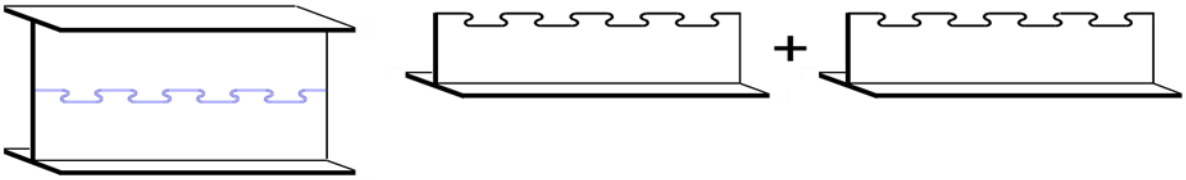

Figure 35 : Manufacture scheme for a Precobeam

Figure 36 : Design and fabrication of Precobeam in the finishing shop of ArcelorMittal

The dowels can be placed in the upper flange or in the lower flange and may have a puzzle shape or a modified clothoide shape (see Figure 37). The steel grade range is from S235 to S460.

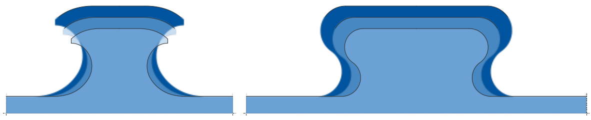

Figure 37 : Modified clothoide shape (MCL) and puzzle shape (PZ)

A typical Precobeam is composed of the following elements (see Figure 38).

(1) Steel flange: Absorbs stresses from bending moments and provides cross-section stiffness.

(2) Steel web: Transmission of longitudinal shear forces, ensures steel flange – concrete web distance where needed (e.g. to avoid concrete cracking).

(3) Composite dowel: Transmit longitudinal shear forces between concrete and steel.

(4) Prefabricated concrete web: designed upon structural demands and is reinforced with the external sections.

(5) Prefabricated concrete plate: 10-12cm thick concrete slab which serves as formwork and scaffolding for the in-situ concrete and is designed for loads from constructions stages.

(6) In situ concrete slab: It completes the prefabricated concrete-plate and is designed upon structural needs for the crucial load combinations in the final stages.

(7) In situ longitudinal reinforcement: It is assembled within the in-situ concrete-slab for the final construction stage.

(8) Precast longitudinal reinforcement: designed upon structural needs for loads from construction stage(s).

(9) Transversal shear reinforcement: designed upon structural needs from transversal shear under special consideration of dowel action.

(**10) Confinement reinforcement:** designed upon approaches from local dowel action. It is essential to ensure a ductile load bearing behaviour.

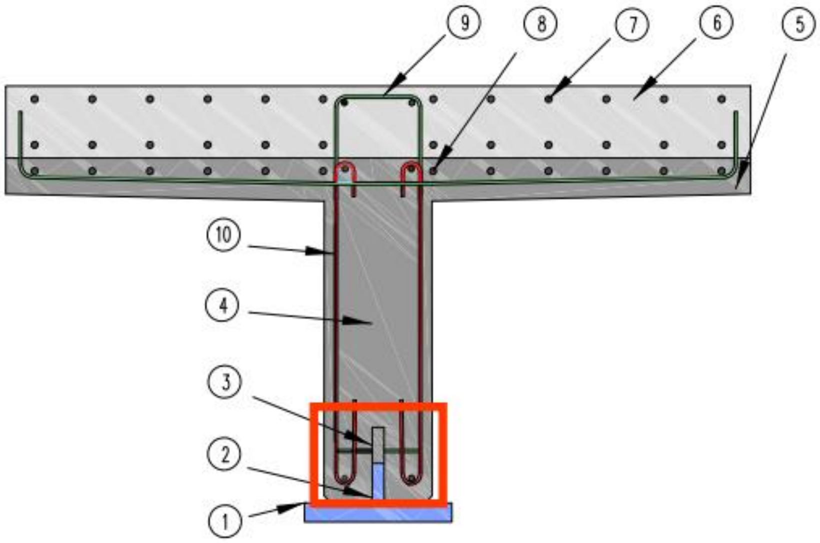

Figure 38 : Main elements of the Precobeam

The construction procedure of a Precobeam can be described in the following steps:

1. Oxygen cutting of the rolled beam section. The composite dowel results of the cutting of a steel girder into two halves.

2. Coating of the girder at the steel plant. This extensive work can be easily done under plant conditions thus high quality and durability can be achieved. Afterwards the girders have to be transported to the pre-casting plant.

3. At the pre-casting plant the reinforcement can be placed directly on the steel girder without any disturbing formwork.

4. Together with the finished reinforcement the steel girders are lifted into the form work. The form work can be used several times and is adapted from prefabricated concrete elements. Afterwards the prefabricated element is concreted.

5. For a certain time the prefabricated element has to be supported in a stainless way. This is necessary to ensure the composite system to act for the dead loads already. Thus the materials can be used in an effective way from the beginning.

6. The prefabricated girders can be transported to the construction site. Due to the comparatively lightweight construction the elements can be transported as usual.

7. The girders are placed on the abutments. The proper fabrication of the elements at the plant avoids problems on the construction site.

8. Finally the in-situ concrete can be added without using any additional formwork. The prefabricated concrete is acting as formwork.

3.1.1 Advantages of Precobeam system

The Precobeam system combines the advantageous of the filler beam plates – like robustness and slenderness – and VFT girders. Due to the high degree of automation even for the fabrication of the connectors and regarding to the high degree of prefabrication shorter construction times and more efficient constructions are possible. Precobeam designs enable the configuration of composite bridges as single span girders or frames with slenderness ratios of 15–30 with spans of up to 50 m. This feature finds application both in the creation of new structures that conserve resources and also in the replacement of existing bridges.

The Precobeam system is notable for its efficient use of material. As determined by the design configuration using steel profiles without an upper chord (e.g. halved rolled girders), the steel in the span is loaded in tension. In the pier and framework corner region there is similarly sufficient material available in order to accommodate the compressive forces without the introduction of additional plates into the concrete.

Due to rapid and easy construction and due to the combination of approved construction systems the costs concerning the production and construction of the Precobeam can be minimized. Closing off periods can be reduced to a minimum because of the high prefabrication level of the superstructure at the plant. Thus high quality standards and a reduction of imponderability at the construction site are possible. Usage of standardised girders of rolled steel simplifies the availability and the delivery times. These low-cost rolled steel sections supersede any welding in the workshop. For the production of Precobeam standard formwork of pre-stressed concrete precast girders can be used; so no new investment in the pre-casting plant is necessary. Thanks to the low installation weight of the girders usual cranes can be used.

Next to the production costs the constructions durability has an important influence to the total lifecycle costs. This asks for structures which are robust, produced with high quality standards and can be inspected easily. The Precobeam system satisfies the demand of durability in several aspects:

- Small corrosion protection surfaces
- Robust reinforced concrete cross section

- High standard of quality thanks to the large degree of prefabrication in the rolled girders and the precast parts
- Open structure for easy structural inspection.

3.1.2 Examples of Precobeam in bridges

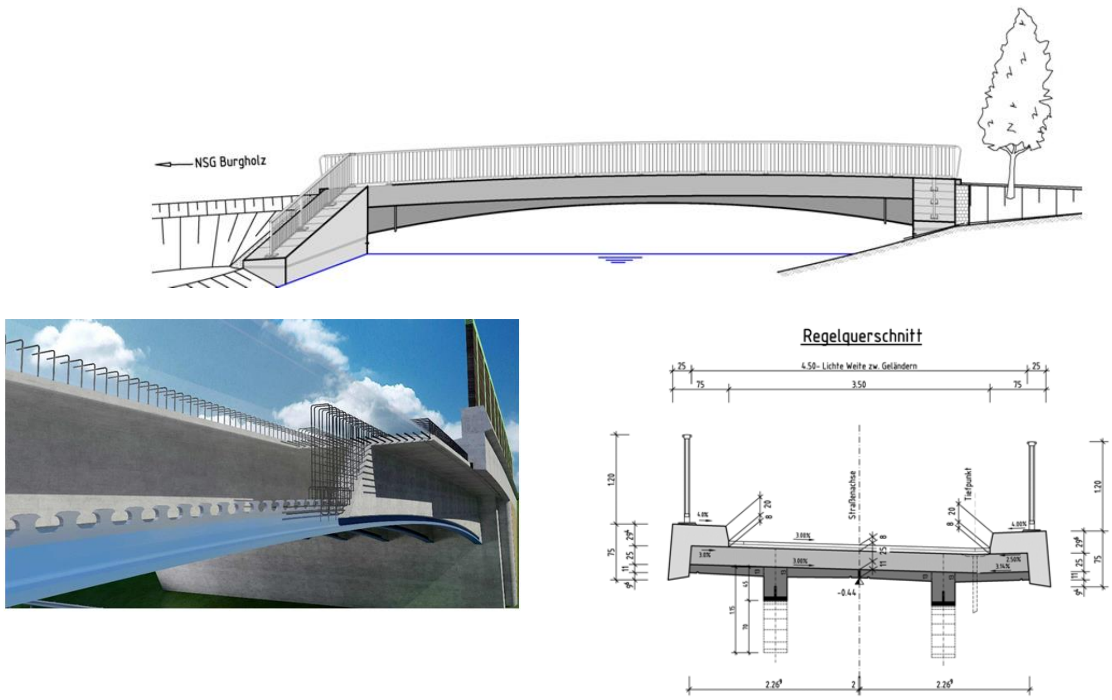

Figure 39 : First hot-dip galvanized Precobeam bridge “Elster bridge Halle-Osendorf (D)“ (SSF Ingenieure and ArcelorMittal)

Figure 40 : Precobeam used for the bridge at Vigaun, Austria

Figure 41 : Further development of Precobeam technology, steel webs with variable height

3.1.3 Definition of the case study

3.1.3.1 Case E1 – Precobeam bridge

The E1 bridge is a Precobeam bridge situated in Poland and links the cities of Gdansk and Gorzyczki. This bridge is a 3 spans road bridge (28 + 35 + 28 m). It has a total length of 92.4 meters. Further in the document, the 'Gdansk deck' refers to the track leading to Gdansk while the 'Gorzyczki deck' refers to the track leading to Gorzyczki (see Figure 42 and Figure 43). The Gdansk deck is 18.28 meters width with 6 beams line. The Gorzyczki deck is 24.28 meters width with 8 beams line.

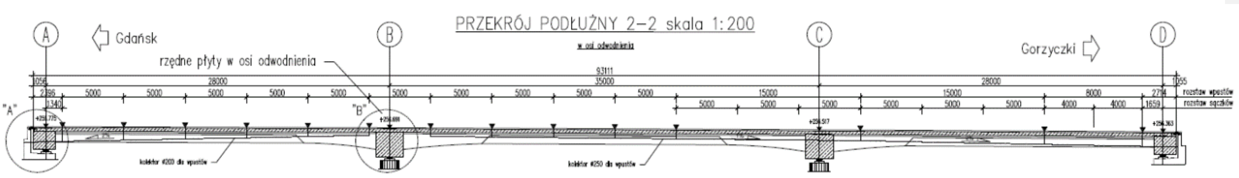

Figure 42 : Precobeam Bridge, Highway D1 object WA352 Case E1. Longitudinal view

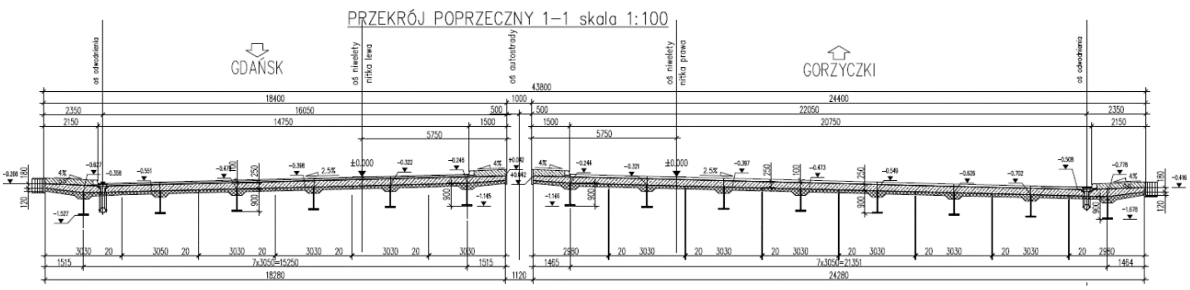

Figure 43 : Precobeam Bridge, Highway D1 object WA352 Case E1. Transversal view

The Precobeam bridge analysed in the frame of this project is the WA-352 viaduct - WA-352 417 + 449 over the PKP line No. 146 in the Road DK 1. The investment is implemented in the "Design and Build" system, which allows the design of the execution to be adjusted to the changing technical conditions, without changing the subject matter of the public contract, thus changing the contract with the general contractor, who undertakes both design and implementation.

The realization of the motorway will be a significant contributor to the economic recovery due to its potential growth in demand for domestic services and goods, and as regards construction investments, it will contribute to the development of the executive companies as well as to other economic operators serving the construction industry.

Amongst the direct benefits of the motorway, the following could be mentioned: take over part of the traffic from existing national and provincial roads; moving heavy traffic from built-up areas; shorter travel times; fuel savings; providing driving comfort; reducing the risk of accidents; reduction of exhaust and noise emissions in relation to existing roads; accelerate the development of adjacent areas.

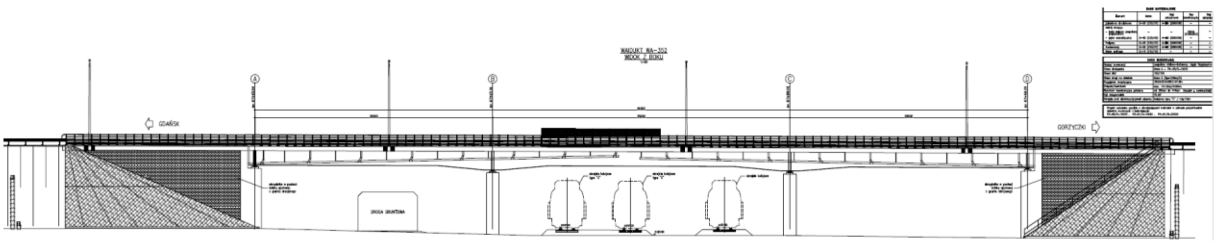

Figure 44 : Precobeam Bridge, Highway D1 object WA352 Case E1. Longitudinal view

3.1.3.2 Case E2 – Steel-concrete composite girders

To emphasize the Precobeam system’s advantages, the bridge E2, a solution using prefabricated composite elements, has been designed and analyzed: bridge decks with partially prefabricated composite elements based on rolled girders and concrete cross beams. The total length and widths of Gdansk and Gorzyczki decks are the same than in case E1. The main girders are hot rolled profiles HL 1000 in HISTAR 460 steel grade.

Figure 45 : Prefabricated composite girder. Case E2

General remarks

This solution is a multi-girder decks with cross beams in span. A concrete cross beam technology for continuous spans is proposed. The concrete cross beam technology allows indirect bearing supports; this is advised to reduce bearing number as well as maintenance costs.

The pre-design has been done in accordance with Eurocode EN with adjustment of loading factors to take into account polish regulations PN-85/S – 10030. The design traffic loads to consider are one point load from vehicle of 958 kN, uniform load on whole carriage width of 4.0 kN/m^2 and pedestrian loads = 2.5 kN/m^2. Temperature loads and concrete shrinkage have been taken into account, but no acceleration/breaking (truck load) and wind loads have been considered. The fatigue design was done considering a bridge life of 100 years and correspond to a traffic category 1. A differential support settlements of **1,0** cm in unfavorable position was also accounted for. It has to be noted that this study is based on an approach analysing a rectangular object without skew.

Construction phase

The composite typology is composed of partially prefabricated concrete flanges with 12 cm completed by in-situ concrete (25 cm) in quality C35/45. The main girders are not propped during concreting phase. The pouring of concrete cross-beams is done simultaneously with the slab.

A stabilization of girders needs to be provided to prevent LTB during construction phase through temporary devices but such devices are not object of this pre-design.

End cross beams: at abutments the beams are just embedded in the concrete cross beams and anchored as in Figure 46.

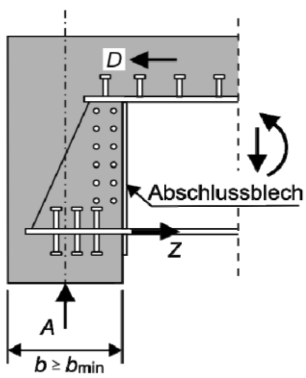

Figure 46 : End cross beams

Intermediate cross beams: at intermediate piles the continuity at the lower flange level is ensured by end plates with studs and continue reinforcement (see Figure 47). Positive moments over supports under SLS combinations are received by additional tension plates with shear studs at the positions where it is necessary. It has to be noted that steel cross beams in span are not provided in the presented predesign. T-rips (stiffeners with end plate) are welded onto the web of the girders and cross beams with end plates are connected with bolts to the rips (see Figure 48).

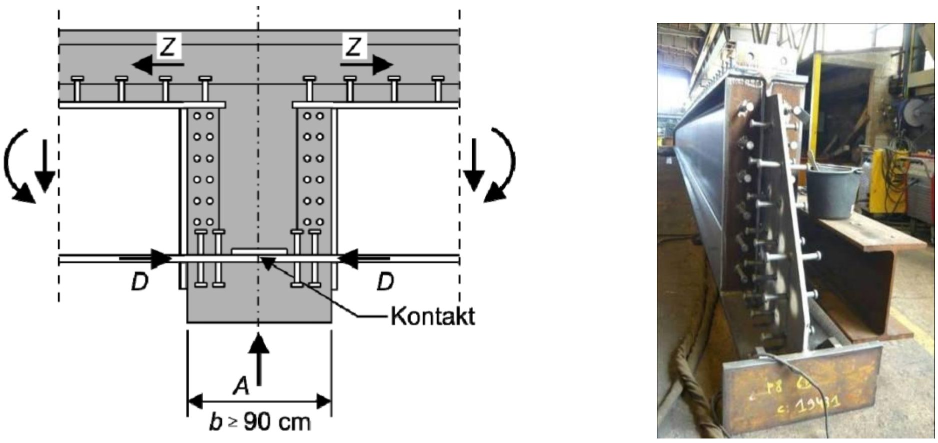

Figure 47 : Intermediate cross beams.

Figure 48 : T-rips and end plates

The cross sections of Gdansk deck and Gorzyczki deck are presented below (Figures 49 and 50). The Gdansk deck is 18.28 meters width with 6 beams line. The Gorzyczki deck is 24.28 meters width with 8 beams line.

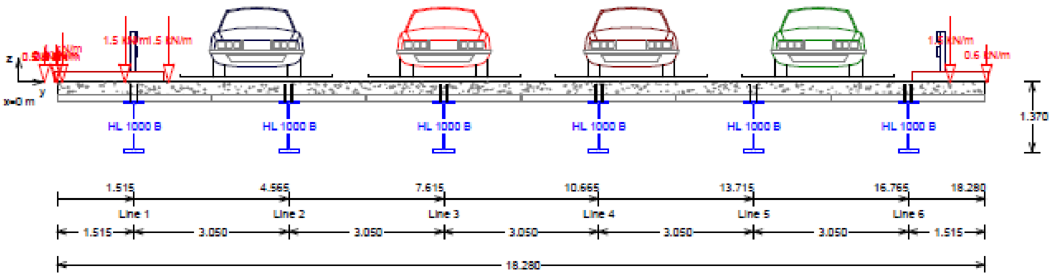

Figure 49 : Cross section of Gdansk deck

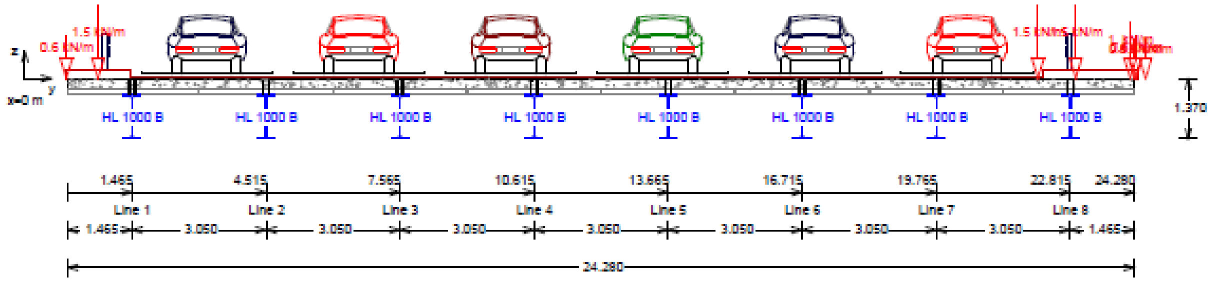

Figure 50 : Cross section of Gorzyczki deck

The most significant quantities of case E are summarized in Table 28.

Table 28: Quantities of cases E1 and E2

Description	unit	E1	E2
Steel beams	**[kg]**	**413 337**	**548 918**
Structural steel S460	*[kg]*	*394 028*	-
Structural steel S355	*[kg]*	*19 309*	*45 168*
Structural steel Histar460	*[kg]*	-	*503 750*
Shear studs	[kg]	550	2 128
Steel plates	[kg]	-	44 143
Precobeam reinforcement BST500S	[kg]	253 556	-
Reinforcement steel S500	**[kg]**	**313 416**	**450 000**
Crossbars reinforcement	*[kg]*	*83 204*	
Concrete slab reinforcement	*[kg]*	*230 212*	
Precobeam concrete C40/50	[m3]	682	-
Crossbeams concrete	[m3]	571	466
Concrete slab	[m3]	982	1455

(*) values indicated in bold are total sums of values presented in italisized text.

3.2 Traffic analysis

It is assumed that the motorway accommodates an Average Daily Traffic (ADT) of 12000 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 51 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 of Manual I [2]) where a growth rate of 0.5% is considered.

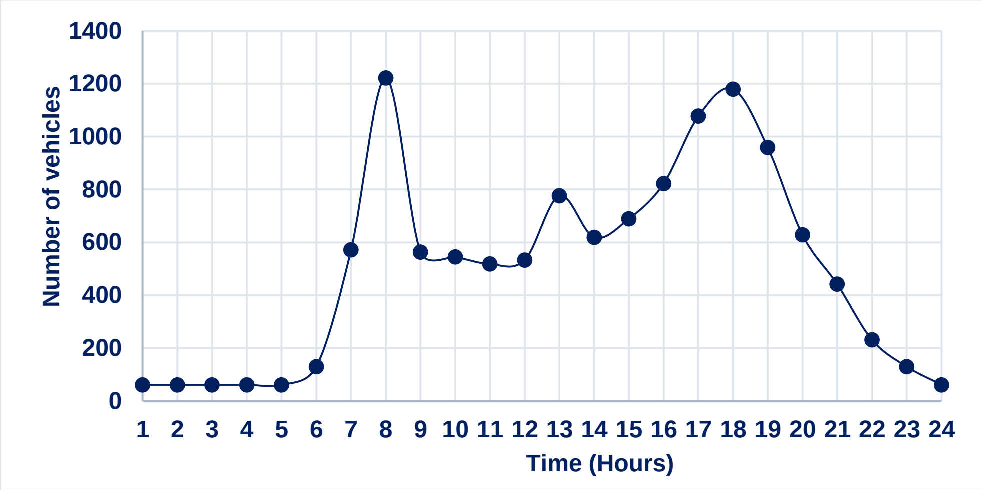

Figure 51: Distribution of hourly traffic for case studies E1 and E2

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 deck, according to Figure 52. Data were collected from the sources indicated in**Erro! A origem da referência não foi encontrada.** Table 5.

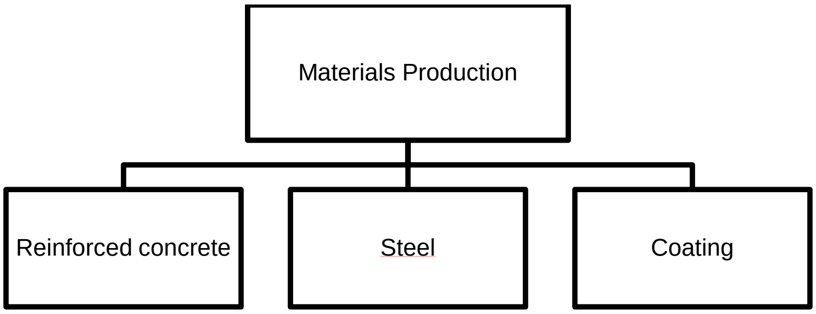

Figure 52: Material production stage

- *Environmental analysis of reference case study E1*

The results obtained for the construction stage are presented in Table 29. 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 53.

Table 29: Environmental impacts at the material production stage per impact category [E1]

Impact Category	Unit	Total	Reinforced Concrete	Steel	Coating
ADP Fossil	MJ	1,87E+07	1,05E+07	8,16E+06	2,55E+04
AP	Kg SO2 eq	5,31E+03	3,22E+03	2,08E+03	5,32E+00
EP	Kg PO4 eq	4,77E+02	3,14E+02	1,62E+02	2,58E-01
GWP	Kg CO2 eq	2,17E+06	1,45E+06	7,23E+05	1,58E+03
ODP	Kg R11 eq	2,33E-02	6,99E-03	1,63E-02	2,95E-09
POCP	Kg C2H4	7,63E+02	3,95E+02	3,66E+02	2,07E+00

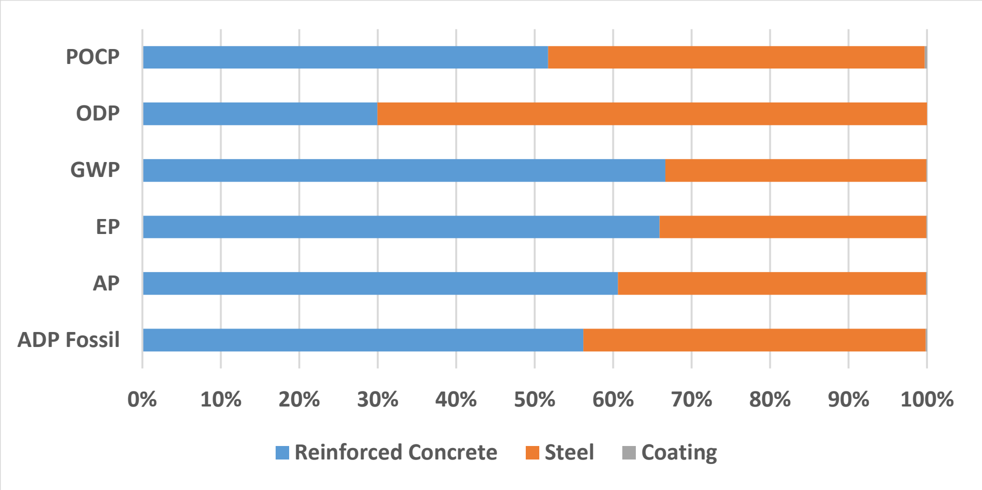

Figure 53: Contribution analysis of processes at the material production stage [E1]

- *Environmental analysis of variant E2*

The results obtained for the variant case study E2 are presented in Table 30 and Figure 54 indicates the variation of the results in comparison to the reference case study E1.

Table 30: Environmental impacts at the material production stage per impact category [E2]

Impact Category	Unit	Total	Reinforced Concrete	Steel	Painting
ADP Fossil	MJ	2,07E+07	8,41E+06	1,21E+07	1,24E+05
AP	Kg SO2 eq	5,72E+03	2,59E+03	3,11E+03	2,60E+01
EP	Kg PO4 eq	4,96E+02	2,55E+02	2,39E+02	1,26E+00
GWP	Kg CO2 eq	2,26E+06	1,17E+06	1,08E+06	7,73E+03
ODP	Kg R11 eq	2,73E-02	5,55E-03	2,18E-02	1,44E-08
POCP	Kg C2H4	8,77E+02	3,13E+02	5,54E+02	1,01E+01

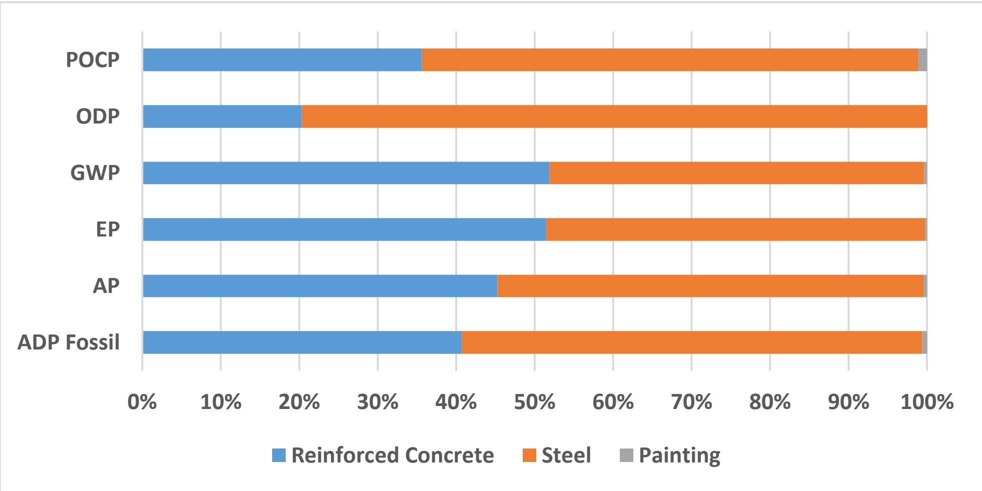

Figure 54: Contribution analysis of processes at the material production stage [E2]

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Table 31: Environmental impacts of E2 at the material production stage relative to E1

Impact Category	Unit	Case Study E1	Case Study E2	Variation relative to E1
ADP Fossil	MJ	1,87E+07	2,07E+07	+10,6%
AP	Kg SO2 eq	5,31E+03	5,72E+03	+7,9%
EP	Kg PO4 eq	4,77E+02	4,96E+02	+4,1%
GWP	Kg CO2 eq	2,17E+06	2,26E+06	+3,9%
ODP	Kg R11 eq	2,33E-02	2,73E-02	+17,0%
POCP	Kg C2H4	7,63E+02	8,77E+02	+15,0%

When compared with E1, higher impacts were calculated in E2 in every impact category in the material production phase.

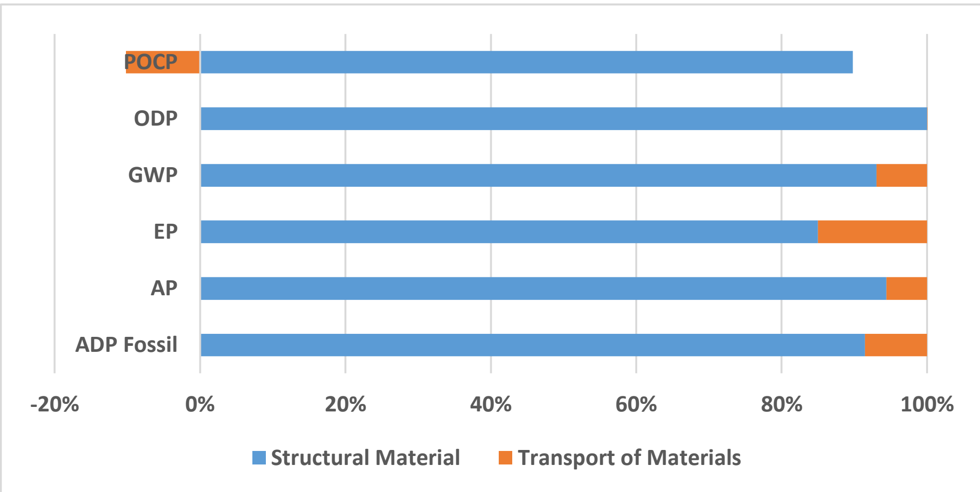
3.3.2 Construction stage

- *Environmental analysis of reference case study E1*

The results of the construction stage for the reference case study E1 are presented in Table 32 and illustrated in Figure 55. The operations related with the structural materials and their transport represent the main contribution for the environmental impacts in this stage.

Table 32: Environmental impact at the construction stage per impact category [E1]

Impact Category	Unit	Total	Structural Material	Transport of Materials
ADP Fossil	MJ	9,36E+05	8,57E+05	7,99E+04
AP	Kg SO2 eq	2,32E+02	2,19E+02	1,29E+01
EP	Kg PO4 eq	2,05E+01	1,74E+01	3,07E+00
GWP	Kg CO2 eq	8,33E+04	7,75E+04	5,79E+03
ODP	Kg R11 eq	1,17E-03	1,17E-03	1,94E-09
POCP	Kg C2H4	3,18E+01	3,58E+01	-4,08E+00



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 [3]. See section 1.4.6.

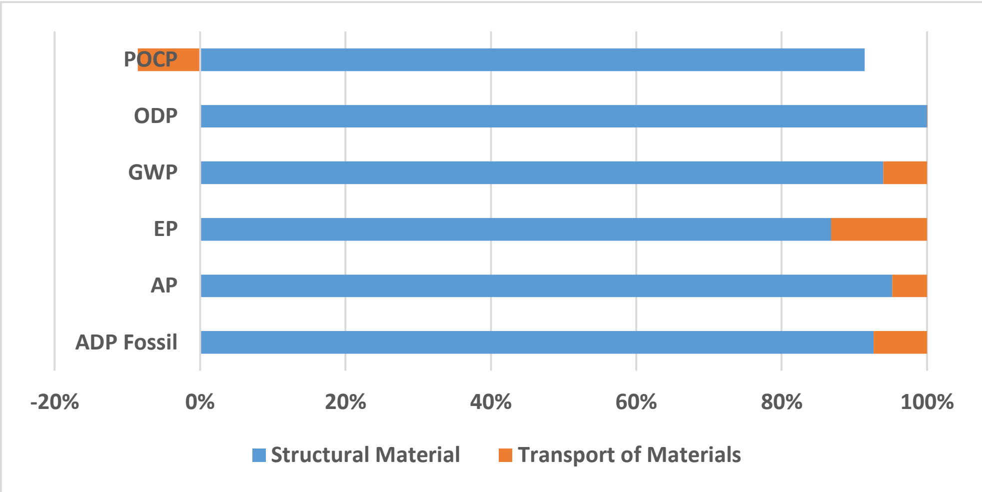
Figure 55: Contribution analysis of processes during the construction stage for case study E1

- *Environmental analysis of variant E2*

The results obtained for the variant case study E2 are presented in Table 33 and Figure 56. Table 34 indicates the variation of the results in comparison to the reference case study E1.

Table 33: Environmental impact at the construction stage per impact category [E2]

Impact Category	Unit	Total	Structural Material	Transport of Materials
ADP Fossil	MJ	1,04E+06	9,64E+05	7,65E+04
AP	Kg SO2 eq	2,59E+02	2,46E+02	1,24E+01
EP	Kg PO4 eq	2,23E+01	1,94E+01	2,94E+00
GWP	Kg CO2 eq	9,25E+04	8,69E+04	5,55E+03
ODP	Kg R11 eq	1,37E-03	1,37E-03	1,86E-09
POCP	Kg C2H4	3,77E+01	4,16E+01	-3,91E+00



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 [3]. See section 1.4.6.

Figure 56: Contribution analysis of processes during the construction stage for case study E2

Table 34: Environmental impacts of E2 compared to E1 at the construction stage

Impact Category	Unit	Case E1	Case E2	Variation relative to E1
ADP Fossil	MJ	9,36E+05	1,04E+06	+11,1%
AP	Kg SO2 eq	2,32E+02	2,59E+02	+11,7%
EP	Kg PO4 eq	2,05E+01	2,23E+01	+9,0%
GWP	Kg CO2 eq	8,33E+04	9,25E+04	+11,0%
ODP	Kg R11 eq	1,17E-03	1,37E-03	+17,0%
POCP	Kg C2H4	3,18E+01	3,77E+01	+18,8%

It is observed that the contribution from structural materials constitutes more than 80% of the total impacts. Case E2 resulted in relatively higher impact than case E1 at this stage too.

3.3.3 Operation stage

- *Environmental analysis of reference case study E1*

The results of the operation stage, for the reference case study E1, are presented in Figure 57, for the "day work" plan and the standard maintenance scenario.

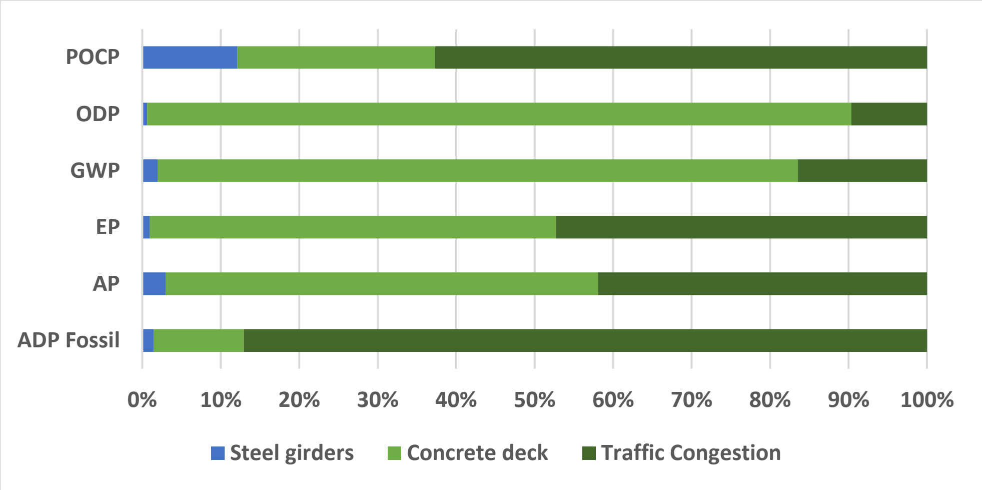


Figure 57: Contribution analysis of processes during the operation stage (day work) E1

Environmental impacts in the "night work" scenario are presented and compared with the results from the "day work" scenario in Table 35.

Table 35: Environmental impacts of E1 comparison between day and night work

Impact Category	Unit	Case Study E1 Day	Case Study E1 Night	Variation relative to E1 Day
ADP Fossil	MJ	4,45E+06	4,38E+06	-1,6%
AP	Kg SO_2 eq.	4,62E+02	4,58E+02	-0,8%
EP	Kg PO_4 eq.	6,94E+01	6,88E+01	-0,9%
GWP	Kg CO_2 eq.	2,08E+05	2,07E+05	-0,3%
ODP	Kg R11 eq.	1,23E-06	1,23E-06	-0,2%
POCP	Kg C_2H_4	4,44E+01	4,39E+01	-1,2%

In both scenarios it is observed the major contribution for all impact categories are related to the maintenance of the concrete deck and traffic congestion. The contribution of the traffic congestion did not show significant reduction in the night scenario for this case. A slightly reduced (<2%) values were computed in all impact categories. This is mainly due to the nature of the limited number of structural elements studied in this case study. Road surface, bearings, expansion joints and other elements were not included in the provided bridge data for this case study.

- *Environmental analysis of variant E2*

The results obtained for the variant case E2 are presented in Figure 58 and Table 36 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 E1.

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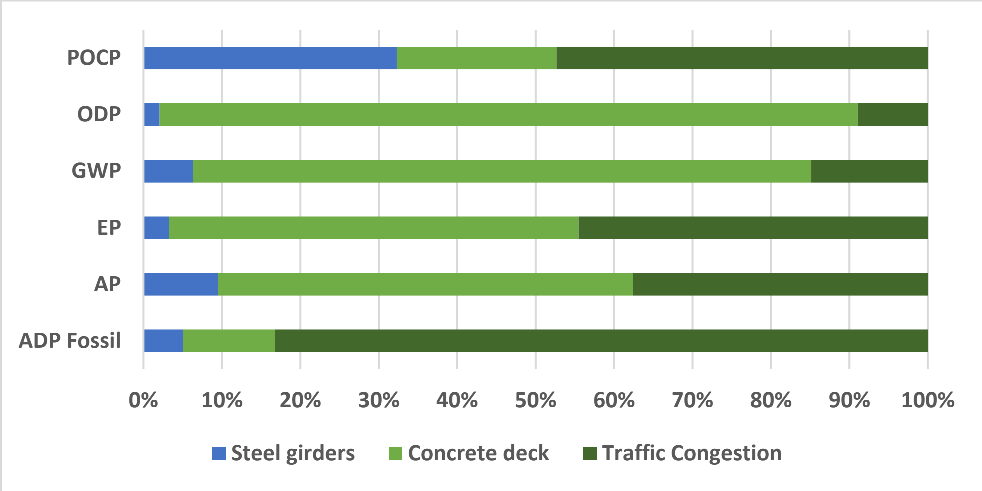

Figure 58: Contribution analysis of processes at the operation stage (E1 day work)

Table 36: Environmental impacts of E2 compared to E1 at the operation stage (day work)k"

Impact Category	Unit	Case Study E1	Case Study E2	Variation relative to E1
ADP Fossil	MJ	4,45E+06	6,44E+06	+44,6%
AP	Kg SO2 eq	4,62E+02	7,12E+02	+54,2%
EP	Kg PO4 eq	6,94E+01	1,02E+02	+46,8%
GWP	Kg CO2 eq	2,08E+05	3,18E+05	+53,3%
ODP	Kg R11 eq	1,23E-06	1,84E-06	+49,3%
POCP	Kg C2H4	4,44E+01	8,14E+01	+83,2%

Considering the “night work” scenario, the results obtained for the variant case study E2 are presented in Table 37.

Table 37: Environmental impacts of E2 compared to E1 at the operation stage (night work)

Impact Category	Unit	Case Study E1	Case Study E2	Variation relative to E1
ADP Fossil	MJ	4,38E+06	6,34E+06	+44,7%
AP	Kg SO2 eq	4,58E+02	7,07E+02	+54,3%
EP	Kg PO4 eq	6,88E+01	1,01E+02	+46,9%
GWP	Kg CO2 eq	2,07E+05	3,17E+05	+53,3%
ODP	Kg R11 eq	1,23E-06	1,84E-06	+49,4%
POCP	Kg C2H4	4,39E+01	8,07E+01	+83,7%

Both in the “day and night work” scenario, the reference case study E1 proves to impart less impact in all categories. This difference arises as a result of the much higher surface area of steel that requires corrosion protection in E2. The PRECOBEAM has considerably lower surface area exposed as most of the section is embedded in concrete (All except the outer surface of the bottom flange is protected.)

3.3.4 End-of-life stage

- *Environmental analysis of reference case study E1*

Total emissions per impact category of this stage are indicated in Table 38. Figure 59 indicates the contribution of each process per impact category. The negative values in the figure represent the credits given to the recycling processes.

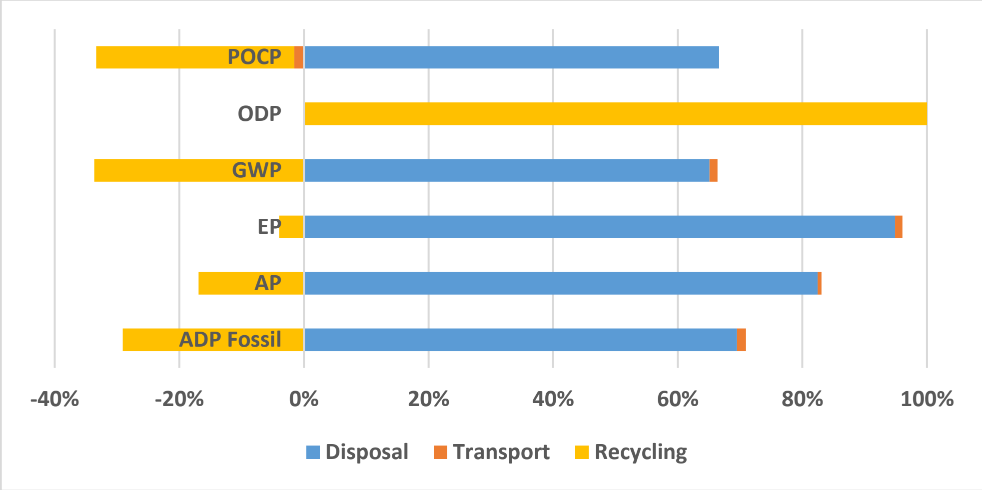

Figure 59: Contribution analysis of processes during the end-of-life stage – Case E1

Disposal contributes the most impact in all categories while recycling contributes in favour of the environment in all impact categories except ODP.

- *Environmental analysis of variant E2*

As can be seen in Figure 60, disposal contributes for the most impact in all categories while transportation causes the least of impacts. Recycling contributes in favour of the environment in all impact categories except ODP.

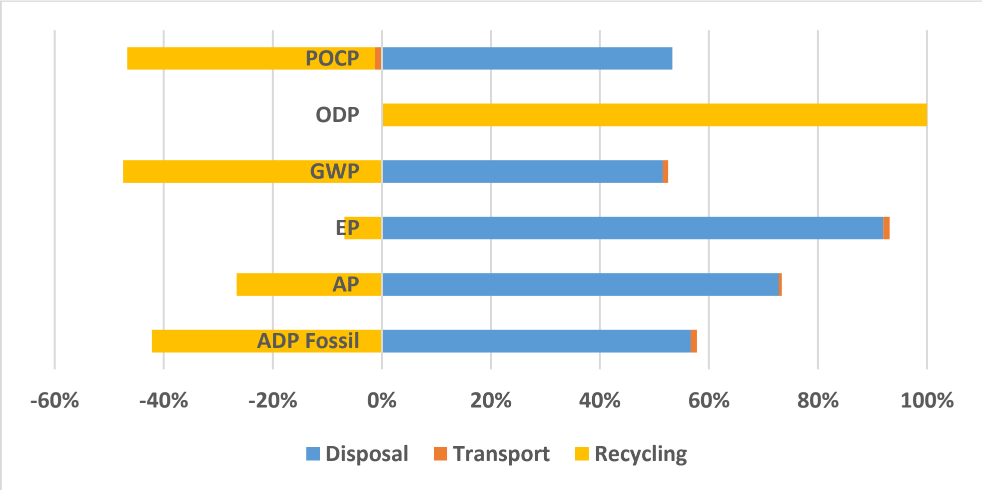

Figure 60: Contribution analysis of processes during the end-of-life stage – Case E2

Total emissions per impact category of this stage for the variant case study E2 are presented in Table 38. This table also indicates the variation of the results for this case study in comparison to the reference case study E1. This results are also illustrated in Figure 61.

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Table 38: Variation of the results for the end-of-life stage in relation to case study E1

Impact Category	Unit	Case Study E1	Case Study E2	Variation relative to E1
ADP Fossil	MJ	3,65E+06	1,44E+06	-60,6%

AP	Kg SO2 eq	2,24E+03	1,54E+03	-31,2%
EP	Kg PO4 eq	3,69E+02	3,07E+02	-16,9%
GWP	Kg CO2 eq	2,35E+05	3,98E+04	-83,1%
ODP	Kg R11 eq	7,68E-03	1,18E-02	+53,2%
POCP	Kg C2H4	1,34E+02	2,88E+01	-78,5%

According to these results it can be concluded that at this stage the reference example led to higher impacts. E1 has the higher concrete volume, which becomes a burden to the environment after demolition, and fewer volume of steel, which would have led to lower recycling possibility that could have beeb appreciated at this stage, than in E2. The results in ODP can be explained as follows. Recycling process (transportation included) benefits the environment in all impact categories except the Ozone Depletion Potential where the recycling process itself gives rise to such emissions. With less steel to recycle in E1 there is less recycling which inturn results in lower emissions related to ODP. However, note that the magnitude of these emissions is very small (in the order of 10^{-2} or lower).

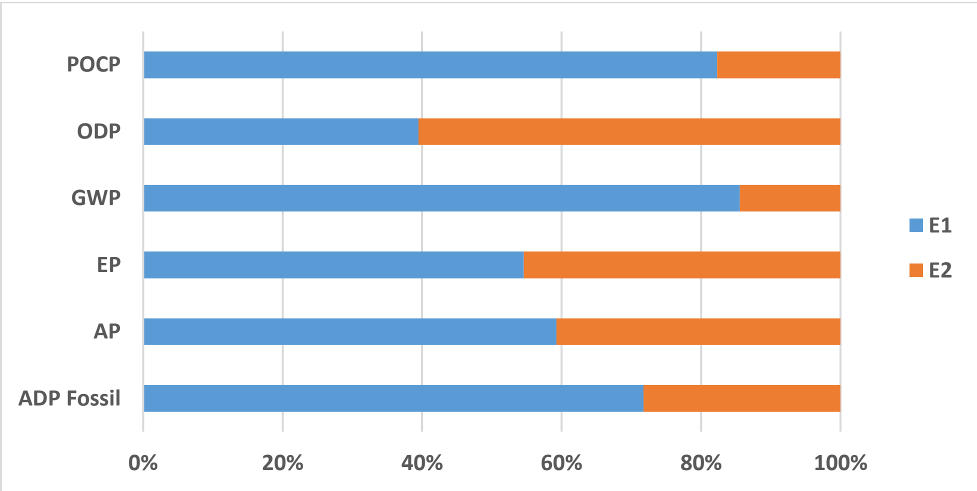

Figure 61: Contribution analysis of each bridge during the end-of-life stage

3.3.5 Results of the environmental lifecycle analysis

- *Aggregate lifecycle results for case study E1*

In the previous sections, the partial results per stage have been presented. In this sub-section the results of the different stages are summed up in relation to each impact category and the aggregate results are presented in Table 39, considering the "day work" plan and standard maintenance scenario.

Table 39: Lifecycle results per life cycle stage ("day work" scenario)

Impact Category	Unit	Total	Material	Construction	Operation	End-of-life
ADP Fossil	MJ	2,77E+07	1,87E+07	9,36E+05	4,45E+06	3,65E+06
AP	Kg SO2 eq	8,24E+03	5,31E+03	2,32E+02	4,62E+02	2,24E+03
EP	Kg PO4 eq	9,36E+02	4,77E+02	2,05E+01	6,94E+01	3,69E+02
GWP	Kg CO2 eq	2,70E+06	2,17E+06	8,33E+04	2,08E+05	2,35E+05
ODP	Kg R11 eq	3,22E-02	2,33E-02	1,17E-03	1,23E-06	7,68E-03
POCP	Kg C2H4	9,73E+02	7,63E+02	3,18E+01	4,44E+01	1,34E+02

To better understand the contribution of each stage to the aggregated result, these results are also illustrated in Figure 62.

The material production stage is the stage that contributes most to all the impact categories. The end of life stage has the second major contribution for the impact categories. The operation stage also contributes considerably while the stage of construction has relatively low contribution for all impact categories.

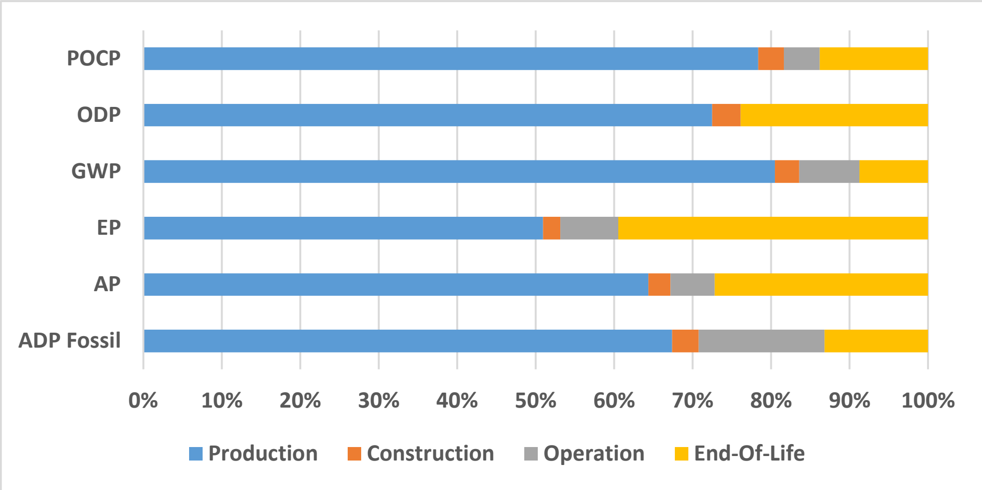

Figure 62: Contribution of each stage to impact category (“day work” scenario)

- *Aggregate lifecycle results for E2*

The results obtained for the variant case studies E2 are represented in Table 40, considering the “day work” scenario in all cases. Table 41 indicates the variation of the results this case study in relation to the reference case study E1.

Table 40: Lifecycle results per life cycle stage (“day work” scenario)

Impact Category	Unit	Total	Production	Construction	Operation	End-of-life
ADP Fossil	MJ	2,96E+07	2,07E+07	1,04E+06	6,44E+06	1,44E+06
AP	Kg SO2 eq	8,24E+03	5,72E+03	2,59E+02	7,12E+02	1,54E+03
EP	Kg PO4 eq	9,27E+02	4,96E+02	2,23E+01	1,02E+02	3,07E+02
GWP	Kg CO2 eq	2,71E+06	2,26E+06	9,25E+04	3,18E+05	3,98E+04
ODP	Kg R11 eq	4,04E-02	2,73E-02	1,37E-03	1,84E-06	1,18E-02
POCP	Kg C2H4	1,03E+03	8,77E+02	3,77E+01	8,14E+01	2,88E+01

Table 41: Variation of the aggregate results in relation to case study E1 (“day work” scenario)

Impact Category	Unit	Case Study E1	Case Study E2	Variation relative to E1
ADP Fossil	MJ	2,77E+07	2,96E+07	+6,7%
AP	Kg SO_2 eq	8,24E+03	8,24E+03	-0,0%
EP	Kg PO_4 eq	9,36E+02	9,27E+02	-0,9%
GWP	Kg CO_2 eq	2,70E+06	2,71E+06	+0,3%
ODP	Kg R11 eq	3,22E-02	4,04E-02	+25,7%
POCP	Kg C_2H_4	9,73E+02	1,03E+03	+5,4%

To better understand the contribution of each case study to the aggregated result, the results are also presented in Figure 63. The results in ODP can be explained as follows.

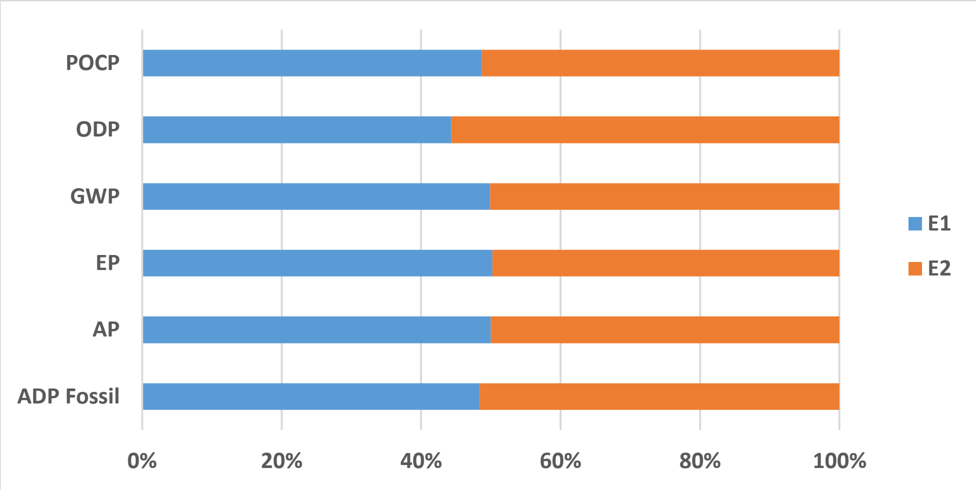

Figure 63: Contribution of each case study to impact category ("day work" scenario)

As it can be seen from the above illustrations, both case studies result in comparable impact in all categories with the reference case gaining slight favourability in ODP impact category. The results in ODP can be explained as follows. The recycling process (transportation included) benefits the environment in all impact categories except the Ozone Depletion Potential where the recycling process itself gives rise to such emissions. With less steel to recycle in E1 there is less recycling which inturn results in lower emissions related to ODP. However, note that the magnitude of these emissions is very small (in the order of 10^{-2}).

3.4 Lifecycle Cost Analysis

Due to the lack of data on the costs, lifecycle cost analysis could not be made in this report.

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 64 details the user costs for case studies E1 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.

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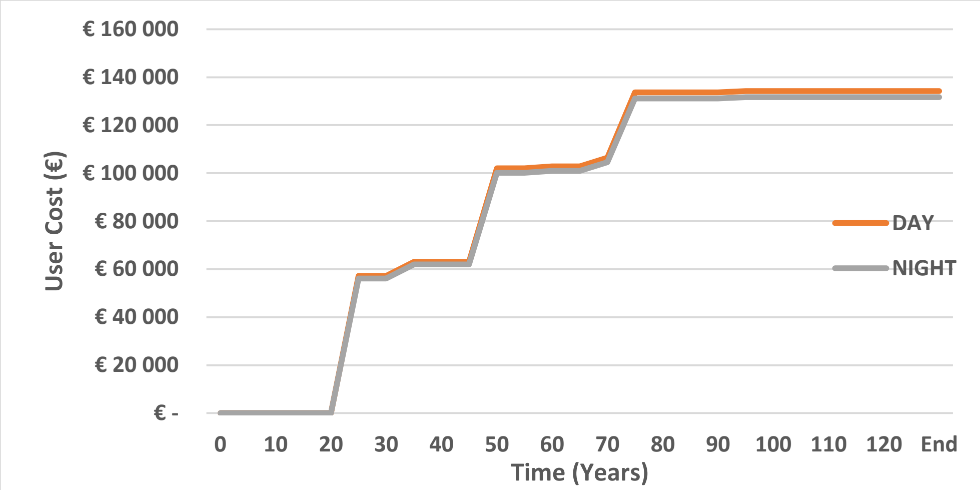

Figure 64: User costs for case studies E1 with "day" and "night" scenarios.

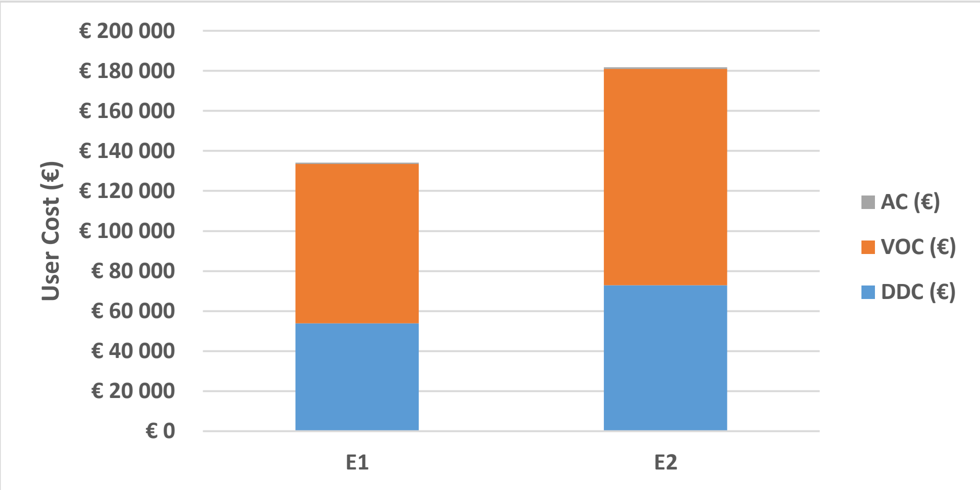

Figure 65: User costs for case studies E1 and E2 with the standard scenario and "day work" plan.

Maintenance actions in E1 take 205 days in the whole lifespan of the bridge while in 283 days are required in E2. The difference arises mainly due to the higher steel surface that requires corrosion protection maintenances in E2. This change is reflected in the user costs can be observed in Figure 65. The user costs associated with case E2 were found to be higher than that for case E1.

3.6 Discussion of the Results for case E

Contrary to the previous two cases, this study put the focus solely to the bridge deck. The Precobeam solution, an innovative bridge construction method, was studied against a conventional composite bridge solution. As a result, it was observed from the lifecycle environmental analysis that the stages of material production and end of life stage dominated in all impact categories. The LCA resulted in a more or less the same impact on the environment for both cases with slight favorability to the conventional solution in the ODP impact category. Life cycle costs were not evaluated for this case study.

Once more, the social aspects of the LCA prove that the night shift is more favourable in reducing the impacts on user cost. The user costs associated with case the precobeam solution were found to be significantly lower than those calculated for the traditional composite bridge.

4 SUMMARY AND CONCLUSIONS

In this project European partners from universities, research centres, 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 order 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 over the lifecycle was reached.

The main objective of this Design Manual II are the analysis of further extended bridges besides the standard situations of the deck bridges studied in the project SBRI [18] and also study of built bridges across the Europe with real data and existing bridge situations such as traffic, inspection and maintenance conditions. For that several bridges types and innovations were analysed as: Integral motorway crossing where hot-dip galvanized girders were considered and also the Precobeam bridge with an innovative shear connection.

The following conclusions can be provided for each bridge type:

Case D - An innovative integral bridge over a motorway.

The bridge here analysed was the first being built (in mid-2014) with hot-dip galvanized girders over a motorway in Germany. The aim of this case study is to elaborate and provide guidance for the design of steel composite bridges with a lifetime-oriented corrosion protection. The comparison of the corrosion protection is made here by using an integral highway composite bridge. For the steel beams, an organic corrosion protection coating is compared with a hot-dip galvanizing system and a duplex system produced during the utilization phase. The composite bridge is considered throughout the entire lifecycle, from manufacturing, through the whole use until demolition.

The bridge studied herein corresponds with the case A1 from Manual I [11]. It is motorway crossing bridge of two traffic lanes with dimensions 45.25 m length and 11.75 m width. It is an integral composite bridge with integral abutments and there is not support in the middle of the highway. Three case studies corresponding with the design variants of the corrosion protection were taken for maintenance over the entire life cycle of the bridge, namely:

Case D1 – Corrosion protection: Hot-dip galvanization (thickness 300 µm) and no renovation is considered during whole life cycle of the bridge;

Case D2 – Corrosion protection: Organic protection coating and complete renovation of the corrosion protection in year 33 and 66 of the life cycle of the bridge;

Case D3 – Corrosion protection: Hot-dip galvanization (thickness 200 µm) and application of an organic corrosion protection in year 66 of the life cycle of the bridge;

In case study D, it was observed from the lifecycle environmental analysis that the stages of material production and end of life dominate all impact categories. The alternative that used conventional coating resulted in higher impacts on the environment and users due to repeated maintenance operations on the steel girder's corrosion protection layers. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides reduction of impacts owing to the fact that traffic count is lesser at night.

In terms of the initial cost, i.e., production and construction costs, the three alternatives of corrosion protection lead to a relatively similar cost with slight favourablility to the ordinary steel coating. And the end of life costs are the same for all the three alternatives. However, the first alternative, 300 µm hot-dip galvanized steel, showed significant reduction in cost in the operation stage as there is no need for maintenance throughout the lifespan of the bridge. The second alternative, which required two full renovations - via organic coating - of the corrosion protection layers, resulted in higher operation costs. The third alternative, where by duplex coating scheme was adopted, is less costly than the second but still more expensive than the first alternative. In conclusion, it can be said that the hot-dip galvanization presents itself as the best alternative in terms of lifecycle cost.

Once more, the social aspects of the lifecycle analysis prove that the night shift is favourable in reducing the impacts on user cost. The user costs associated with D1 were found to be 29.8% and 11.9% lower than those for cases D2 and D3, respectively. Comparing LCC of the three alternatives with the user costs included, the hot-dip galvanized bridge is 21.3% cheaper than the one with the customary organic coating, instead of the 5.4% difference while not considering the user costs. It was also noted that the user costs make up for more than 65% of the total lifecycle costs.

Case E - An innovative composite bridge PRECOBEAM

The Precobeam (prefabricated composite beam) solution is a new bridge construction method invented in the beginning of the new millennium. It is an example for economic bridge solutions with rolled beams and a high degree of prefabrication. This method is based on a rolled steel beam, oxycut longitudinally in two T-sections with a special shape. This shape works as a continuous shear connector which allows for the shear connection between profile and slab without the use of studs, and thus without any welding. The method is a very flexible solution offering various cross section possibilities according to the design requirements.

The Precobeam bridge (E1 bridge) analysed in the frame of this project is the WA-352 viaduct - WA-352 417 + 449 over the PKP line No. 146 in the Road DK 1. To emphasize the Precobeam system's advantages, the bridge E2, a solution using prefabricated composite elements, has been designed and analyzed: bridge decks with partially prefabricated composite elements based on rolled girders and concrete cross beams.

Contrary to the previous two cases, Case study E, put the focus solely to the bridge deck. The Precobeam solution, an innovative bridge construction method, was studied against a conventional composite bridge solution. As a result, it was observed from the lifecycle environmental analysis that the stages of material production and end of life stage dominated in all impact categories. The LCA resulted in a more or less the same impact on the environment for both cases with slight favorability to the conventional solution in the ODP impact category. Life cycle costs were not evaluated for this case study.

Concerning the social aspects of the LCA prove that the night shift is more favourable in reducing the impacts on user cost. The user costs associated with case the precobeam solution were found to be significantly lower than those calculated for the traditional composite bridge.

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5 TABLE OF FIGURES

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ANNEX A: MAINTENANCE SCENARIOS & TRAFFIC RESTRICTIONS

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: Traffic restriction for case D

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	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 A3: Traffic restriction for case E

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)