Benchmarking of Life Cycle Assessment for bridges

Author:

Liliia Pylypchyk

Supervisors:

Prof. Maria Constança Simões Rigueiro,

Prof. Helena Maria dos Santos Gervásio

University of Coimbra

European Commission
ERASMUS MUNDUS

Coimbra, Portugal

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To the memory of my father
Petro Fedorovych Pylypchyk

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Contents

Abstract

Bridges play essential role in the infrastructure network and are covered with the significant investment volume. In comparison to buildings, bridges are long-living structures and are designed for the minimum service life of 100 years according to Eurocode. Consequently, it draws the special focus on the sustainability of bridge construction.

In a global term, benchmarking is used as a project management tool. It found its particular application to bridges in measuring the level of structural performance of its structural components at operation stage or assessing the “reasonable” cost of its critical components when comparing with projects of similar size and scope.

Despite the effort for sustainability studies in buildings, the *sustainable* benchmarking of infrastructural network, and, particularly, bridges, remains understudied.

Here in this work the sustainable benchmarking of the motorway bridges is proposed. Based on the certified methodology of the life cycle assessment and being compliant with the prescriptions of Eurocodes, the results can be easily incorporated to the whole concept of sustainable bridge design.

The work can be split in two main parts. First one is dedicated to the compilation of the case studies and assessment of the environmental and social life cycle performance of the bridges using the methodology of the integral life cycle assessment, developed in [1] and valorized in [2] and [3]. Three different types of reference bridges were studied over the entire life-cycle. Second part of the thesis is dedicated to the establishment of the reference values (benchmarks) of the environmental and social sustainable indicators of the life cycle performance of the selected bridges.

The summary of the results of life cycle assessment and sustainable benchmarks are the quantitative outcome of present research work. The conclusions for three types of motorway bridges are given along with the recommendations for the potential improvement and development.

Established values may be used by designers and authorities for the assessment of sustainable environmental and social life cycle performance gap for the considered bridge, giving the quantitative esteem. The provided benchmarks can also be used guiding the designers in the setting targets for the potential improvement in the sustainable performance of the bridge under consideration.

1 Introduction

1.1 Overview

“If you can’t measure it, you can’t manage it”
Peter Drucker

Construction sector has a major share in the global economy. According to recent surveys, construction market reached more than 13% of global GDP counting for US $ 9.5 trillion in 2015, out of which US $ 2.5 trillion was spent on infrastructure development [4], [5]. Within the global construction market, infrastructure accounts for 26% [5], but yet sustainability implementation in this sector remains understudied, giving a major focus for buildings.

Bridges have an important role in the transportation network, assuring functionality and providing uninterrupted traffic flow. Violation of this requirements can lead to traffic interruption and congestion, inducing additional environmental burdens as well as causing a high impact on economy and society. For example, in 2014, *The Economist* analyzed the cost of imposed by traffic jams caused by accidents, poor infrastructure, peak hours and variation of the traffic speeds on congested roads [6]. Three types of cost were analyzed, namely (i) how sitting in traffic reduces productivity of the labour force; (ii) how inflated transport costs push up the price of goods; and (iii) the carbon equivalent cost of the fumes. It was concluded that expenses from congestion accounted for total of US$ 200 billion (0.8% of GDP) among the investigated countries (United Kingdom, Germany, France and United States) [6].

Further, contrast to buildings, bridges are long living structures, having the lifespan of 100 years, which draws special focus when talking about sustainable development. Therefore, infrastructure projects, and specifically bridges, require sustainability management strategies aimed on the minimization of the negative environmental, economic and social impacts.

In construction, benchmarking is typically used as a project management tool, providing the equivalent assessment of the performance of the project in question. This way, it gives a possibility for construction companies to trace the improvement in the organizational performance as it is important part of management of the cross company competition.

To date, benchmarking of bridges is considered from different perspective. Last decades, the extensive studies were conducted in United Stated by American Association of State Highway and Transportation Officials (AASHTO) and were dedicated to the detailed benchmarking of the bridge conditions at operation stage aiming to establish its structural performance by examining nearly 100 “commonly recognized structural elements” [7]. This measures are implied to be further incorporated to maintenance plans considering the cost of each action in order to rate the extent to which they are structurally deficient or obsolete.

Other benchmarking approaches address problems like overlooked items, poor engineering and planning, which cause work repetition or delays and lead to the increase of the initial cost. This issues are dealt by comparison of the project in question with the existing ones of similar size and scope. Such benchmarking strategy was implemented by McKinsey for establishing the “reasonable” bridge costs, by categorising bridges according to its length, number of lanes, location etc. and comparison with existing projects available in database [8]. This way the benchmark of the cost of critical components can be assessed and further used as a powerful negotiation tool.

Having addressed the issues related to the project cost and structural performance, yet there is no standardized methodology for *sustainable* benchmarking of bridges. Further, the existing rating systems (e.g. BREEAM, LEED, HQE, SBTool, DGNB, etc) are developed for the assessment of the sustainability levels of buildings by estimation of the selected criteria and comparing it with pre-defined reference values or thresholds. Giving a special focus to the energy efficiency issues and indoor quality of buildings, the issues related to the traffic flow and social impact intrinsic for bridges remain out of the scope [9]. The first step towards the implementation of sustainable benchmarking of bridges using the rating systems was made by Whittemore [10]. Having analysed the LEED design goals, he defined a set of questions to guide designers in the areas of Sustainable Sites, Water Efficiency, Energy and Transportation, Material and Resources and Innovation in Design resulting in remarkable advance in sustainability. It is worth mentioning, that the aforementioned rating systems are developed by national and international green council organizations and are voluntary certification schemes.

To date, the Life Cycle Analysis (LCA) becomes increasingly popular among the scientific community when referring to the sustainable performance of constructions, as it enables to evaluate the performance of the objects of infrastructure throughout the whole service life. Thus, it has got its particular focus considering the sustainable bridge design [1] and well as has been extensively used for life-cycle management of civil infrastructure considering risk and sustainability as a whole [11].

Currently, the implementation of the benchmarking of Life Cycle Analysis (LCA) faces its early development in the construction sector. Recent studies show the successful implementation of such a strategy for the buildings [12], making the sustainable benchmarking of bridges based on the Life Cycle Analysis (LCA) the central topic of present master's thesis.

1.2 Goals and scope

The thesis has two main goals (i) to perform the sustainability benchmarking of the of life cycle assessment bridges and (ii) to compile the study cases considered in projects SBRI+ [3] and SBRI [2]. The employed methodology of the life cycle assessment was developed in the framework of a research work [1] and adopted according to the purpose of present thesis. The benchmarking is focused on motorway bridges supporting dual carriageway and based on the case studies presented in the research work carried out in the framework of the European research projects SBRI: Sustainable Steel-Composite Bridges [2] in Built Environment and SBRI+: Valorization of Knowledge for Sustainable Steel-Composite Bridges in Built Environment [3].

The main objectives of the thesis are:

1. To analyse the case studies considered in the projects SBRI+ [3] and SBRI [2] as well as examples presented in related publications [1].

2. To carry out the life cycle sustainability assessment of selected case studies according the methodology developed in [1] and adopted in the projects SBRI + and SBRI.

3. To perform the benchmarking of the environmental and social sustainability indicators.
4. To discuss the life cycle performance in light of benchmarking procedure.
5. To identify potential improvements for the evaluation of the sustainable performance of bridges.

1.3 Thesis outline

The present master's thesis is organized as presented further.

Current Chapter 1 intends to familiarize the reader with the benchmarking and its role in the sustainable construction management along with the state of art of the ongoing scientific studies and its implementation in industry.

Chapter 2 entails to introduce the methodology of the integral life cycle analysis of bridges in light of purpose of this thesis.

Chapter 3 contains representation of the case studies considered in [3], [2] and [1], highlighting main design considerations governing the life cycle performance. The case studies were analysed and compiled. Special focus was given to the harmonization of the life cycle assumptions to enable further benchmarking on a common basis as it is required by the procedure.

Chapter 4 presents the description of the approach adopted for the sustainable benchmarking of the life cycle assessment.

Chapters 5 and 6 are dedicated to the detailed discussion of the results of the life cycle analysis along with established benchmarks.

Finally, Chapter 7 presents the conclusions of this work as well as identifies potential improvements for the evaluation of the sustainable performance of bridges.

2 Life cycle sustainability assessment of the bridge

2.1 General

This chapter describes the main principles of the life cycle assessment of a bridge from the perspective of sustainable design. Bridges are long living structures with the life span of 100 years, when the stage of operation takes the major role. Three pillars of sustainability are defined for bridges and formulated in the holistic approach.

The main stages of life of bridges are defined and the concept of the integral life cycle analysis developed in the frame of PhD thesis [1] is presented. In order to perform the sustainability benchmarking of bridges, it is essential to present the methodology of the assessment of each type of integral life cycle analysis.

2.2 Principles of sustainable bridge design

The main principle of sustainable bridge design is the consideration of the structural performance not only in the stage of construction, when the reliability is ensured by compliance with the Eurocodes, but taking into account the whole service life of 100 years. The particular feature of this type of structures is that they start deteriorating immediately after entering the service life. Several degradation processes, mainly, fatigue, corrosion and carbonation [2] affect the details and, consequently, the structure as a whole, see **Figure 2.1**. Thus, contradictory preserving measures, namely maintenance or repair actions are foreseen depending on maintenance strategy, decided upon the results of the inspection.

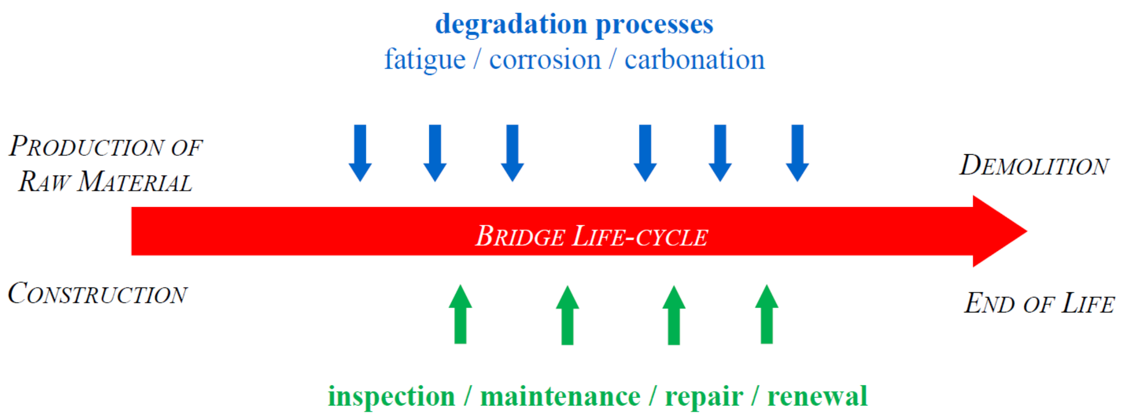


Figure 2.1 – Life cycle of the bridge [2].

The consideration of the whole life cycle also aims to balance the traffic management in an effective way, which is strongly related to the bridge typology itself. The possible traffic growth can be foreseen by the proper modifications in the initial design, paying forward towards the improvement the transportation networking problems in congested locations.

Moreover, sustainable bridge design gives the possibility to evaluate the performance of the structure in the end of life when the deposition or recycling of the materials takes place, bringing additional environmental and economical expenses. Thus, in contrast to the traditional design, governed by requirements of safety, sustainable bridge design aims to consider the performance of the whole life span of the structure, starting from production of raw material and followed by stages of construction, operation and end-of-life.

2.3 Holistic approach

The holistic approach developed in [1] and adopted in [2] and [3] aims to address the three pillars of sustainability to the life cycle assessment, see **Figure 2.2**.

Figure 2.2 – Holistic approach to life cycle analysis (adopted from [2]).

To begin with, the environmental quality is represented by the analysis of emissions in the frame of the environmental Life Cycle Assessment (LCA). The Life Cycle Costs (LCC) represent the economic quality and entails the costs emerging over the entire life cycle of the bridge. The social quality is represented by the user costs and analysed in the Life Cycle Social Assessment. The main difference between the life cycle cost and user cost is that first one is related to the bridge itself and is the expense of the bridge owner, while social cost is related to the expenses of users of the bridge and result from the traffic limitation or disruption due to activities carried out on the bridge.

All three dimensions of the holistic approach are interrelated in life cycle assessment of the bridge. Thus, initial design defines the content and frequency of maintenance events, which may lead to an additional emissions (LCA), related costs (LCC), as well as may cause traffic limitations or disruptions (LCS). Moreover, the initial design defines the allocation of the materials in the end-of-life stage, which leads to related environmental and financial burdens.

The holistic approach is the fundamental concept for the definition of the Integral Life Cycle Analysis and a basis for the transmission from the traditional construction cost based design to a sustainable design taking into account the long term advantages of durability, efficient material use along with the social quality.

2.4 Integral Life Cycle Analysis

2.4.1 General procedure

An integral life cycle approach for the assessment of motorway bridges was developed in the framework of the project SBRI [2] and valorised in the Design Manual I of project SBRI+ [3]. The aim of the approach is the performance of the life cycle assessment from the point of view of sustainable constructions, considering all three dimensions of sustainability.

To date, there is no standardize procedure for the performance of the integral life cycle analysis of a construction system [1], therefore the structure of well-described methodology of the environmental life cycle assessment (LCA), standardized by the series of ISO [13] and [14], was used to establish the generalized framework of integral life cycle assessment and was further adopted to accommodate the assessment of the life cycle cost (LCC) and user costs (LCS).

The generalised framework of integral LCA consists of four main steps aligned with the ISO 14040 [13]: goal and scope; inventory analysis; impact assessment; interpretation step. As it was mentioned, this scheme was modified in order to adopt the integration of economic and social aspects in the life cycle analysis.

In this approach the initial safety of the structure is assumed to be fulfilled and compliant with the requirements of rules and codes. Yet, in the life cycle approach the maintenance and rehabilitation events need to be foreseen in order to keep the structure above the admissible performance level, due to its degradation at different rate soon after entering the service life. The consideration of this events is of an importance since each time interventions to the bridge case emissions coming from the new materials and its transportation, traffic interruptions and monetary expenses that need to be considered in the life cycle analysis [2]. Consequently, all three type of life cycle assessment are interrelated and directly depend on the life span of the bridge, as presented in **Figure 2.3**.

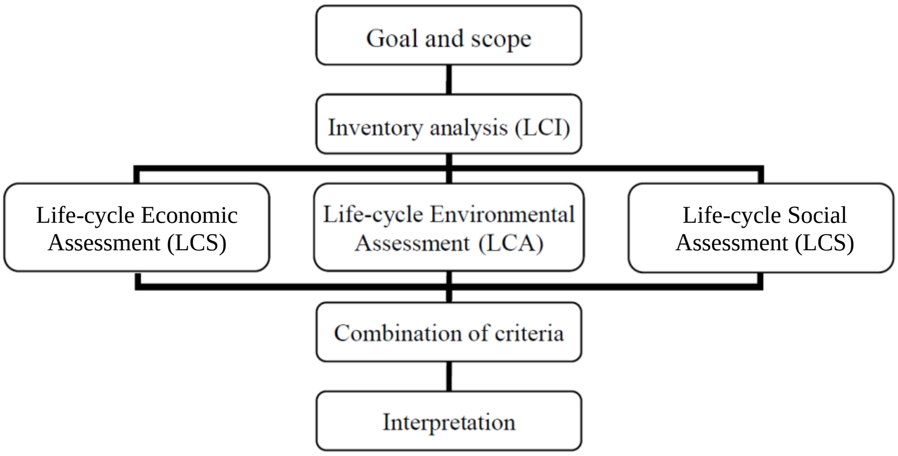


Figure 2.3 – Life cycle integral analysis (adopted from [2]).

It is implied that all three analyses share the same goal and scope and are based on the same inventory analysis, though the impact assessment is done separately for each criteria. The combination criteria depend on the goal of the analysis. Since the particular purpose of this thesis is to perform the sustainability benchmarking, all three criteria were assessed and interpreted separately.

2.4.2 Life Cycle Environmental Assessment (LCA)

2.4.2.1 General

The framework for Lifecycle Environmental Analysis (LCA) adopted in this project is according to ISO standards 14040 [13] and 14044 [14]. These standards specify the general framework, principles, and requirements for conducting and reporting lifecycle assessment studies.

According to these standards, the lifecycle assessment shall include (i) definition of goal and scope, (ii) inventory analysis, (iii) impact assessment, (iv) normalization and weighting, and (v) interpretation of results. The step of normalization and weighting is considered to be optional in ISO standards and will not be addressed in the lifecycle environmental analysis. Thus, the complete flowchart for the environmental lifecycle analysis is detailed in **Figure 2.4**.

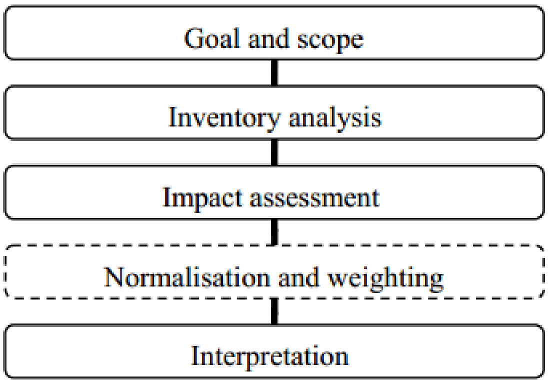


Figure 2.4 – Flowchart for environmental Life Cycle Assessment (LCA) [2].

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

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

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

2.4.2.2 Goal and Scope of the LCA

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

The system boundaries determine which unit process shall be included within the LCA [13]. Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The system boundary adopted in this project is introduced in Figure 2.5. All stages of the complete lifecycle of the bridges, from raw material extraction until end-of-life procedures, are included; the analysis takes into account the cradle-to-cradle approach. Furthermore, the transportation of materials and equipment are also within the system boundary.

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

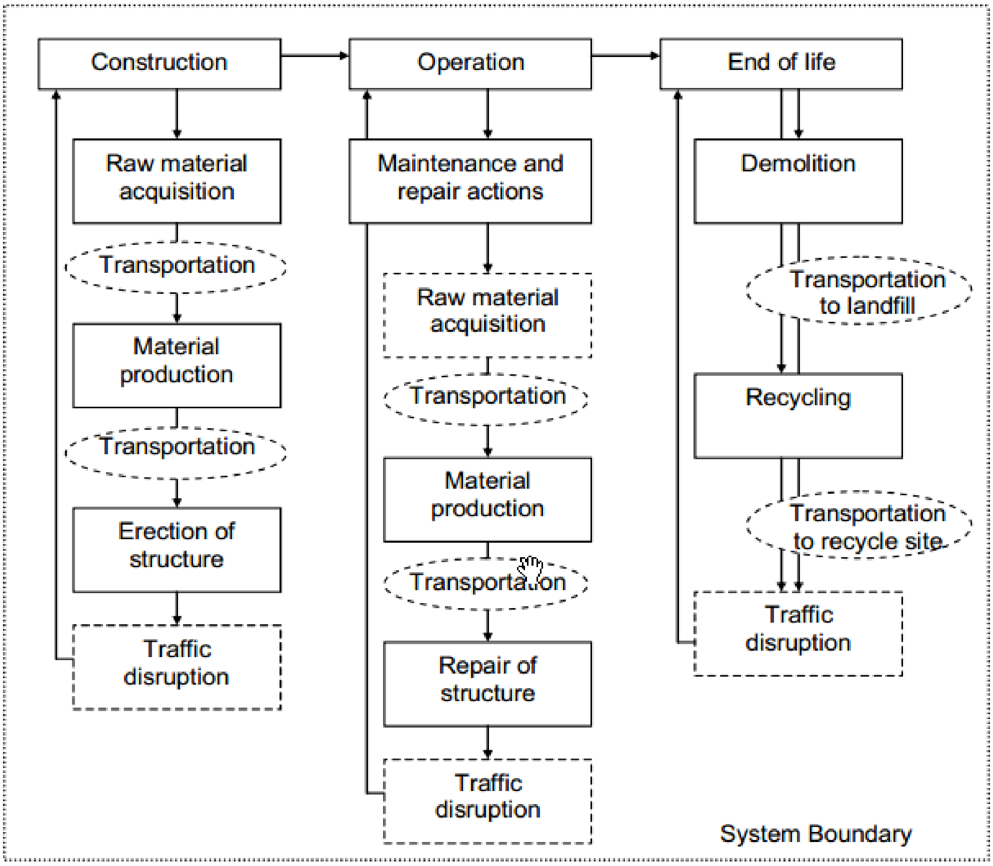


Figure 2.5 - System boundary of the LCA [2].

2.4.2.3 Methodology for Impact Assessment

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

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

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

The environmental indicators used in the lifecycle approach are adopted from ISO 14044 [14] and listed in **Table 1**.

Table 1- Environmental indicators for LCA [3]

Indicator		Unit	Timescale
Abiotic Depletion Potential, fossil fuels	$ADP_{fossils}$	MJ.	
Acidification Potential	AP	Kg SO_2 eq.	∞
Eutrophication Potential	EP	Kg PO_4 eq.	∞
Global Warming Potential	GWP	Kg CO_2 eq.	100 years
Ozone Depletion Potential	ODP	Kg CFC eq.	∞
Photo Ozone Creation Potential	POCP	Kg C_2H_4 eq.	-

2.4.2.4 Environmental Indicators

2.4.2.4.1 Abiotic Depletion Potential (ADP)

The indicator abiotic depletion aims to evaluate the environmental problem related to the decreasing availability of natural resources. By natural resources, it is understood the minerals and materials found in the earth, sea, or atmosphere and biota, that have not yet been industrially processed [15].

The model [15] adopted for abiotic depletion in this work, assumes that ultimate reserves and extraction rates together are the best way to represent the seriousness of resource depletion. This model is a global model based on ultimate reserves in the world combined with yearly depletion on a world level.

2.4.2.4.2 Acidification Potential (AP)

Acidification in one of the impact categories in which local sensitivity plays an important role. The characterization factors adopted in this work are based on the model RAINS-LCA, which takes fate, background depositions and effects into account [16]. This indicator is expressed in kg of SO2 equivalents.

2.4.2.4.3 Eutrophication Potential (EP)

The eutrophication indicator is given by the aggregation of the potential contribution of emissions of N, P and C (given in terms of chemical oxygen demand, COD) to biomass formation [17]. The Eutrophication Potential of substance i reflects its potential contribution to biomass formation. This indicator is expressed in kg of PO4 equivalents.

2.4.2.4.4 Global Warming Potential (GWP)

The global warming indicator measures the impact of human emissions on the radiative forcing of the atmosphere. GWPs are defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas [18]. For the definition of GWPs, the reference gas is carbon dioxide (CO_2).

2.4.2.4.5 Ozone Depletion Potential (ODP)

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

2.4.2.4.6 Photochemical Ozone Creation Potential (POCP)

Photo-oxidants may be formed in the troposphere under the influence of ultraviolet light, through photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) [17]. This chemical reaction is "non-linear," meaning that sometimes the NOx concentration will drive the reaction, and other times, it’s the VOC that drive the reaction. Various indicators take low, average and high NOx concentrations to calculate an overall score. Photochemical ozone creation potentials assess various emission scenarios for VOCs. Therefore, the photochemical ozone creation potential of a VOC (POCP) is given by the ratio between the change in ozone concentration due to a change in the emission of that VOC and the change in the ozone concentration due to a change in the emission of ethylene (C_2H_4) [17].

2.4.3 Life Cycle Cost Assessment (LCC)

2.4.3.1 Goals and scope

The traditional structural design is focused on the optimization of the cost on the construction stage only, while the cost of inspection, operation and end-of-life may represent the significant portion of the total life cycle cost. Thus a conventional design concepts are reconsidered here to make shift to the life cycle level, which gives a possibility to take into account the costs emerging at different stages of the over the whole life span of the structure.

Lifecycle cost (LCC) is an economic evaluation method that takes account of all relevant costs over the defined time horizon (period of study), including adjusting for the time value of money [3]. The total lifecycle costs include not only construction costs but also other costs such as design, maintenance and dismantlement which may represent a significant portion of the total lifecycle costs as illustrated in **Figure 2.6**.

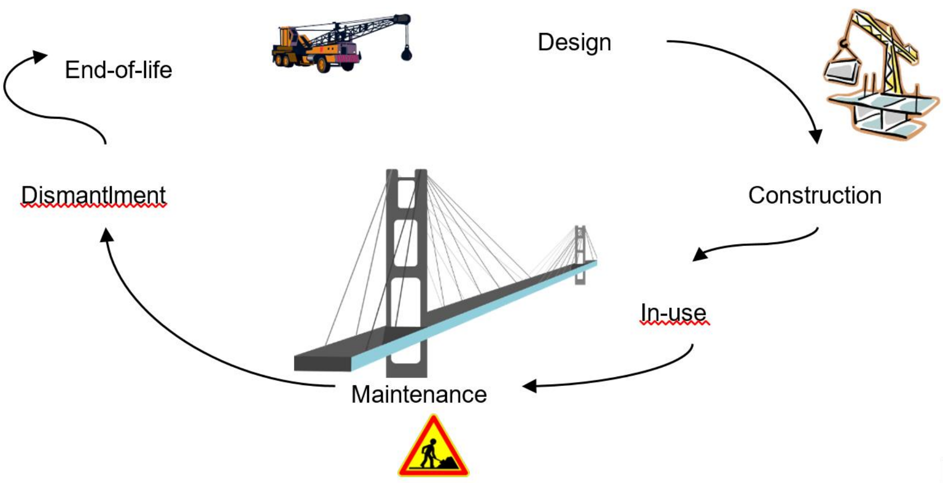


Figure 2.6 - Lifecycle stages/costs from design to bridge end-of-life [2].

The ISO 15686-5 methodology [19] defines the lifecycle costing as a technique which enables systematic economic evaluation of the lifecycle costs over the period of analysis. **Figure 2.7** summarises the concept of whole life and Lifecycle cost. One important motivation to use lifecycle cost analysis (LCC) is to balance the decrease of operation and maintenance costs with a possible increase of initial costs [2].

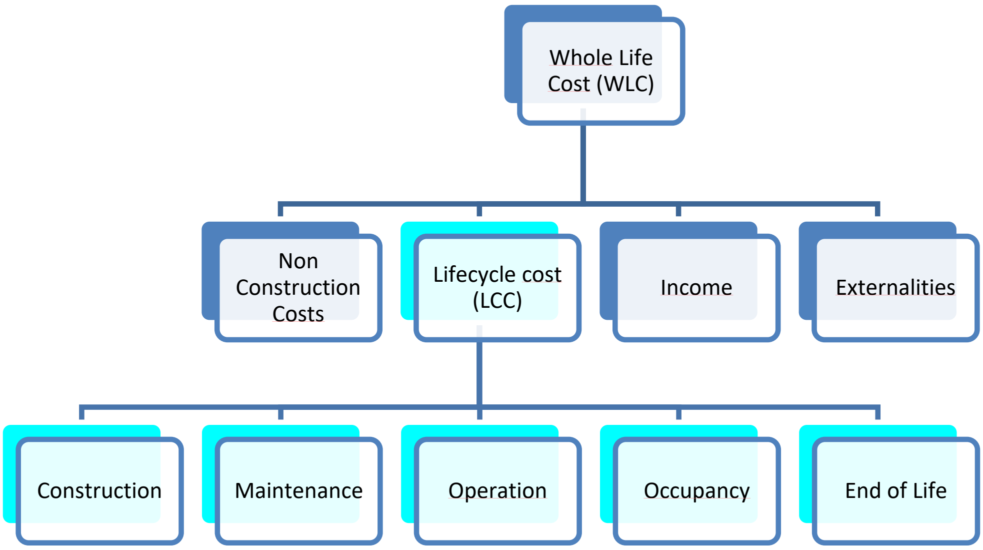


Figure 2.7 – Total life cycle cost [2].

Following the concept presented in **Figure 2.7**, the LCC analysis methodology can be expressed as in the equation (2):

$$C = C_c + C_o + C_d \tag{2}$$

where C_c - construction (initial) costs, C_o - operation costs, and C_d - demolition.

All three categories of cost are described further in subchapters 2.4.3.2, 2.4.3.3 and 2.4.3.4.

By considering all these costs in the decision process and ensuring performance constraints are satisfied, solutions that may be more expensive than others at the construction stage can finally be more attractive when considering the overall life service of the structure **Figure 2.8**.

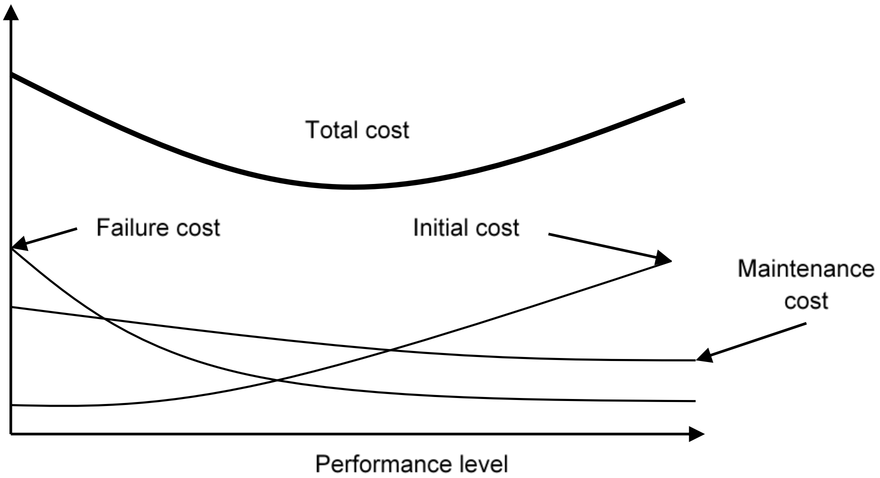


Figure 2.8 - Schematic representation of the life cycle costs [2].

2.4.3.2 Construction stage

Expenses associated with steel-concrete composite bridge construction mainly include costs for (i) foundation, (ii) substructure with abutments, piles and bearings, (iii) superstructure with steel girder/box (for composite bridge), concrete deck and equipment (expansion joints, road surface, waterproofing layer, metal cornice gutter, railing and protection). It is noted that these costs should include all materials and work costs needed for each component

It is noted that most construction materials consume energy for production and transportation. This aspect is taken into account in [20] by multiplying all costs for materials for construction and repair with some factor due to energy consumption for manufacturing and transportation. The use of non-renewable materials is also considered by involving costs for reproducing or reusing materials when the structure is decommissioned.

2.4.3.3 Operation stage

All structures have to be inspected and maintained. In particular, bridge inspections are essential for the determination of intervention strategies. The time intervals between these measures depend on the type of bridge, the experience in the different countries, the economic resources available, the average daily traffic value, the use of de-icing salt and so on. Also, inspection strategies (intensities and frequencies of inspections) may be different in each country based on climate conditions and prioritization strategies proper to each country (Woodward 1997).

During the bridge operation stage, some maintenance activities are taken into account, the objective ensuring that the bridge performance (associated with serviceability and safety concepts) always remains above a minimum threshold. This point corresponds to the end of the service life if no other rehabilitation action is conducted.

2.4.3.4 End-of-life

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

2.4.3.5 Economic Evaluation Method for LCC

Life cycle costs occur at different time of the service life, therefore they need to be converted to a common time point taking into account the money depreciation over time.

Understanding the time value of money and the fact that the costs reflected in an LCC analysis are incurred at varying points in time, a need to convert all cost values into a value at a common point in time arises. Several methods exist to lead to LCC. Here in this work the net present value approach was adopted. It implies direct application of discount factors to the cost emerging in corresponding year.

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

$$NPV = \sum_{k=1}^{N} \frac{C_k}{(1+r)^k} \tag{3}$$

where

NPV lifecycle costs expressed as a present value,

k year considered,

C_k sum of all cash flows in year K,

r discount rate,

N number of actions to be considered during the service lifetime.

The yearly profile of one unit of money is shown for illustration in **Figure 2.9**. It is noted that a steep drop in the discounted costs is observed for high discount rate values. Also, it is shown that choosing r = 6 or 8% leads to a monetary value close to zero after sixty years.

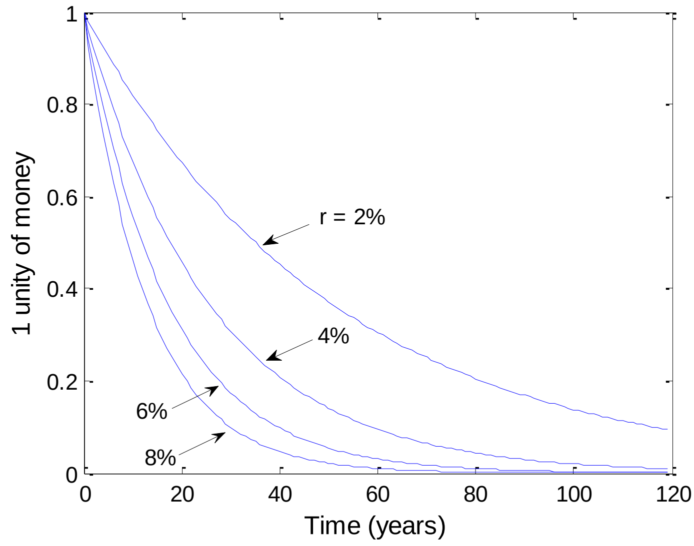


Figure 2.9 - Profile of one unit of money for different values of *r*.

The value of the yearly discount rate used is crucial since the current worth of money (*NPV*) is highly sensitive to this parameter. Indeed, the higher the discount rate, the more importance is given to the near-present. Choosing a high discount rate may then promote management strategies with low initial costs and a costly end-of-life. Therefore, the choice of the discount rate is delicate and has to be in agreement with the time horizon.

2.4.4 Life Cycle Social Assessment (LCS)

Contrary to the owner costs that are directly measurable costs, the user costs are indirect and hardly measurable. In the case of highway bridges, these costs are those incurred by the users due to maintenance operations of highway structure causing congestion or disruption of the normal traffic flow. These costs are not directly measurable but the traffic delays that lead to them can be measured.

The evaluation of the social criteria fully respects the boundary system of the integral analysis (see **Figure 2.5**). Social criteria enable us to quantify the impacts of the bridge on its direct users and surrounding population. Users of the bridge are all people traveling through the roads, beneath and above the bridge.

Originally, to perform the life cycle social analysis, two types of indicators are assessed: mandatory, those which are recommended to be always included in the life cycle analysis; and optional, those that can be included or not, depending on the aim of the analysis [3]. Here in this work, only the mandatory indicators were assessed; optional ones, namely noise and aesthetics, were left out of the scope.

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

2.4.4.1 Driver's delay cost

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

2.4.4.2 Vehicle operation costs

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

2.4.4.3 Accident costs

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

3 Case studies

This chapter describes the case studies considered in the projects SBRI+ [3], SBRI [2] and in a PhD thesis [1] as well as the assumptions made in order to perform the integral life cycle analysis and benchmarking.

3.1 General

Topology of motorway bridges may vary significantly depending on its structural scheme defined by its use and choice of material. Modern motorway bridges are built in a lot of various configurations, starting from small motorway overpasses to a long span highway bridges, leading to the differences in the initial design and further maintenance strategies. Thus, following the practice established in reference projects [2] and [3], all the examples were distributed between three groups (Type A, B or C) according to its span length as well as cross section outline and operational purpose.

Type A is represented by small motorway bridges with the span length up to 60 meters with still concrete composite or pre-stresses concrete girders. Bridges of type B are similar to those of Type A, however being a crossings of motorways are distinguished by the presence of the traffic also underneath the bridge. Span lengths up to 120 meters are the scope of big motorway bridges and are located to type C with box-girder composite sections.

All case studies are motorway bridges supporting dual carriage way.

3.2 Bridge types

Here in this section the detailed description the design solutions of the considered cases studies is given. In total, 21 bridge were gathered from the projects [2] and [3] and research work [1]. The case studies are allocated as presented in Table 2.

Table 2 – Allocation of the case studies

Original project/research	Case studies
SBRI+ [3], 2018	A1, A2, A3, A4 B1, B2, B3 C1
SBRI [2], 2013	A5, A6 B4 – B11 C2
PhD thesis [1] Helena Gervasio, 2010	B12, B13

The bills of quantities were analysed for each case study and are presented in the comparative form for each bridge type.

3.2.1 Bridges of Type A

Bridges allocated to the Type A are characterised by span length up to 60 meters. All cases considered for the Type A designed with two independent structures, one for each direction of traffic. Each bridge of type A supports a highway with two or three 3.5 m wide lanes per traffic direction. The whole roadway is bordered by normalised safety barriers. All bridges have a symmetrical structure. Six bridges were considered in this group and described as following.

Case A1 describes a single span motorway bridge with theoretical length equal to 34.80 m and deck width of 12.14 m. The composite deck solution consists of two welded I-shaped girders S355-N, with 1.85 m high, with a centre-to-centre spacing equal to 7.00 m, placed on-site by light cranes. The bridge is located in Albania. The design solution is presented in the Figure 3.1 and Figure 3.2.

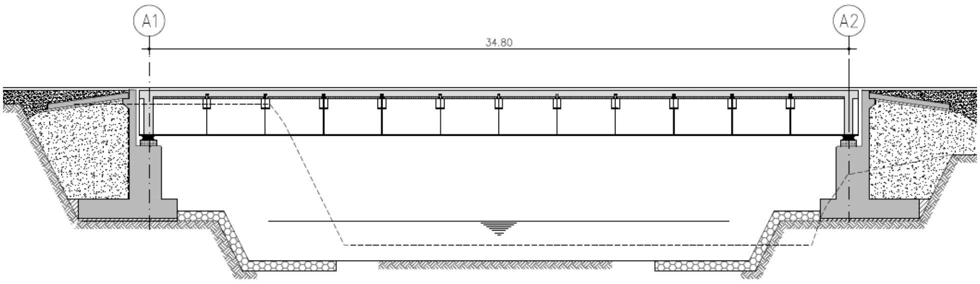


Figure 3.1 - Case A1: Longitudinal section [3].

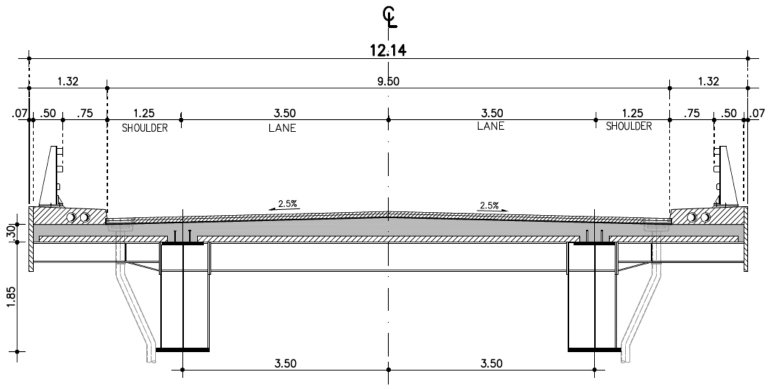


Figure 3.2 - Case A1: Typical cross section [3].

Case A2 is a concrete solution, which consists of 4 precast pre-stressed I-shaped girders, 2.20 m high, with a centre-to-centre spacing equal to 3.50 m, placed on-site also by cranes. This bridge was designed (not built) for the purpose of the comparison with case A1. The design solution for the case A2 is presented in Figure 3.3 and Figure 3.4.

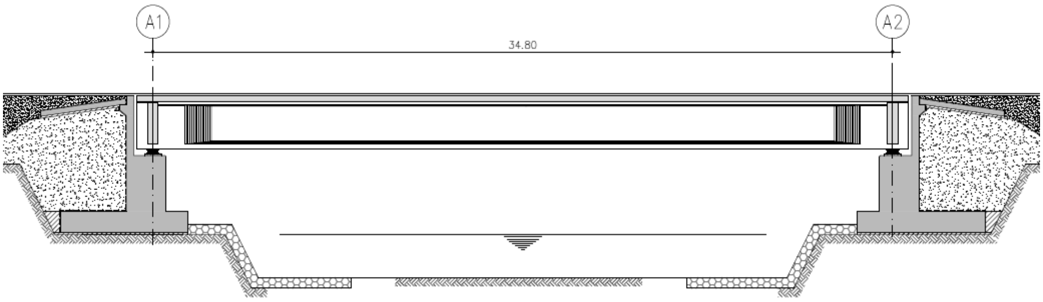


Figure 3.3 - Case A2: Longitudinal section [3].

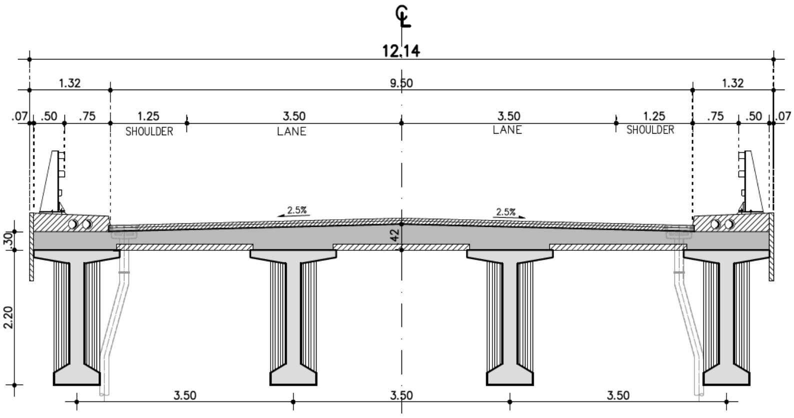


Figure 3.4 - Case A2: Typical cross-section [3].

The structural typology of the **Case A3** is a continuous beam with a total length of 308 m distributed over nine spans of 28 m+7x36 m+28 m and has a total width of 36.40 m. Each deck consists of a composite section made up of a reinforced concrete slab supported by two "I-shape" steel plate girders of 1750 mm high. Cross-girders, placed every 4m, provide additional support to the concrete slab allowing it to span in two directions. In these alignments, cantilever cross-girders were used for the same purpose. Every support is provided with load bearing stiffener arrangements on both sides of the webs. The construction of the reinforced concrete slab is carried out with precast concrete planks used as lost formwork. The bridge is located in Portugal. The design solution for the case A3 is illustrated in Figure 3.5 and Figure 3.6.

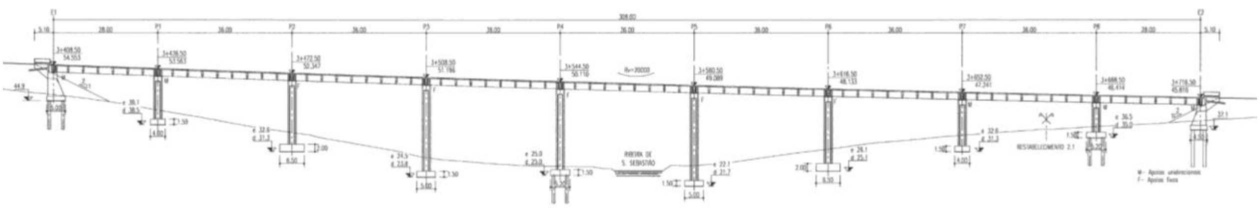


Figure 3.5 - Case A3 Longitudinal section [3].

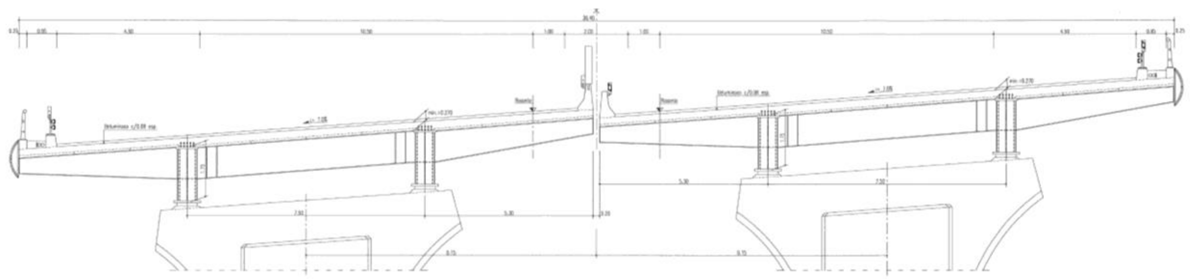


Figure 3.6 - Case A3 Typical cross-section [3].

The structural typology of the **Case A4** is similar to the previous one. It is also a continuous beam with a total length of 308 m distributed for nine spans of 28 m + 7x36 m +28 m and has a total width of 37.12 m. Each deck consists of a classical post-tensioned reinforced concrete section. The deck slab between girders has a variable thickness of 0.45 m to 0.30 m. The cantilever slabs also have a variable thickness of 0.45 m to 0.20 m. All girders have constant height of 2.70 m. The deck was constructed with a launching girder. The bridge is located in Portugal. The design solution for the case A4 is presented in Figure 3.7 and Figure 3.8.

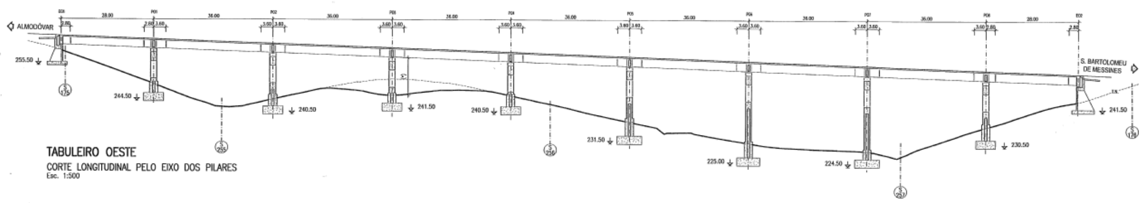


Figure 3.7 - Case A4: Longitudinal section [3].

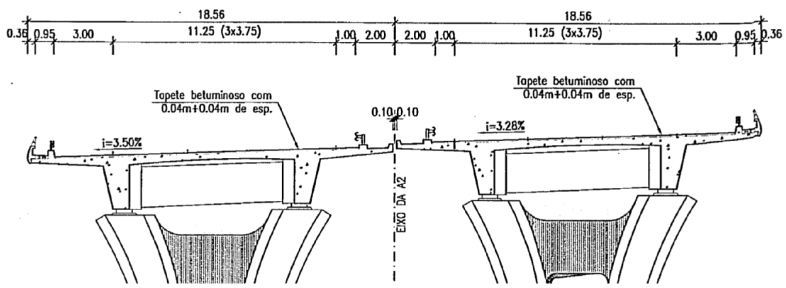


Figure 3.8 - Case A4: Typical cross-section [3].

Case A5 is a symmetrical structure with three spans of 50 m, 60 m and 50 m; the deck is represented by steel-concrete main girders of constant height 2400 mm. The total slab width is 12 m. For the construction, the structural steel is first installed by launching and then the 16 concrete slab segments (10 m long each) are poured on-site. The design solution is specified in the Figure 3.9.

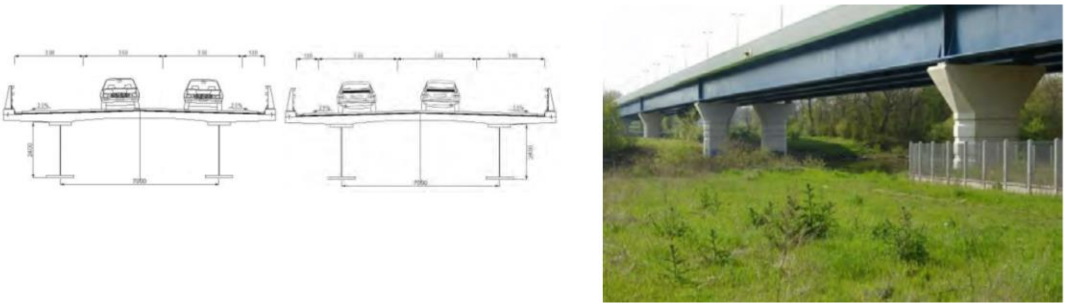


Figure 3.9 – The design solution for the Case A5 [2].

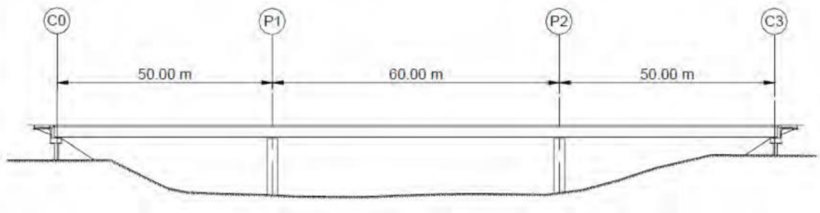


Figure 3.10 – Case A5. A6: span distribution [2].

The design solution of the **Case A6** is based on the solution used for the case A5 and entails the consideration of three lanes instead of two forecasting the possibility of traffic growth and use of HSS. This variant allows reducing potential maintenance and strengthening actions or reconstruction of the structure (durability loss). This case was designed (not built) for the comparison with the case A5.

The comparative bills of quantities used for the calculation of LCA of the bridges of Type A are presented in Table 3.

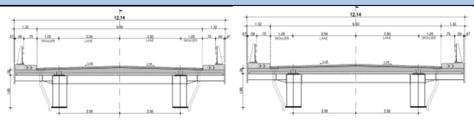
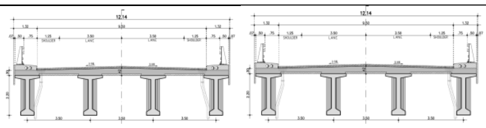
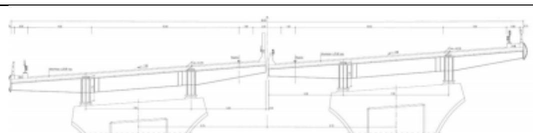
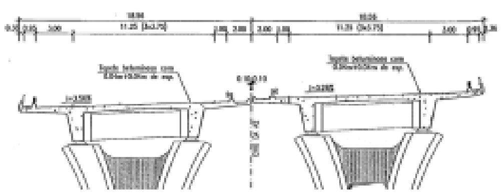
Table 3 - Quantities of case studies A1-A6 considered in LCA [3].

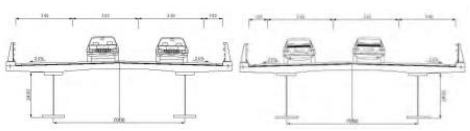
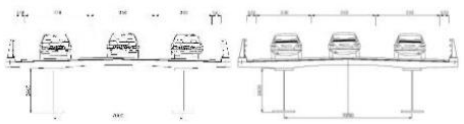
Description	Unit	Case A1	Case A2	Case A3	Case A4	Case A5	Case A6
Substructure							
Excavation	[m^3]	2200	2400	3310	11077		
Backfilling	[m^3]	530	600	1810	2846		
Formwork - for abutments and columns	[m^2]			8395	12387		
Reinforcement steel - except concrete deck	[kg]	22530	26180	897600	1210090,30		
Concrete - C16/20 - C12/15 - C25/30 - C30/37	[m^3]	 300 	 350 	 89 3386	 191 7893		
Superstructure							
Structural steel S355 N/NL	[kg]	94000		1521000		405 000	430000
Formwork	[m^2]			1325	18161		
Reinforcement steel - concrete deck	[kg]	37350	41790	371400	511481,70	124000	124000
Pre-stressing steel			8460				
Concrete - light weight	[m^3]			96	170107,03		
Concrete precast beams C30/37	[m^3]		148				
Concrete slab C 30/37	[m^3]	210	212				
Concrete slab C 35/45						624	624
Concrete for safety barriers C 35/45						32	32
Concrete C 40/50	[m^3]			3095	7049		

Description	Unit	Case A1	Case A2	Case A3	Case A4	Case A5	Case A6
Steel connectors including Implementation and quality control	[kg]			31655	45	1500	1500
Left-in-place formwork planks C40/50 with reinforcement steel A500NR	[m^2]			9850	691		
Concrete or steel cornice	[m]			620	24		
Pot-bearings and elastomeric reinforced bearings	[pcs]	4	8	40	44		
Lamelle (roadway slats steel/ plastic and similar)	[pcs]			108	112		
Corrosion protection	[m^2]	720				3000	3000
Roadway							
Surface levelling with concrete bituminous & single bituminous surfacing	[m^2]	2x340	2x345	22360	19036	1833	1833
Waterproofing	[m^2]	418	422			1792	1792
Protective device - guardrail	[m]			637	5847		
Covering of buried elements	[m^2]				1323		
Protective equipment - railings	[m]			637	691		
Safety barriers, S235 JR	[kg]					20800	20800
Expansion joint	[m]	24,30	24,30	72	74	24	24

The summary of the case studies with essential design considerations is presented in Table 4.

Table 4 – Description of the case studies allocated to the Type A.

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes
A1	 Single span,34.8 m	Composite bridge. Welded girders	2x2
A2	 Single span, 34.8 m	Concrete bridge. Precast pre-stressed girders	2x2
A3	 9 spans, 28-7x36-28 m	Composite bridge. Concrete slab, Steel plate girder	3x2
A4	 9 spans, 28-7x36-28 m	Concrete bridge. Post tensioned deck	3x2

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes
A5	 3 spans, 50-60-50 m	Composite bridge. Prefabricated slab, rolled steel girder	2x2
A6	 3 spans, 50-60-50 m	Composite bridge. Prefabricated slab, rolled steel girder (HSS)	3x2

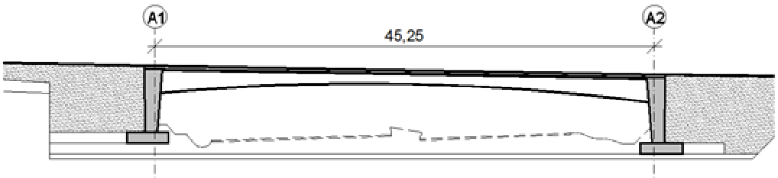
3.2.2 Bridges of Type B

Bridges of type B are supposed to be representative for short span bridges (under 60 m) spanning over a motorway of dual carriage 4 lanes each. In the initial projects there were difference in the traffic intencity and number of lanes of the motorway lying under the bridge. However, to make a comparison on the common basis, it was assumed that all bridges overpass the motorway of 8 lanes with given traffic intensity.

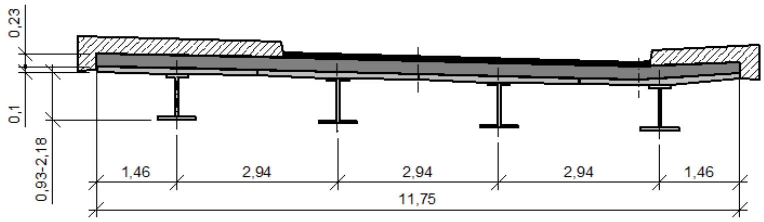
The span distribution can possibly take into account an intermediate support in the middle of the highway between the two directions of traffic. For this bridge type steel concrete composite and typical solutions in concrete have been considered. Cases B1, B9 and B10 are integral composite bridges; meaning that no intermediate support is provided (single span bridge) and no bearings needed. Cases B3, B7 and B8 are 2 span composite and B2, B5, B6 and B12 are concrete bridges, and case B11 and B13 are 3 span composite and concrete bridges respectively. More detailed description of the bridges of Type B and are described as following.

Case B1 is an integral bridge with a 45.25 m single span and has integral abutments. The deck consists of four composite girders, which are made of plated steel with variable height ranging from 0.93 m at mid-span to 2.18 m in the abutments. The girders are transversally separated. The deck slab consists of a layer of concrete cast in-situ on precast slabs. The bridge is located in Germany. The design solution of the case B1 is presented in Figure 3.11.

a1)



a2)

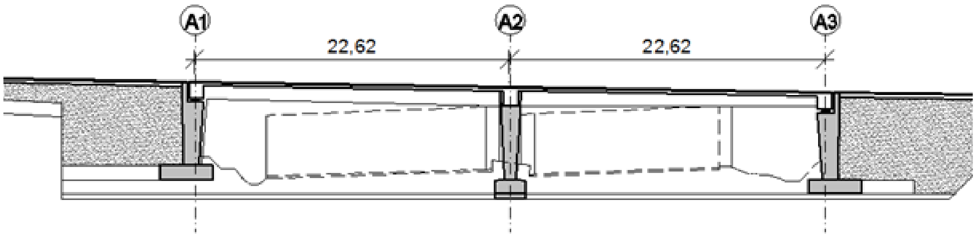


b)

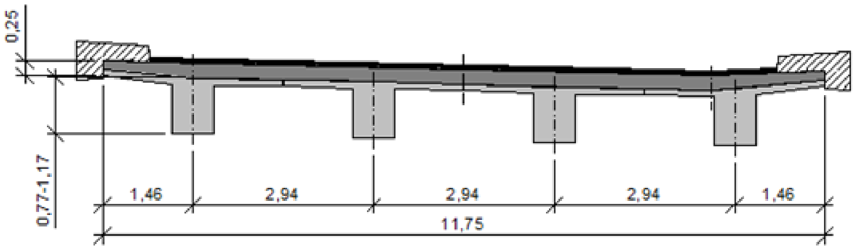
Figure 3.11 - Case B1: Integral composite bridge: a1) and a2) Longitudinal view; b) Cross section with girders of variable height [3].

Case B2 is a pre-stressed concrete bridge the original dimensions were two spans of 25.20 m and 26.70 m and a slab width of 7.9 m. But it was scaled for the comparison, the total length between abutments of 51.90 m to 45.25 m. The slab has been scaled to 11.75 m. The deck consists of rectangular cast in-situ girders. On the girders, a 25 mm thick concrete cast in-situ slab is lying. The bridge is located in Germany. The design solution of the case B2 is presented in Figure 3.12.

a1)



a2)

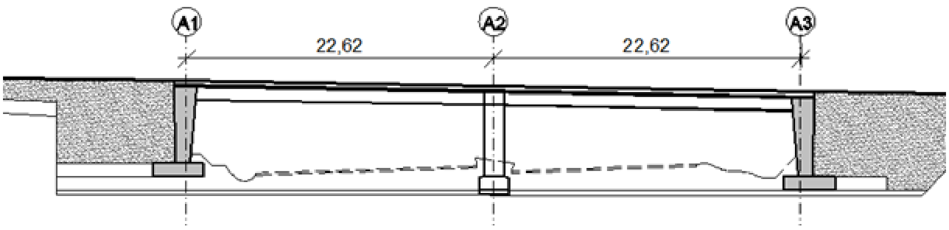


b)

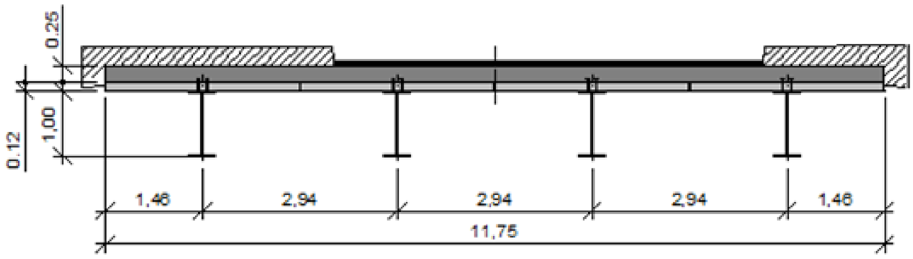
Figure 3.12 - Case B2: Prestressed cast in-situ concrete girder. a1) and a2) Longitudinal view; b) Cross section with girders of variable height [3].

Case B3 is a four girded steel-concrete composite bridge. The bridge has a symmetrical structure with two spans of 22.62 m (i.e. a total length between abutments of 45.25 m). The total slab width is 11.55 m. The girders are HL 1000 A S355 J2 G3 steel profiles. The deck slab consists of a 0.25 m layer cast in-situ on precast slabs. The bridge is located in Germany. The design solution for the case B3 is presented in **Figure 3.13**.

a1)



a2)



b)

Figure 3.13 - Case B3: Composite bridge. a1) and a2) Longitudinal view; b) Cross section [3].

Case B4 is a steel-concrete composite twin-girder bridge. The bridge has a symmetrical structure with two spans of 22.5 m (i.e. a total length between abutments of 45 m) and the total slab width of 11.70 m. For the construction, the structural steel is first installed with a crane and then the 23 pre-cast concrete slab segments (1.95 m long each) are installed and keyed.

Case B5 is a concrete bridge cast in place. The bridge has a symmetrical structure with two spans of 22.5 m (i.e. a total length between abutments of 45 m). The total slab width is 13.10 m.

Case B6 is a pre-cast concrete bridge. The bridge has a symmetrical structure with two spans of 27 m (i.e. a total length between abutments of 54 m). The total slab width is 12.50 m.

Case B7 is a steel-concrete composite multiple-girder bridge. Girders are made of steel grade S355. Girders are rolled girders HE 900 A. The bridge has a symmetrical structure with two spans of 22.5 m (i.e. a total length between abutments of 45 m). The total slab width is 13.40 m.

Case B8 is design variation (not built) of the case B7 with the uses HSS (steel grade S460 for girders), which leads to reduction of steel weight (girders are rolled girders HE 800 A).

Case B9 is a design variation (not built) of the case B4. It represents the design case with integral abutments with a 40.8 m single span. Main girders are made of plated steel. This variant is 9.3 % shorter than case B4, but allows saving of structural steel and concrete (mainly due to the elimination of the intermediate pier). Moreover, it eliminates some maintenance actions: replacement of expansion joints and bearings.

Case B10 consists of the use of integral abutments with a 40.8 m single span, and main girders made of high strength (S460) rolled steel. This variant is 9.3 % shorter than case B4, but requires 55.9 % more structural steel. This case was designed (not built) for the comparison with the case B4.

Case B11 consists of the use of "counterweight" spans instead of integral abutments. The bridge has a symmetrical structure with three spans of 18.50 m, 40.80 m and 18.50 m (i.e. a total length between abutments of 77.80 m). This design solution allows building a central span with almost the same dimensions than the case B9 single span, that is to say no support in the middle of the highway is needed. Compared to the case B9, this case has simple abutments but the bridge is twice as long. The bridge is located in Portugal. The design solution is presented on the Figure 3.14.

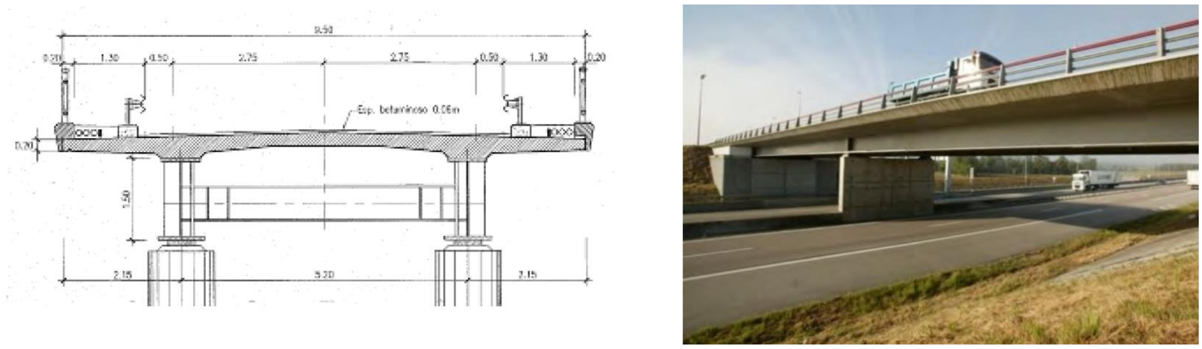


Figure 3.14 - Design solution for the Case B11 [2].

Case B12 is a concrete bridge of two spans of 29 and 31 m and a cross-section of 7.14 m wide. The cross-section of the deck is made of one longitudinal precast concrete girder with a "U" shape and a cast "in-situ" concrete slab. The concrete slab is cast on top of precast concrete forms that act as a composite slab. The bridge is built in Portugal. The design solution is presented in Figure 3.15 and Figure 3.16.

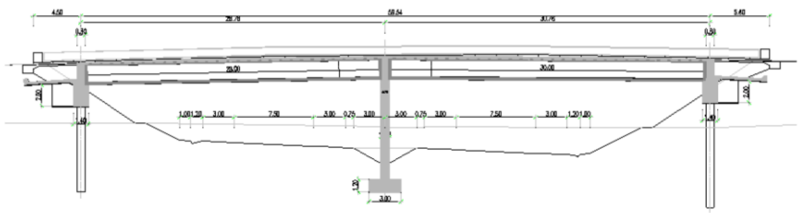


Figure 3.15 - Case B12: Elevation view [1].

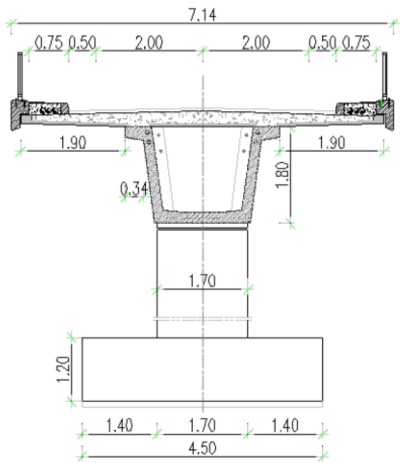


Figure 3.16 - Case B12: Typical cross-section [1].

Finally**, Case B13** has a three spans of 16.6 m, 48.5 m and 16.6 m. The deck is fully supported over the middle piers and simply supported at the abutments. The deck is composed of two longitudinal pre-stressed concrete girders and concrete slab, both cast "in-situ". The beams in the middle span are hollowed in order to reduce the self-weight of the structure. The bridge is built in Portugal. The design solution is presented in Figure 3.17 and Figure 3.18.

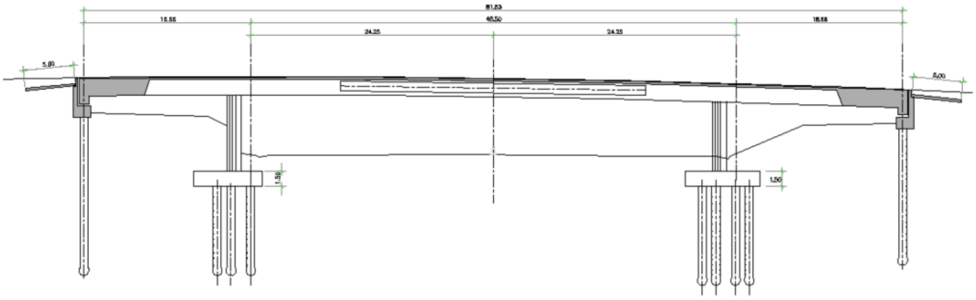


Figure 3.17 – Case B13: Elevation view [1].

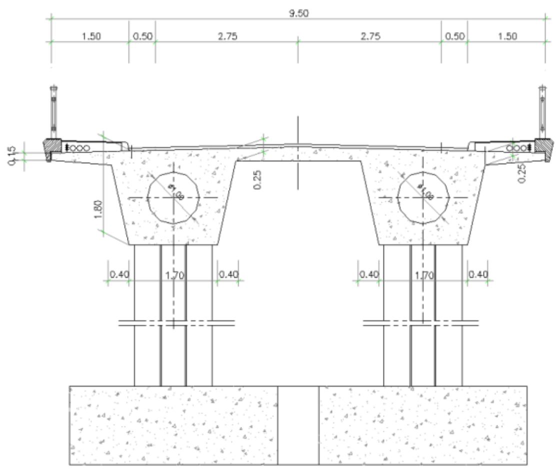


Figure 3.18 – Case B13: Typical cross-section [1].

The comparative bills of quantities used for the calculation of LCA of the bridges of Type B are presented in the Table 5 - Quantities of case studies B1-B3 considered in LCA .Table 5, Table 6 and Table 7.

Table 5 - Quantities of case studies B1-B3 considered in LCA [3].

Description	Unit	Case B1	Case B2	Case B3
Substructure				
Foundations' concrete C25/30	[m^3]	254	223,81	
Abutments' + piles concrete C30/37	[m^3]	746,20	681,97	969,6
Reinforcement S500	[kg]	90600	90690	64326,6
Superstructure				
Structural steel S355 J2 G3	[kg]	81800		
Structural steel S355 J2 G3 in HL1000A	[kg]			58084,35
Corrosion protection	[m^2]	896		575,58
Concrete precast C30/37	[m^3]	58		52,26
Concrete C35/45	[m^3]	144,20	571,20	130,66
Concrete C45/55	[m^3]		172,82	
Reinforcement S500	[kg]	44600	63038,3	44266,58
Steel connectors	[kg]	1382	-	748,7
Bearings Elastomeric	[pcs]		12	12

Description	Unit	Case B1	Case B2	Case B3
Bearing Calote	[pcs]		2	2
Roadway				
Pavement's asphalt layers	[m^2]	309	309	309
Pavement's waterproofing member	[m^2]	309	309	309
Safety barriers	[kg]	7429,20	7429,20	7429,20

Table 6 Quantities of case studies B4-B8 considered in LCA, adopted from [2].

Description	Unit	Case B4	Case B5	Case B6	Case B7	Case B8
Substructure						
Abutment C35/45	[m^3]	522.7	522.7	522.7	522.7	522.7
Reinforcement S500	[kg]	45784.5	45784.5	45784.5	45784.5	45784.5
Superstructure						
Structural steel (main girders + bracing frames) S355 N/NL	[kg]	63500			56500	
Structural steel (main girders) S460 M/ML	[kg]					50300
Corrosion protection - paint	[m^2]	450			584	540
Concrete precast C30/37	[m^3]					
Concrete C35/45 – main slab	[m^3]	152			152	152
Concrete C30/37 – main slab	[m^3]		409.3	192		
Light-weight concrete	[m^3]			42		
Pre-stressed beams	[m^3]			230		
Concrete C35/45 – support for safety barriers	[m^3]	29			29	29
Pre-stressed steel	[kg]	0	6839.5	1664.0		
Reinforcement S500 - concrete slab	[kg]	31000	82621.5	40577.0	31000	31000
Reinforcement S500 - concrete support for the safety barriers	[kg]	5700			5700	5700
Steel connectors	[kg]	680			680	680
Roadway						
Pavement's asphalt layers	[m^2]	375	359	349	375	375
Pavement's waterproofing member	[m^2]	503	590	675	503	503
Safety barriers	[kg]	4500	4500	4500	4500	4500

Table 7 Quantities of case studies B9-B13 considered in LCA, adopted from [2], [1].

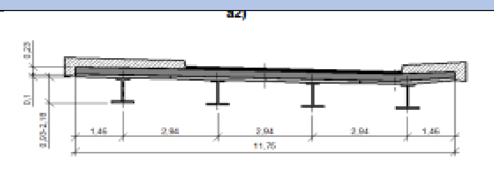
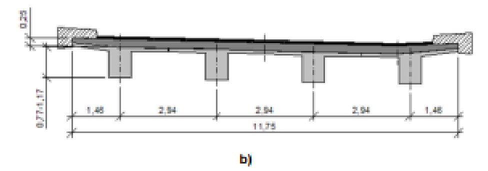
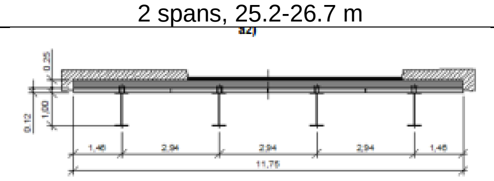
Description	Unit	Case B9	Case B10	Case B11	Case B12	Case B13
Substructure						
Foundations' concrete C25/30	[m^3]		78000	223		387
Foundations' concrete C30/37	[m^3]				91.33	
Abutment C35/45	[m^3]	370	72			
Abutment C30/37	[m^3]			156[1]	54.33[1]	
Abutment C25/30						96
Piers C30/37						29
Reinforcement S500	[kg]	50000	18000	57595[2]		

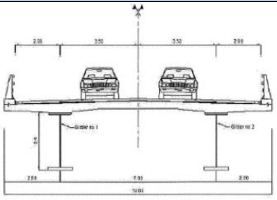
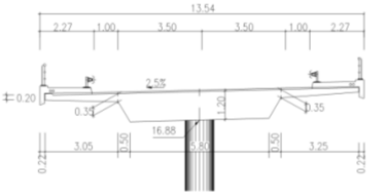
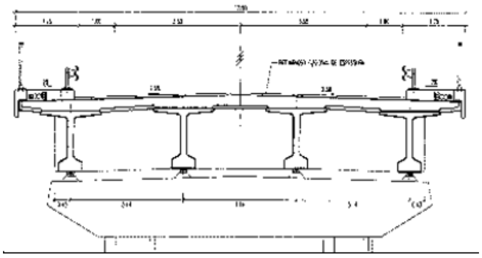
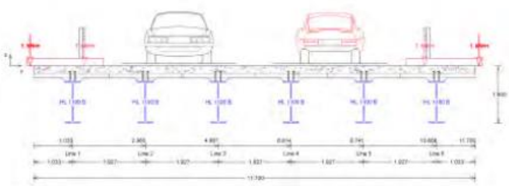
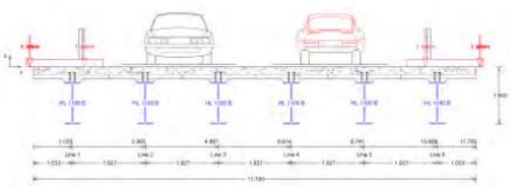
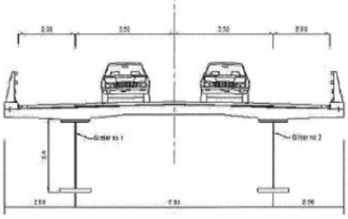
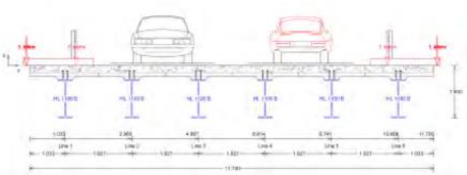
Description	Unit	Case B9	Case B10	Case B11	Case B12	Case B13
Superstructure						
Structural steel (main girders + bracing frames) S355 N/NL	[kg]	56500		145678		
Structural steel (main girders) HL 1100B	[kg]		99000			
Corrosion protection - paint	[m^2]	530	814.2	2292		
Concrete precast C35/45	[m^3]			161		
Concrete precast C45/55					33.12	
Concrete C35/45 – main slab	[m^3]	131	153	164		
Concrete C30/37 – main slab	[m^3]				157.88	779
Light-weight concrete	[m^3]			38	14.09	44
Pre-stressed beams, C45/55	[m^3]				74.26	
Concrete C35/45 – support for safety barriers	[m^3]	26				
Pre-stressed steel	[kg]				4275	21666
Reinforcement S500 - concrete slab	[kg]	26000	30000	76.177	33471[3]	82414[3]
Reinforcement S500 - concrete support for the safety barriers	[kg]	5400				
Steel connectors	[kg]	710		3328		
Bearings	[pcs]			8		
Roadway						
Pavement's asphalt layers	[m^2]	339	316	622.4	297.7	
Pavement's waterproofing member	[m^2]	456	393			
Safety barriers	[kg]	4100	4100			

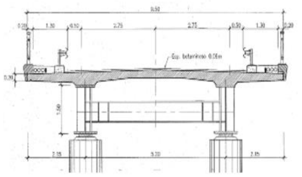
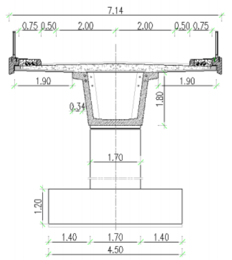
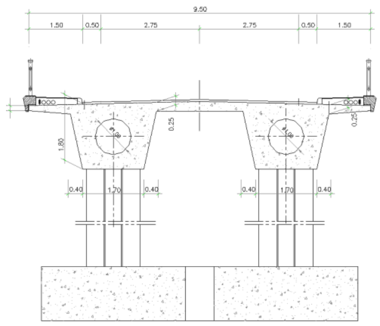
[1] – including piers; [2] – the quantity of the reinforcement of all elements except the deck; [3] – the total value of the reinforcement used per bridge.

The summary of Type B cases and its representative cross-sections are presented in the Table 8.

Table 8 - Description of the case studies allocated to the Type B.

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes (over/under the bridge)
B1	 Integral bridge, 45.25 m	Composite bridge.	2/8
B2	 2 spans, 25.2-26.7 m	Concrete bridge. Pre-stressed RC, cast in situ	2/8
B3	 2 spans, 22.6-22.6 m	Composite bridge.	2/8

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes (over/under the bridge)
B4	 2 spans, 22.5-22.5 m	Composite bridge. Prefabricated slab, plated steel girder	2/8
B5	 2 spans, 22.5-22.5 m	Concrete bridge. Cast in-situ	2/8
B6	 2 spans, 27-27 m	Concrete bridge. Precast	2/8
B7	 2 spans, 22.5-22.5 m	Composite bridge. Prefabricated slab, concrete cross girder, Rolled steel girder S355	2/8
B8	 2 span, 22.5-22.5 m	Composite bridge. Prefabricated slab and girder, Rolled steel girder (HSS)	2/8
B9	 Integral, 40.8 m	Composite bridge. Prefabricated slab and girder, plated steel	2/8
B10	 Integral, 40.8 m	Composite bridge. Prefabricated slab and girder, plated steel	2/8

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes (over/under the bridge)
B11	 3 span, 19-41-19 m	Composite bridge. prefabricated slab and girder, rolled cross beams, plated steel girder	2/8
B12	 2 span, 29-31 m	Concrete bridge. Precast girder, cast in-situ slab+precast forms	2/8
B13	 3 spans, 16.6-48.5-16.6 m	Concrete bridge. Prestressed cast in-situ girder, cast in-situ slab	2/8

3.2.3 Bridges of Type C

Bridges of Type C are supposed to be representative for long span bridges (up to 120m) for which a box girder design is classically preferred. Similar to the Type A, only traffic over the bridge is implied, however, significant length of the span requires different conceptual solutions. In this work, only two bridges were allocated to the type C. Both of them are steel concrete composite bridges.

Two independent structures for each direction of traffic were considered in the **Case C1.** The structure is a three-span highway bridge with theoretical length equal to 44.00+77.50+44.00=165.60 m and deck width equal to 11.50 m. The steel-concrete composite deck consists of 3 welded I-shaped steel girders, placed on-site by launching. The deck slab consists of a 0.20 m layer cast in-situ on precast slabs 0.10 m thick. The bridge is located in Greece. The design solution is presented in **Figure 3.19 - Case C1 Longitudinal view .**Figure 3.20.

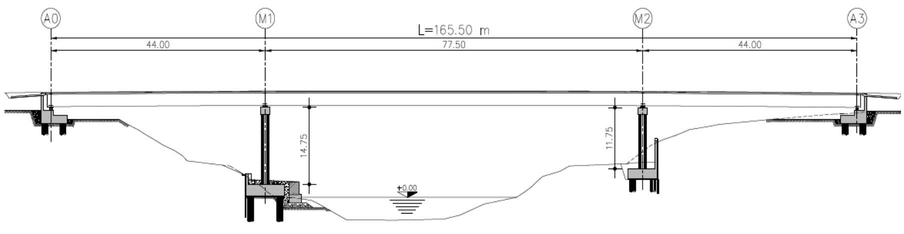


Figure 3.19 - Case C1 Longitudinal view [3].

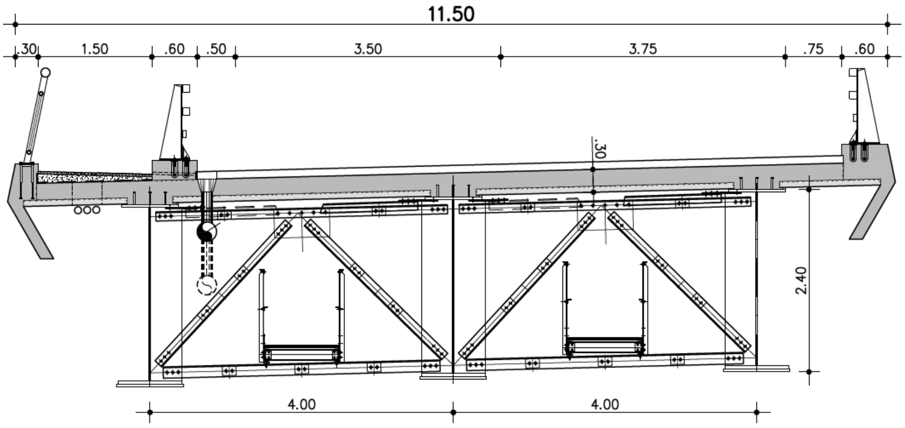


Figure 3.20 - Case C1 Typical cross section [3].

Case C2 supports a highway with 4 lanes (2 per each direction of traffic). The bridge has a symmetrical structure with five spans of 90 m, 3x120 m and 90 m. The total slab width is 21.50 m. For the construction, the structural steel is first installed by launching and then the 45 concrete slab segments (12 m long each) are poured on-site. The design solution and span distribution is presented on Figure 3.21 and Figure 3.22.

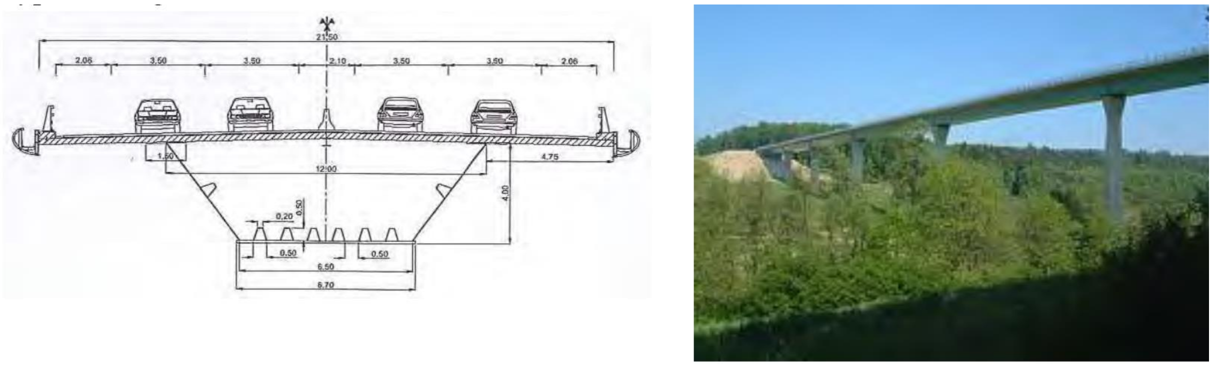


Figure 3.21 - Design solution for the Case C2 [2].

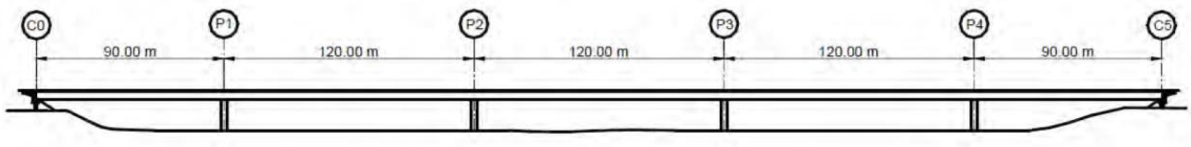
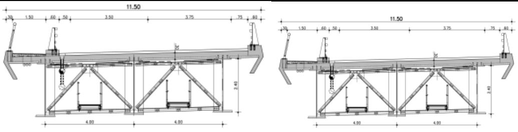
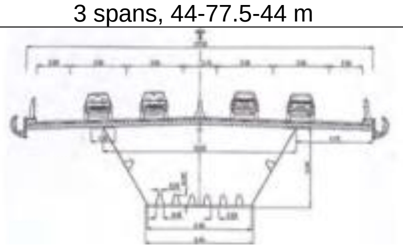


Figure 3.22 – Case C2: span distribution [2].

The summary of Type C cases and its representative cross-sections are presented in the Table 9.

Table 9 - Description of the case studies allocated to the Type C.

Case	Cross section and topology description	Selective data regarding the design solution	Number of lanes
C1	 3 spans, 44-77.5-44 m	Composite bridge. Plated steel box girder	2x2
C0	 5 spans, 90-3x120-90 m	Composite bridge. Plated steel box girder	4

3.3 Assumptions and design consideration

This chapter mentions main design considerations and assumptions, as well as noteworthy remarks related to the performance the benchmarking.

For each case study the following information was gathered from the projects SBRI and SBRI+ ([2] and [3]) as well as from [1] for case B12 and B13, and adopted according to the purpose of present work.

3.3.1 Considerations for the life cycle cost (LCC)

Special considerations were made regarding the life cycle cost (LCC). It was observed, that since bridges are coming from different parts of Europe, the unit cost of the materials or non-structural equipment may vary significantly. Even comparing projects coming from the same country, different manufacturers provide different rates.

In the same time, to proceed with the benchmarking, the normalization of the unit cost is required to ensure functional equivalence of the compared case studies. Such a process require additional studies, as established unique cost data base should also ensure that the results achieved with such a cost database would not compromise the results achieved for the original case studies when they were considered as individual cases in the reference projects [2] and [3] as well as examples considered in [1].

In this regard, it was decided to leave the benchmarking of the sustainable indicators of the life cycle cost (LCC) beyond the scope of present work, suggesting it as one of the main possibilities for the future improvement and development.

3.3.2 Inspection and maintenance

After entering the service life, bridges start deteriorating immediately. Consequently, renovation countermeasures should be foreseen throughout the whole life of the structure in order to maintain its performance above an admissible level. This leads to the implementation of the inspection and maintenance strategies through the whole service life of bridge. The frequency of inspection and maintenance evens depend on the bridge type, its location and climate, thus, requirements differ from country to country.

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

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

Principal inspection – detailed visual inspection with special means of access. The aim is the assessment of the bridge condition rating evolution, with the definition of potential repair/rehabilitation actions;

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

Following the approach adopted in [1], [2] and [3], the inspection types and respective frequencies were defined based on the comparison of the inspection actions established for countries involved in the project. The frequency assumed for each type of inspection for the standard scenario is shown in **Table 1**.

Table 10 - Standard scenario - Inspection frequency and average occurrence [3].

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

Maintenance events are coming as a direct consequence of the inspection actions. As inspection actions, the content of maintenance events depends on the local regulations. Different maintenance strategies were collected and compared. The adopted frequency of the maintenance events is based on the average service life of the structural and non-structural elements. Thus, standards maintenance scenario, related to capacity rates and units, allow the elaboration of the adequate maintenance strategy.

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.

Further differentiation was made according to the time when maintenance events should take place. The life cycle assessment and further benchmarking was performed assuming a day work scenario, meaning that maintenance events carried out during the day (6:00 AM. to 10:00 PM).

Table 11 - Average service life assumed for bridge elements [3].

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

Table 12 - Standard scenario - average maintenance/repair work frequency [3].

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

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

3.3.3 Traffic

Traffic analysis plays essential role in the life social analysis. Traffic congestion due to restrictions in the work zone lead to the driver's delays, affect the vehicle operational capacity and increase the rate of the accidents.

Moreover, traffic congestion causes additional environmental burdens, subjected to the environmental LCA. Thus, the traffic intensity as well as restrictions of the working zone during maintenance (Type A, B and C), as well as construction and demolition of the bridge (Type B only) should be properly described.

The value of the average daily traffic (ADT, vehicles/day) depends on the location of the bridge as defined by the traffic density of the place where the bridge is supposed to be built. The current value of ADT should be acquired from the traffic monitoring section.

Such factors, as population growth and economic prosperity cause the traffic growth. The yearly increase of the traffic was estimated as:

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

ADT_t is the average daily traffic to be used in the analysis at year t (vehicles/day),

r_{tg} is the expected traffic growth rate,

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

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

Coming from the different partners, initially case studies were calculated according to the real traffic data. Thus, the ADT over the bridge considered in the projects was varying significantly depending on data provided by the partners; for the Type A the data were varying from 8000 to 36254 vehicles per day (vpd), from 4528 to 9064 vpd for Type B, and was recorded as 12000 vpd for the Type C. However, to perform benchmarking is it required to make an assessment on the common basis. Thus, taking into account the fact of the variation in the design solutions of the considered bridges, in this work it was decided to normalize the value of ADT taking into account the lane capacity of the bridge by assuming weighted ADT of 4000 vpd per lane. Regarding the traffic under the bridge, the value of ADP=49485 vpd was adopted, as given in [3]. The specific value of the ADT adopted for the cases considered in this thesis are specified in **Table 13.**

Table 13 - Average daily traffic.

Number of lanes	Cases	ADT base year, vpd
2	All cases of Type B	8000
4	A1, A2, A5, A6 All cases of Type C	16000
6	A3, A4	24000
Traffic under the bridge	All cases of Type B	49485

Another important characteristic associated with the traffic is the traffic flow over the working zone. It is assumed that during the performance of the construction works the traffic may be restricted according to the working scenario (day or night work) and number of days of construction work.

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 [21]. The Queue and User Cost Evaluation of Work Zones model analyses traffic flows through motorway work zones and allows to estimate the traditional road user costs and air pollution on various lane closure strategies. 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.

Here in this work it was assumed that only one lane of traffic would be closed per each direction of traffic.

3.3.4 Transportation

Transportation of the materials take place during the stage of construction and operation (transporting of new materials) as well as end-of-life (transporting of the debris to the recycling plant/landfill).

Construction materials assumed to be transported to the construction site by tracks. The traveling distances estimated for each case are indicated in **Table 14**. The consumption of diesel is also calculated based on the travel distances displayed in this table.

Table 14: Transportation of materials for the construction stage [3]

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

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 15**.

Table 15: Transportation of materials for the end-of-life stage [3]

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

4 Benchmarking of bridges

This chapter describes the general framework of the benchmarking as well as the evaluation method employed for the statistical treatment of the data.

The definition of the benchmarking is given and the benchmark levels are defined. Further, the choice of the life cycle assessment as the basis for the sustainable benchmarking is justified with its advantages and compliance criteria fulfilled.

Finally, the comprehensive guidelines explaining the assessment of the chosen benchmarks is provided.

4.1 General framework

Nowadays the concept of the benchmarking is frequently used in different areas of the economy and defined differently depending on the goals and scope of the assessment. In construction sector, the closest definition can be defined according to the standard BS EN 16231 – Energy Efficiency Benchmarking Methodology [22], which is been developed to provide the guidance for the analysing energy data and comparing energy efficiency of buildings, the benchmarking is defined as *“process of collecting, analysing and relating performance data of comparable activities with the purpose of evaluating and comparing performance between or within entities”*. Hence, a benchmark can be defined as a *“reference or standard value for comparison derived from the benchmarking”*.

To date, there are only a few available definitions of benchmarking levels as limit or target values in literature [23, p. 191]. According to [23, p. 192] the most commonly used benchmark levels are:

- Limit value – value representing the minimum acceptable performance. Thus value can be considered as optional, as it guides the designer whether the whole sustainability assessment should be accepted or not. It is worth noticing, that this value may vary depending whether the structure is new or already built.

- *Reference value (conventional practice)* – value, which represents the current state of art and can be described as the mean or the median value.

- *Best practise* – value, that actually have been reached or measured in the experimental or demonstration projects according to the current level of technological advancement.

- *Target value* – the highest theoretically possible level to be achieved in the medium- or long term prospective according to the available level of the technology.

Established values may be used for the assessment of the performance gap for the considered project. The provided benchmarks can also be used as a quantitative target for the potential improvement of the performance.

Conceptually, the benchmarking levels and where do they take place in the project performance can be illustrated as in Figure 4.1. It should be noted that better level of performance corresponds to the lower values of indicators.

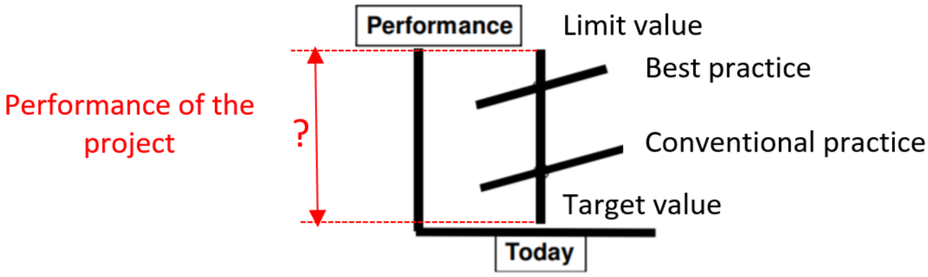


Figure 4.1 The concept of the benchmarking, adopted from [22].

Regarding the sustainable benchmarking of the life cycle assessment in construction, it is a common trend, that there are not statistically significant references values available, as the development of the benchmarks goes in parallel with the development of the evaluation methods.

The establishment of the sustainable benchmarks based on the life cycle have two main advantages over the benchmarking based on the rating systems:

- Benchmarking of the indicators is based on the life cycle assessment methodology compliant with the existing ISO [13], [14] and [19], which ensures a strong scientific basis for the evaluation;
- As the proposed model of the life cycle assessment goes in line with the design rules and reliability requirements of the Eurocodes, it ensures the genuine compliance of structural and sustainability criteria in the design process.

Central role in the benchmarking plays functional equivalence, thus special attention to this aspect was paid in this thesis. The functional equivalence implies that (i) the inputs and provided outputs are related; (ii) evaluation was done based on the common assumptions; (iii) the reference values are expressed in the reference units which would enable comparison of different case studies and (iv) reference values respect design considerations and local conditions.

In light of considered case studies, these requirements were fulfilled on the stage of the performance of the life cycle assessment, namely:

- The same input categories were considered for each case, except of cases A5, A6 and C2 when the substructure was not considered due to the lack of data;
- The maintenance plans were based on the average of service life of respective bridge elements, common operation types and rate of maintenance work as specified in Tables A1 and A4 in the Annex;
- The plans of the traffic restrictions due to execution of the maintenance events were established for each bridge type as specified in Tables A2 and A3;
- The distances used for the assessment of the transportation of the material to the site during the stage of construction and operation as well as its allocation for the recycling/landfilling in the end of life are assumed to be common for all cases, as explained in the Capter 3;
- to ensure the same traffic density, the traffic was weighted and normalized with a value of ADT per lane, giving possibility to assess bridges located in different areas and having different number of lanes;

- to enable the comparison of bridges with different geometry, all indicators used for benchmarking were normalised per m^2 of the area of the deck.

The correlation of the inputs and outputs are ensured by the fact that inventory analysis performed in the early stage of the life cycle assessment and is in accordance with the prescriptions of ISO standards.

4.2 Evaluation of the benchmarks

The scope of the present benchmarking is to define and analyse the values for *common* and *best practice* for the life cycle environmental and life cycle social assessment indicators defined in Chapter Life cycle sustainability assessment of the bridge2.

It is considered that the conventional practice is given by median of the values and the best practice is given by the first quartile (25%) as lower boundary means the minimisation of the investigated parameters [12], [23].

According to the design considerations specified in Chapter 3, the results were analysed in groups defined by the bridge type: 6 bridges of Type A, 13 bridges of Type B and 2 bridges of Type C, which means that the size of the sample is 6, 13 and 2 variables respectively.

Taking into account relatively poor sample size, it was decided to treat the data as a discrete random variables using the methods of the descriptive statistics.

To represent the benchmarks, a *five-number summary* or box-and-whiskers plot was used. It gives a possibility simultaneously describe several important features of dataset, intrinsic for the processing of the data as well as the definition of the common and best practice, as three quartiles and the minimum and maximum of the data. The quartiles are enclosed in the box, while whiskers represent the error bars. Despite the simplicity, box-and-whiskers plots give high visual impact along with the comprehensive representation of all necessary statistic characteristics, as described in the **Figure 4.2**.

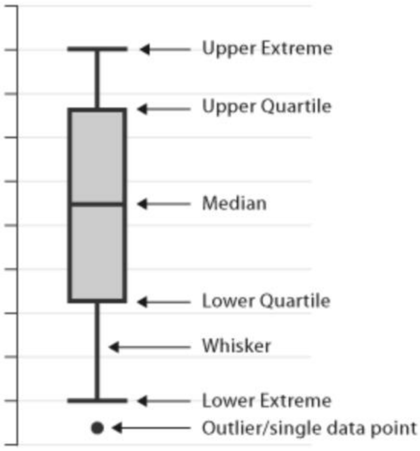


Figure 4.2- Five-number summery (box-and-whiskers plot), adopted from [23].

The *lower and upper extremes* represent the minimum and maximum value of the indicator observed in the sample.

The *lowest (first) quartile (Q1)* is the median of the lower half of the data set. This means that about 25% of the numbers in the data set lie below Q1 and about 75% lie above Q1.

The *second quartile (Q2)* is the median, which is the centre of the data.

The *upper (third) quartile (Q3)* is the median of the upper half of the data set. This means that about 75% of the numbers in the data set lie below Q3 and about 25% lie above Q3.

Hence, the common practice is represented by the median of the sample, while the best practice is presented by the value of lower (first) quartile, as it represents the 25% boundary for the lowest values.

The *outliner/single data point* is not considered in the present evaluation; however, it shows a great example of the case when results of the assessment of a single performance is beyond the scope of the established sustainable values.

5 Results of the integral Life Cycle Analysis

The results of the integral life cycle assessment are analysed in this chapter. The indicators of the environmental life cycle assessment (LCA) and life cycle social assessment (LCS) were evaluated, as the life cycle cost assessment (LCC) was left out of the scope of present work. To enable the comparison of the bridges of different geometrical outline, the indicators were normalized per m^2 of the deck.

The calculations were performed using the integral life cycle assessment tool developed in the framework of the project SBRI+ [3]. The results are grouped according to the bridge types established in Chapter 3.

5.1 Bridges of Type A

Overall, it was observed, that the environmental and social performance of the case studies of Type A are comparable for the bridges of similar size and scope, which are bridges A1 and A2, A3 and A4, and A5 and A6. It should be noted, that due to the lack of data, the waterproofing was not considered in the bill of quantities for the cases A3 and A4; for the same reason the quantities of the reinforced concrete used for the abutments were missed in the life cycle assessment of the cases A5 and A6.

5.1.1 Environmental Life Cycle Assessment (LCA)

5.1.1.1 Material production stage

This stage takes into consideration the production of all the materials needed to build the bridge, which means that it is directly affected by the content and quantities of the material considered for the assessment. At the material production stage the environmental impacts due to the production of reinforced concrete, structural steel, coating, asphalt layer and waterproofing are assessed [3].

Overall, it can be clearly seen, that the lack of data about the quantities of the materials, which lead to its omission from the analysis, affects the overall performance of the case studies. Thus, having comparable quantities of steel and concrete per m^2 of the deck for cases A1 and A3 (composite bridges) and A2 and A4 (concrete bridges), the normalized emissions evaluated for cases A1 and A2 are considerably higher compared to one obtained for cases A3 and A4, which is caused by omission of the waterproofing in the bill of quantities for the latter cases.

The impacts of the composite bridges A5 and A6 is always lower than one of the bridge A1, since for the cases A5 and A6 the quantities of the reinforced concrete used in the substructure was omitted in the bill of quantities.

The performance of the indicators $ADP_{fossils}$, AP, ODP and POCP is dominated by the composite bridges, as at the stage of production steel has a major environmental impact (according to the database of the values of the impacts per unit quantity established in the life cycle assessment tool developed in [3]), also considering the ratio of the quantity versus impact intensity.

The performance of the indicators EP and GWP has greater influence of the emissions caused by the production of concrete, which causes the comparative increase in the level of emissions for bridges A2 and A4.

The values of the indicators assessed for the material production stage are presented in Figure 5.1. The values are normalised per m^2 of the deck.

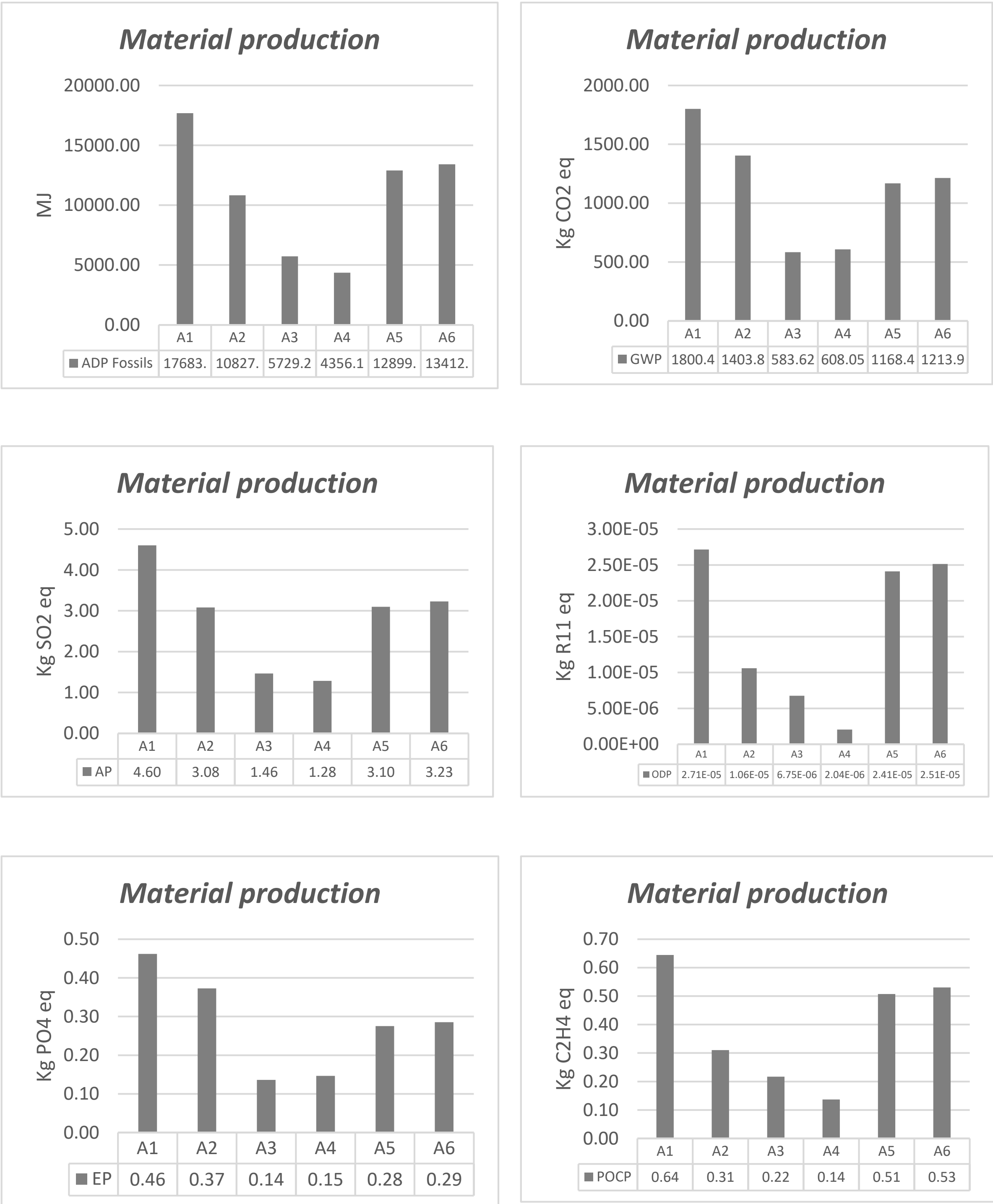


Figure 5.1- Results of material production stage normalised per m^2 of the deck

5.1.1.2 Construction stage

The construction stage covers all the processes needed for and affected by the construction of the bridge. Hence, the emissions due to the construction and transportation of materials to the construction site is considered.

The results show similar pattern observed at the material production stage, as they are affected by the quantities of materials used for the erection of the bridge. For the stage of construction, steel has a higher impact in both processes erection and transportation [3], which is also amplified by the longer transportation distance of this material. Thus, the results see the relative overall drop in the level of the emissions estimated for the concrete bridges A2 and A4 compared to its performance at the stage of material production.

The values of the indicators assessed at the construction stage are presented in Figure 5.2. The values are normalised per m² of the deck.

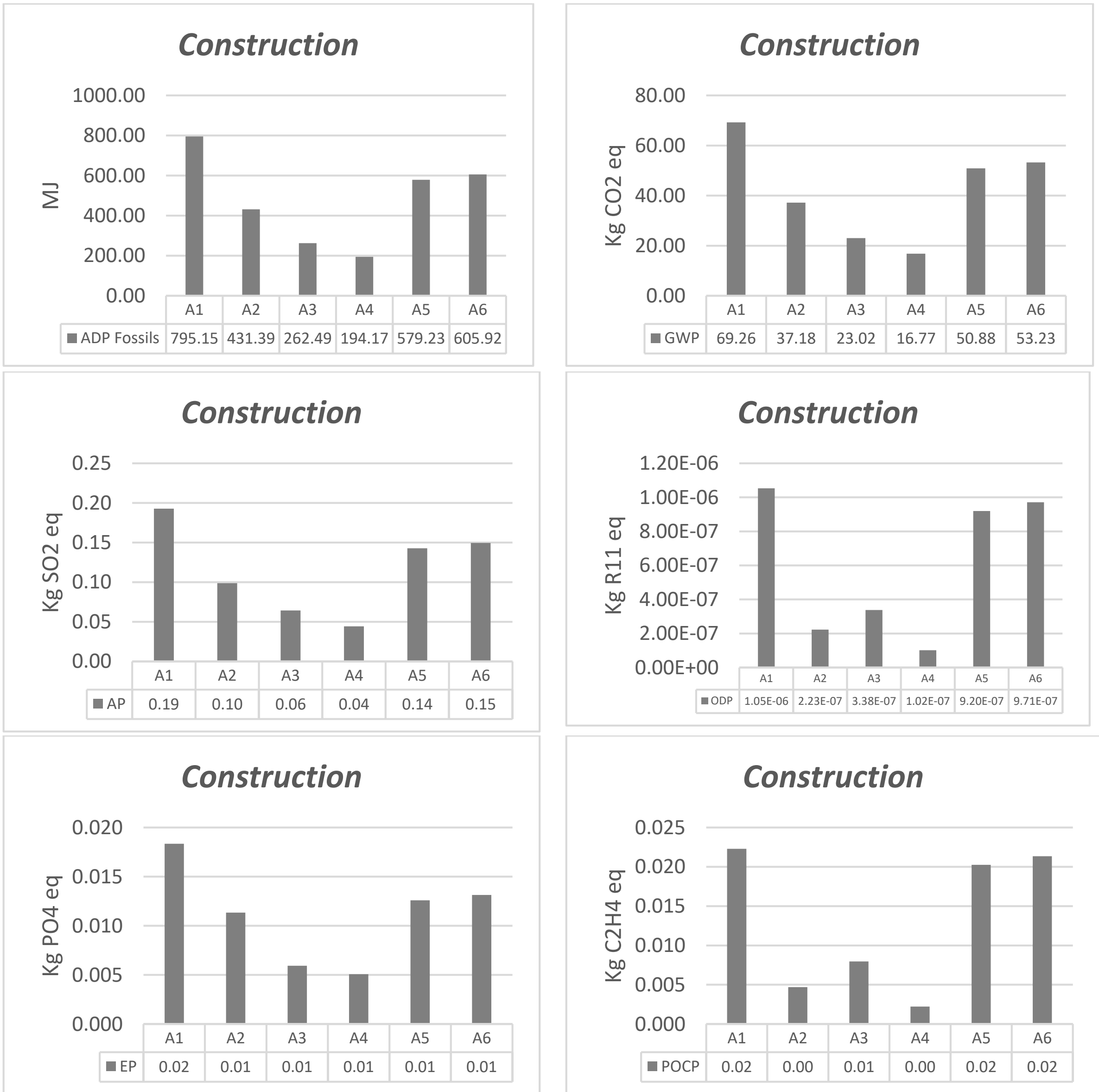


Figure 5.2 - Results of construction stage normalised per m² of the deck

5.1.1.3 Operation stage

The operation stage is directly influenced by the established maintenance events. Each time the bridge undergoes an activity of maintenance or rehabilitation, the new materials have to be produces and transported to the bridge site. The traveling distances considered at this stage are the same as in the construction stage unless indicated otherwise. Secondly, the traffic restrictions due to the performance of the maintenance works causes additional emissions due to traffic congestion.

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, work during the day (from 6:00 AM to 10:00 PM) is considered.

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

Here it can be clearly seen, that overall the maintenance of concrete causes higher environmental impact, as the emissions caused by the concrete bridges A2 and A4 dominate the performance when comparing to the cases A1 and A3 respectively.

The significant difference of approximately 400% in the emissions assessed for bridges A3 and A4 accounted for the indicator ODP is caused by the fact that the waterproofing layer was not considered in the bill of quantities for this case, which causes significant environmental burden according to its quantity, level of the emissions related to its production and frequency of the replacement, although it is too low.

Considering the performance of the cases A5 and A6, it is worth noticing, that even being different by only slightly higher quantity of the steel, at the stage of operation case A6 shows lower level of the emission among all indicators. This highlights the clear influence of the lane capacity on the traffic congestion, as the bridge A6 has three lanes per each direction of traffic, compared to the case A5 which has two.

The values of the indicators assessed at the operation stage are presented in Figure 5.3. The values are normalised per m² of the deck.

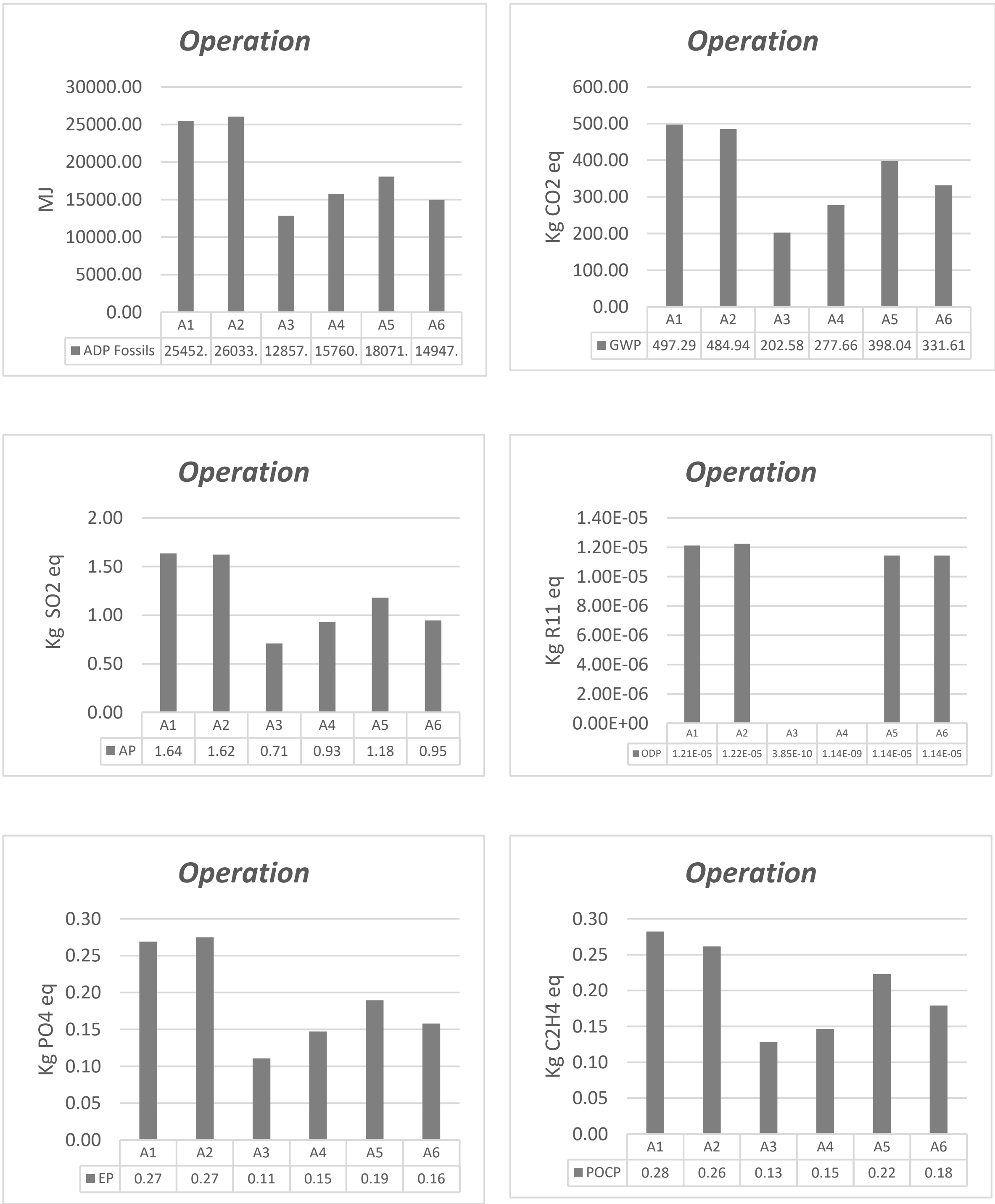


Figure 5.3 - Results of operation stage normalised per m^2 of the deck

5.1.1.4 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.

The negative values in the figure represent the credits given to the recycling process. It is assumed that all credits are allocated to the present system.

The performance of the bridges A1, A3, A5 and A6 clearly shows the benefits of the composite design solutions of the deck due to the benefits coming from the recycling of the steel. The degree of benefit depends on the relative influence of the steel to a specific indicator.

The reverse trend is seen for the indicator ODP, where the emissions caused by the dismantlement and post treatment of the components of the concrete bridges A2 and A4 has the best performance.

The values of the indicators assessed at the end of life stage are presented in Figure 5.4. The values are normalised per m^2 of the deck.

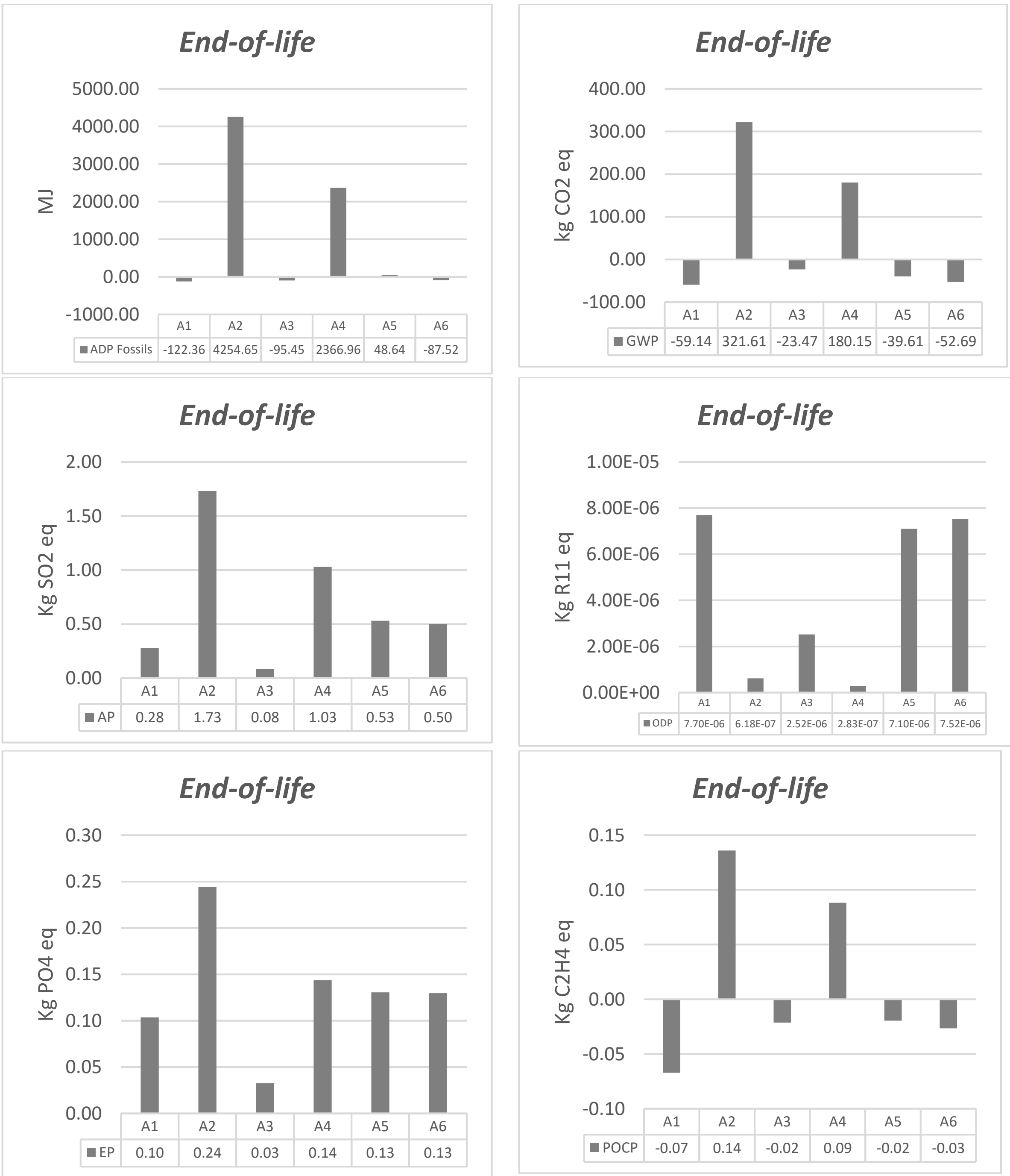


Figure 5.4 – Results of end of life stage normalised per m² of the deck

5.1.1.5 Aggregate results

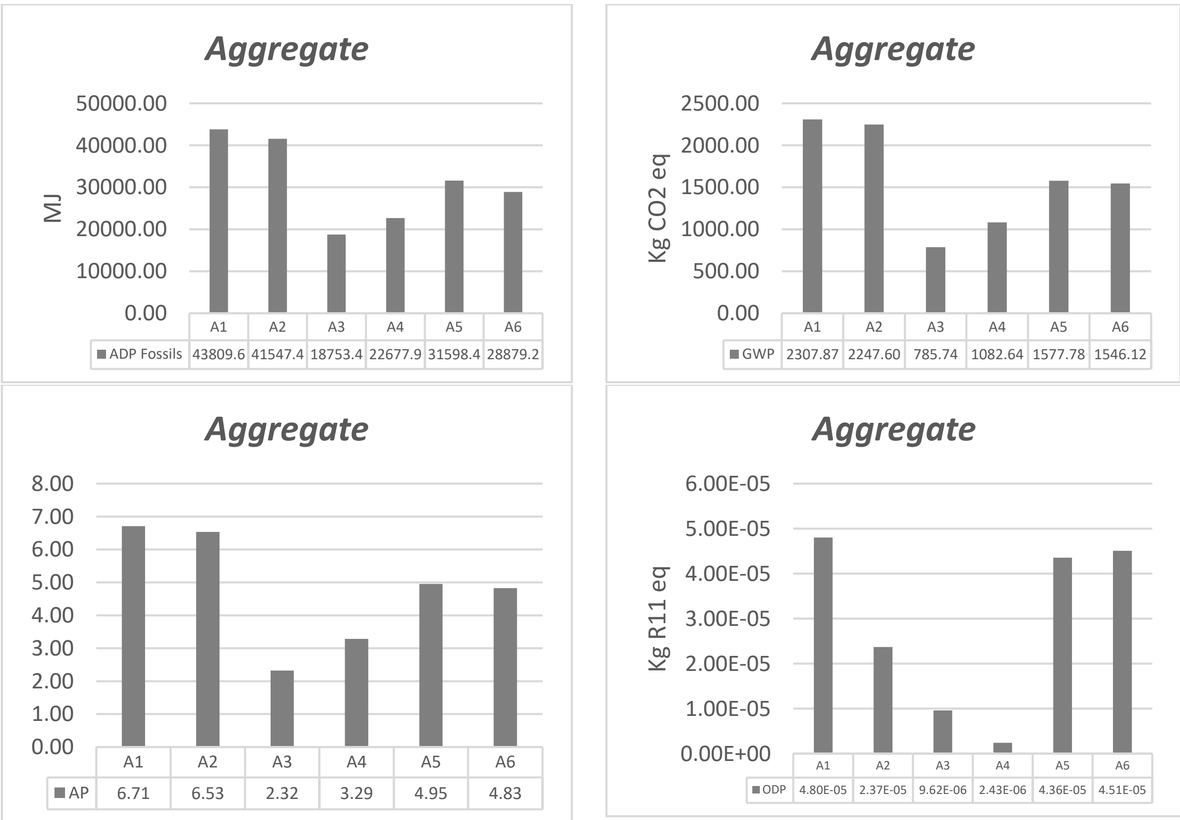
In the previous sections, the results of the environmental life cycle assessment evaluated per each stage have been presented. In this subsection, the results of all stages are summed up in relation to each impact category and the aggregate results are presented.

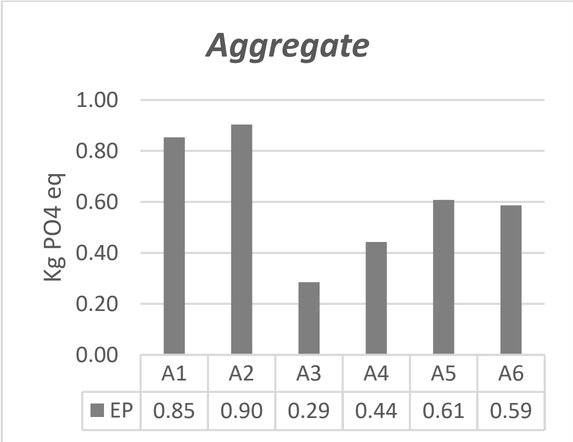
The stage of material production has a greater impact on the results, governing the overall performance. The stage of operation has a second major impact.

For all of the indicators, except ODP, the composite bridge A3 outperforms the concrete bridge A4, which are one of the similar size and scope and also comparable from the point of view of the content of quantities considered for LCA. This trend is partially valid for the bridges A1 and A2 as bridge A2 has less degree of the design optimization, meaning that the quantities of concrete is underestimated.

Being highly affected by the stage of operation, the overall performance of the cases A5 and A6 shows slightly lower level of emissions estimated for the case A6 among all indicators except ODP. As the traffic congestion has significant contribution to the environmental burdens at the stage of operation, the higher lane capacity of variant A6 justifies the lower level of the overall performance.

The aggregate results are presented in Figure 5.5. The values are normalised per m² of the deck.





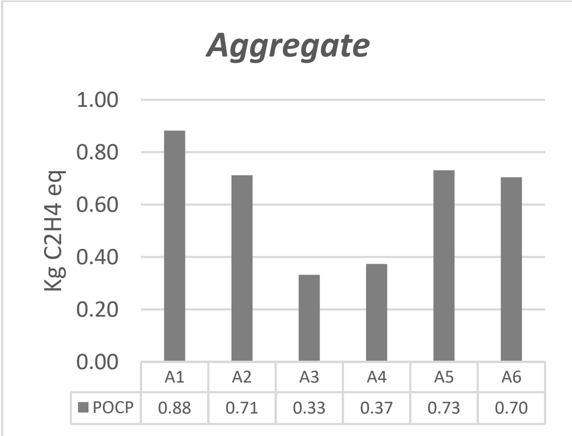


Figure 5.5 - Aggregate results normalised per m² of the deck

5.1.2 Life cycle social analysis (LCS)

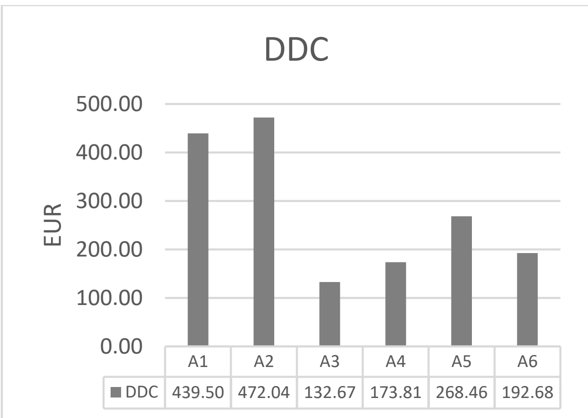
The results of the life cycle social assessment are expressed in three indicators representing user costs, namely Driver's Delay Cost (DDC), Vehicle Operation Cost (VOC) and Accidental Cost (AC); the Total user cost was estimated as the sum of aforementioned costs.

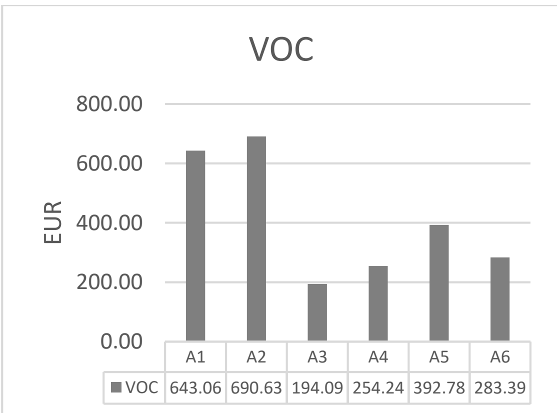
The user costs are caused by the traffic congestion. For the bridges of the Type A, the user costs occur due to the traffic restriction caused by the maintenance events at operation stage.

All user costs exhibit a quite strong correlation, as all of them are traffic depended and rely on the same assumptions for the maintenance planning. It can be seen, that the user costs for concrete bridges A2 and A4 are higher, as concrete bridges require more maintenance work to be done in the time scale, compared to the respective composite solutions A1 and A3.

Comparing two composite cases A5 and A6, described by almost equal material quantities, the design case A6 shows better performance (lower user costs) due to the one extra lane compared to the case A5.

The values of the indicators of life cycle assessment are presented in Figure 5.6. The values are normalised per m² of the deck.





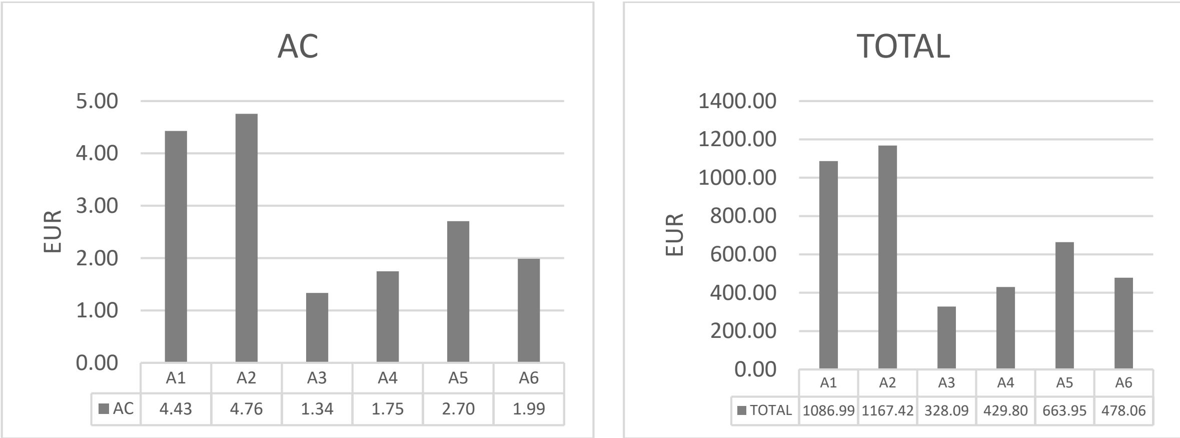


Figure 5.6 – Results of the LCS for bridges of Type A normalised per m^2 of the deck

5.2 Bridges of Type B

5.2.1 Environmental Life Cycle Assessment (LCA)

Compared to the system boundary of bridges of Type A and C, the feature of the cases of Type B is the presence of the traffic also under the bridge, which is influenced at the period of erection at the construction stage, maintenance at the operation stage and demolition at the stage of end-of-life, causing additional traffic congestion due to its restriction.

Overall, the bridges of the Type B are characterised by the same lane capacity and traffic density.

The group is dominated by the composite bridges; cases B2, B5, B6 and B12, B13 are the composite solutions.

It can be seen throughout the level of performance of all indicators, that bridges B1, B2 and B3 have relatively higher performance compared to other cases, which is related to the higher quantities of material per m^2 of the deck considered for this cases.

It is worth noticing, that due to the lack of data, the waterproofing layer was not considered in the bill of quantities of cases B1, B2, B3 and B11, B12, B13.

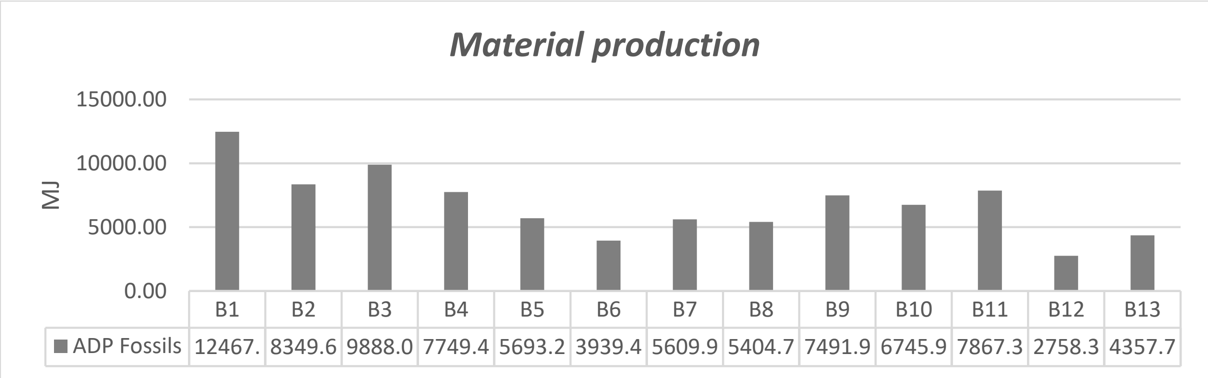
5.2.1.1 Material production stage

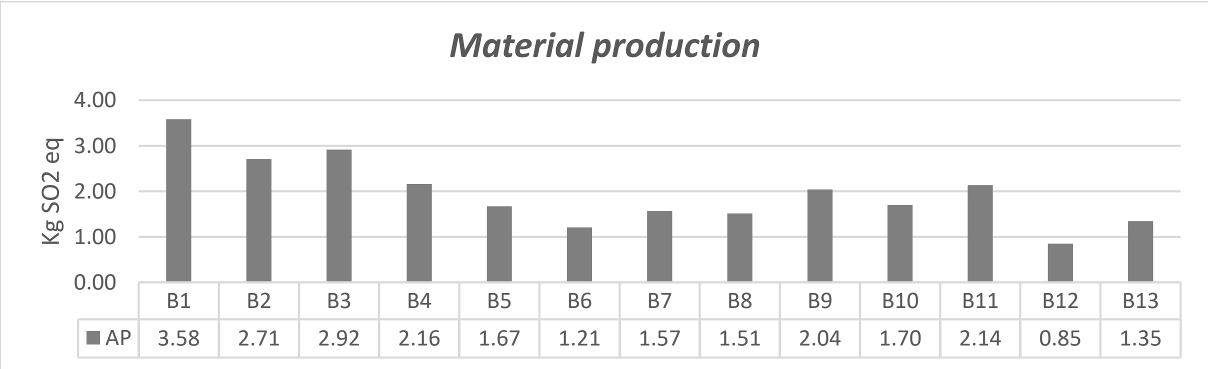
This stage takes into consideration the production of all the materials needed to build the bridge, which means that it is directly affected by the content and quantities of the material considered for the assessment. At the material production stage the environmental impacts due to the production of reinforced concrete, structural steel, coating, asphalt layer and waterproofing are assessed [3].

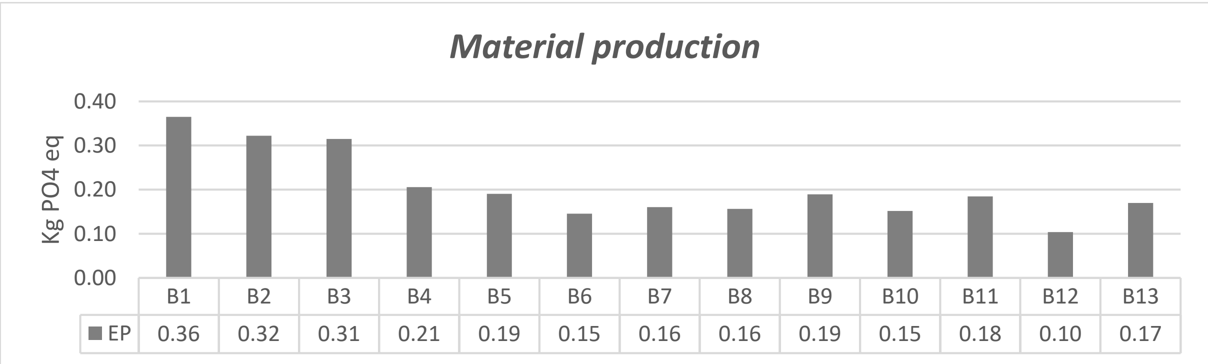
Here it can be seen, that production of the material for the erection of composite bridges cause higher environmental impact, compared with the respective concrete solutions.

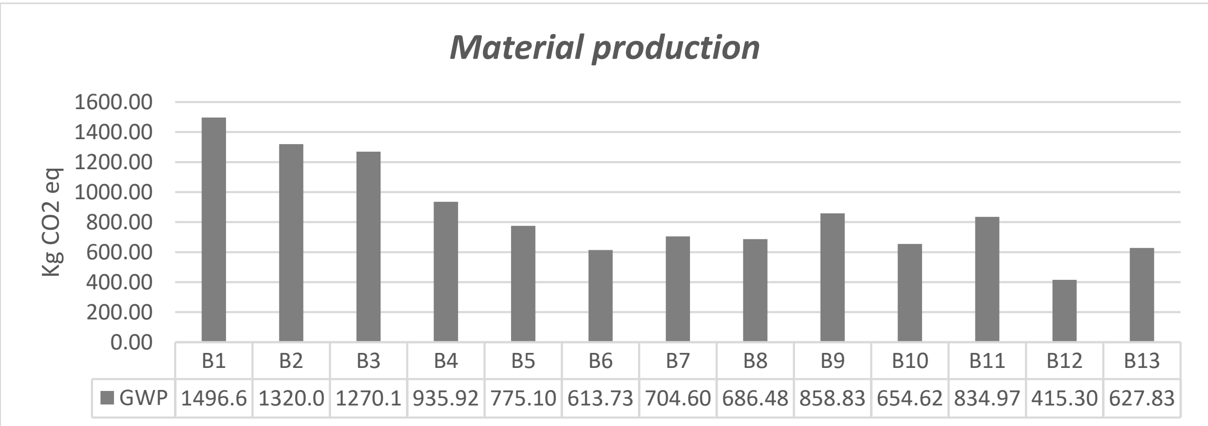
It is worth noticing, that the level of ODP for case B10 is 50% higher than the one of case B7 which is of similar size and scope. This is caused by the fact that the quantity of the structural steel used for the case B10 is almost twice higher than for the case B7, which plays essential role in the assessment of the level of ODP, as steel has much higher influence then concrete considering the level of the emission per unit quantity and quantities of steel and concrete considered [3].

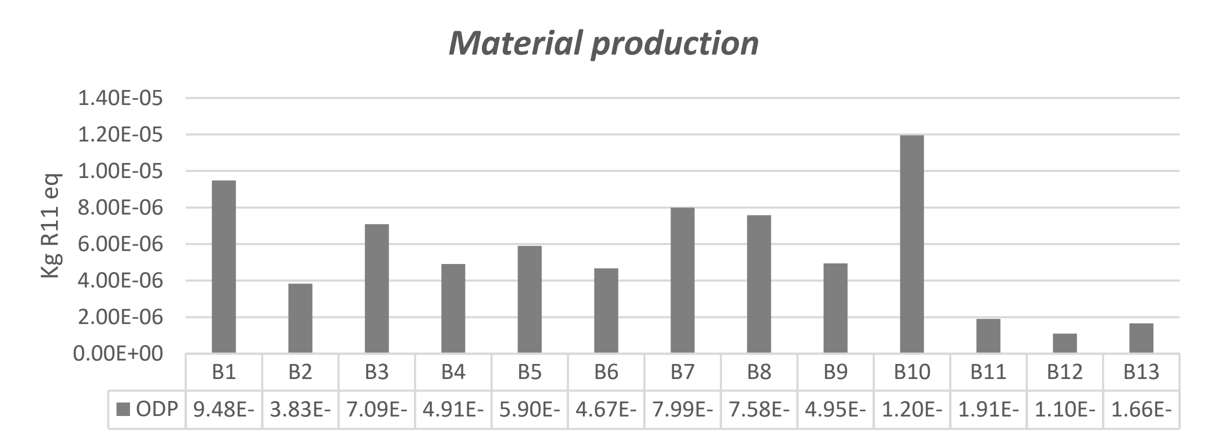
The values of the indicators assessed for the material production stage are presented in Figure 5.7. The values are normalised per m^2 of the deck.











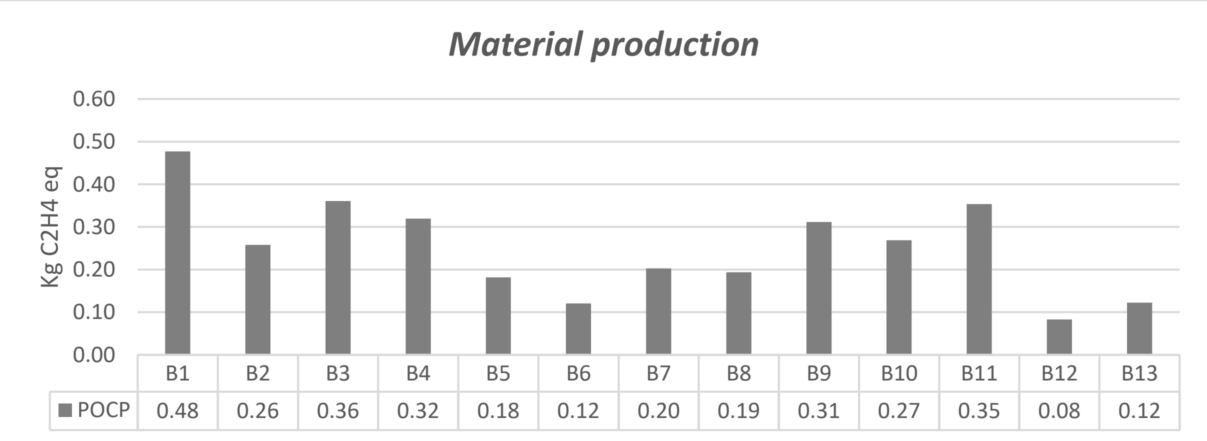


Figure 5.7 – Results of material production normalised per m^2 of the deck

5.2.1.2 Construction stage

The construction stage covers all the processes needed for and affected by the construction of the bridge. Hence, the emissions due to the construction and transportation of materials to the construction site, as well as traffic congestion due to the restriction of the existing traffic under the bridge are considered.

Comparing to the results obtained for the Type A, which are highly influenced by the quantities of the materials, the performance of the bridges of Type B among all indicators except ODP is dominated by the influence of the traffic congestion under the bridge, which depends on the assumed days of construction when the traffic restriction is needed, as specified in Table 16. Due to the lack of data regarding the construction period of the case studies coming from the project SBRI [2], namely cases B4-B11, the number of days of construction and days with the limited number of lanes was assumed to be the same based on the data available for the case B11.

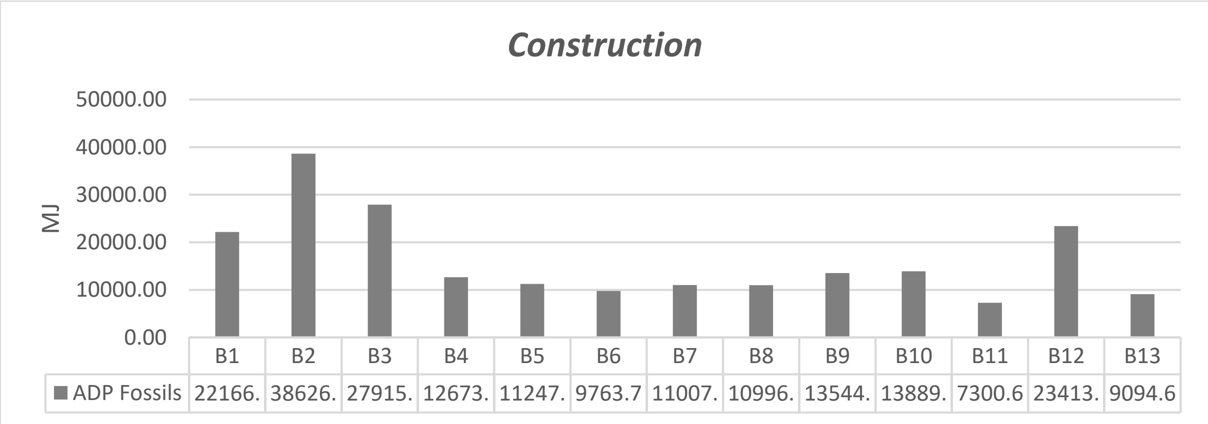
The highest level of emissions among all indicators, except ODP exhibits case B2, which has the longest assumed period of lane restriction.

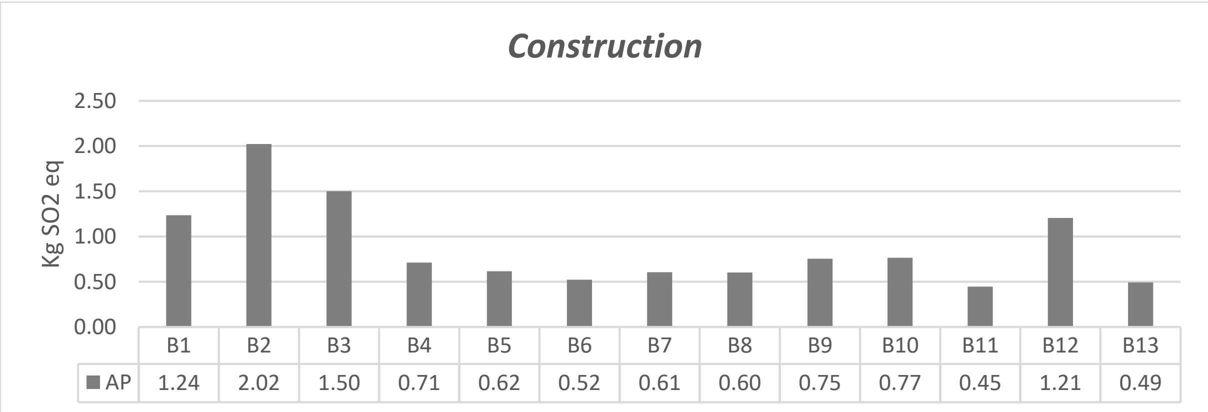
Similarly to the stage of production, considerably high level of ODP is seen for the case B10, which is related to the high relative quantity of steel per m2 of the deck as well as construction processes involved.

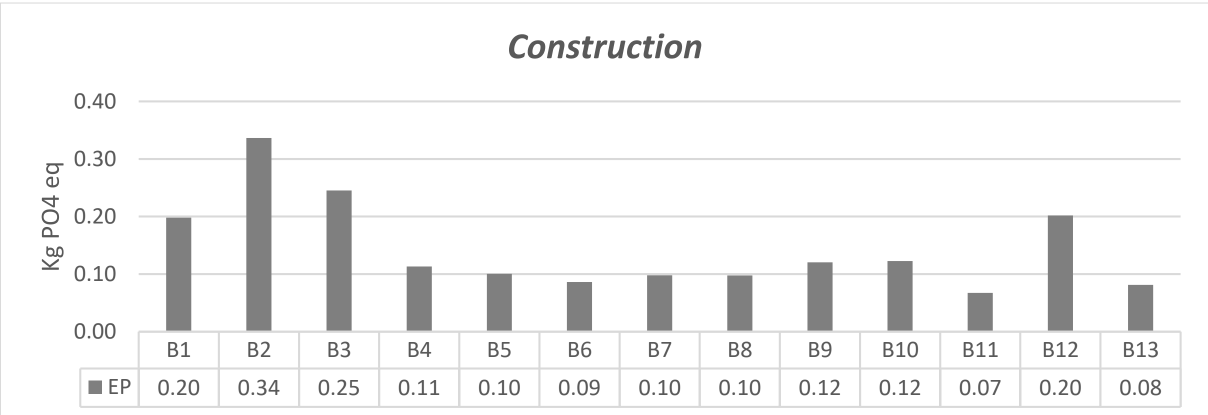
Table 16 – The number of days of construction and days with the limited lane capacity for the case studies of the Type B.

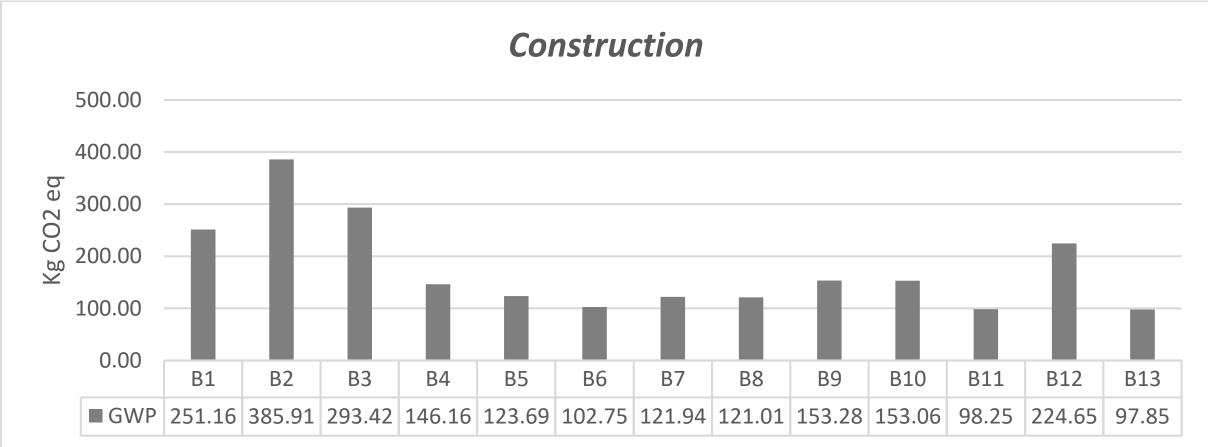
Case study	Number of days of construction	Number of days with limited lanes under bridge	Case study	Number of days of construction	Number of days with limited lanes under bridge
B1	154	154	**B8**	87	87
B2	273	273	**B9**	87	87
B3	196	196	**B10**	87	87
B4	87	87	**B11**	87	87
B5	87	87	**B12**	133	133
B6	87	87	**B13**	93	93
B7	87	87			

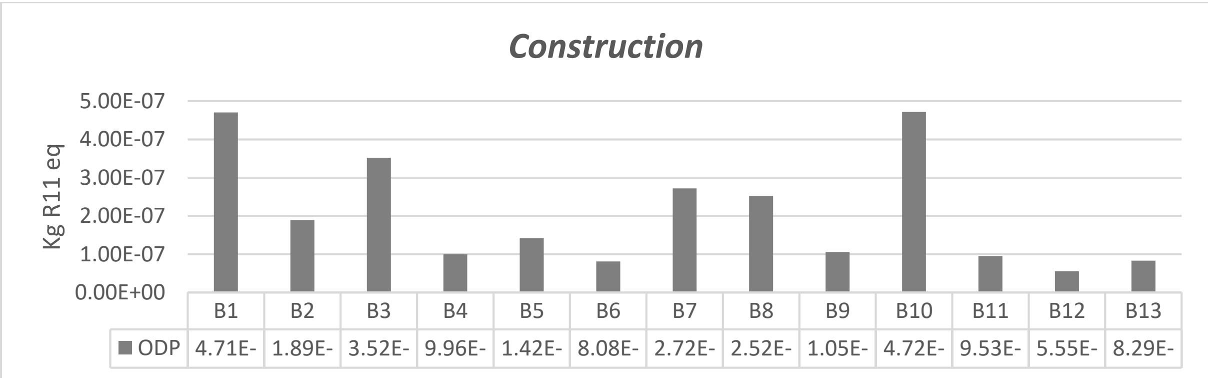
The values of the indicators assessed for the construction stage are presented in Figure 5.8. The values are normalised per m² of the deck.











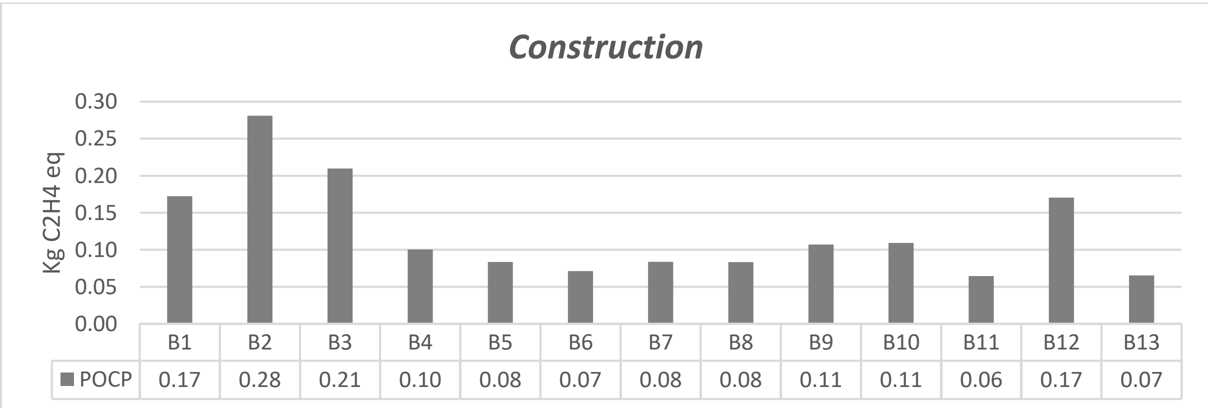


Figure 5.8 - Results of construction stage normalised per m^2 of the deck

5.2.1.3 Operation stage

The operation stage is directly influenced by the established maintenance events. Each time the bridge undergoes an activity of maintenance or rehabilitation, the new materials have to be produces and transported to the bridge site. The traveling distances considered at this stage are the same as in the construction stage unless indicated otherwise. Secondly, the restriction of the traffic over the bridge due to the performance of the maintenance works causes additional emissions due to traffic congestion.

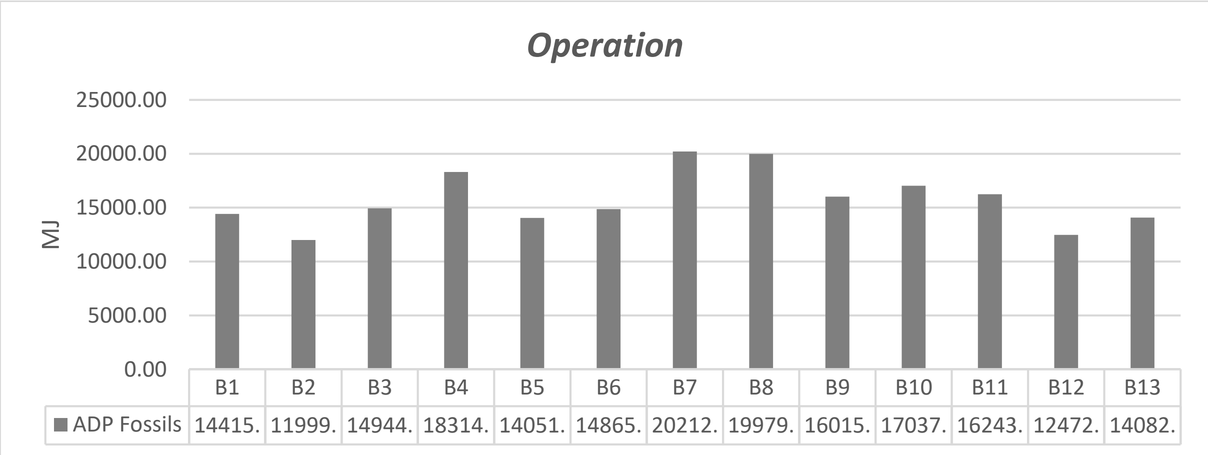
For the calculation of fuel consumption and vehicles' emissions for each combined activity, the standard maintenance scenario is considered. It is implied that, there will always be (at least) one lane of traffic open in each direction. When it is required to close a lane, work during the day (from 6:00 AM to 10:00 PM) is assumed.

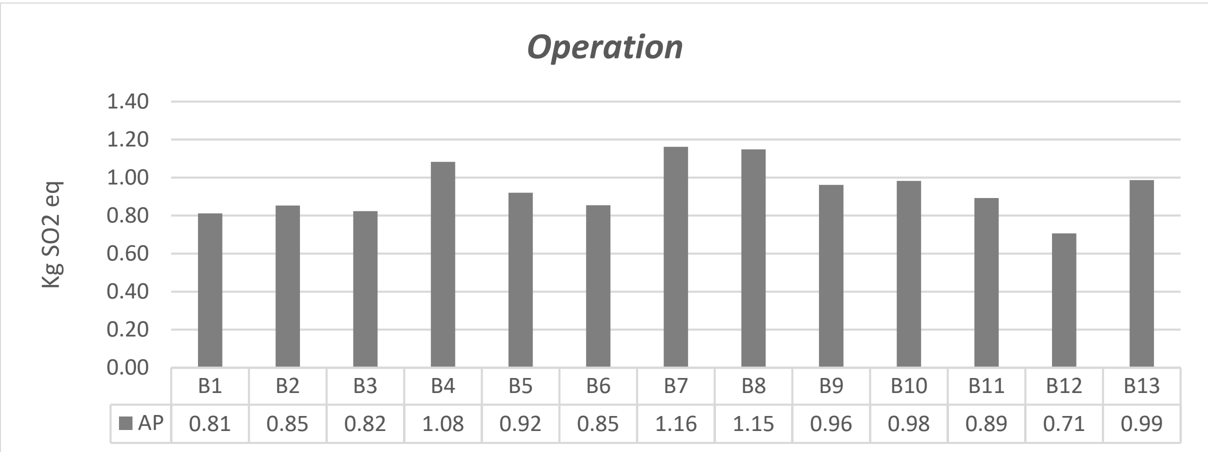
The maintenance schemes provided in Annex A indicate the traffic restraints over the bridge over the years in which maintenance activities take place.

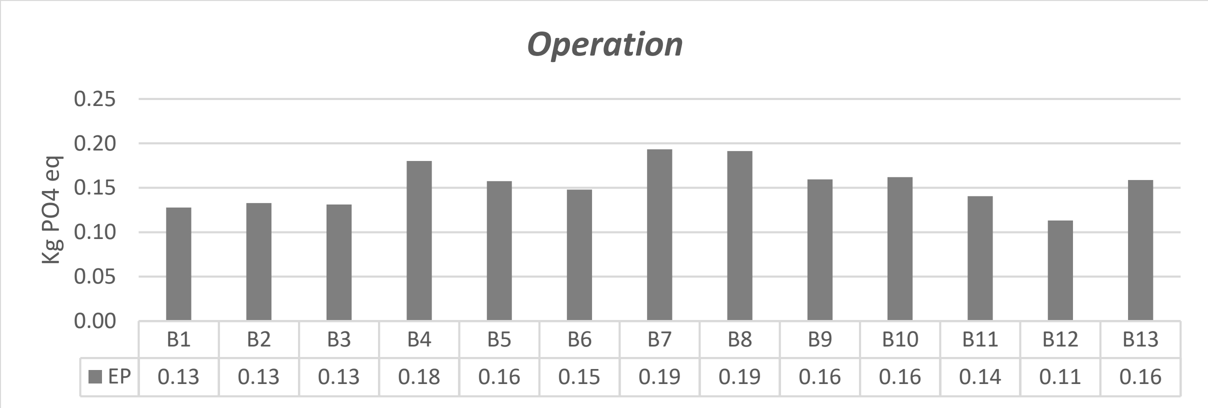
Overall, the performance of the case studies of the bridges of Type B is quite homogeneous, showing the comparable level of emissions for all cases.

The performance of the cases B1, B2, B3 and B11, B12, B13 shows distinct results of the ODP. The four order of magnitude drop in the results is directly related to the fact that waterproofing layer was not considered for this cases in the respective bills of quantities, though the value is too low.

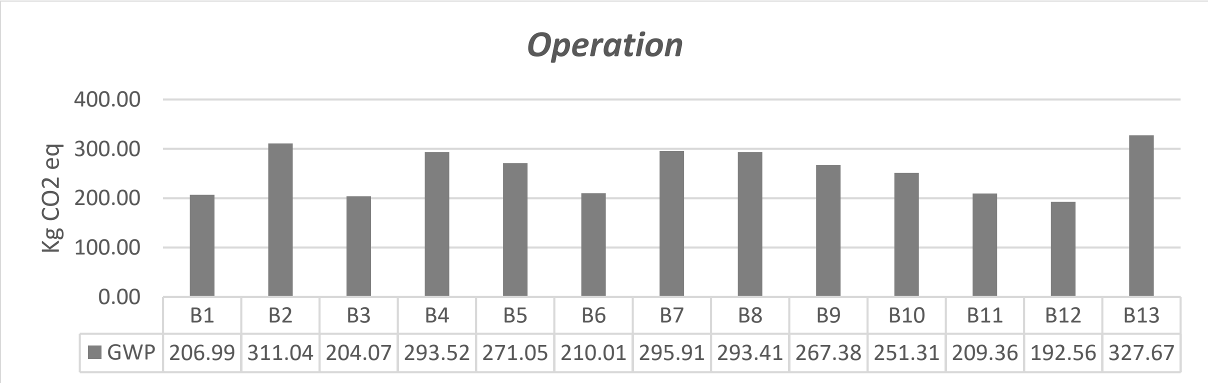
The values of the indicators assessed for the operation stage are presented in Figure 5.9. The values are normalised per m^2 of the deck.



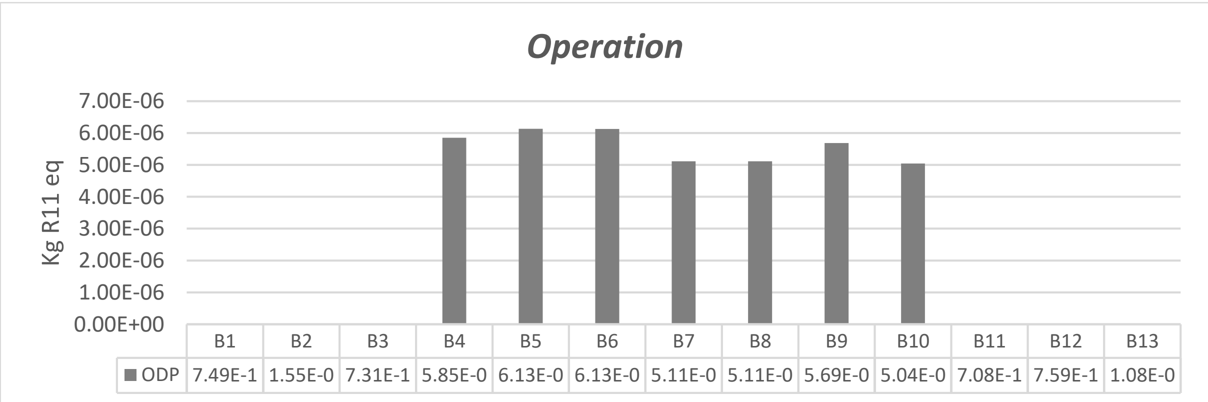




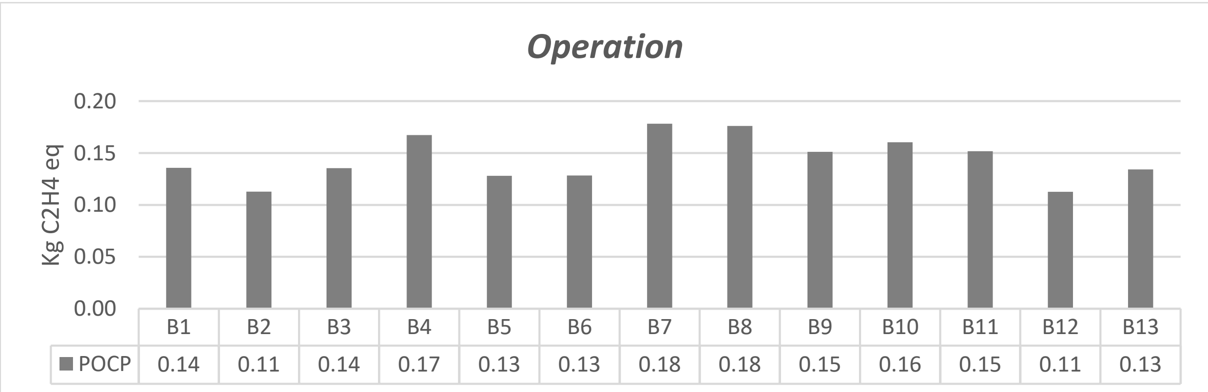
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
EP	0.13	0.13	0.13	0.18	0.16	0.15	0.19	0.19	0.16	0.16	0.14	0.11	0.16



	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
GWP	206.99	311.04	204.07	293.52	271.05	210.01	295.91	293.41	267.38	251.31	209.36	192.56	327.67



	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
ODP	7.49E-1	1.55E-0	7.31E-1	5.85E-0	6.13E-0	6.13E-0	5.11E-0	5.11E-0	5.69E-0	5.04E-0	7.08E-1	7.59E-1	1.08E-0



	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
POCP	0.14	0.11	0.14	0.17	0.13	0.13	0.18	0.18	0.15	0.16	0.15	0.11	0.13

Figure 5.9 - Results of operation stage normalised per m^2 of the deck

5.2.1.4 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. The credits given to the recycling process is assumed to be allocated to the present system.

Due to the lack of data, the same number of days of deconstruction was assumed for all the cases.

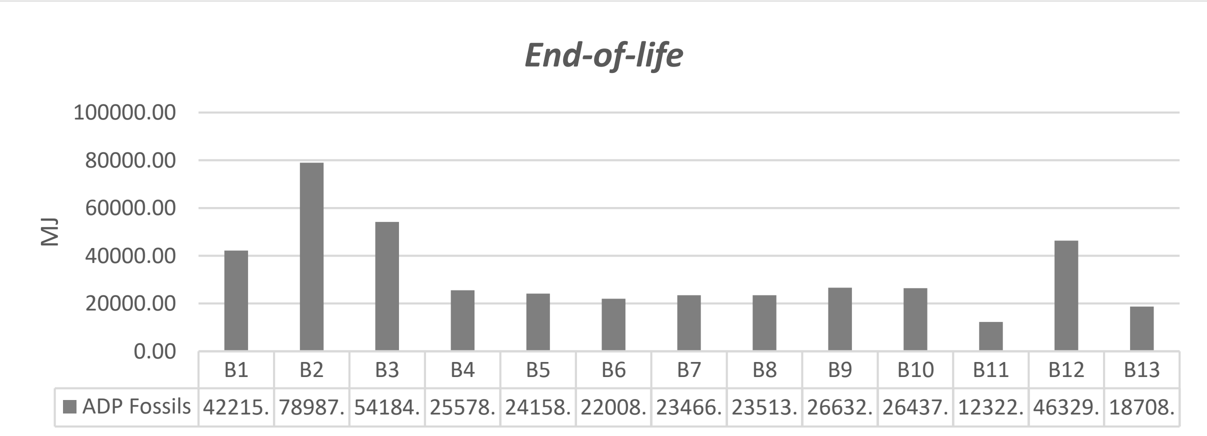
It is assumed, that deconstruction affects the traffic under the bridge, thus traffic congestion is taken into account.

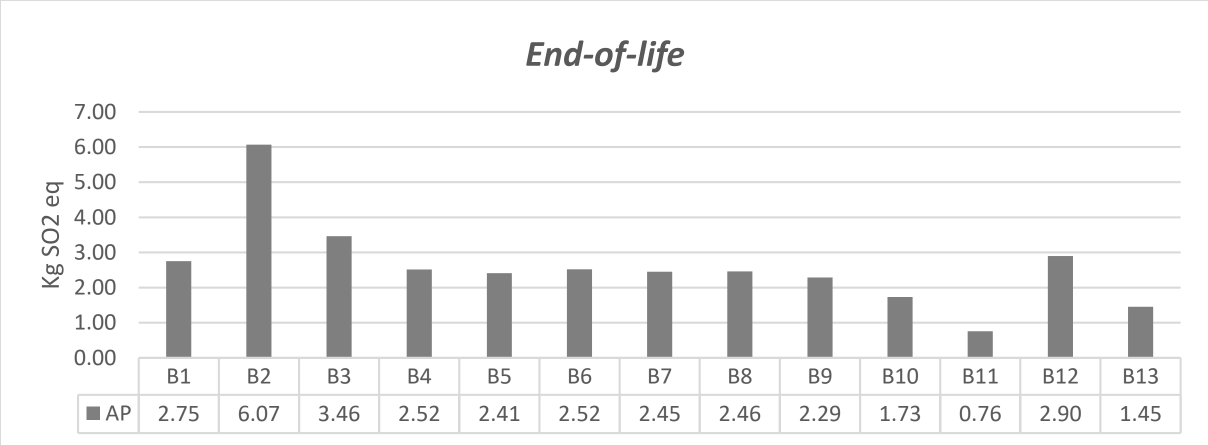
Overall, it was observed, that, as for the stage of construction, the impact due to the traffic congestion is governing the environmental performance of the case studies of Type B at the end-of-life stage.

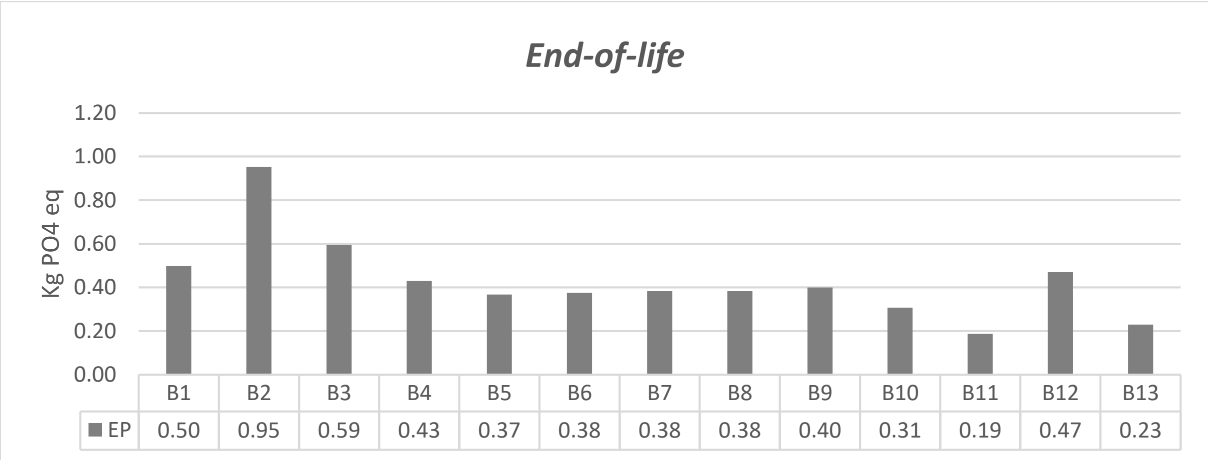
For all of the indicators, except ODP, the composite solutions show comparatively lower level of emissions due to the environmental benefits from the recycling of the steel. Conversely, the concrete bridges B2, B5, B6 and B12, B13 show the lowest impact on ODP, as steel has a major contribution to the environmental burdens for this indicator.

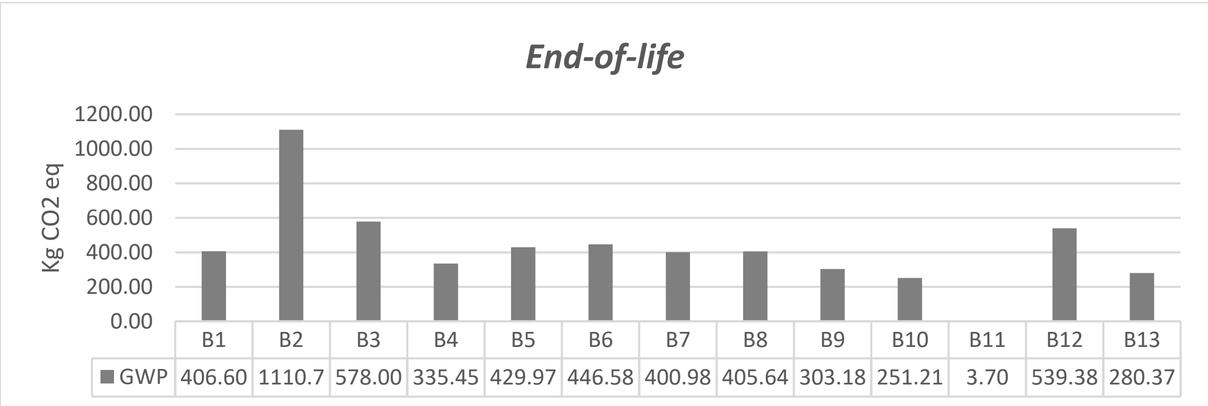
Due to the fact, that the values of indicators were normalized per m^2 of the deck including the emissions caused by the interruption of the traffic, the results are considerably lower for the case B11 as it has almost twice bigger are of the deck.

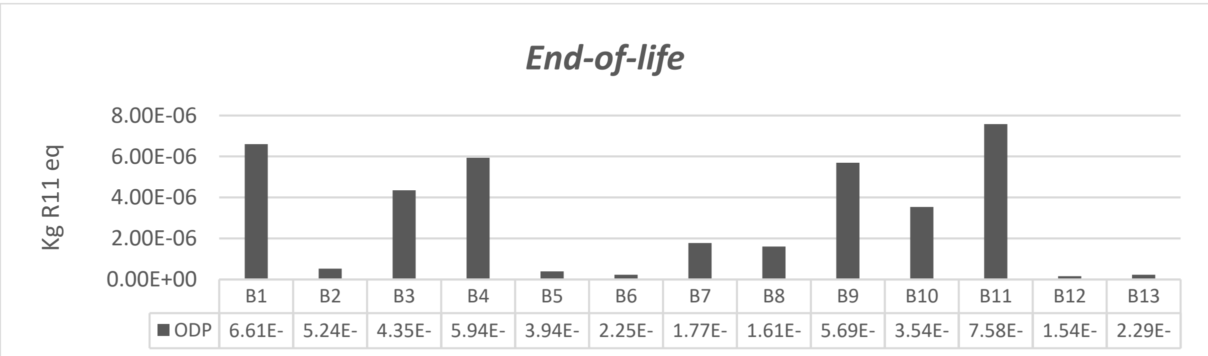
The values of the indicators assessed for the end-of-life stage are presented in Figure 5.10. The values are normalised per m^2 of the deck.




End-of-life
Kg SO2 eq
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
AP 2.75 6.07 3.46 2.52 2.41 2.52 2.45 2.46 2.29 1.73 0.76 2.90 1.45


End-of-life
Kg PO4 eq
1.20
1.00
0.80
0.60
0.40
0.20
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 0.50 0.95 0.59 0.43 0.37 0.38 0.38 0.38 0.40 0.31 0.19 0.47 0.23


End-of-life
Kg CO2 eq
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 406.60 1110.7 578.00 335.45 429.97 446.58 400.98 405.64 303.18 251.21 3.70 539.38 280.37


End-of-life
Kg R11 eq
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 6.61E- 5.24E- 4.35E- 5.94E- 3.94E- 2.25E- 1.77E- 1.61E- 5.69E- 3.54E- 7.58E- 1.54E- 2.29E-

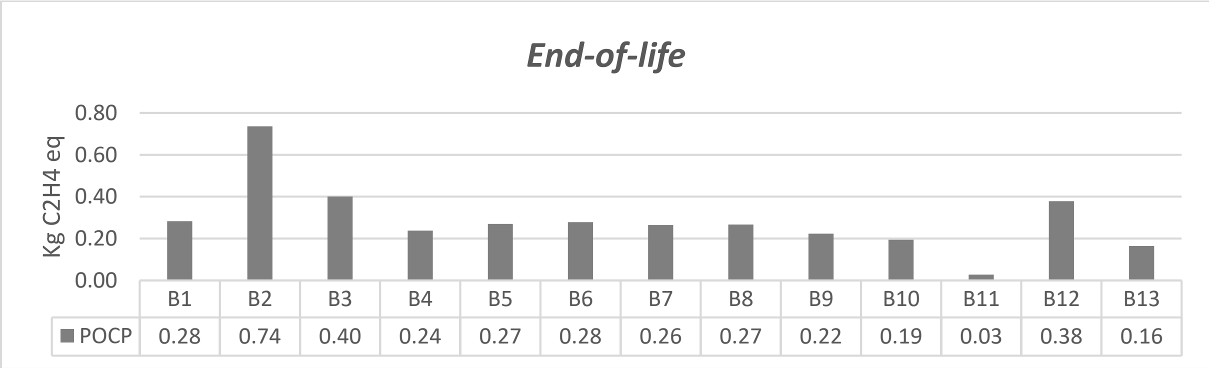


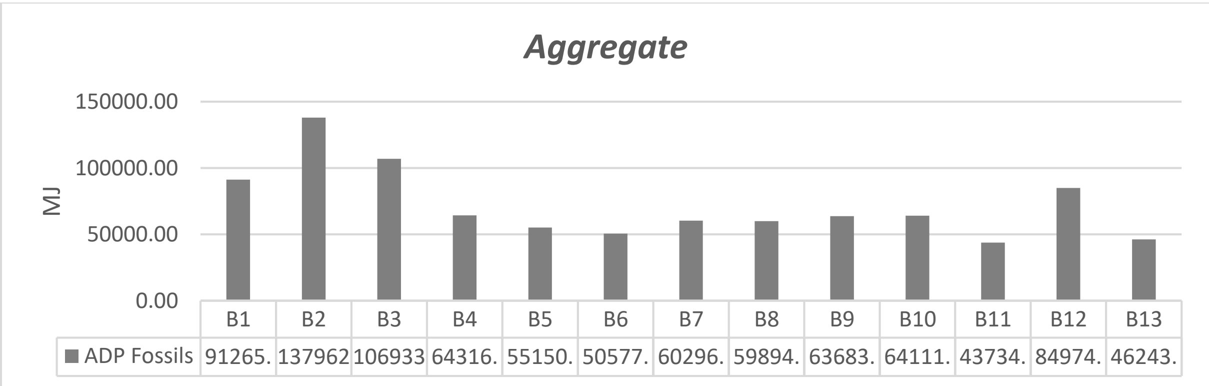
Figure 5.10 - Results of end-of life stage normalised per m² of the deck

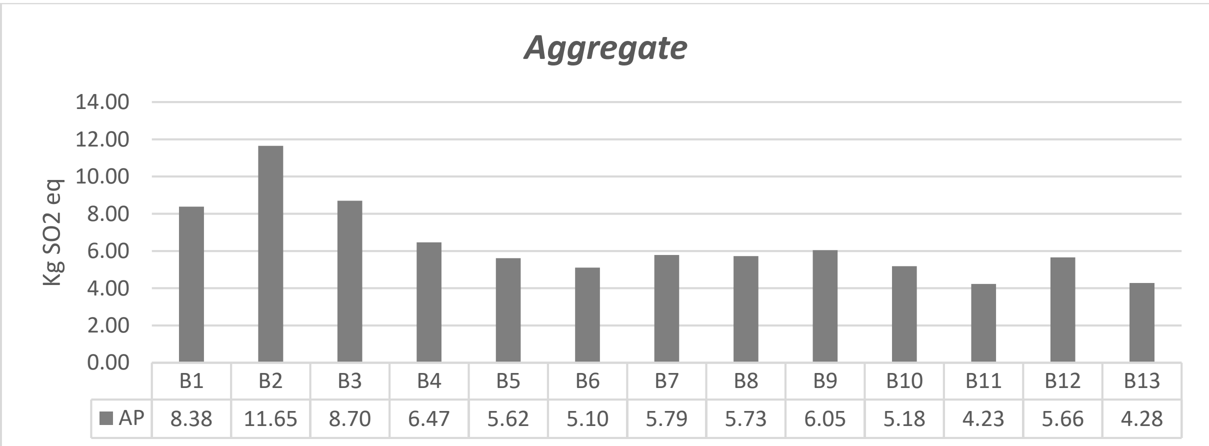
5.2.1.5 Aggregate results

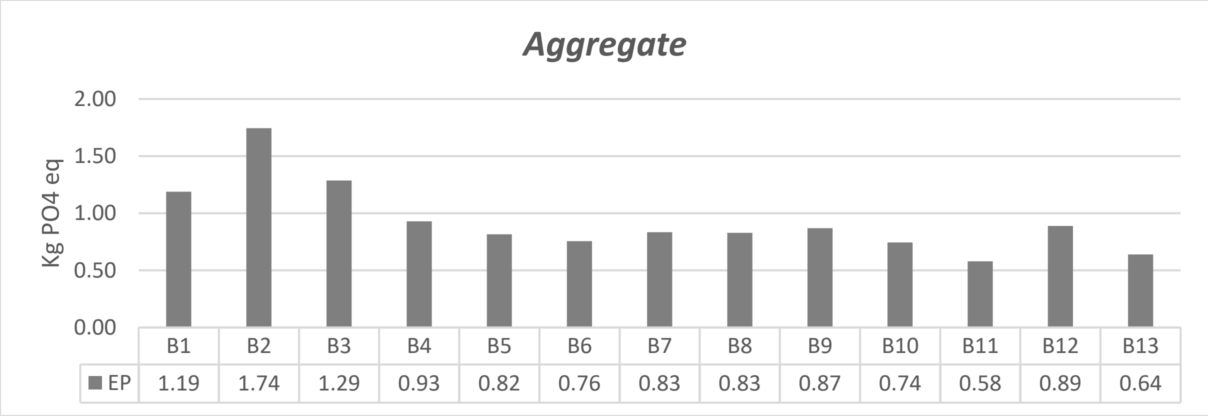
The overall aggregate results are highly affected by the performance at the stage of production and end-of-life, as the interruption of the traffic took place for the latter.

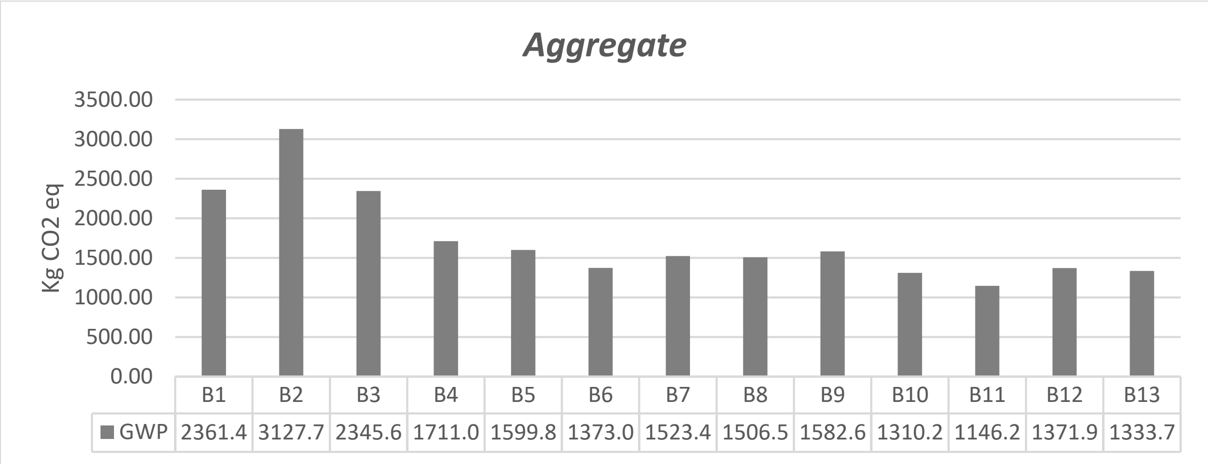
Thus, overall performance shows higher level of emission for the concrete bridges among all indicators except ODP, when the concrete solution appeared to be the most favourable

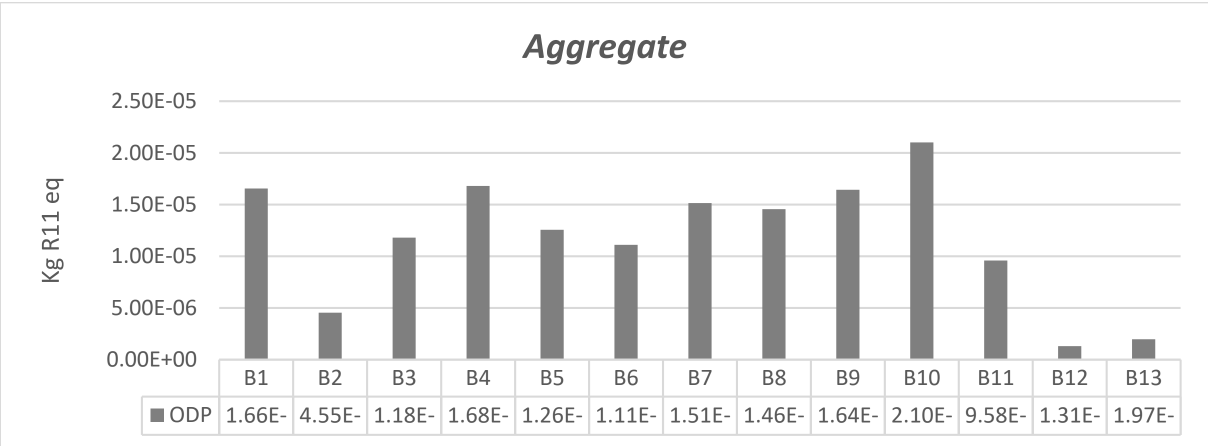
The aggregate results are presented in Figure 5.11. The values are normalised per m² of the deck.






Aggregate
Kg PO4 eq
2.00
1.50
1.00
0.50
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 1.19 1.74 1.29 0.93 0.82 0.76 0.83 0.83 0.87 0.74 0.58 0.89 0.64


Aggregate
Kg CO2 eq
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 2361.4 3127.7 2345.6 1711.0 1599.8 1373.0 1523.4 1506.5 1582.6 1310.2 1146.2 1371.9 1333.7


Aggregate
Kg R11 eq
2.50E-05
2.00E-05
1.50E-05
1.00E-05
5.00E-06
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 1.66E- 4.55E- 1.18E- 1.68E- 1.26E- 1.11E- 1.51E- 1.46E- 1.64E- 2.10E- 9.58E- 1.31E- 1.97E-

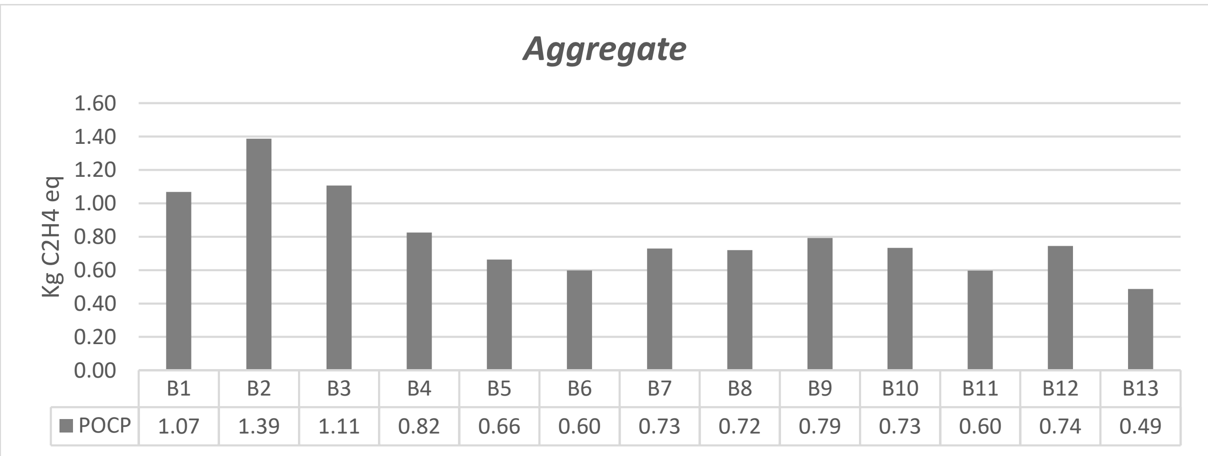

Aggregate
Kg C2H4 eq
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
POCP 1.07 1.39 1.11 0.82 0.66 0.60 0.73 0.72 0.79 0.73 0.60 0.74 0.49

Figure 5.11 - Aggregate results normalised per m^2 of the deck

5.2.2 Life cycle social analysis (LCS)

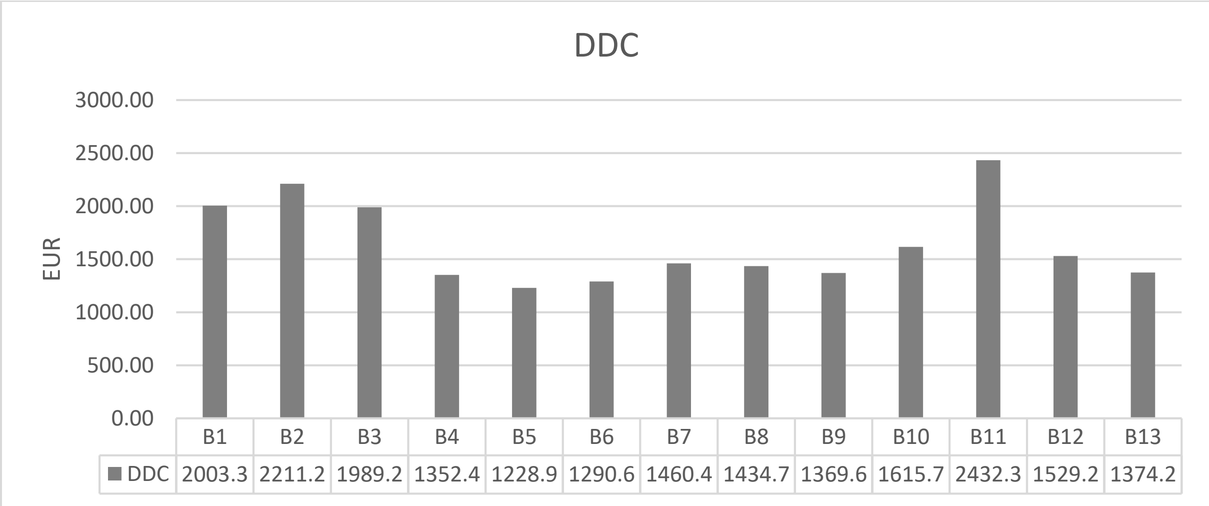
The results of the life cycle social assessment are expressed in three indicators representing user costs, namely Driver's Delay Cost (DDC), Vehicle Operation Cost (VOC) and Accidental Cost (AC); the Total user cost was estimated as the sum of aforementioned costs.

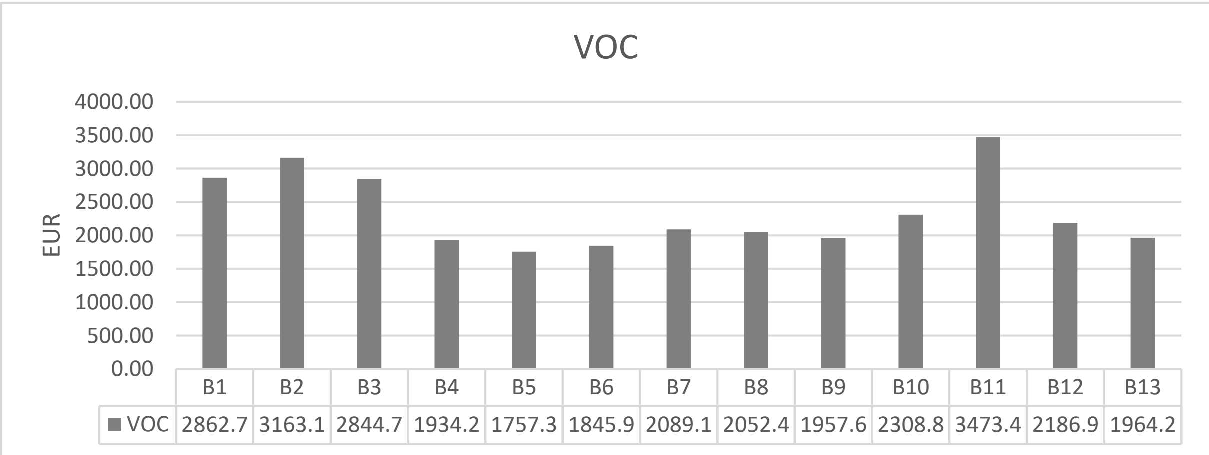
The user costs are caused by the traffic congestion. For the bridges of the Type B, the user costs occur due to the restriction of traffic under the bridge for the stage of construction and end-of-life and when the maintenance events take place at operation stage.

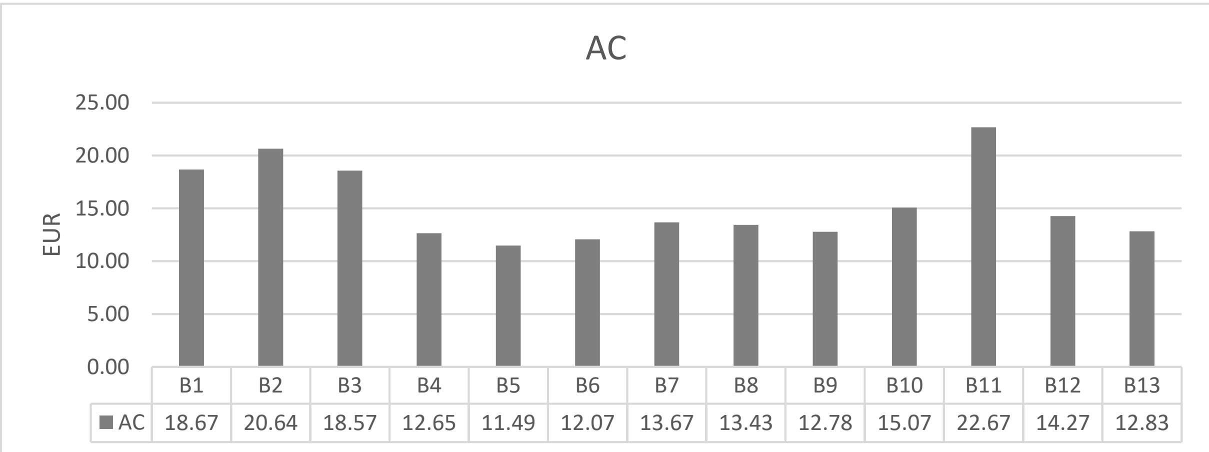
All user costs exhibit a quite strong correlation, as all of them are traffic depended and rely on the same assumptions for the maintenance planning.

It is noticeable, that user costs of the case B11 is distinctly higher, which is related to the fact that more maintenance is required for this case compared to the other case studies.

The values of the indicators of life cycle social assessment are presented in Figure 5.12. The values are normalised per m^2 of the deck.


DDC
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
EUR
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
DDC 2003.3 2211.2 1989.2 1352.4 1228.9 1290.6 1460.4 1434.7 1369.6 1615.7 2432.3 1529.2 1374.2


VOC
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
EUR
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
VOC 2862.7 3163.1 2844.7 1934.2 1757.3 1845.9 2089.1 2052.4 1957.6 2308.8 3473.4 2186.9 1964.2


AC
25.00
20.00
15.00
10.00
5.00
0.00
EUR
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
AC 18.67 20.64 18.57 12.65 11.49 12.07 13.67 13.43 12.78 15.07 22.67 14.27 12.83

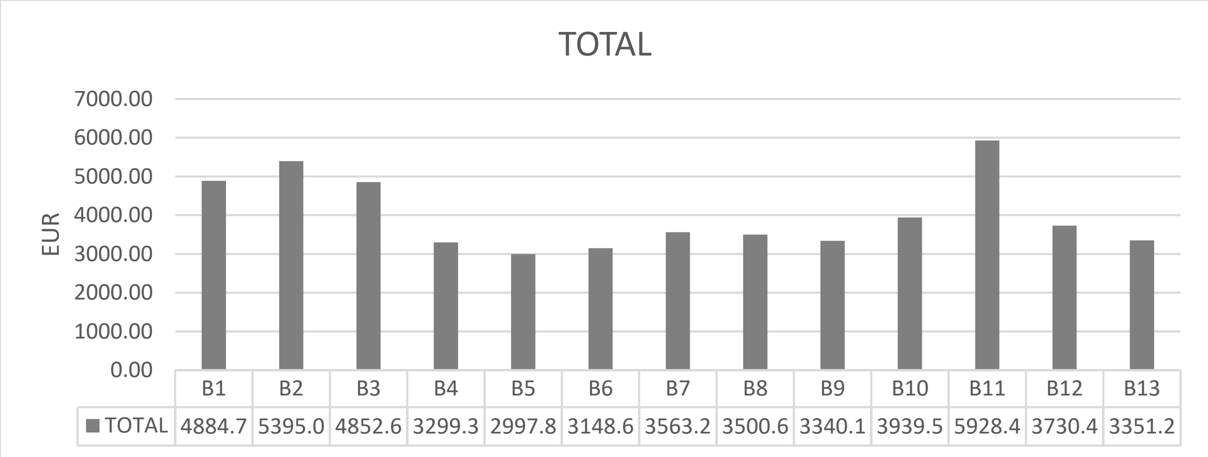


Figure 5.12 – Results of LCS of bridges of Type B normalised per m^2 of the deck

5.3 Bridges of Type C

Only two bridges were considered for the Type C. Both case studies are composite bridges with box girder deck and same lane capacity.

Due to the lack of data, the materials used for the substructure of the case C2, namely for abutments and foundation, was not considered.

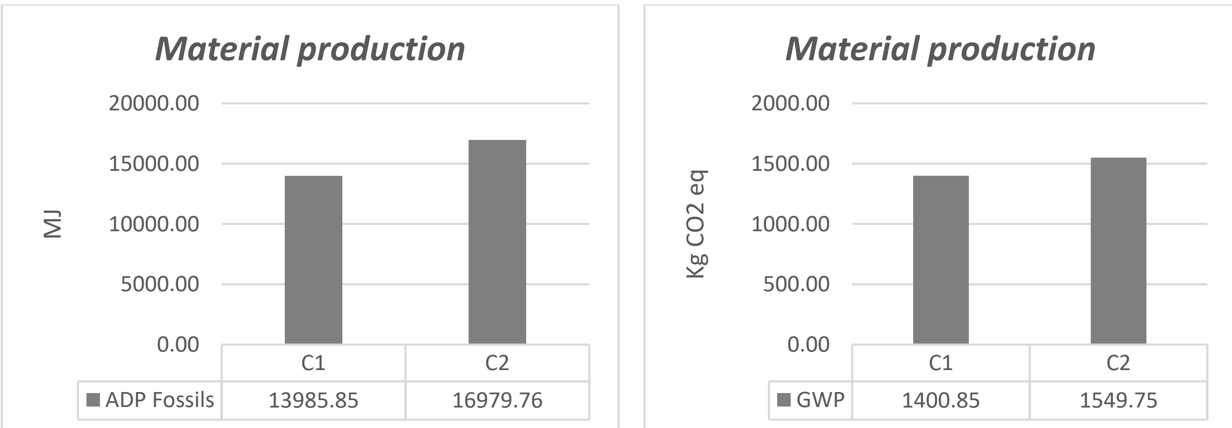
5.3.1 Environmental Life Cycle Assessment (LCA)

5.3.1.1 Material production stage

This stage takes into consideration the production of all the materials needed to build the bridge, which means that it is directly affected by the content and quantities of the material considered for the assessment. At the material production stage the environmental impacts due to the production of reinforced concrete, structural steel, coating, asphalt layer and waterproofing are assessed [3].

Having an overall trend of higher level of emissions for the case C2, the significant drop at the level of ODP is related to the fact that plated steel has zero influence on this indicator and in the same time has a significant share in the quantity of steel used for this case.

The values of the indicators assessed for the material production stage are presented in Figure 5.13. The values are normalised per m^2 of the deck.



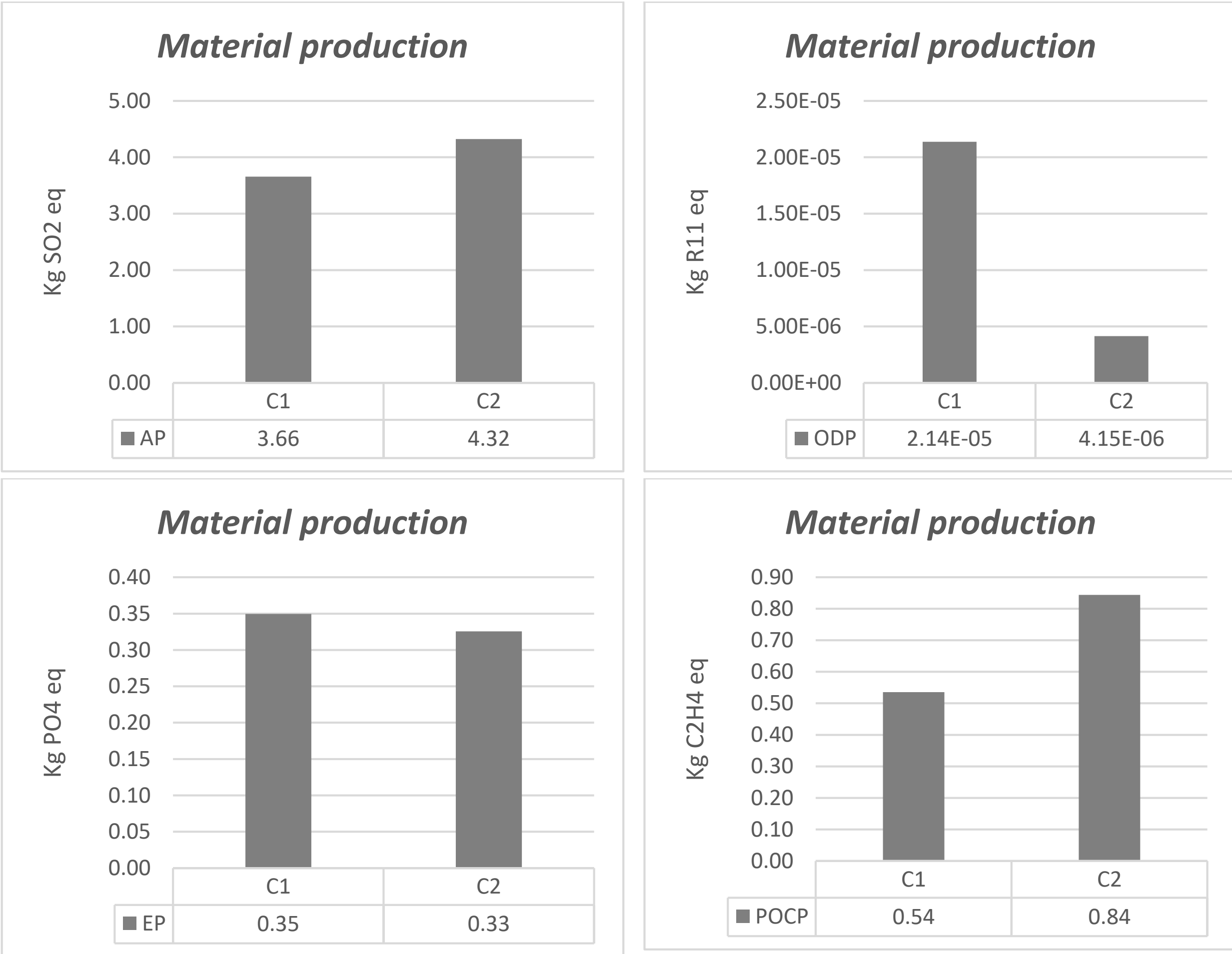


Figure 5.13 - Results of material production stage normalised per m^2 of the deck

5.3.1.2 Construction stage

The construction stage covers all the processes needed for and affected by the construction of the bridge. Hence, the emissions due to the construction and transportation of materials to the construction site is considered.

The results show similar pattern observed at the material production stage, as they are affected mostly by the quantities of materials used for the erection of the bridge. Thus, similar drop in the level of OPD related to the use of plated steel is observed for the case C2.

The values of the indicators assessed for the construction stage are presented in Figure 5.14. The values are normalised per m^2 of the deck.

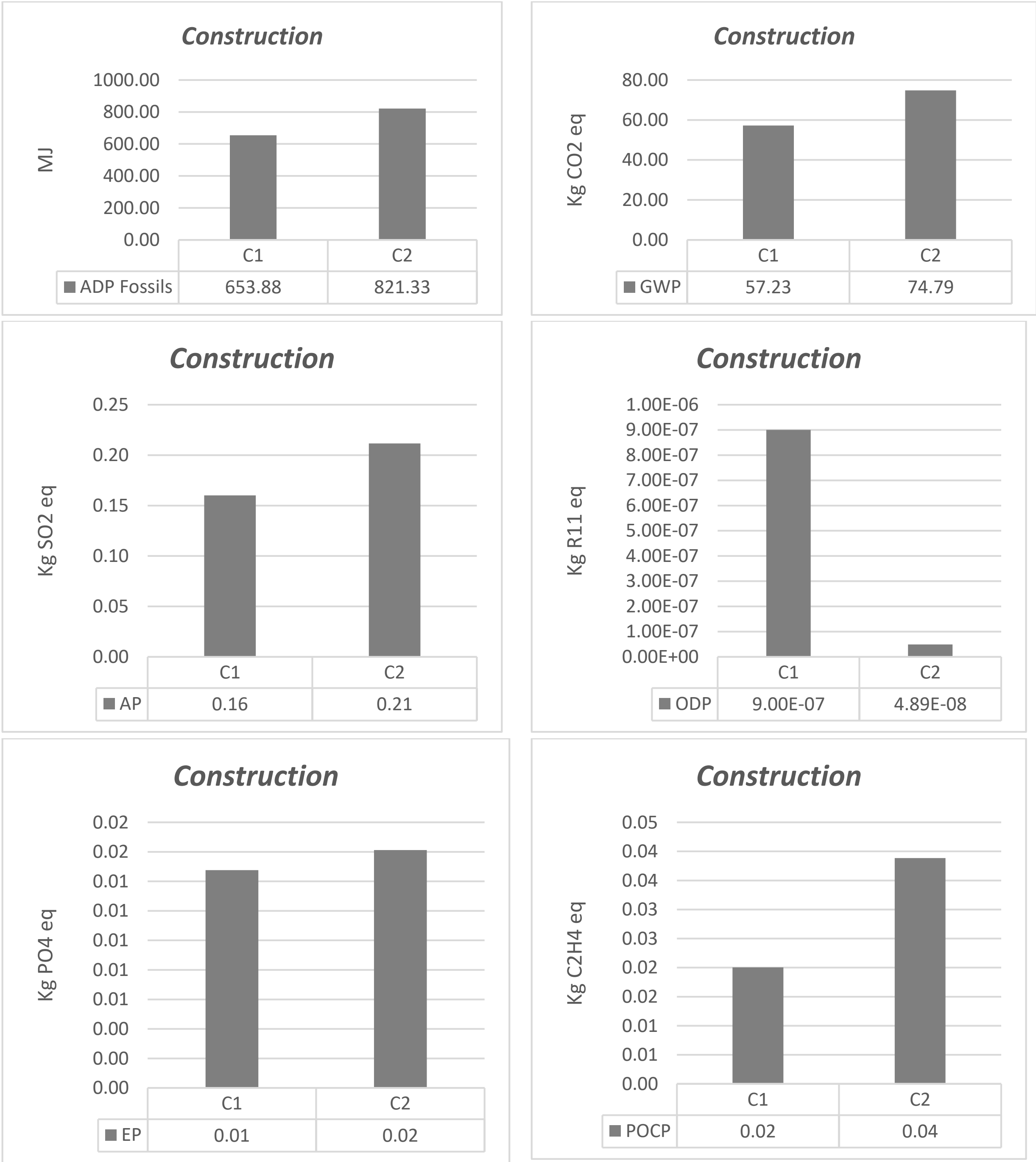


Figure 5.14 - Results of construction stage normalised per m² of the deck

5.3.1.3 Operation stage

The operation stage is directly influenced by the established maintenance events. Each time the bridge undergoes an activity of maintenance or rehabilitation, the new materials have to be produces and transported to the bridge site. The traveling distances considered at this stage are the same as in the construction stage unless indicated otherwise. Secondly, the traffic restrictions due to the performance of the maintenance works causes additional emissions due to traffic congestion.

For the calculation of fuel consumption and vehicles' emissions for each combined activity, the standard maintenance scenario is considered. It is implied that, there will always be (at least) one lane of traffic open in each direction. When it is required to close a lane, work during the day (from 6:00 AM to 10:00 PM) is assumed.

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

The values of the indicators assessed for the operation stage are presented in Figure 5.15. The values are normalised per m² of the deck.

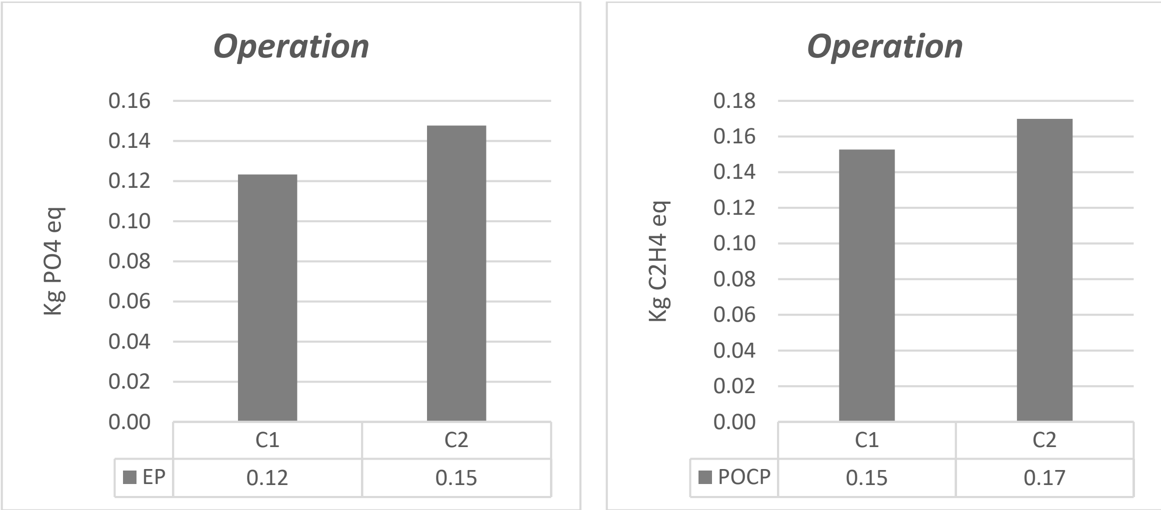


Figure 5.15 – Results of operation stage normalised per m^2 of the deck

5.3.1.4 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.

Overall it can be seen, that case C2 shows much lower values of the emissions among all indicators (except ODP). Such a difference is caused by the fact, that for the case C1 much higher quantity of concrete was considered and the benefit from the recycling of the steel is counterweighted by the unfavourable influence of the latter.

The opposite trend is seen for the levels of ODP. The much higher level of emission for the case C2 is caused by the fact that plated steel used in case C2 has much greater environmental burdens to the ODP coming from recycling, than the steel section used for the box girder of case C1.

The values of the indicators assessed for the end-of-life stage are presented in Figure 5.16. The values are normalised per m^2 of the deck.

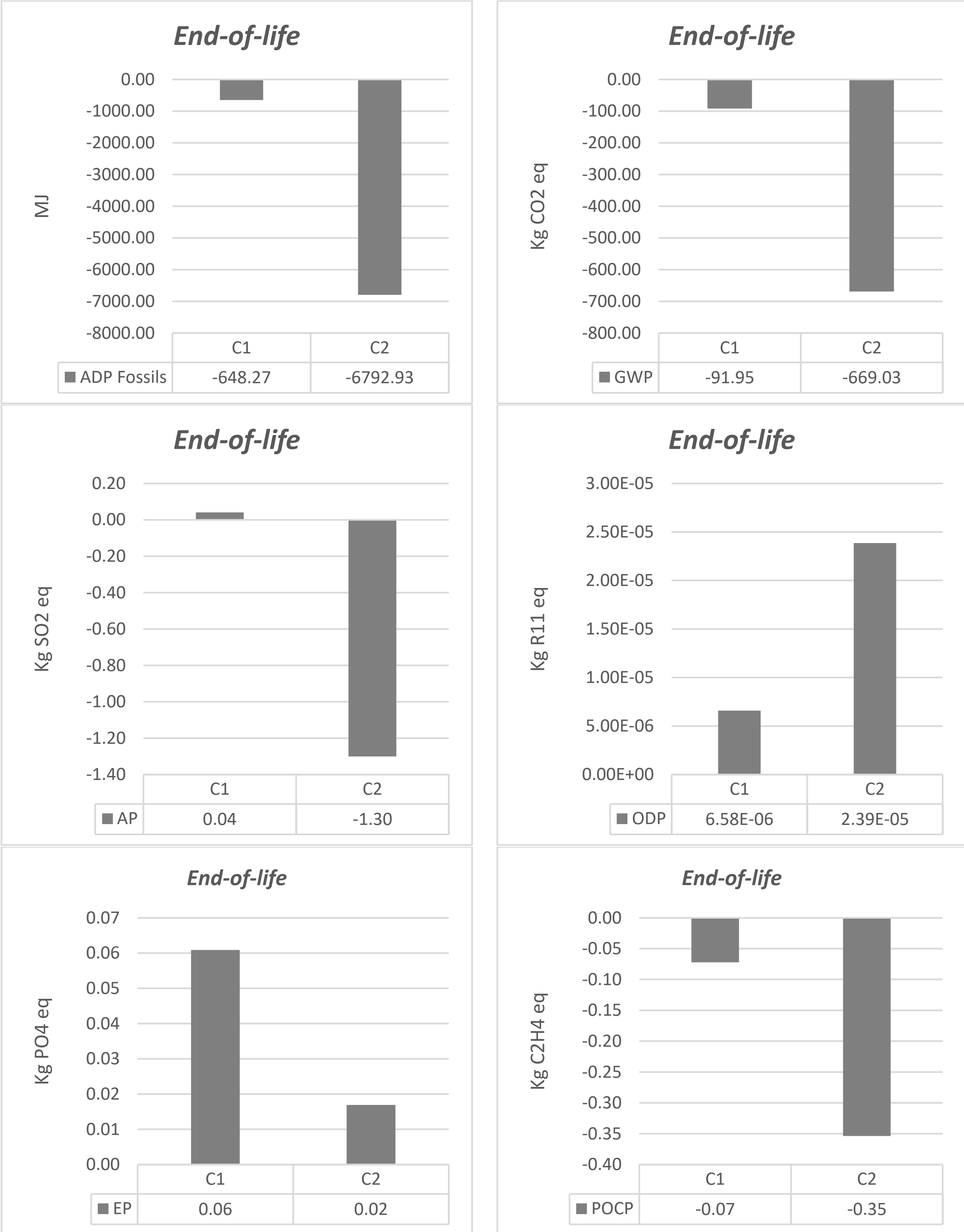


Figure 5.16 – Results of end-of-life stage normalised per m^2 of the deck

5.3.1.5 Aggregate results

To obtain the aggregate results, the emissions at all stages were summed up for each impact category.

Though the stage of material production has the greatest share in the aggregate results, the benefits gained from the recycling show the overall better performance for the case C2.

The aggregate results are presented in Figure 5.17. The values are normalised per m² of the deck.

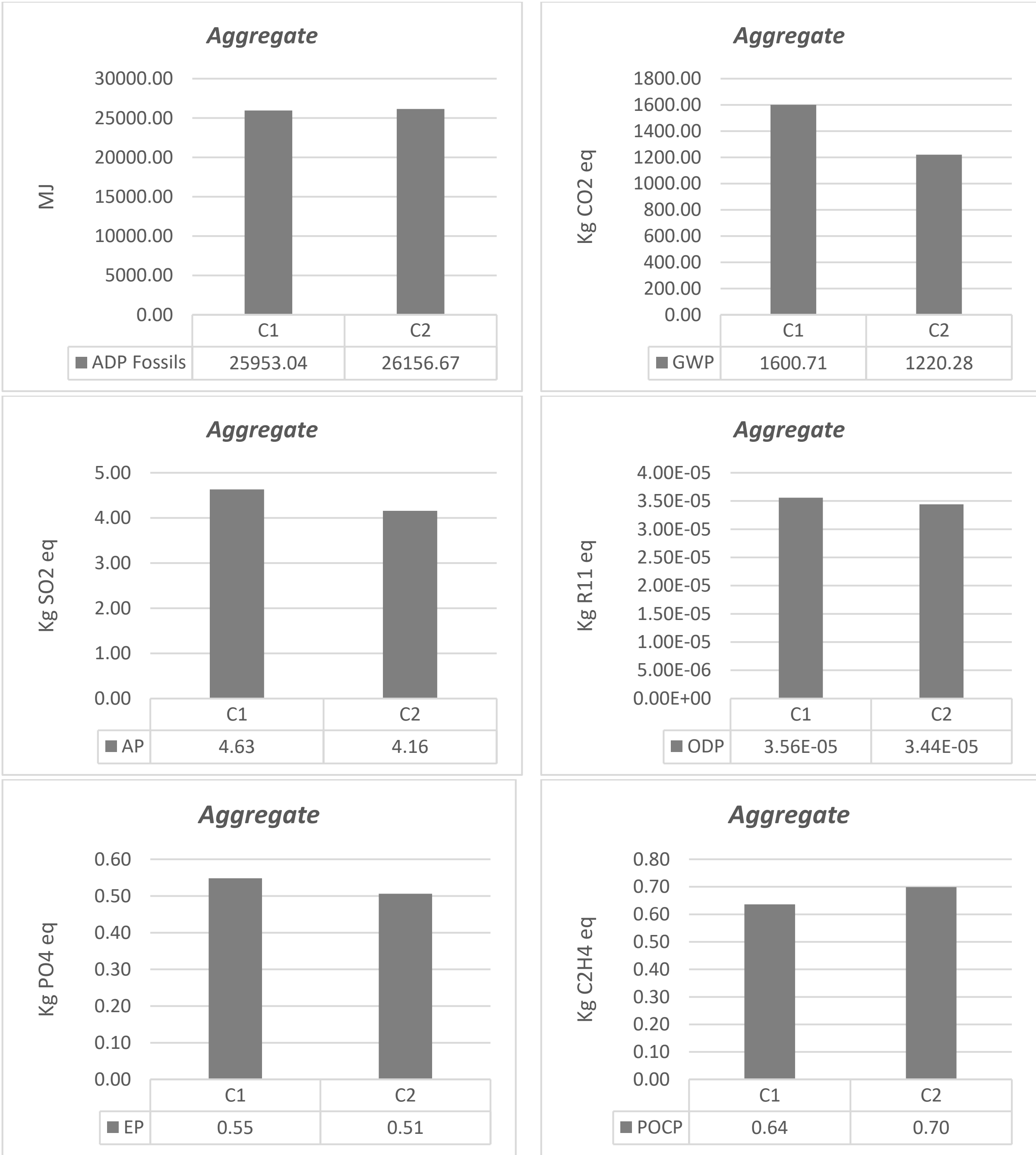


Figure 5.17 – Aggregate results normalised per m² of the deck

5.3.2 Life cycle social analysis (LCS)

The results of the life cycle social assessment are expressed in three indicators representing user costs, namely Driver's Delay Cost (DDC), Vehicle Operation Cost (VOC) and Accidental Cost (AC); the Total user cost was estimated as the sum of aforementioned costs.

The user costs are caused by the traffic congestion. For the bridges of the Type C, the user costs occur due to the traffic restriction caused by the maintenance events at operation stage.

All user costs exhibit a strong correlation, as all of them are traffic depended and rely on the same assumptions for the maintenance planning. The results of the life cycle social assessment are presented in Figure 5.18. The values are normalised per m^2 of the deck.

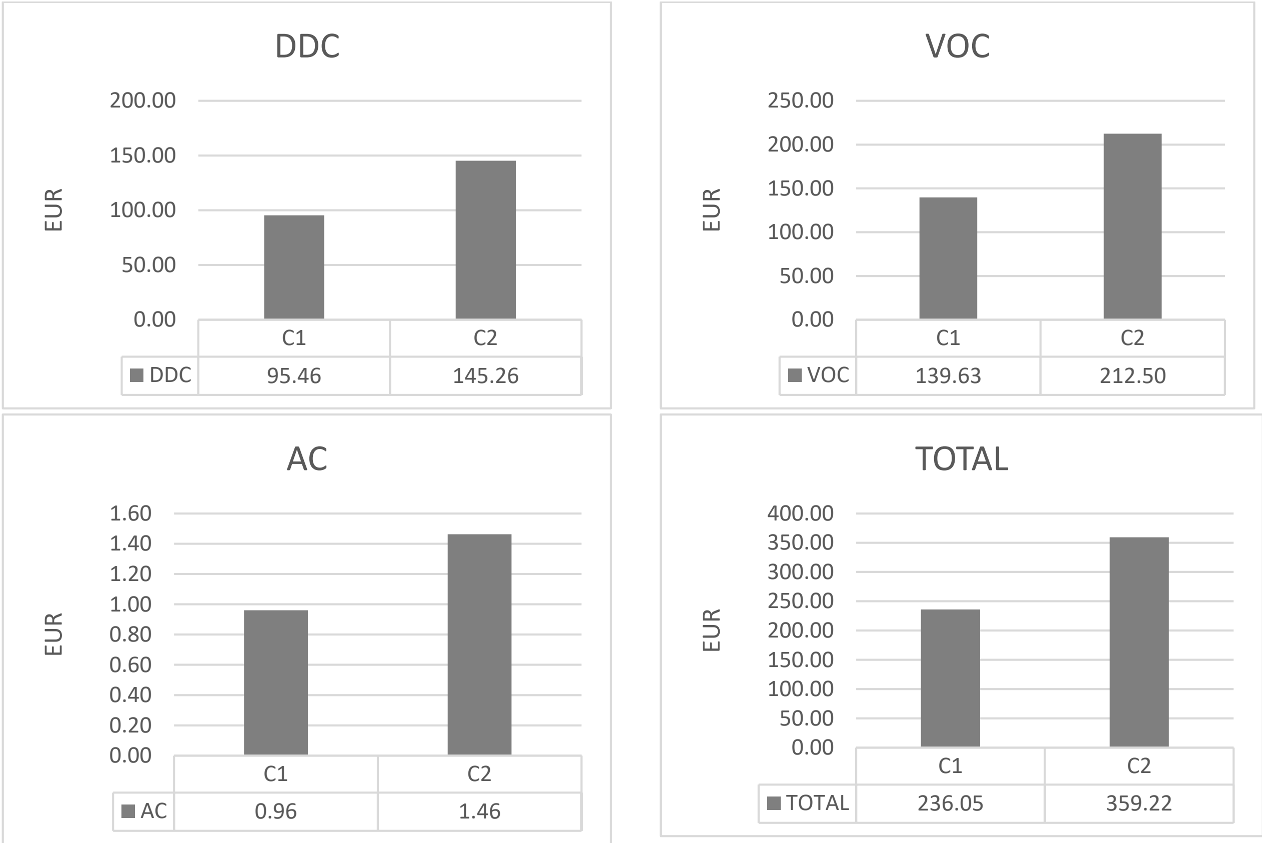


Figure 5.18 – Results of LCS of bridges of Type C normalised per m^2 of the deck

6 Results of the sustainable benchmarking

The results of the sustainable benchmarking are analysed in this chapter. The results are presented per each bridge Type and reflect the variability of the emissions observed in each group.

The excel calculation tool was developed in order to perform the statistical treatment of the data. To enable the comprehensive interpretation of the results, the box-whiskers plots are provided along with the relative results of the life cycle assessment. The benchmarks are established for the indicators normalized per m^2 of the area of the deck.

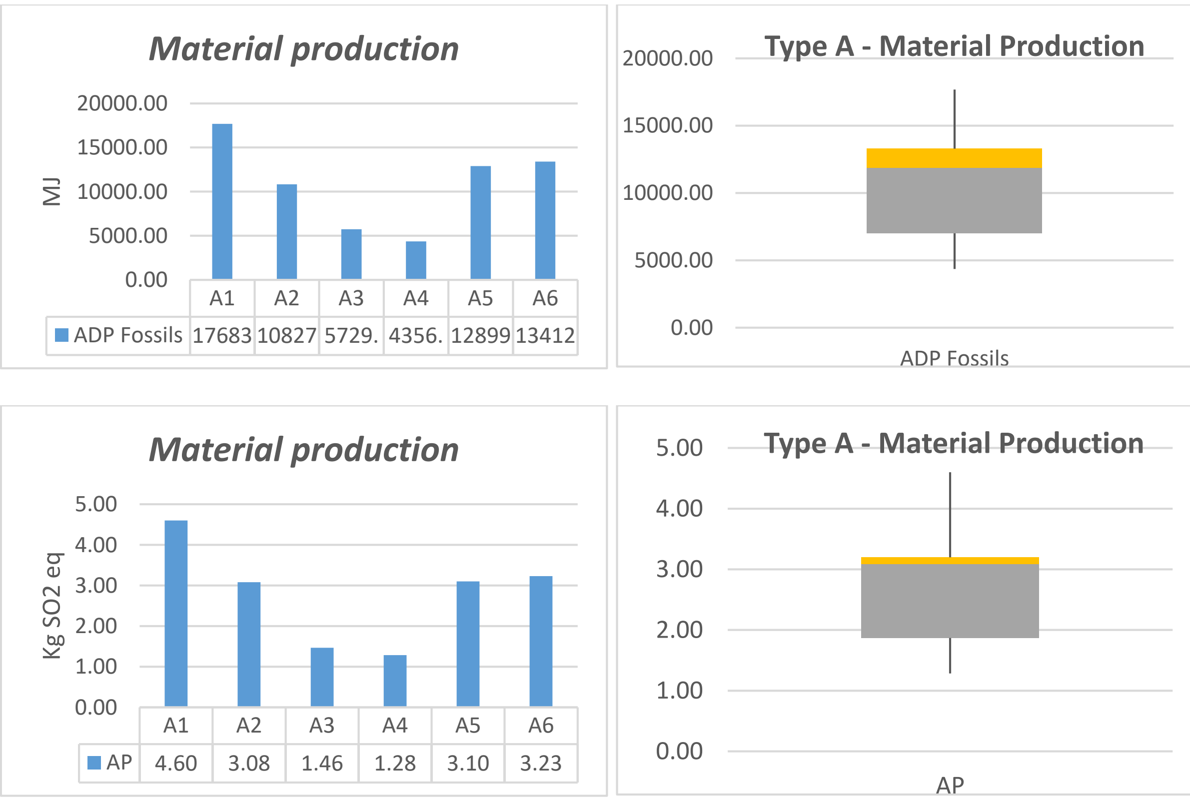
6.1 Bridges of Type A

6.1.1 Benchmarking of life cycle environmental assessment

6.1.1.1 Material production stage

The environmental benchmarking of the material production stage of the bridges of the Type A reflects the overall variability of the results of life cycle analysis. It also shows overall symmetry of the established values, as well as moderate values of the error bars. Less symmetry can be observed for the indicators of EP and GWP, while values for the AP are unfavourably skewed, which signifies, that greater effort for the achievement of the potential improvements towards the best practice should be made.

The results of the benchmarking along with the results of the life cycle environmental assessment at the material production stage are presented in Figure 6.1. The values are normalised per m^2 of the deck.



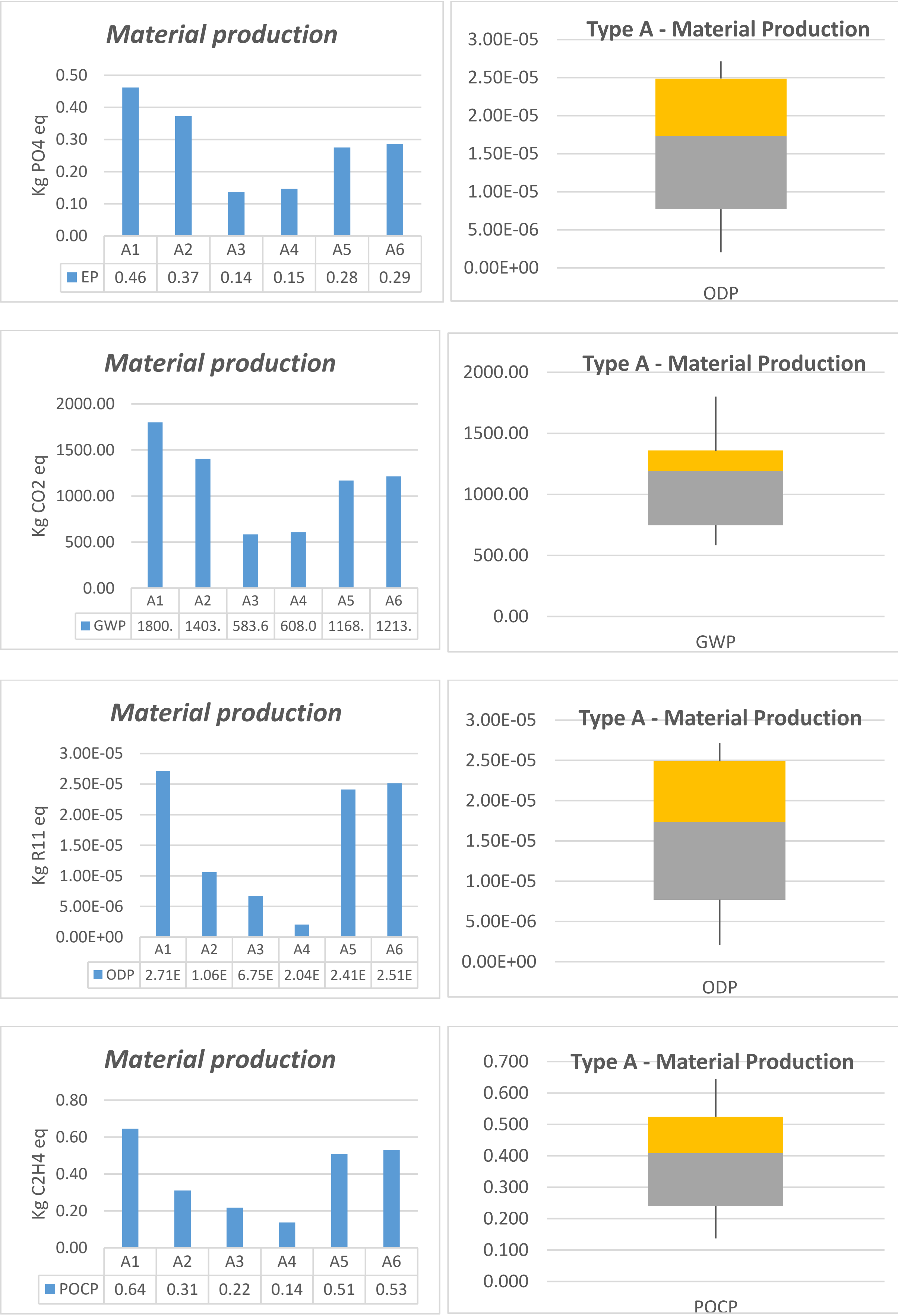


Figure 6.1 – Benchmarking of material production stage normalised per m^2 of the deck

6.1.1.2 Construction stage

In comparison to the stage of the material production, the results for the POCP draw the special attention, as they show significant scatter. For this indicator the value of the common practice is more than doubled in comparison to the best practice established.

The results of the benchmarking along with the results of the life cycle environmental assessment at the construction stage are presented in Figure 6.2. The values are normalised per m^2 of the deck.

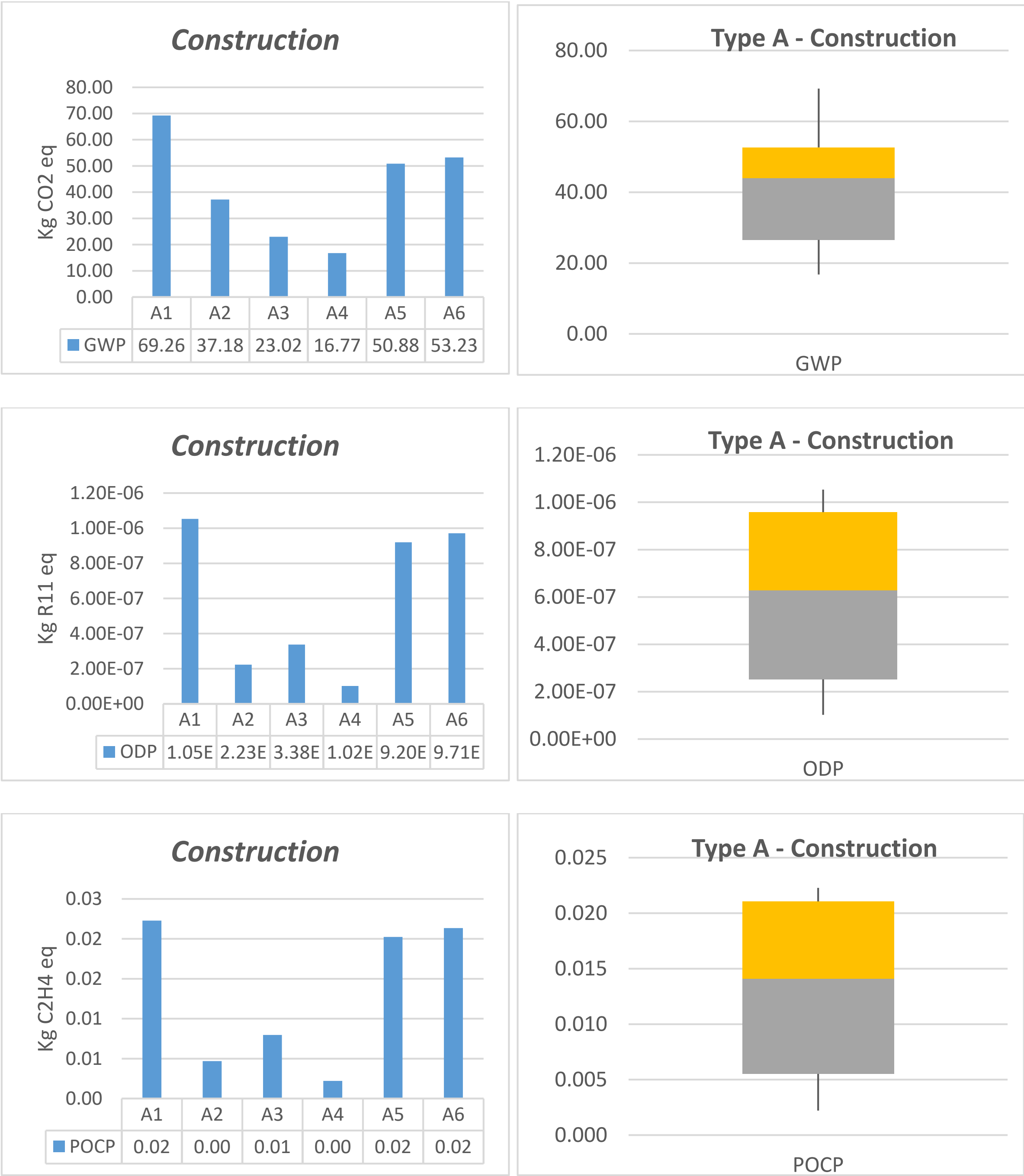


Figure 6.2 – Benchmarking of construction stage normalised per m^2 of the deck

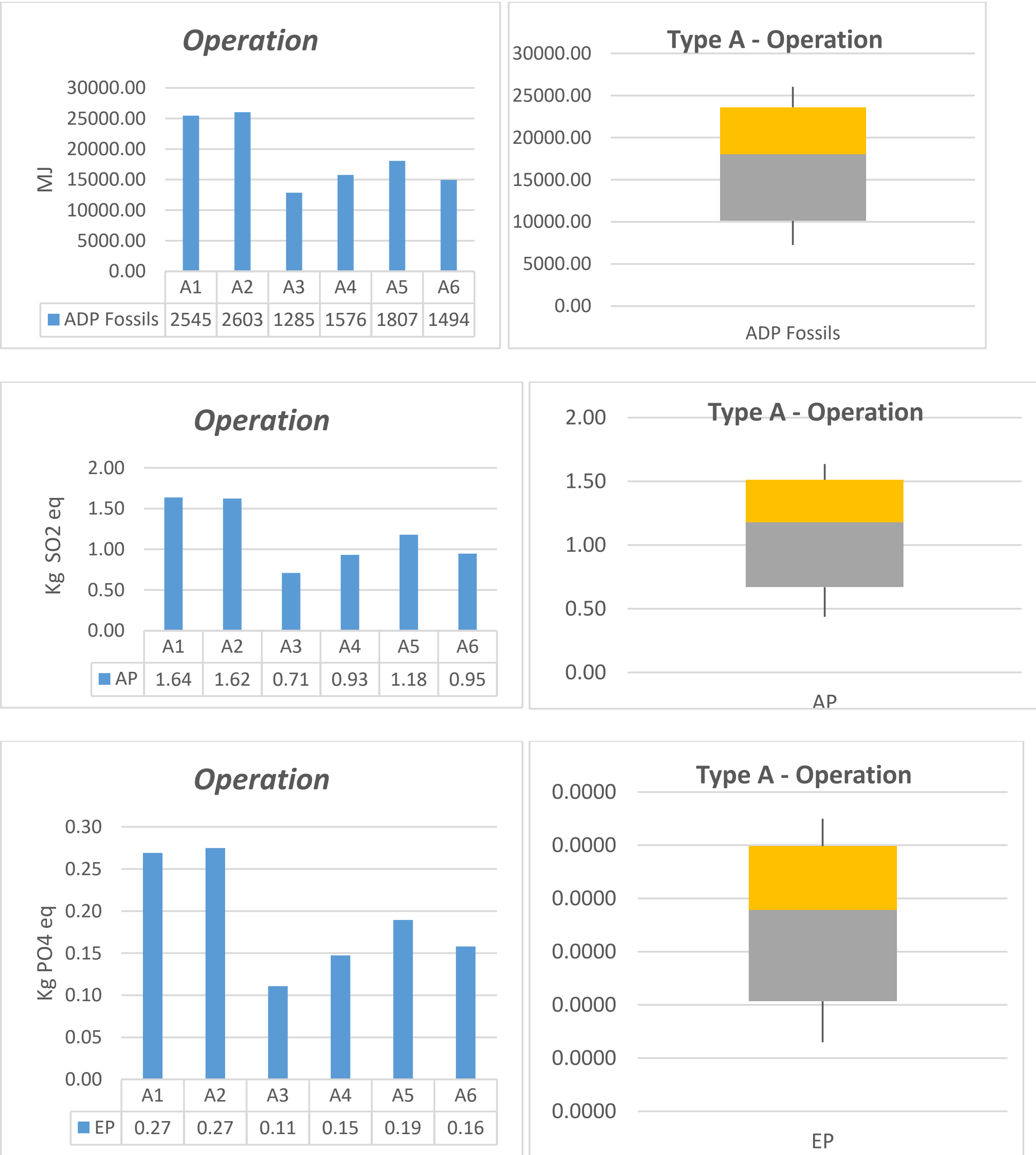
6.1.1.3 Operation stage

The benchmarks established for the operation stage show overall quite smooth distribution and moderate scatter, reflecting the distribution of the values established for the life cycle environmental assessment.

However, the considerably low ODP performance of the cases A3 and A4 lead to the significant skew of the data, quadrupling the value of the common practice, which otherwise would be quite homogeneous comparing with rest of the cases.

It is noteworthy, that the operation stage governs the life cycle performance, thus the bemchmarks established at this stage may be considered as one of the leading levels of the sustainable performance.

The results of the benchmarking along with the results of the life cycle environmental assessment at the operation stage are presented in Figure 6.3. The values are normalised per m^2 of the deck.



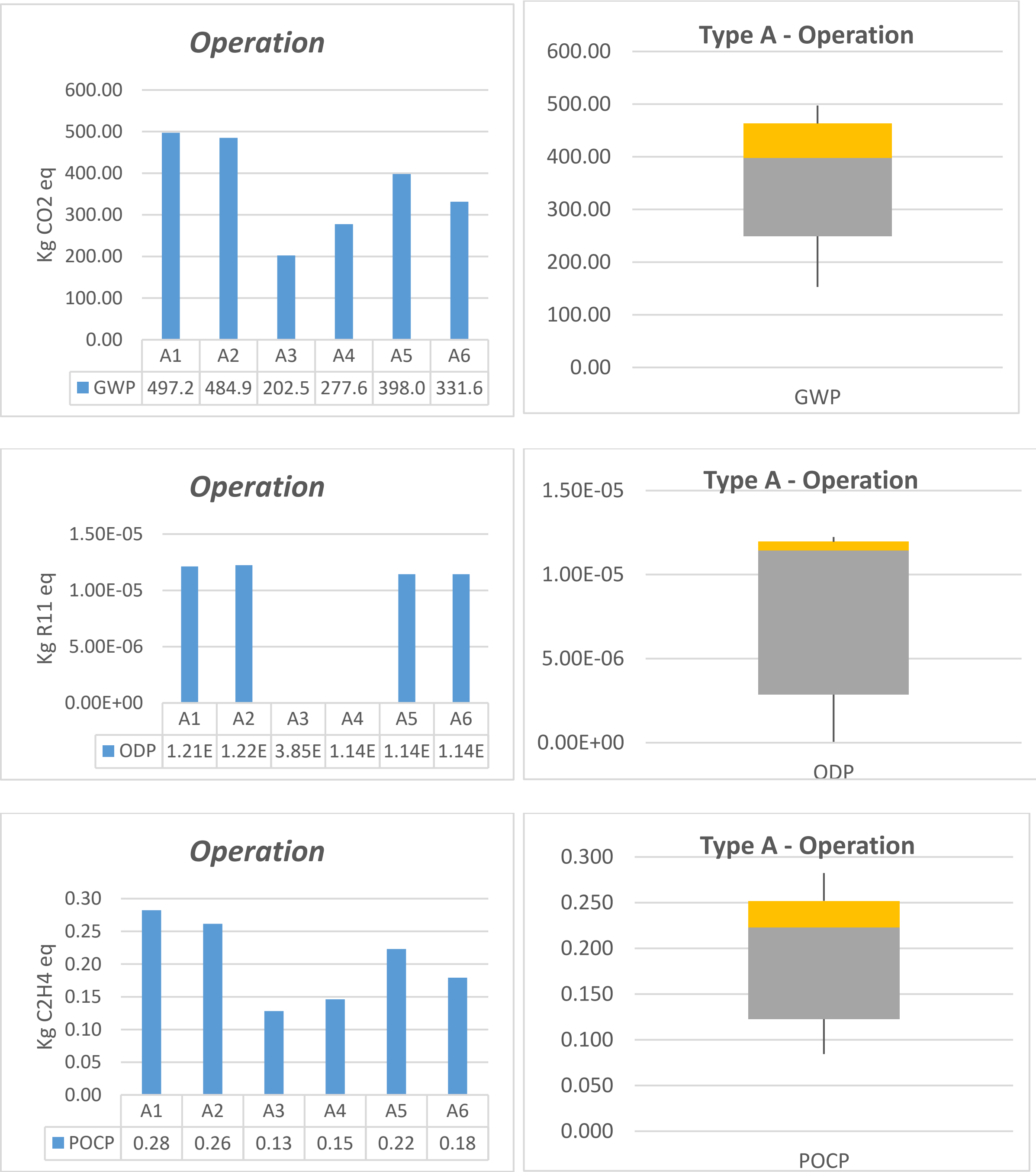


Figure 6.3 – Benchmarking of operation stage normalised per m^2 of the deck

6.1.1.4 End-of-life stage

The benchmarking of the performance of bridges of the Type A at the stage of the end-of-life shows (i) quite low and (ii) quite close values for the common and best practice for all of the cases except ODP performance. This can be explained by the dominance of the composite bridges in the set of considered values, as it shows low values for the indicators meaning the benefit coming from the recycling of the steel. As the ODP performance, conversely, governed by the concrete bridges, it exhibits relatively large scatter of the data as well as significant error bars due to controversial nature of the performance of chosen indicators.

The results of the benchmarking along with the results of the life cycle environmental assessment at the end-of-life stage are presented in Figure 6.4. The values are normalised per m^2 of the deck.

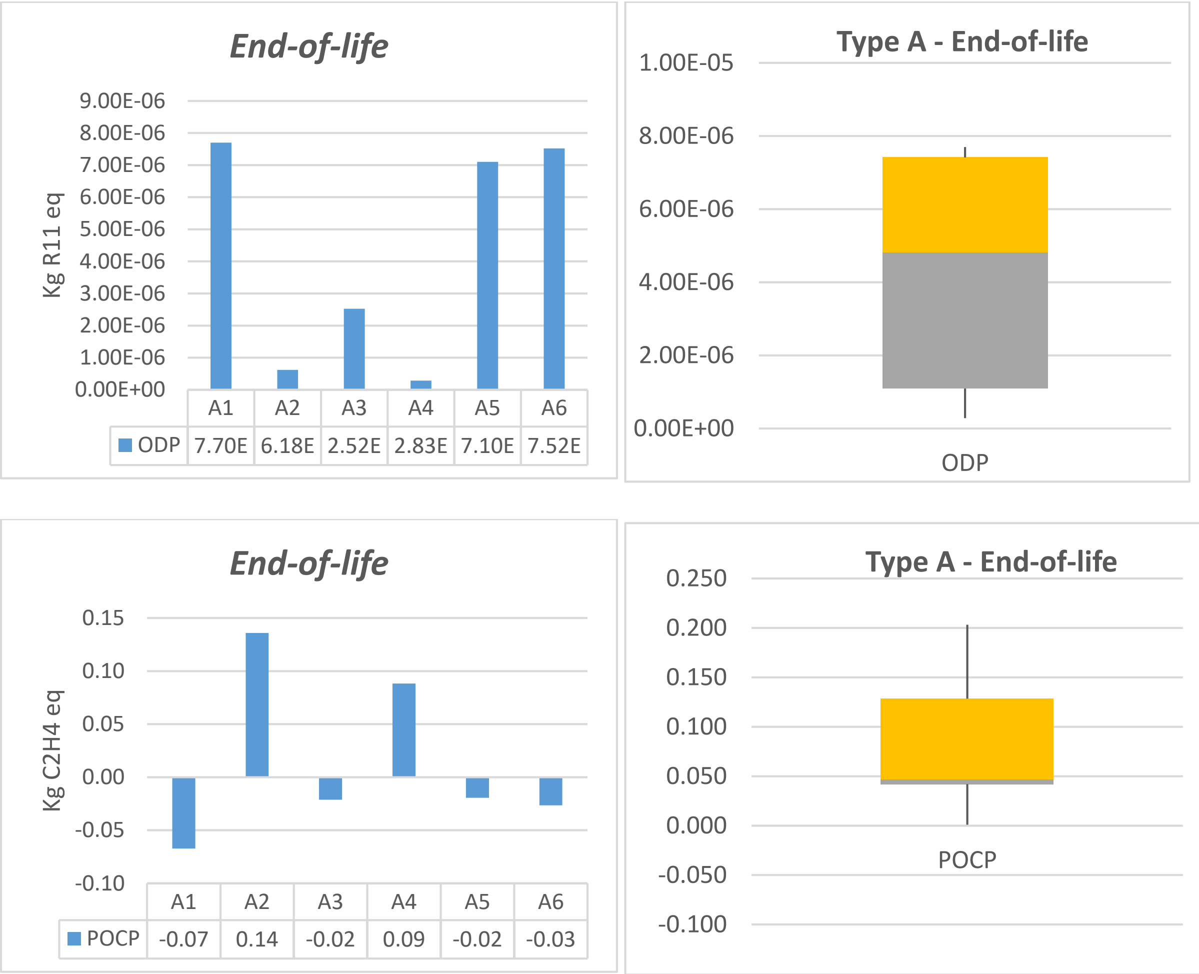
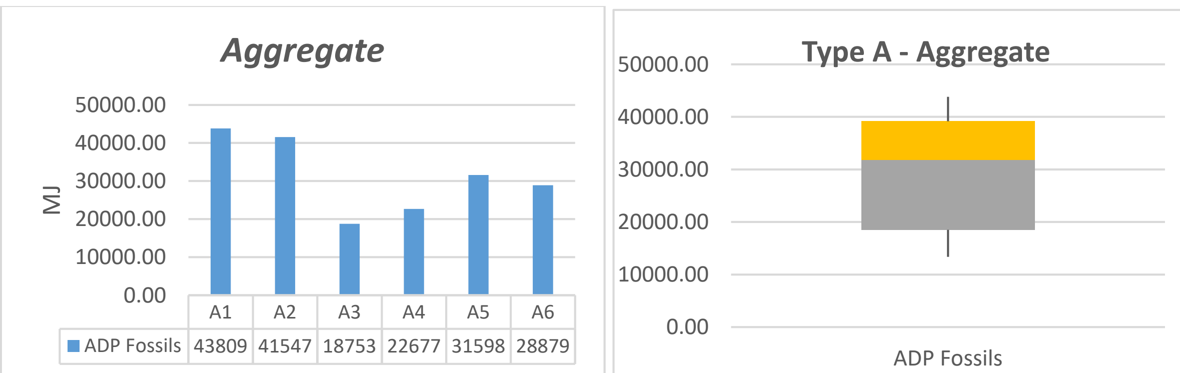


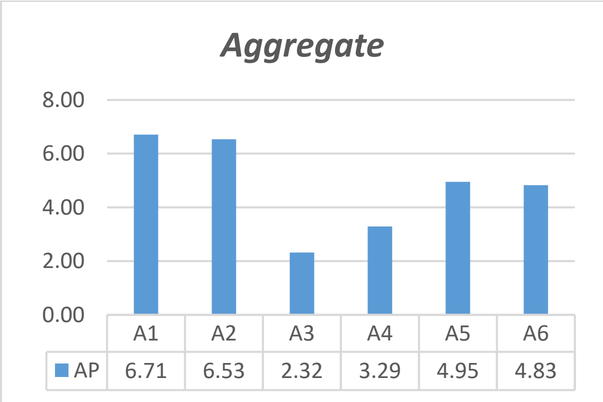
Figure 6.4 – Benchmarking of end-of-life stage normalised per m² of the deck

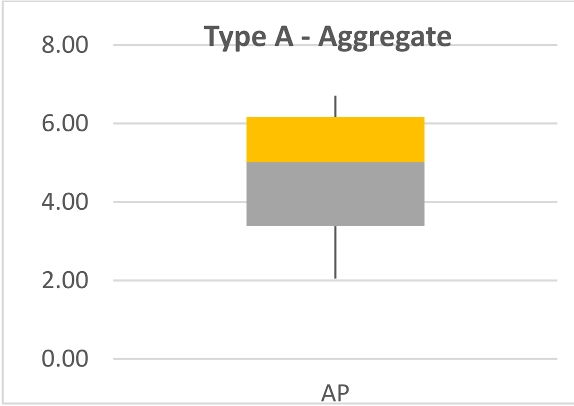
6.1.1.5 Aggregate results

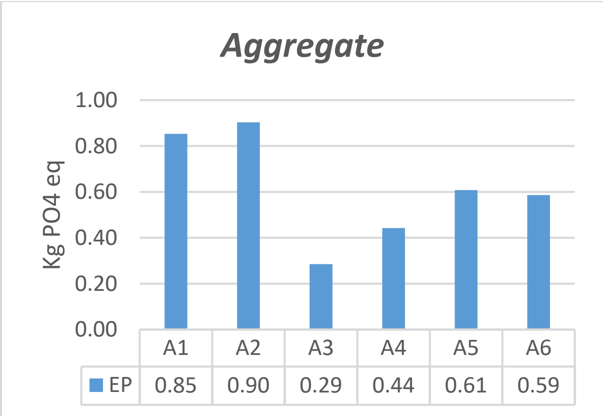
Considering the aggregate performance, it shows symmetrical distribution with the moderate scatter of the data for ADP fossils, AP, EP and GWP. However, the performance of the indicators of ODP and POCP is unfavourably skewed, almost doubling the performance level of the common practice, which implies significant effort to be made in order to potentially improve the sustainable performance of the bridge.

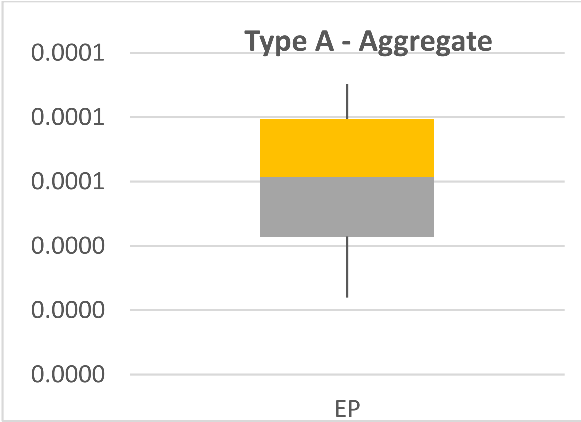
The results of the benchmarking along with the results of the aggregate results of the life cycle environmental assessment are presented in Figure 6.5. The values are normalised per m² of the deck.

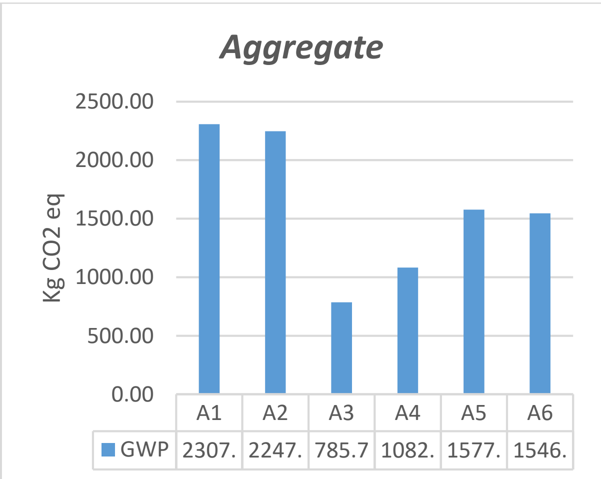


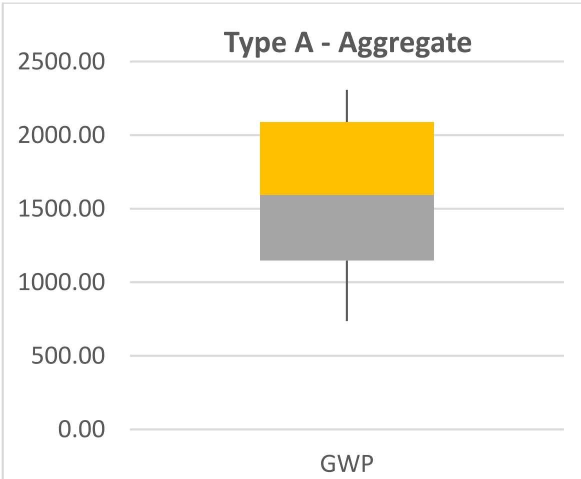

Aggregate
8.00
6.00
4.00
2.00
0.00
A1 A2 A3 A4 A5 A6
AP 6.71 6.53 2.32 3.29 4.95 4.83

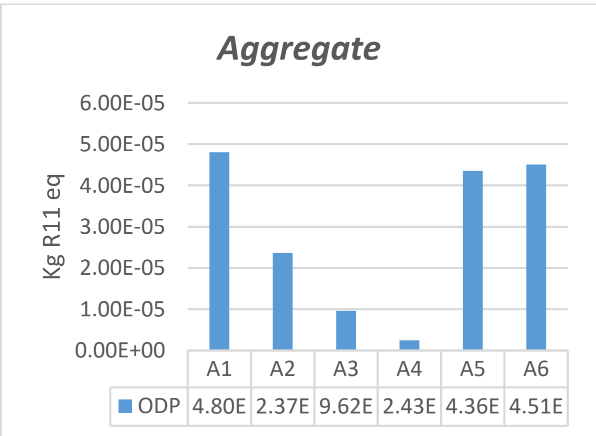

Type A - Aggregate
8.00
6.00
4.00
2.00
0.00
AP

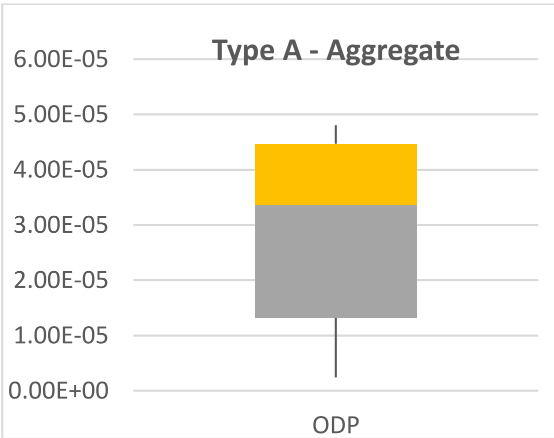

Aggregate
Kg PO4 eq
1.00
0.80
0.60
0.40
0.20
0.00
A1 A2 A3 A4 A5 A6
EP 0.85 0.90 0.29 0.44 0.61 0.59


Type A - Aggregate
0.0001
0.0001
0.0001
0.0000
0.0000
0.0000
EP


Aggregate
Kg CO2 eq
2500.00
2000.00
1500.00
1000.00
500.00
0.00
A1 A2 A3 A4 A5 A6
GWP 2307. 2247. 785.7 1082. 1577. 1546.


Type A - Aggregate
2500.00
2000.00
1500.00
1000.00
500.00
0.00
GWP


Aggregate
Kg R11 eq
6.00E-05
5.00E-05
4.00E-05
3.00E-05
2.00E-05
1.00E-05
0.00E+00
A1 A2 A3 A4 A5 A6
ODP 4.80E 2.37E 9.62E 2.43E 4.36E 4.51E


Type A - Aggregate
6.00E-05
5.00E-05
4.00E-05
3.00E-05
2.00E-05
1.00E-05
0.00E+00
ODP

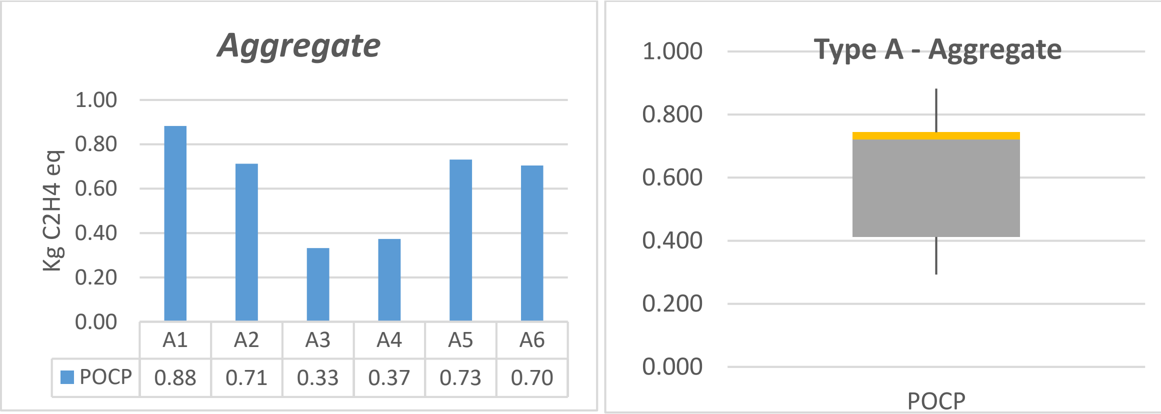
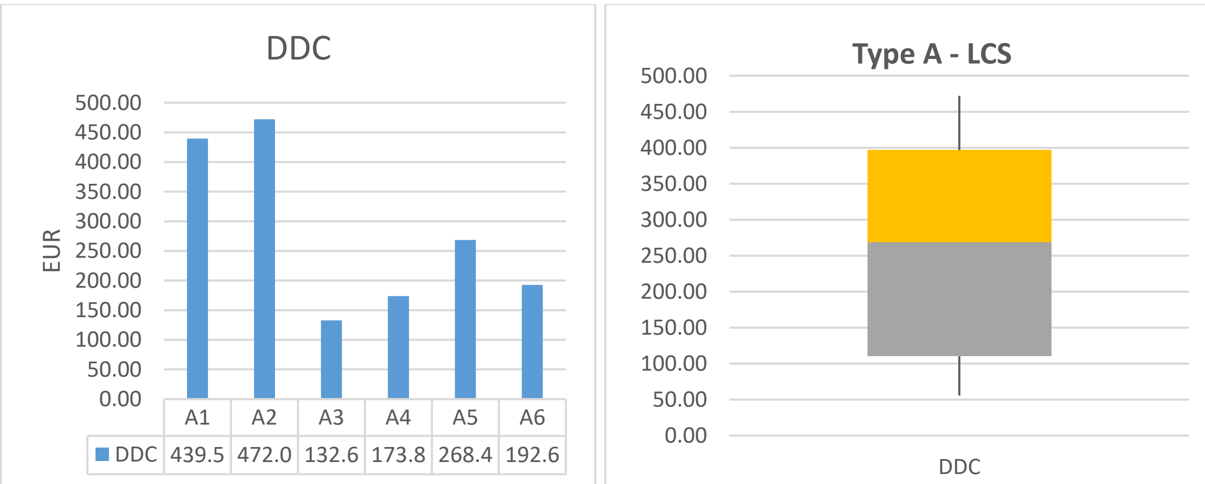


Figure 6.5 – Benchmarking of aggregate results of the life cycle environmental assessment normalised per m² of the deck

6.1.2 Benchmarking of life cycle social assessment

The results of the life cycle social benchmarking show the same pattern for all of the indicators, as the same trend was observed for the results of the life cycle assessment The established benchmarks for the bridges of type A show significant variability, as the established value for the common practice more than twice greater, then its respective best practice, meaning that greater effort should be put for the potential improvement of the results. However, this pattern can be justified by the fact that the case studies considered for the type A is represented by the bridges with quite different design considerations, namely the materials considered for the maintenance as well as the number of lanes.

The results of the benchmarking along with the results of the life cycle social assessment are presented in Figure 6.6. The values are normalised per m² of the deck.



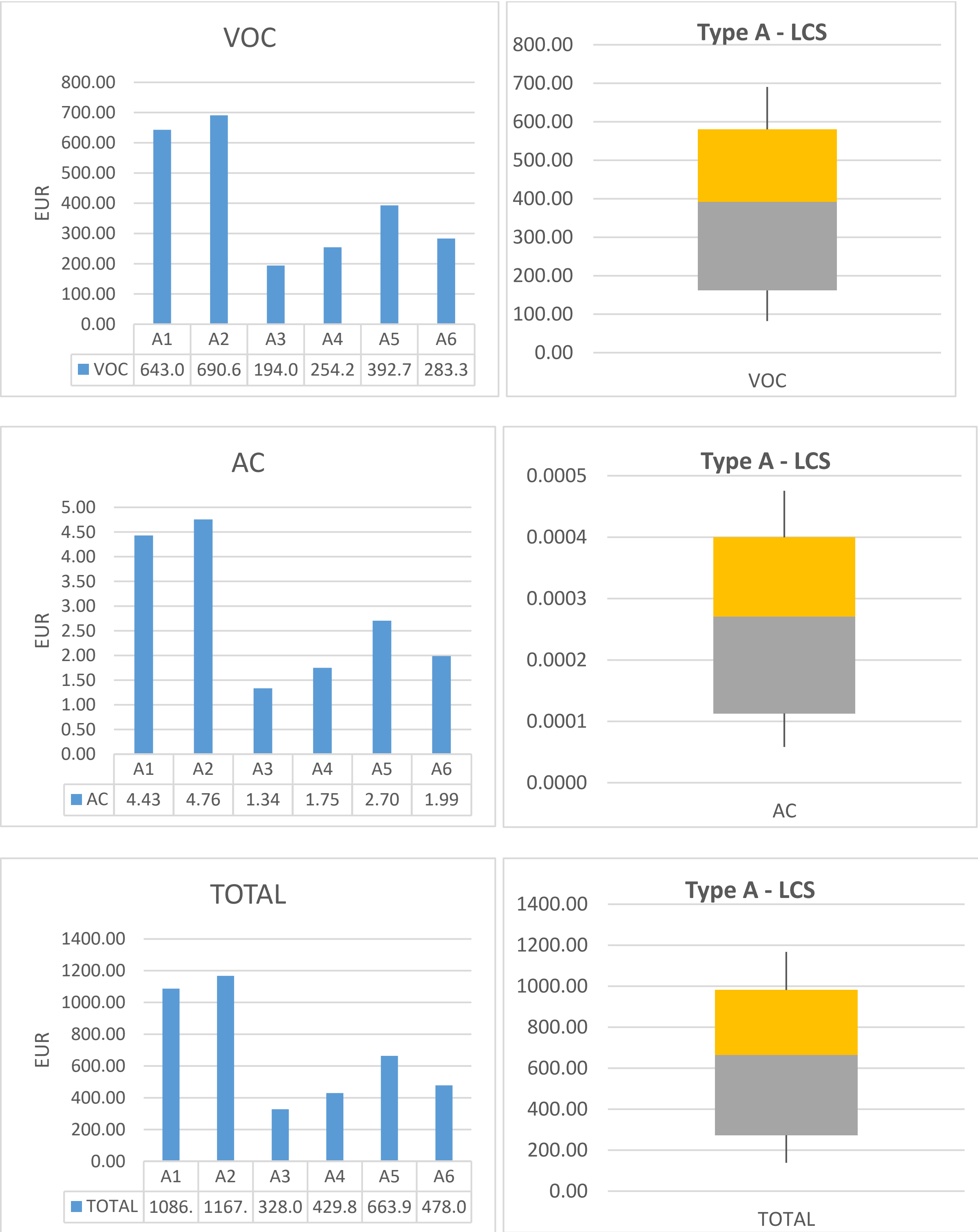


Figure 6.6 – Benchmarking of the life cycle social assessment normalised per m² of the deck

6.2 Bridges of Type B

Overall, the benchmarking of the results of both, life cycle environmental and life cycle social analysis show the small difference between common and best practice, meaning that following current design considerations, the high level of sustainable performance can be achieved.

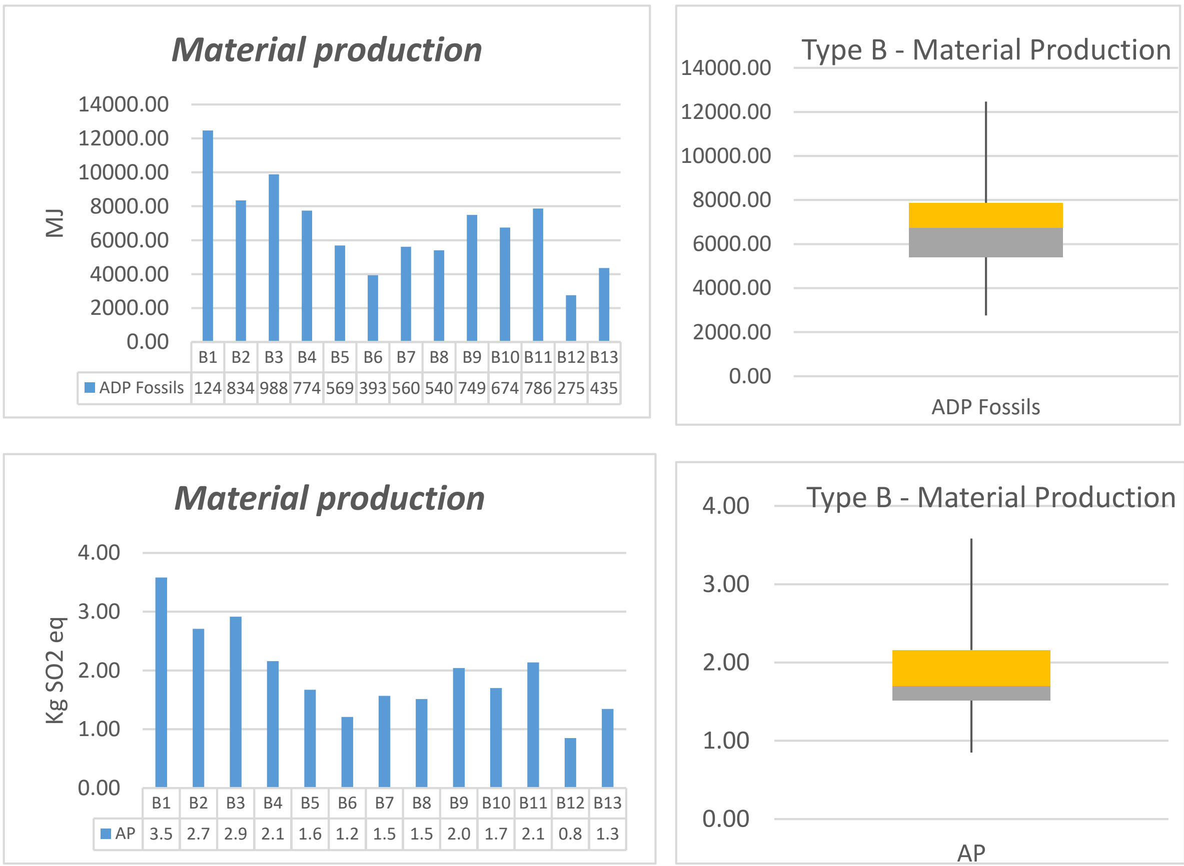
Such level of vicinity of the common and best practice was achieved despite the high deviation of the results, as can be seen from the significant value of the error bars of the box plot.

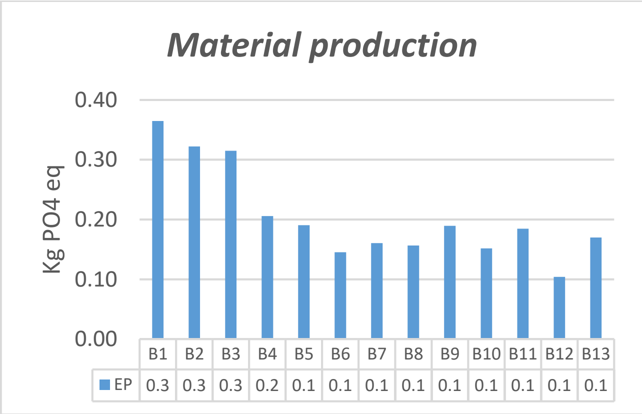
6.2.1 Environmental Life Cycle Assessment (LCA)

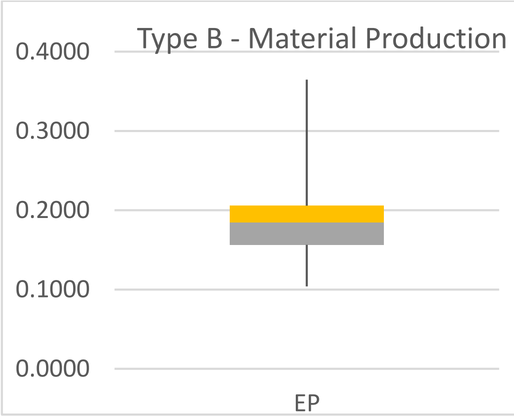
6.2.1.1 Material production stage

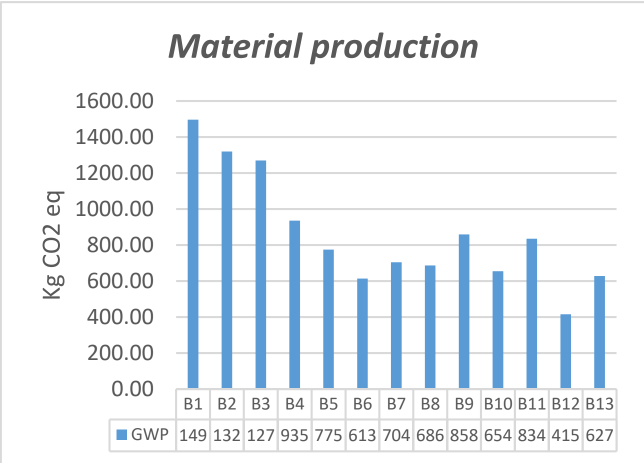
The stage of material production shows relatively close values for the conventional and best practice as the results of the moderate variability of the recorded emissions. However, the results exhibit significant deviation, comparing to the minimum and maximum values of the considered samples.

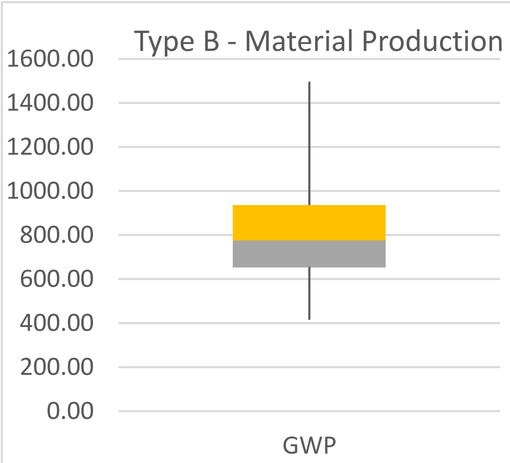
The results of the benchmarking along with the results of the life cycle environmental assessment at the material production stage are presented in Figure 6.7. The values are normalised per m^2 of the deck.

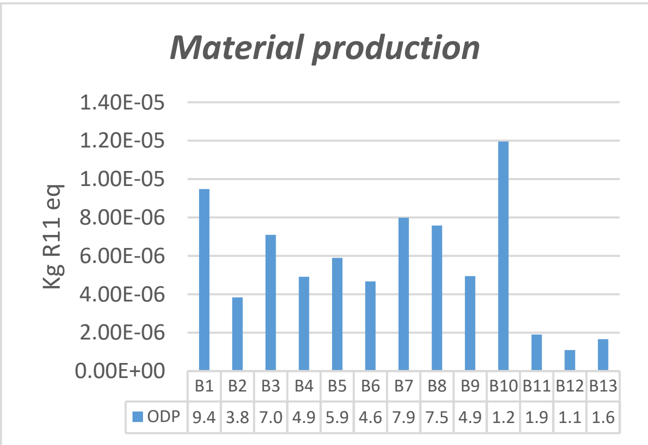


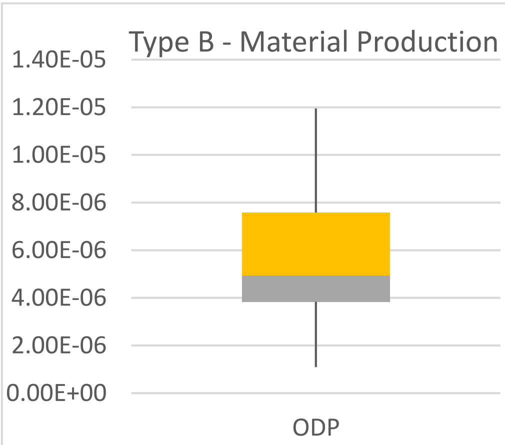

Material production
Kg PO4 eq
0.40
0.30
0.20
0.10
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 0.3 0.3 0.3 0.2 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1


Type B - Material Production
0.4000
0.3000
0.2000
0.1000
0.0000
EP


Material production
Kg CO2 eq
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 149 132 127 935 775 613 704 686 858 654 834 415 627


Type B - Material Production
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
GWP


Material production
Kg R11 eq
1.40E-05
1.20E-05
1.00E-05
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 9.4 3.8 7.0 4.9 5.9 4.6 7.9 7.5 4.9 1.2 1.9 1.1 1.6


Type B - Material Production
1.40E-05
1.20E-05
1.00E-05
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
ODP

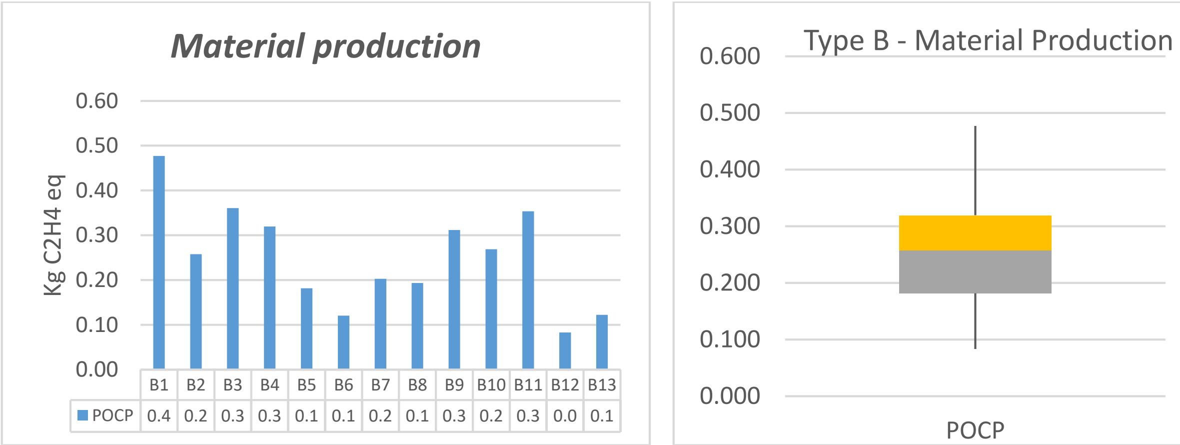
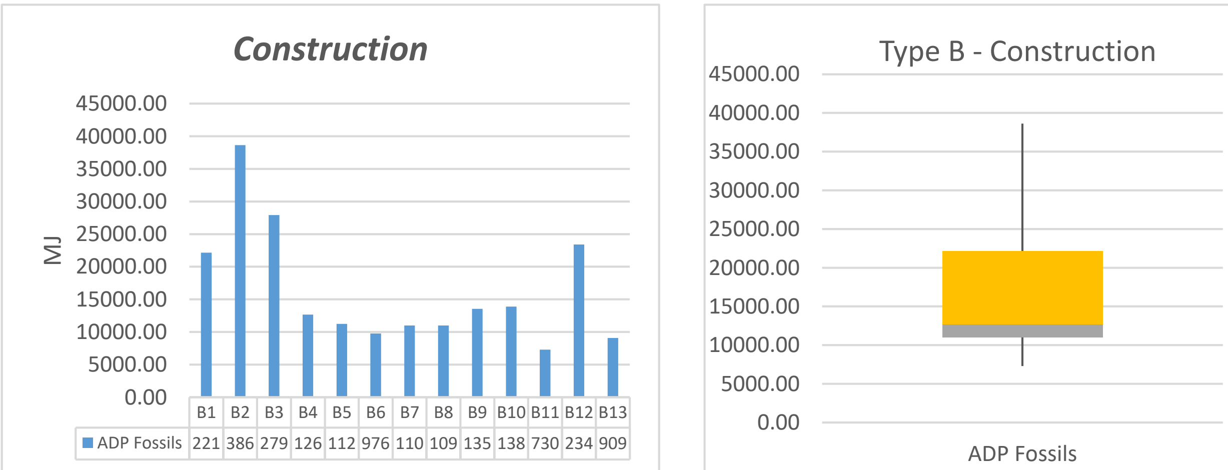


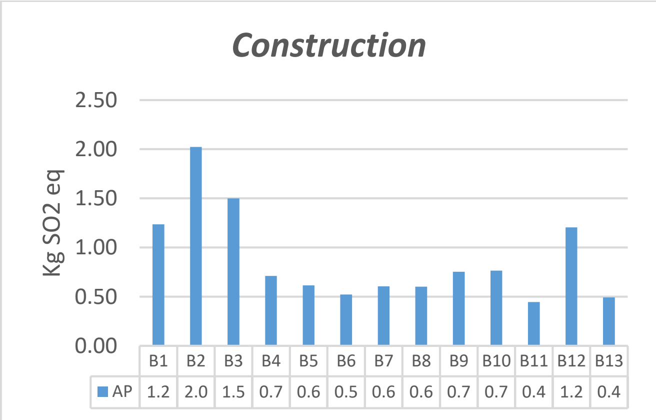
Figure 6.7 – Benchmarking of material production stage normalised per m^2 of the deck

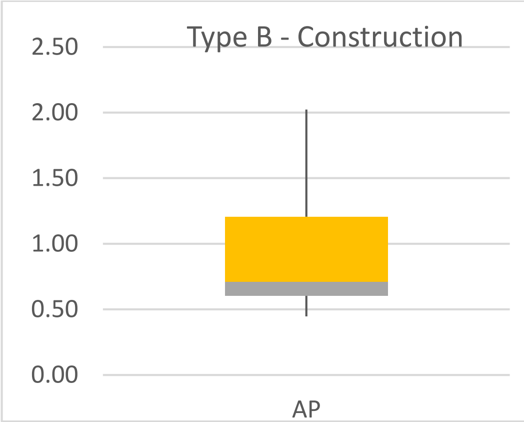
6.2.1.2 Construction stage

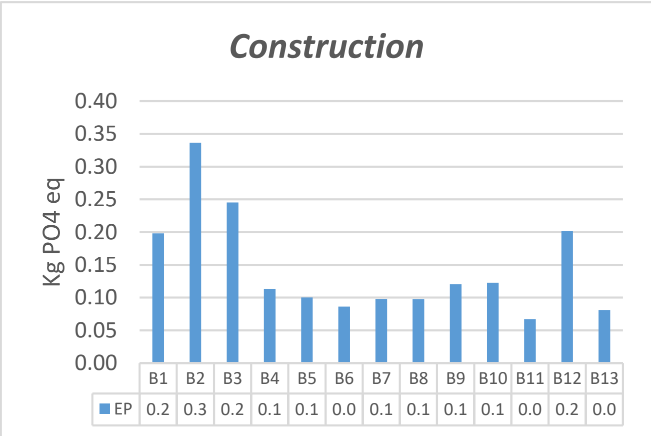
Similarly to the benchmarking of the indicators at the stage of material production, the results for the stage of construction show close values for the conventional and best practice. Here, at this stage, the upper limit is affected by the distinctly high values of the emissions evaluated for the cases B1, B2 and B3.

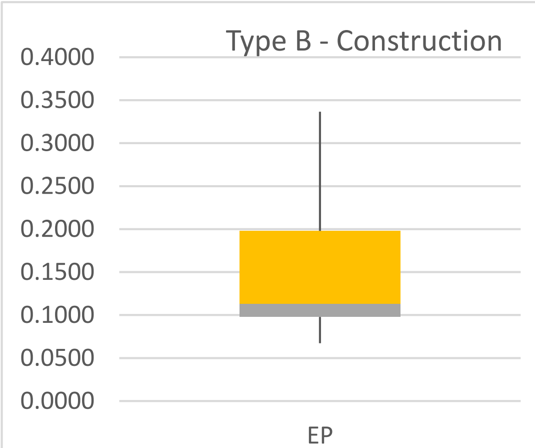
The results of the benchmarking along with the results of the life cycle environmental assessment at the construction stage are presented in Figure 6.8. The values are normalised per m^2 of the deck.

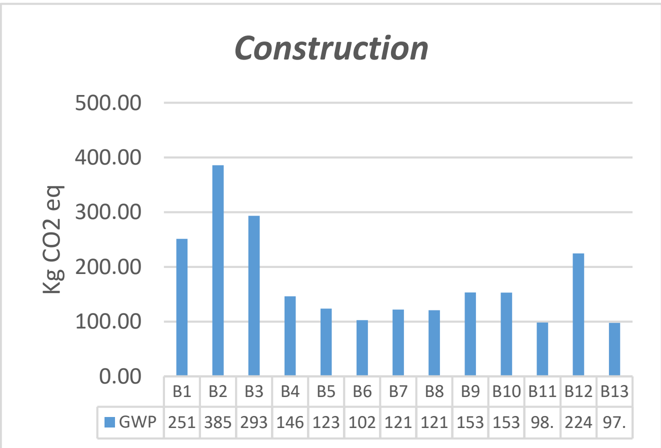


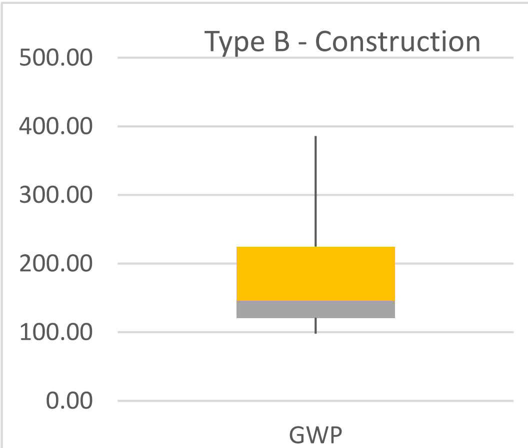

Construction
Kg SO2 eq
2.50
2.00
1.50
1.00
0.50
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
AP 1.2 2.0 1.5 0.7 0.6 0.5 0.6 0.6 0.7 0.7 0.4 1.2 0.4

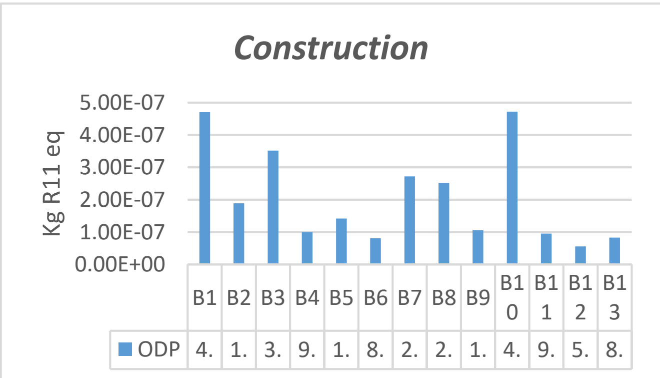

Type B - Construction
2.50
2.00
1.50
1.00
0.50
0.00
AP

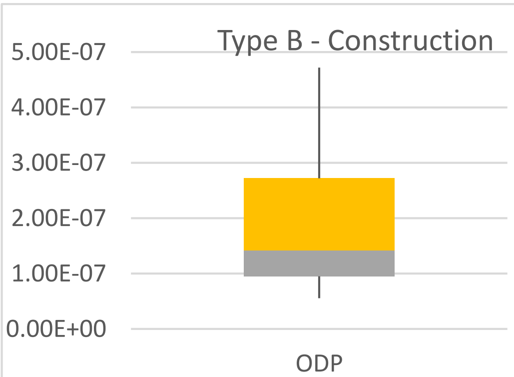

Construction
Kg PO4 eq
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 0.2 0.3 0.2 0.1 0.1 0.0 0.1 0.1 0.1 0.1 0.0 0.2 0.0


Type B - Construction
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
EP


Construction
Kg CO2 eq
500.00
400.00
300.00
200.00
100.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 251 385 293 146 123 102 121 121 153 153 98. 224 97.


Type B - Construction
500.00
400.00
300.00
200.00
100.00
0.00
GWP


Construction
Kg R11 eq
5.00E-07
4.00E-07
3.00E-07
2.00E-07
1.00E-07
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 4. 1. 3. 9. 1. 8. 2. 2. 1. 4. 9. 5. 8.


Type B - Construction
5.00E-07
4.00E-07
3.00E-07
2.00E-07
1.00E-07
0.00E+00
ODP

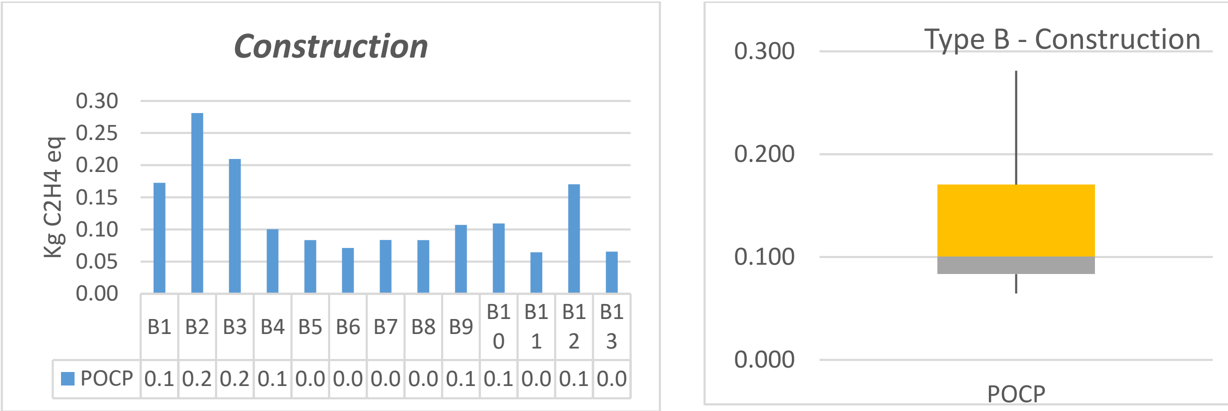


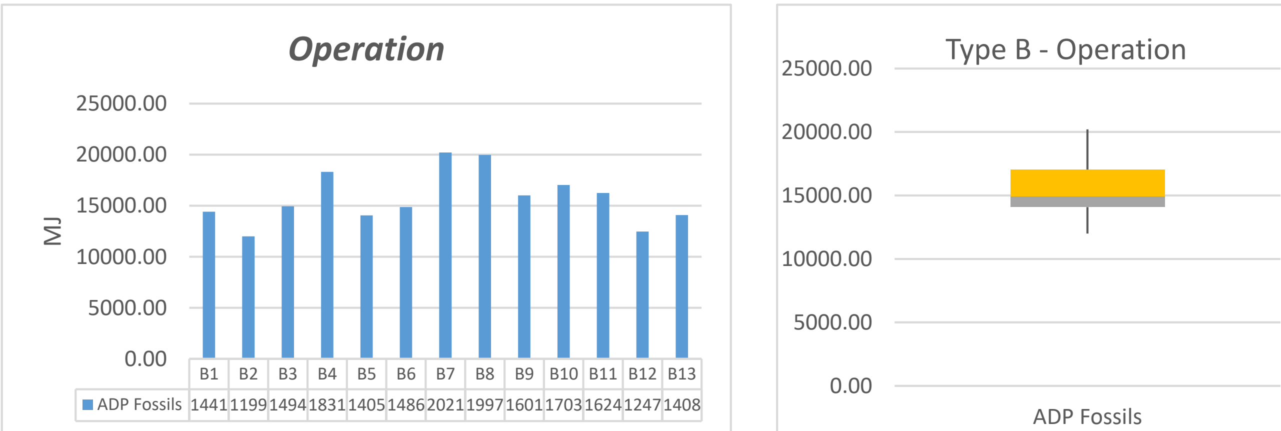
Figure 6.8 – Benchmarking of construction stage normalised per m² of the deck

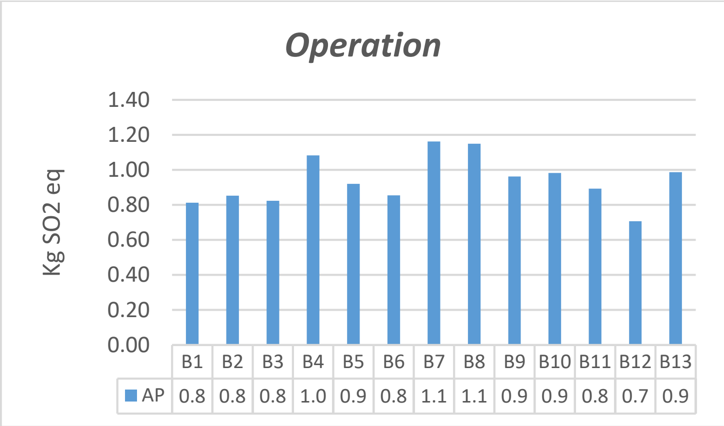
6.2.1.3 Operation stage

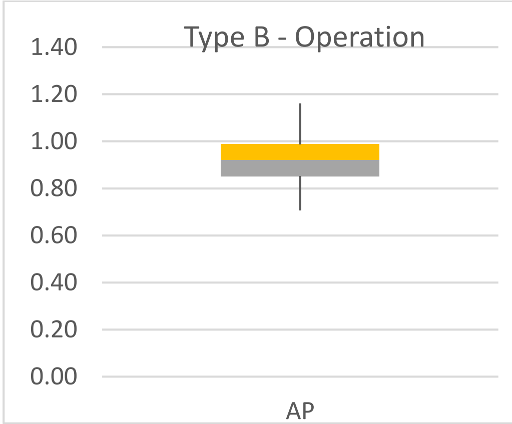
The results at the stage of operation show overall moderate scatter and relatively small deviation.

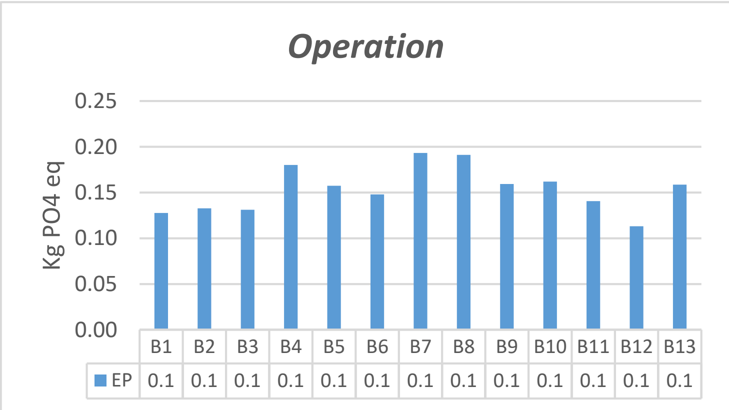
The great difference between common and best practice observed for the ODP is related to the fact, that nearly half of the cases show drastically lower values of the emissions.

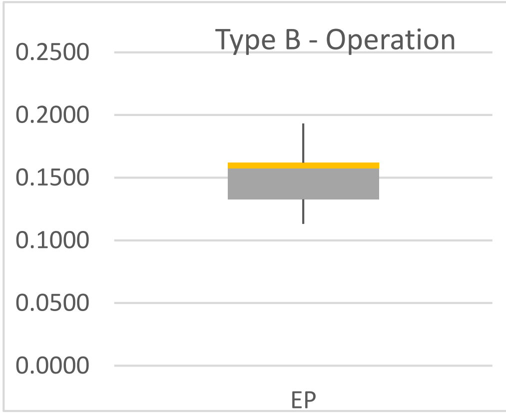
The results of the benchmarking along with the results of the life cycle environmental assessment at the operation stage are presented in Figure 6.9. The values are normalised per m² of the deck.

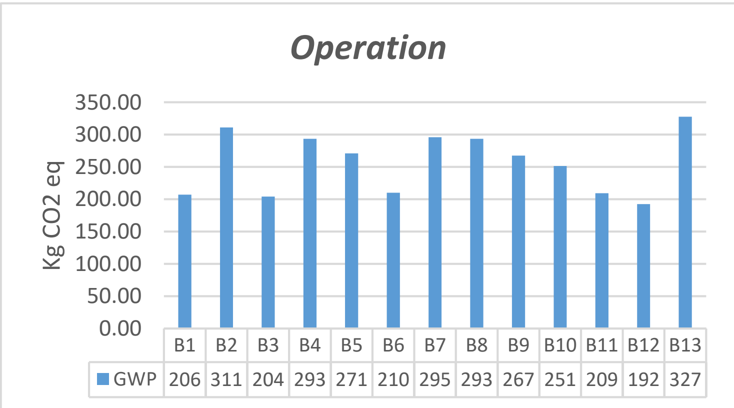


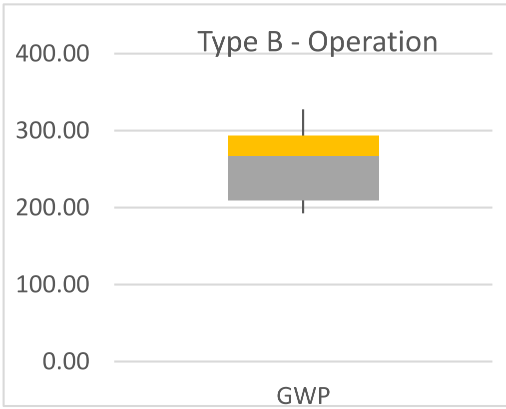

Operation
Kg SO2 eq
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
AP 0.8 0.8 0.8 1.0 0.9 0.8 1.1 1.1 0.9 0.9 0.8 0.7 0.9

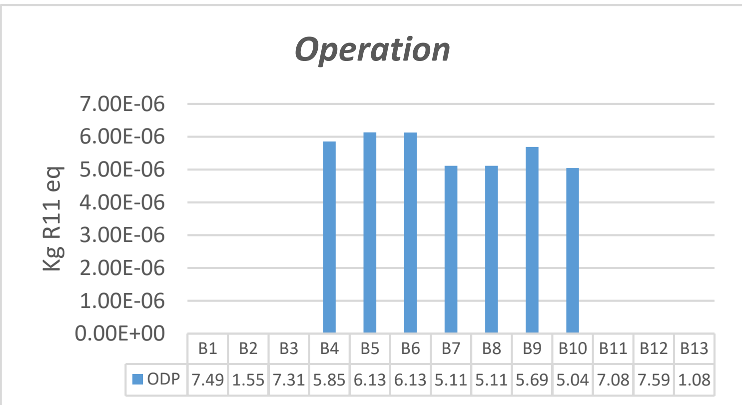

Type B - Operation
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
AP

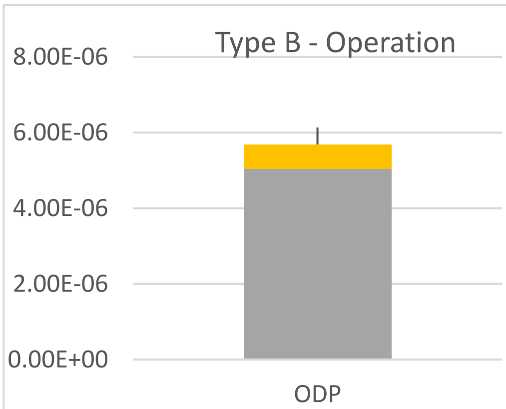

Operation
Kg PO4 eq
0.25
0.20
0.15
0.10
0.05
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1


Type B - Operation
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
EP


Operation
Kg CO2 eq
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 206 311 204 293 271 210 295 293 267 251 209 192 327


Type B - Operation
400.00
300.00
200.00
100.00
0.00
GWP


Operation
Kg R11 eq
7.00E-06
6.00E-06
5.00E-06
4.00E-06
3.00E-06
2.00E-06
1.00E-06
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 7.49 1.55 7.31 5.85 6.13 6.13 5.11 5.11 5.69 5.04 7.08 7.59 1.08


Type B - Operation
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
ODP

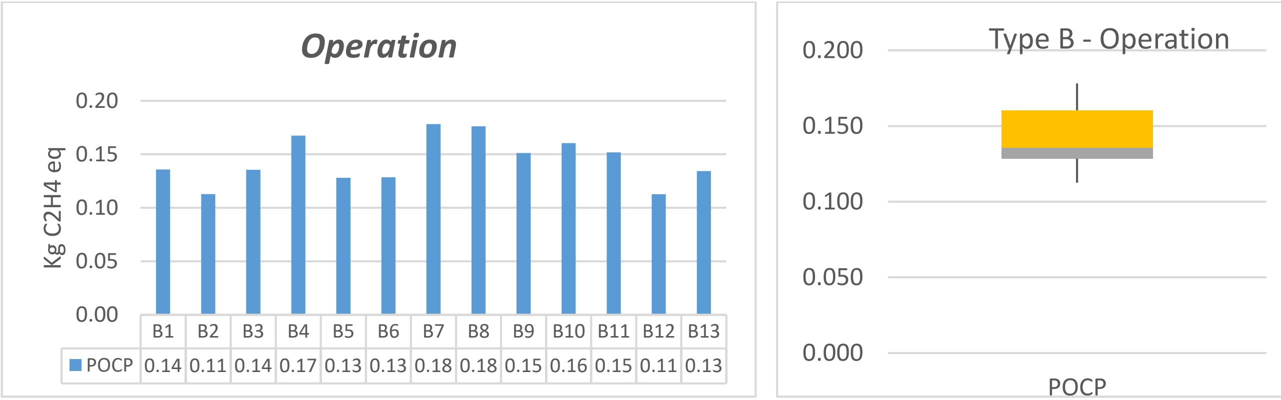
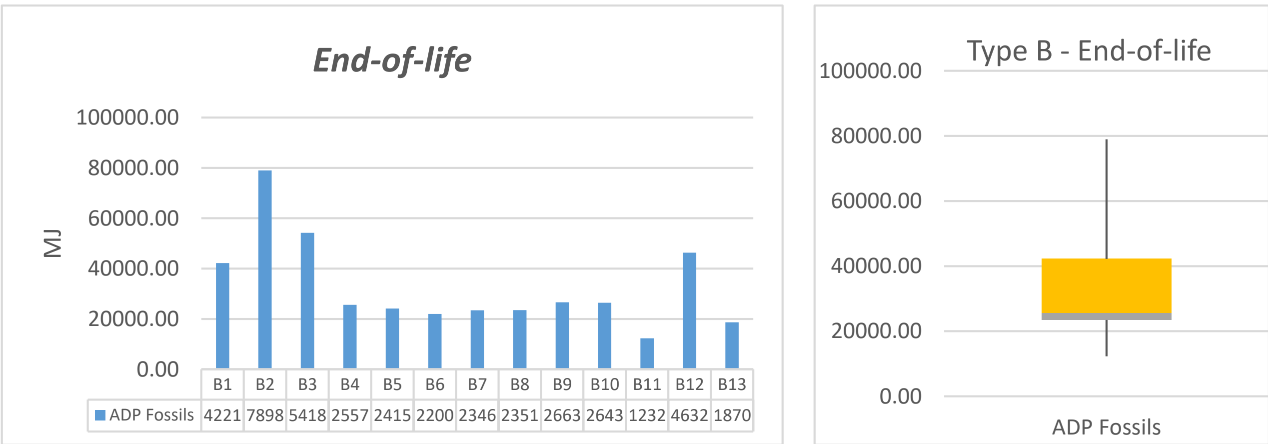


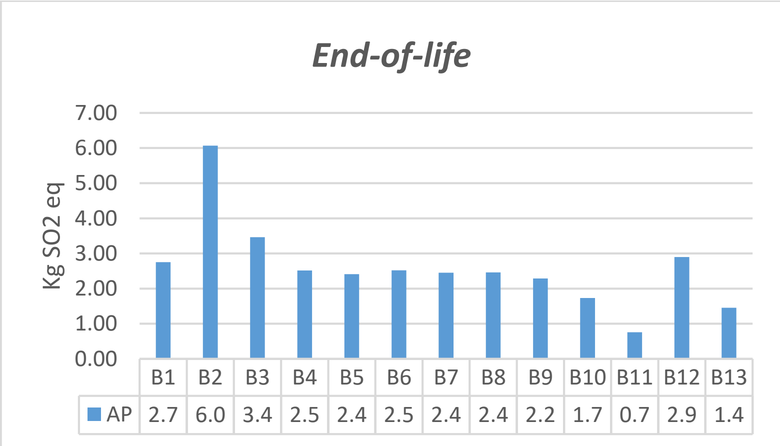
Figure 6.9 – Benchmarking of operation stage normalised per m^2 of the deck

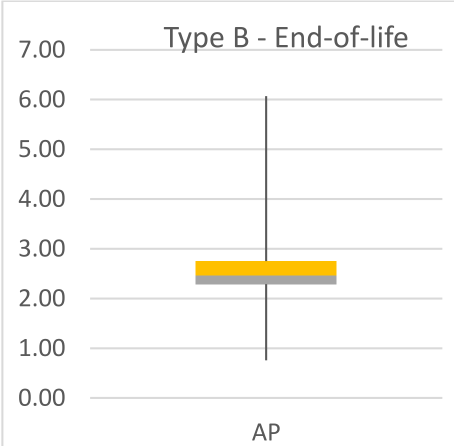
6.2.1.4 End-of-life stage

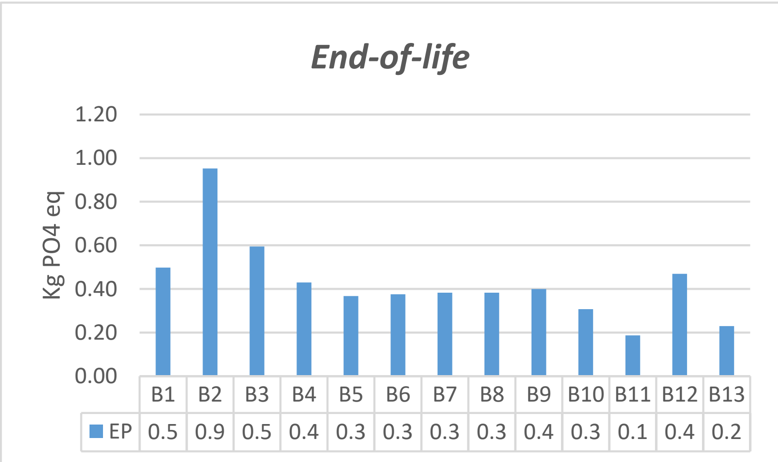
Overall, the results show quite close values for common and best practice. The great deviation is caused by the fact, that concrete and composite bridges have controversial performance from the point of view of recycling and disposal, which is escalated the most for the case of ODP.

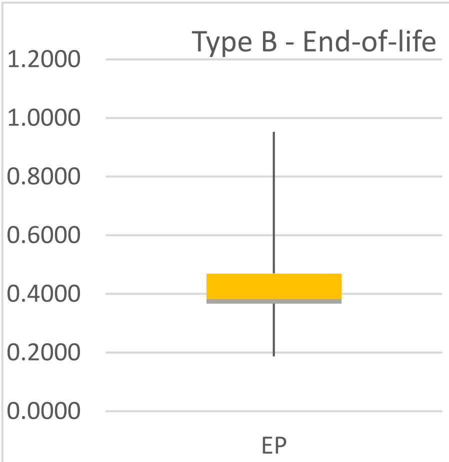
The results of the benchmarking along with the results of the life cycle environmental assessment at the end-of-life stage are presented in Figure 6.10. The values are normalised per m^2 of the deck.

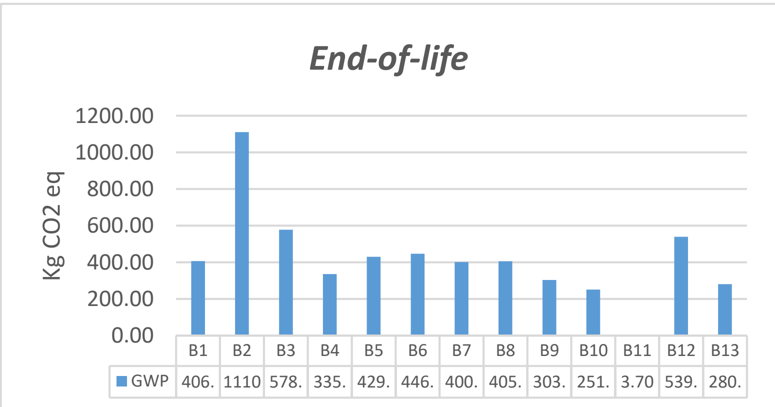


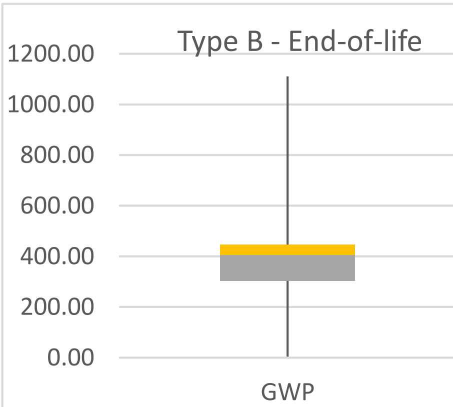

End-of-life
Kg SO2 eq
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
AP 2.7 6.0 3.4 2.5 2.4 2.5 2.4 2.4 2.2 1.7 0.7 2.9 1.4

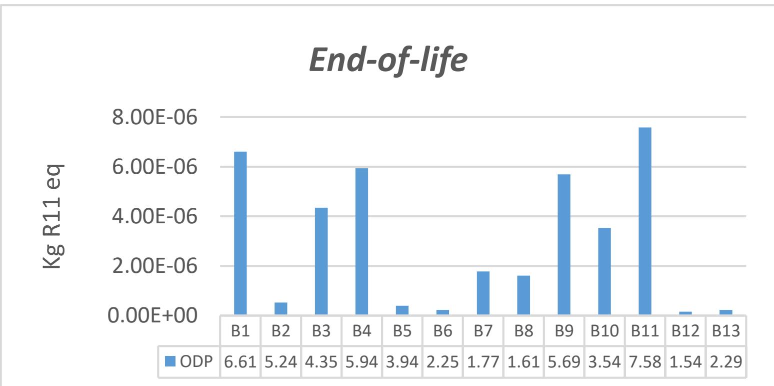

Type B - End-of-life
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
AP

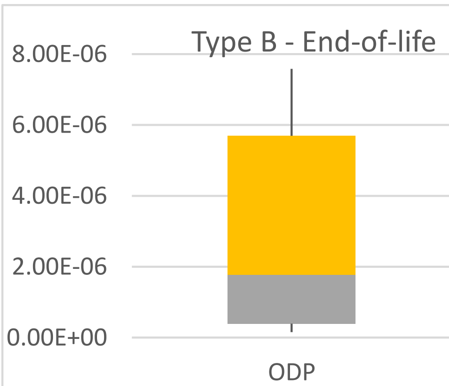

End-of-life
Kg PO4 eq
1.20
1.00
0.80
0.60
0.40
0.20
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
EP 0.5 0.9 0.5 0.4 0.3 0.3 0.3 0.3 0.4 0.3 0.1 0.4 0.2


Type B - End-of-life
1.2000
1.0000
0.8000
0.6000
0.4000
0.2000
0.0000
EP


End-of-life
Kg CO2 eq
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
GWP 406. 1110 578. 335. 429. 446. 400. 405. 303. 251. 3.70 539. 280.


Type B - End-of-life
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
GWP


End-of-life
Kg R11 eq
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
B1 B2 B3 B4 B5 B6 B7 B8 B9 B10 B11 B12 B13
ODP 6.61 5.24 4.35 5.94 3.94 2.25 1.77 1.61 5.69 3.54 7.58 1.54 2.29


Type B - End-of-life
8.00E-06
6.00E-06
4.00E-06
2.00E-06
0.00E+00
ODP

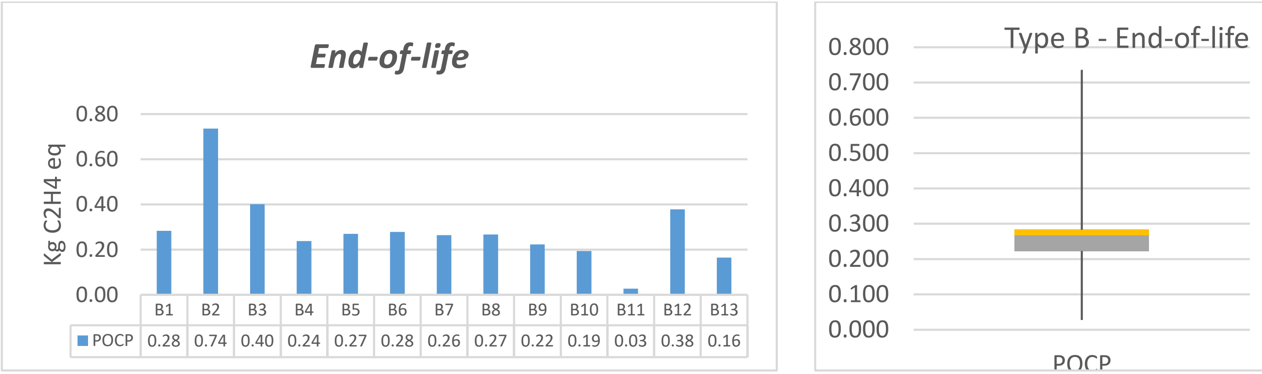


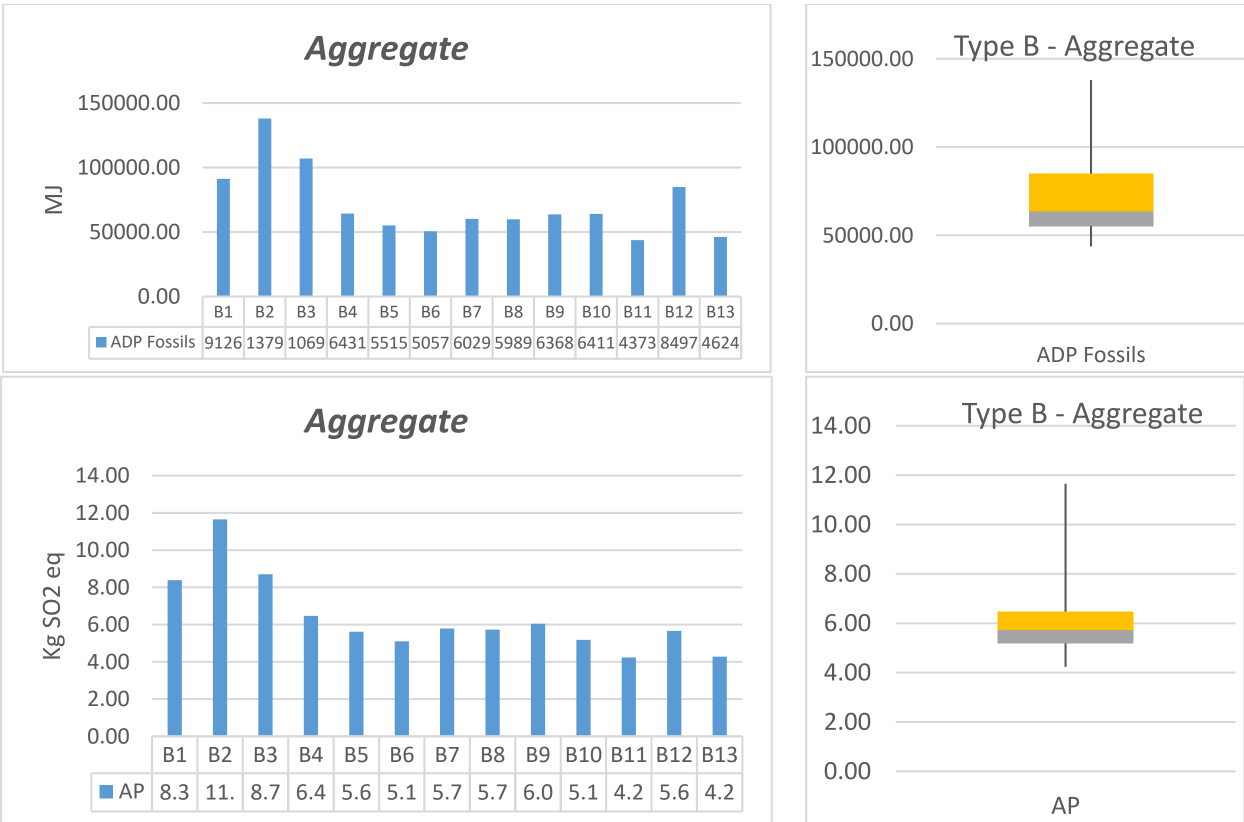
Figure 6.10 – Benchmarking of end-of-life stage normalised per m² of the deck

6.2.1.5 Aggregate results

As it was observed for all stages, the aggregate results show close values for common and best practice, meaning that average performance is of a high level and minimal actions would be taken in order to improve the performance.

Higher variability is observed for the ODP due to the influence of the performance at the stage of operation.

The results of the benchmarking along with the aggregate results of the life cycle environmental assessment are presented in Figure 6.11. The values are normalised per m² of the deck.



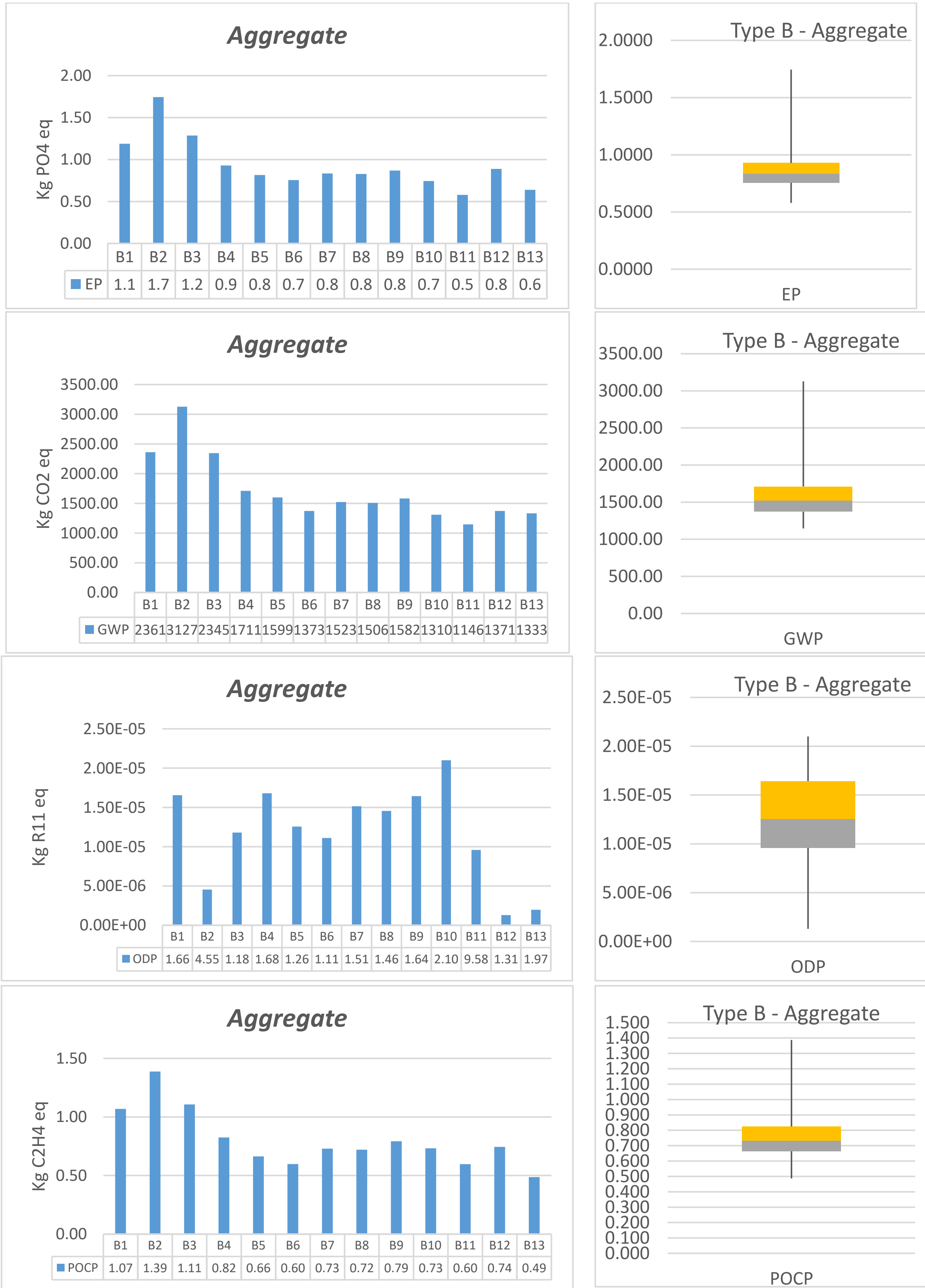


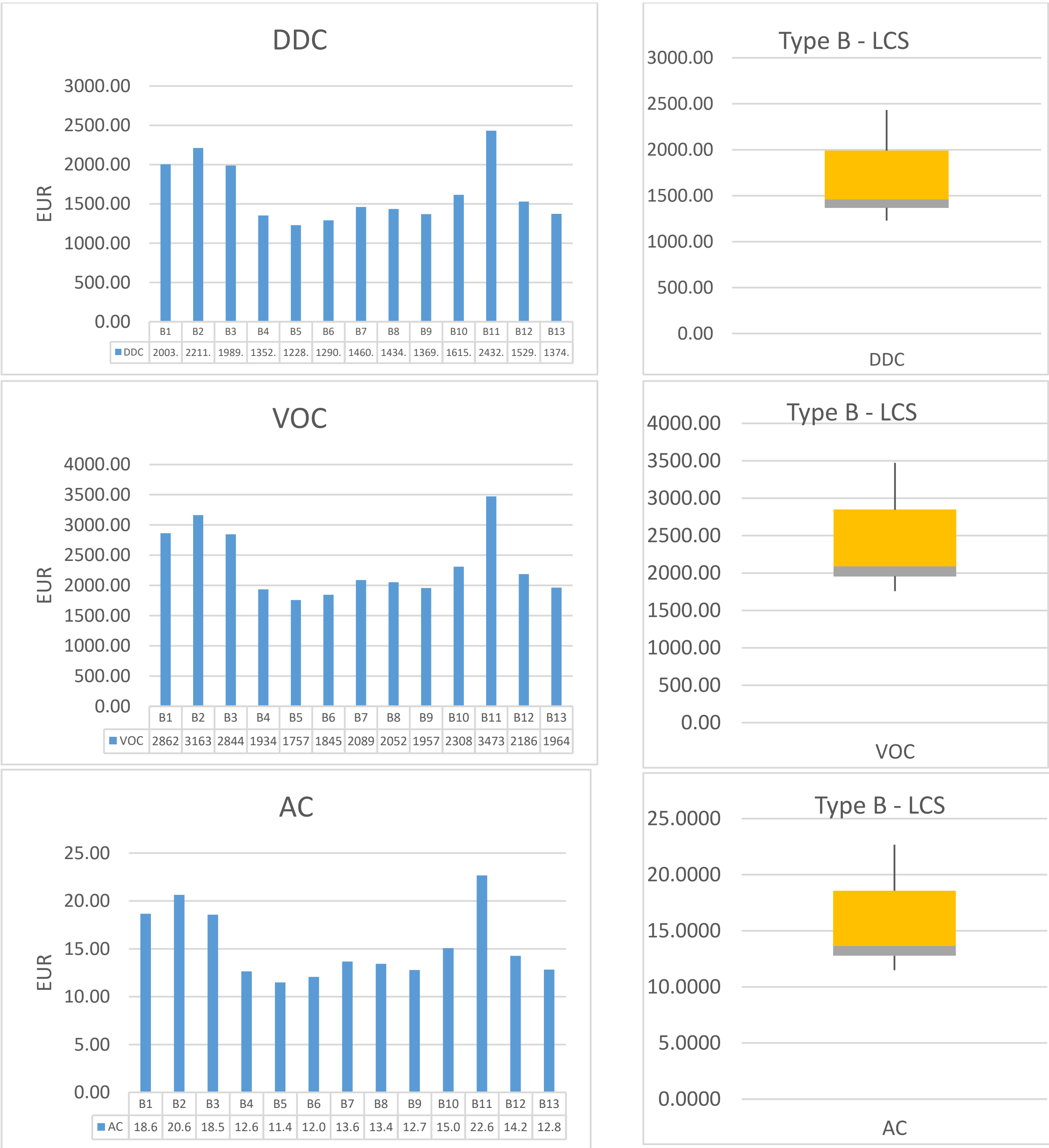
Figure 6.11 – Benchmarking of the aggregate results normalised per m² of the deck

6.2.2 Life cycle social analysis (LCS)

Being dependent on the same assumptions for the maintenance and traffic and having the same lane capacity, the results show overall quite homogeneous distribution, exhibiting close values for the common and best practice and moderate deviation for the upper and lower extremes.

The upper boundary is affected by the alternated performance of bridges B1, B2 and B3 and bridge B11.

The results of the benchmarking along with the results of the life cycle social assessment are presented in Figure 6.12. The values are normalised per m² of the deck.



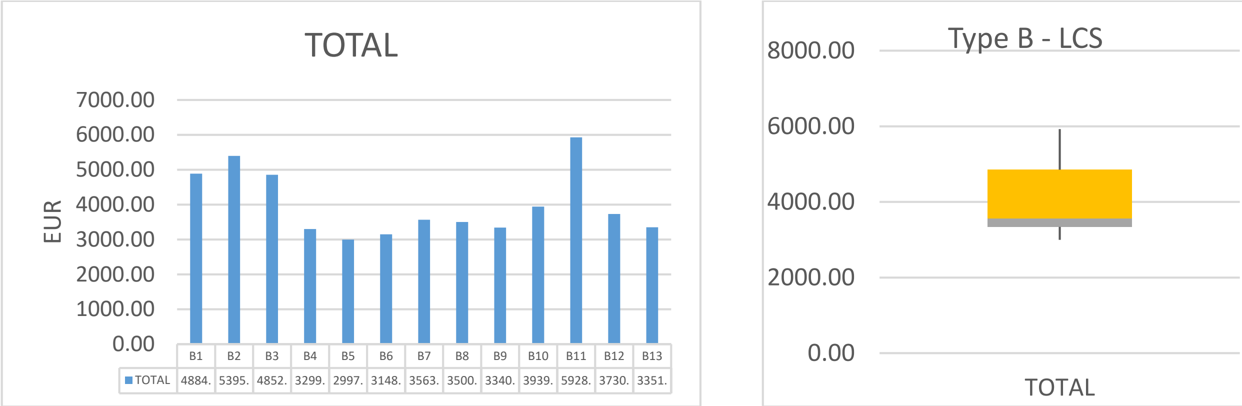


Figure 6.12 – Benchmarking of the life cycle social assessment normalised per m² of the deck

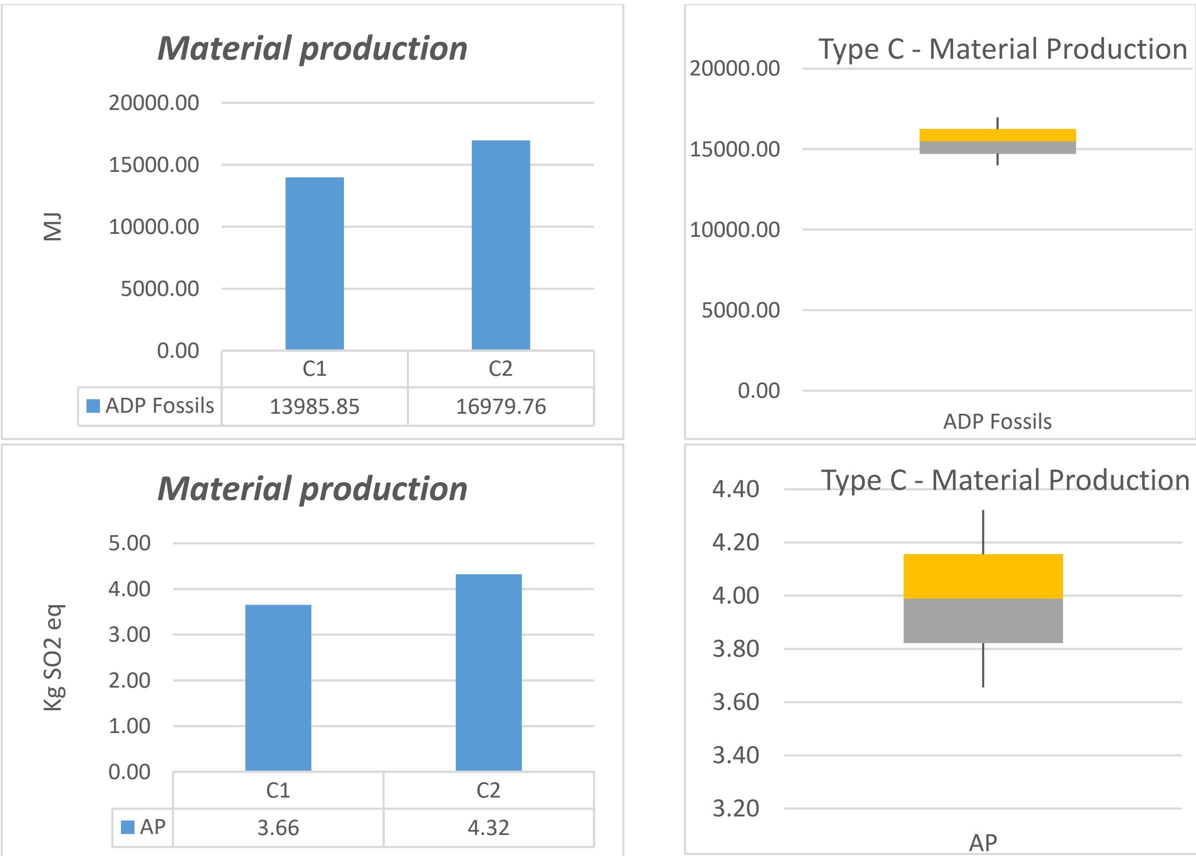
6.3 Bridges of Type C

Overall, the results of the sustainable benchmarking of the bridges of the Type C are (i) symmetrical and (ii) show relatively close values for both environmental and social benchmarks. It can be explained by the fact that only two cases were considered in this bridge type, being of the similar scope, namely solution (composite), traffic intensity and lane capacity.

6.3.1 Environmental Life Cycle Assessment (LCA)

6.3.1.1 Material production stage

The results of the benchmarking along with the results of the life cycle environmental assessment at the material production stage are presented in Figure 6.13. The values are normalised per m² of the deck.



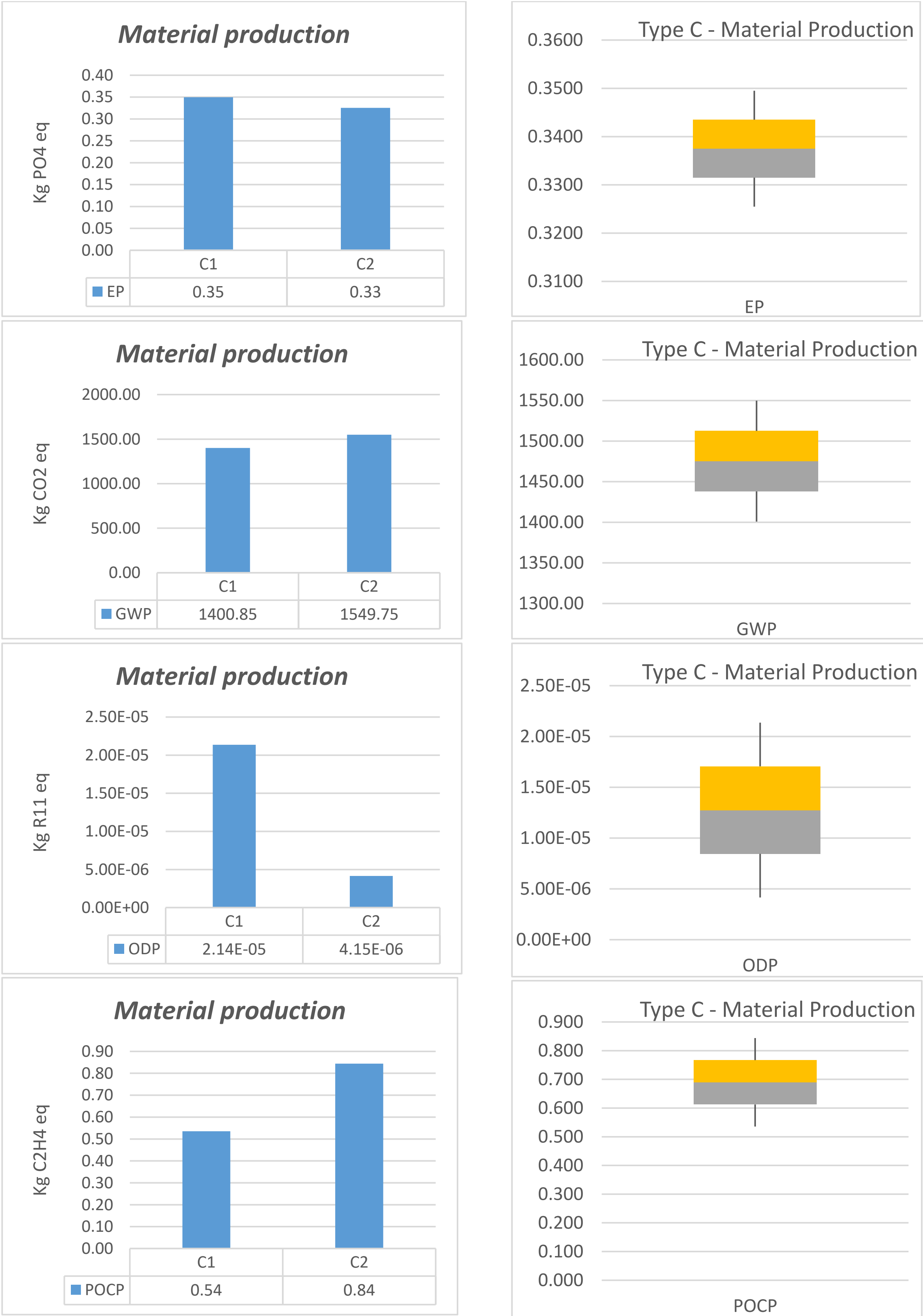


Figure 6.13 – Benchmarking of material production stage normalised per m² of the deck

6.3.1.2 Construction stage

The results of the benchmarking along with the results of the life cycle environmental assessment at the construction stage are presented in Figure 6.14. The values are normalised per m^2 of the deck.

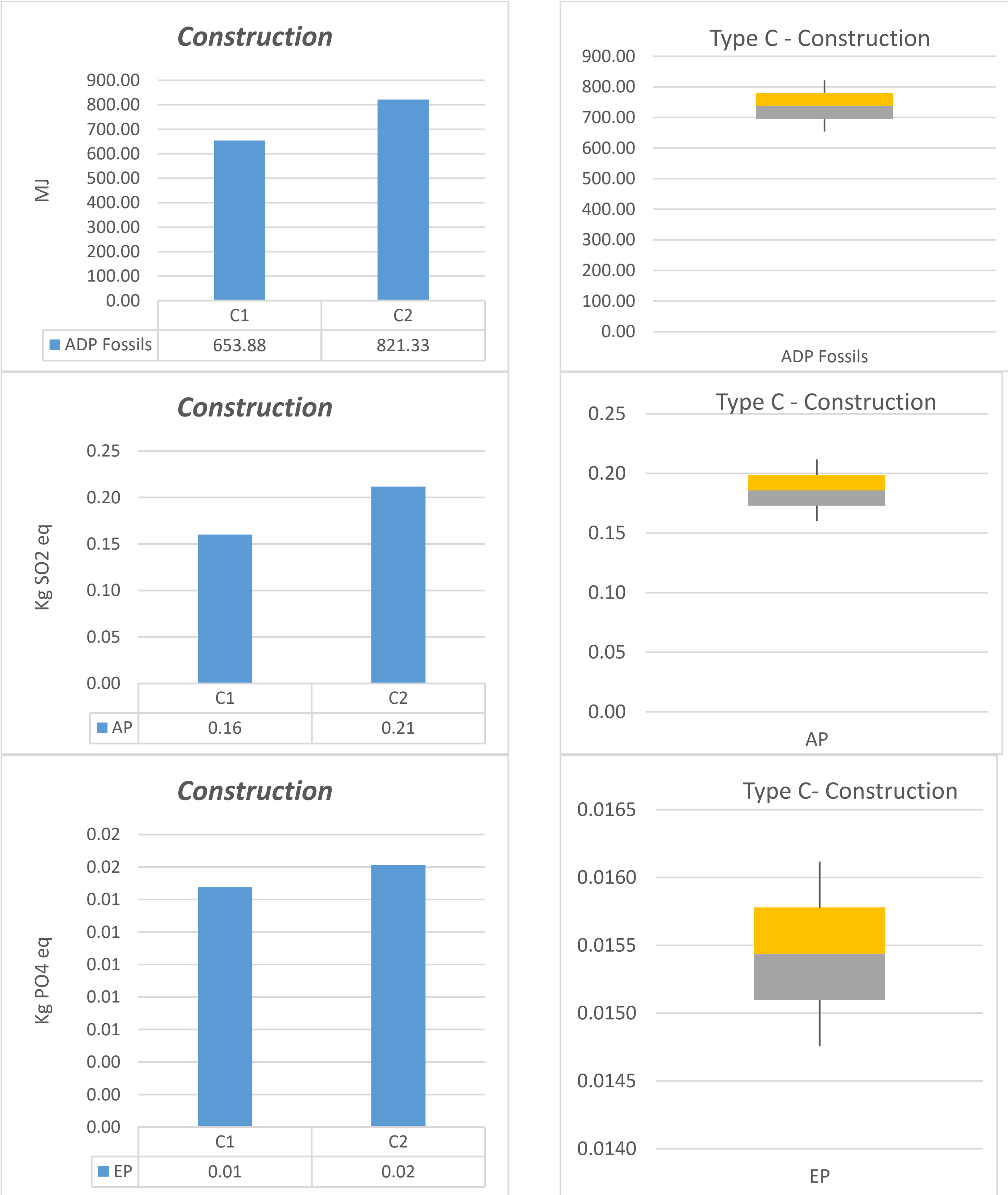


Figure 6.14 – Benchmarking of construction stage normalised per m^2 of the deck

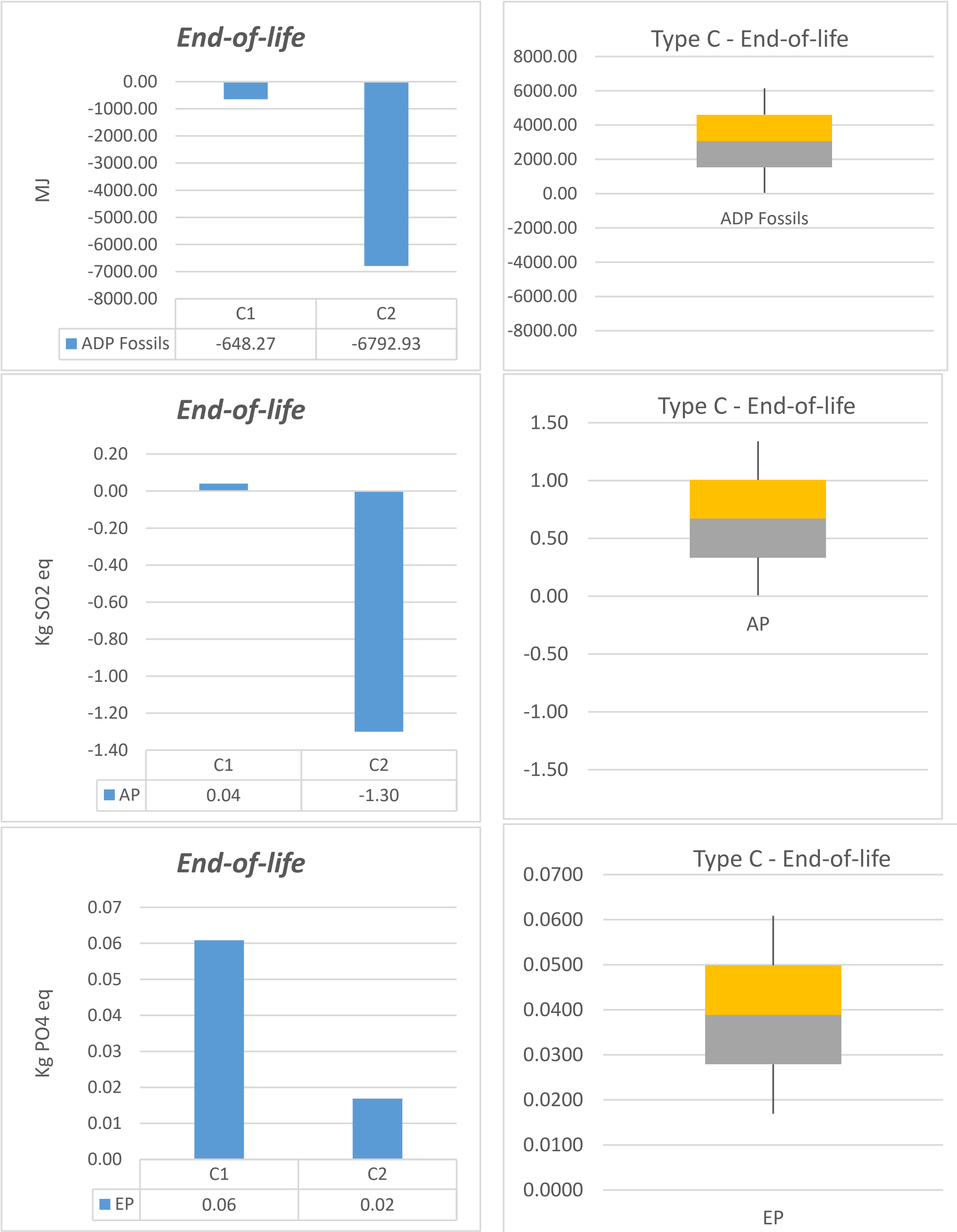
6.3.1.3 Operation stage

The results of the benchmarking along with the results of the life cycle environmental assessment at the operation stage are presented in Figure 6.15. The values are normalised per m^2 of the deck.

Figure 6.15 – Benchmarking of operation stage normalised per m^2 of the deck

6.3.1.4 End-of-life stage

The results of the benchmarking along with the results of the life cycle environmental assessment at the operation stage are presented in Figure 6.16. The values are normalised per m^2 of the deck.



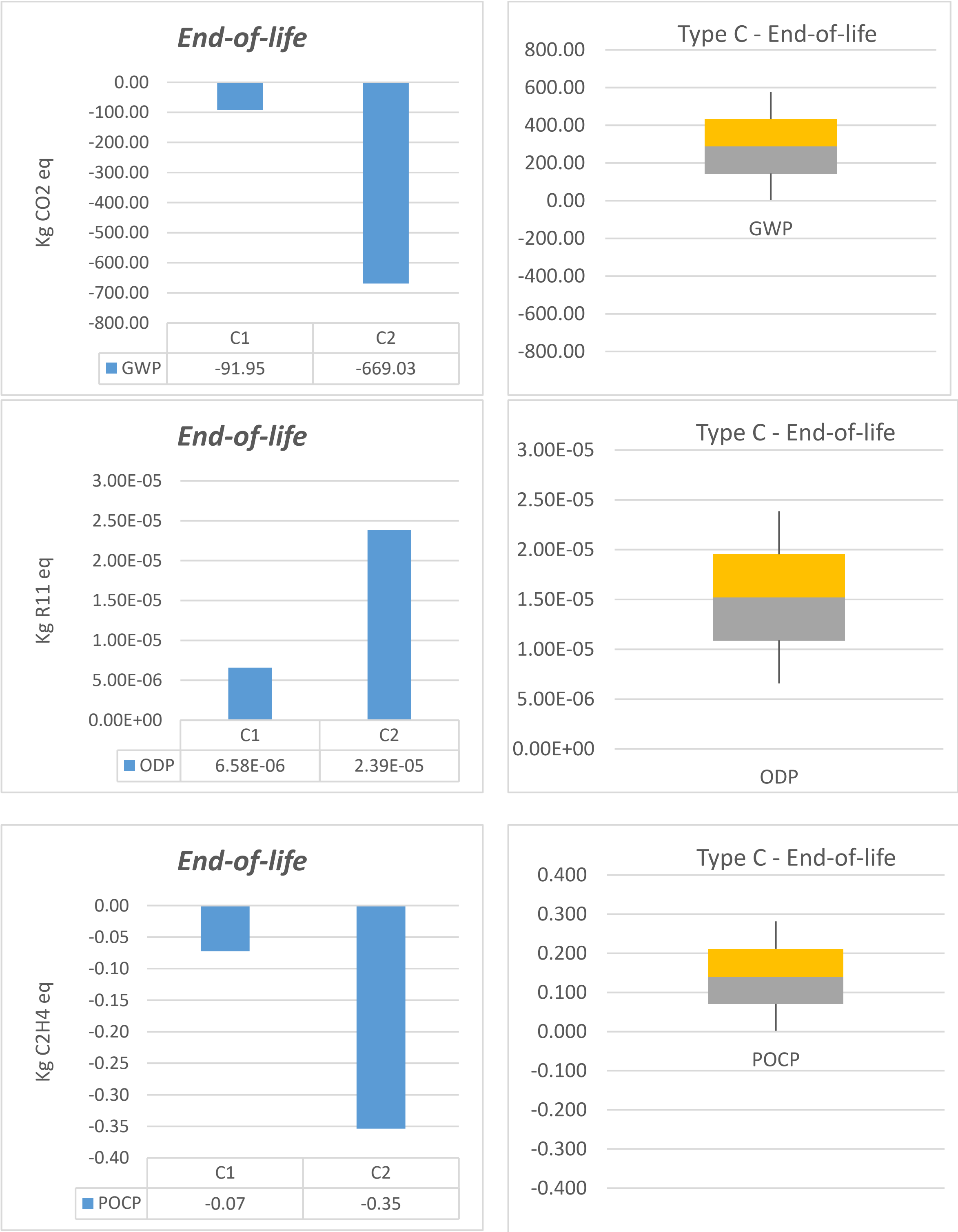
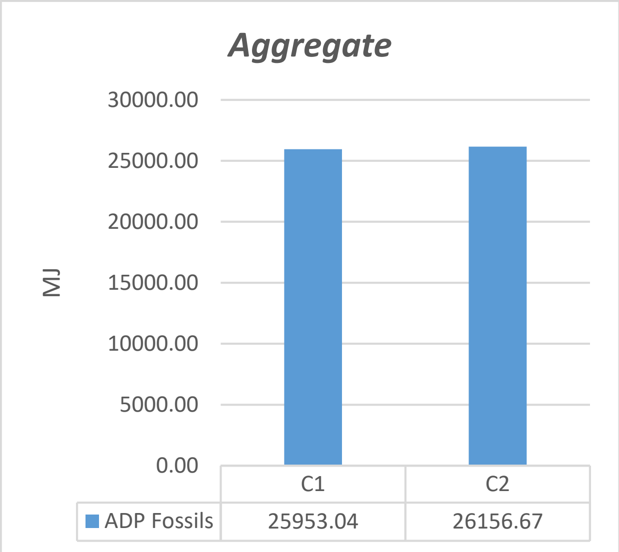
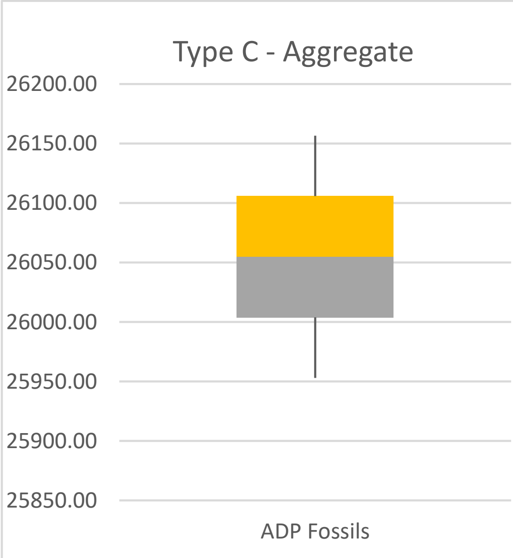


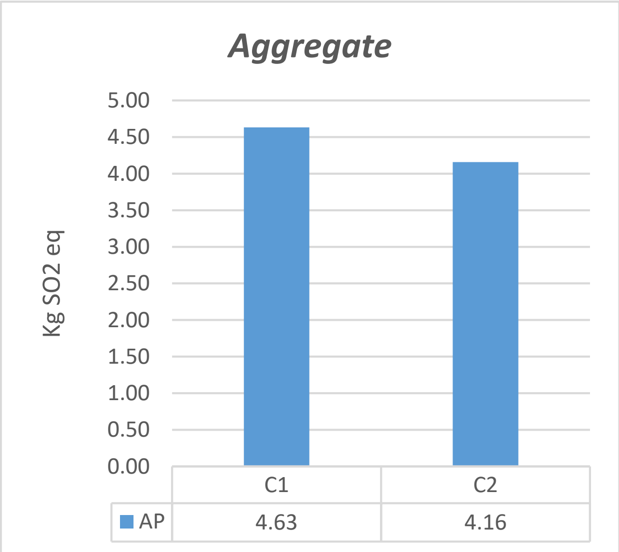
Figure 6.16 – Benchmarking of end-of-life stage normalised per m² of the deck

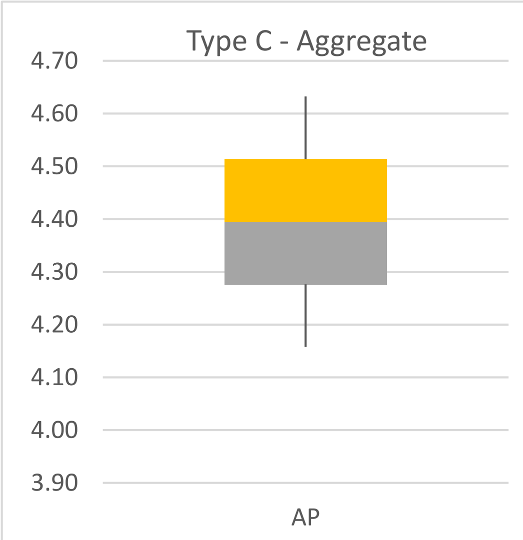
6.3.1.5 Aggregate results

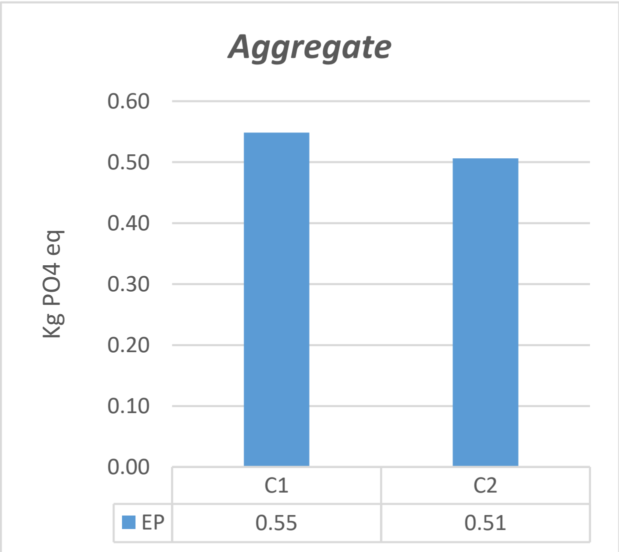
The results of the benchmarking along with the aggregate results of the life cycle environmental assessment are presented in Figure 6.17. The values are normalised per m² of the deck.

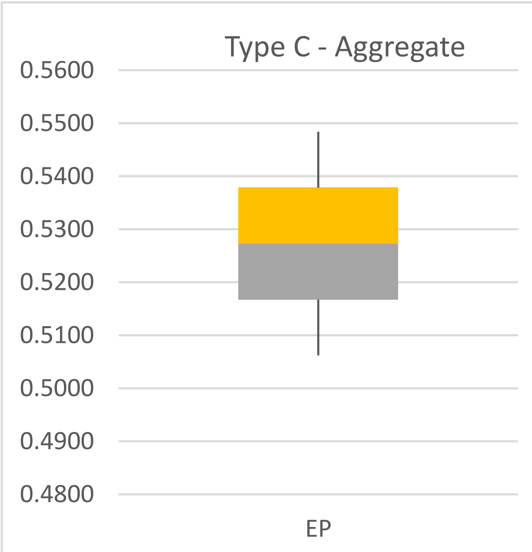

Aggregate
MJ
30000.00
25000.00
20000.00
15000.00
10000.00
5000.00
0.00
C1
C2
ADP Fossils
25953.04
26156.67

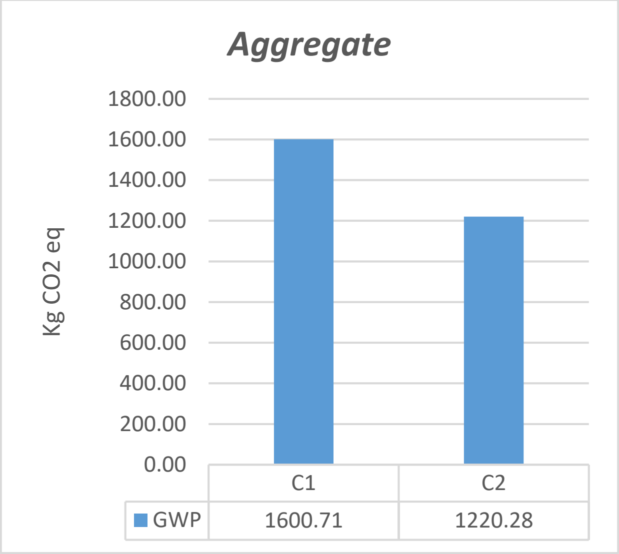

Type C - Aggregate
26200.00
26150.00
26100.00
26050.00
26000.00
25950.00
25900.00
25850.00
ADP Fossils

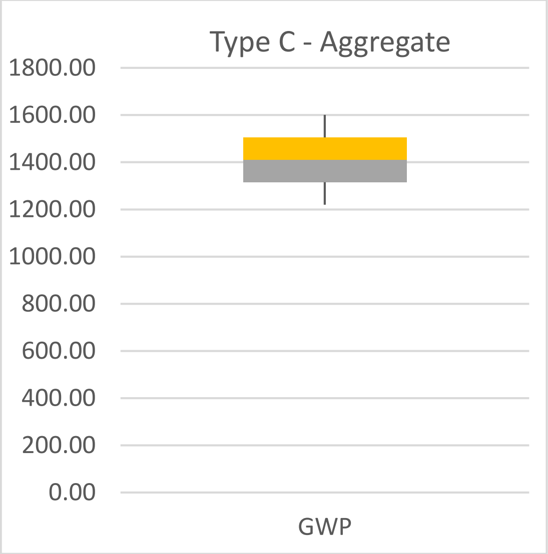

Aggregate
Kg SO2 eq
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
C1
C2
AP
4.63
4.16

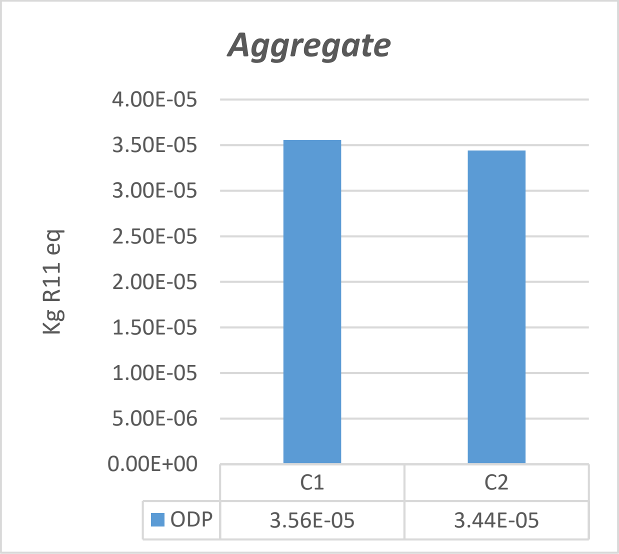

Type C - Aggregate
4.70
4.60
4.50
4.40
4.30
4.20
4.10
4.00
3.90
AP

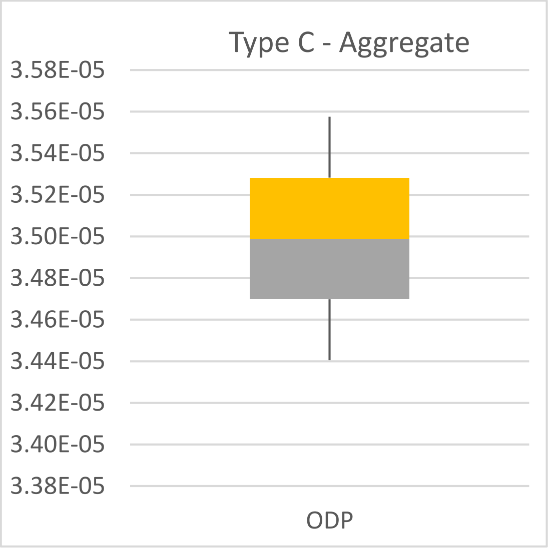

Aggregate
Kg PO4 eq
0.60
0.50
0.40
0.30
0.20
0.10
0.00
C1
C2
EP
0.55
0.51

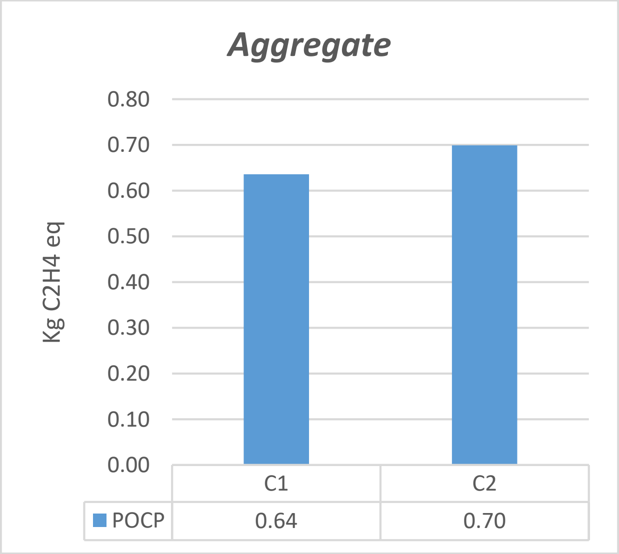

Type C - Aggregate
0.5600
0.5500
0.5400
0.5300
0.5200
0.5100
0.5000
0.4900
0.4800
EP











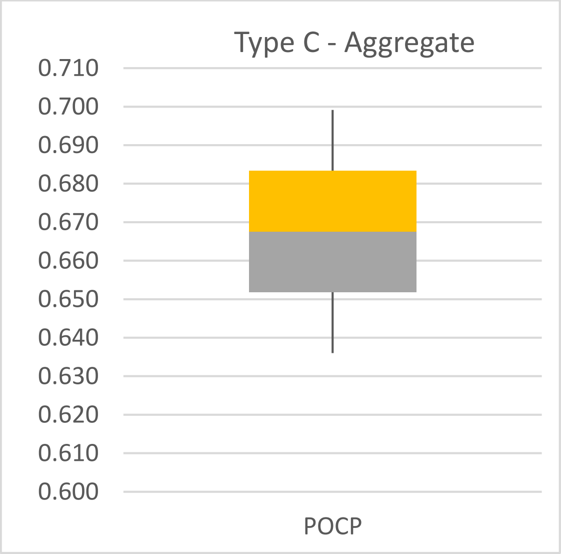


Figure 6.17 – Benchmarking of aggregate results normalised per m^2 of the dec

6.3.2 Life cycle social analysis (LCS)

The results of the benchmarking along with the results of the life cycle social assessment are presented in Figure 6.18. The values are normalised per m^2 of the deck.

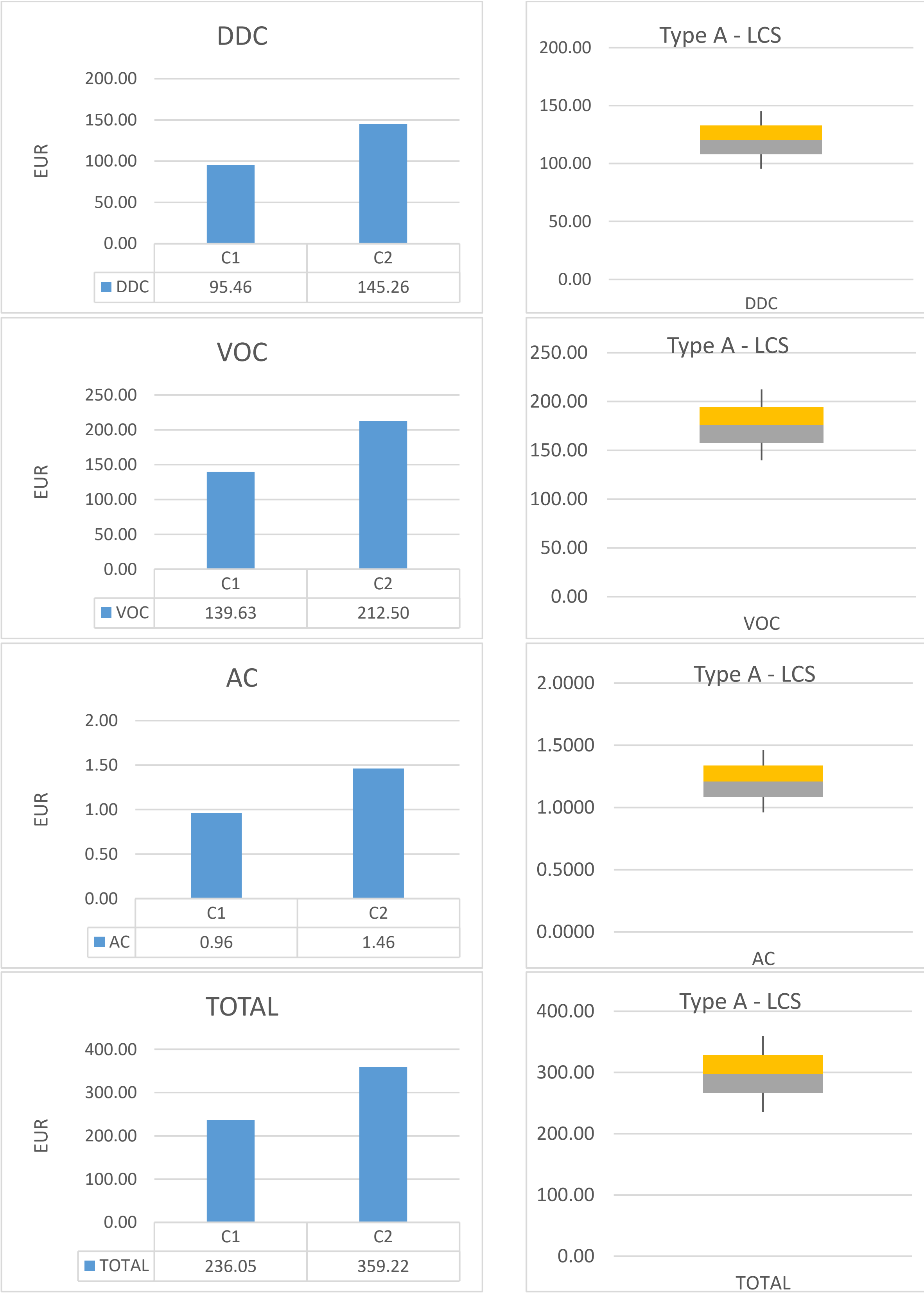


Figure 6.18 – Benchmarking of the life cycle social assessment normalised per m^2 of the deck

7 Conclusions and future developments

7.1 Conclusions

The goal of this thesis was to perform a sustainable benchmarking of motorway bridges, based on the integral life cycle assessment as well as the analysis of the evaluated benchmarks are intended to be used as the levels of sustainability performance guiding potential users in the pursuit of sustainable bridge design, helping to evaluate performance gaps and set design goals for the potential improvement.

In the course of the literature review, it was concluded that to date, benchmarking of bridges is considered as a project management tool, mainly providing guidance for the assessment of the structural performance during the inspections or considered when establishing the “reasonable” cost of the project by considering the comparison of the cost of the critical bridge element with those of projects of similar size and scope. Being well established for buildings, the sustainable benchmarking of bridges is described conceptually and no standardized procedure is established.

The first part of the thesis was dedicated to the evaluation of the sustainability indicators of the integral life cycle analysis of the motorway bridges. The integral life cycle analysis of bridges aims to convey the performance in all three dimensions of sustainability through the mutual consideration of the Life Cycle Environmental Assessment (LCA), Life Cycle Social (LCS) and Life Cycle Cost (LCC). The methodology was developed in PhD thesis [1] was further adopted in present thesis in order to make a quantitative assessment of the sustainable life cycle performance of bridges. The sustainability indicators of the life cycle environmental (LCA) and life cycle social assessment (LCS) were evaluated.

The case studies considered in this work were taken from the research projects SBRI+, SBRI and the PhD thesis [1] and were re-evaluated according to the assumptions made for the further performance of the sustainable benchmarking as it is required to make the assessment ensuring the functional equivalence. As bridges were designed for different countries, special attention was payed to the inspection and maintenance strategies, normalization of the traffic density and assumed transportation distances. The bills of quantities were closely analysed in order to ensure that the materials are taken into account considering the same structural groups. While analysing the unit cost, it was observed that unit cost depends on the location of the bridge as also experience significant variability even for projects executed in the same countries. Thus, it was decided to exclude the life cycle cost assessment (LCC) and benchmarking of its indicators from the scope of the present thesis as the establishing of the unique values for unit cost to be applied for all cases requires more detailed investigations.

The second part of the thesis is dedicated to the performance of the sustainable benchmarking of bridges. As currently only some general recommendations regarding the framework of the sustainable benchmarking of bridges were found to be available, the suggested benchmarking levels and methodology of the assessment were developed relying of the previous experience of the sustainable benchmarking of buildings. In the frame of present work, the values of common and best practice were established for the sustainability indicators defined from the integral life cycle assessment.

The extensive discussion of the results of the life cycle assessment and benchmarking were offered in the Chapters 6 and 7. Overall, it was observed that the results of the life cycle environmental assessment and life cycle social analysis follow different trends among all bridge types. The variability of the results was highly affected by the fact, that there were presented bridges from the design families (concrete and composite), having different number of lanes or relatively different number of spans along with different degree of design optimization.

The results of the life cycle social assessment exhibit the same trend for all four indicators, which can be explained by the fact that, contrast to the environmental indicators, all three parameters of the life cycle social analysis are based on the same assumptions for the traffic restrictions. It was also observed, that the main criteria for the life cycle social performance is the frequency and timeframe of the maintenance interventions as well as the available number of lanes for all cases. The vehicle operation cost is proved to be the indicator exhibiting the biggest share in the total user costs.

Regarding the benchmarking, it can be seen, that the scatter of the results highly sensitive to the precision of the functional equivalence achieved for the considered case studies.

The results of the benchmarking of the bridges of the Type A overall characterised by the significant gap between the value of common and best practice, as the results of the life cycle assessment vary significantly due to the variability in the size and scope of assigned case studies.

Bridges of the Type B characterised by the relatively big number of examples, when comparing to the case studies of Type A and C. The benchmarking shows the values for common and best practice to be relatively close for most of the cases, however also characterised by the significant value of errors, highlighting the overall scatter of the values of sustainable indicators.

The benchmarking of the bridges of the Type C always shows symmetric results, which is derived from the fact, that only two bridges of the similar scope were considered for this case.

7.2 Future developments

While progressing on this thesis, several areas for further development and improvement were identified. There aspects provided as a basis for the further development and improvement.

One of the main considerations to be taken into account is the implementation of the life cycle cost assessment as it directly addresses the dimension of the sustainable performance. As case studies belong from different countries and composed from materials provided by different suppliers, the unit cost exhibited a significant variance, which require additional studies to ensure that the established values would not compromise the data achieved in original projects where the bridges were analysed as individual cases.

Second group of the considerations is related to the assumptions regarding operation and traffic. As this work was the first attempt to the establishing the benchmarks, the focus was giving to the comparison to be made on the common basis. Since current work presents the assessment performed for the one type of maintenance scenario (standard maintenance scenario) and only day work was considered, following the consideration of the SBRI+ project, further benchmarks can be established for the Lack-of-money and Prolonged life scenarios, taking into consideration the possibility of performance of the maintenance works over night hours.

Thirdly, here in this work the benchmarks were established for the fixed traffic density. Going further, the normalization of the ADT can be done, establishing the values for low, medium and high traffic intensity, and the influence of different ADT can be studies.

By its nature, the life cycle assessment is subjected to a high degree of uncertainties, the probabilistic studies can be made aiming to minimize the influence of uncertainties on the final results.

Finally, the present set of case studies can be expanded with new examples, as it would improve the accuracy of the results in the future.

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TABLE OF FIGURES

LIST OF TABLES

ANNEX A: Supplementary data for LCA

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 Cases A and C

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

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

Table A3: Traffic restriction for Case B

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 A4: Operation types and rates of maintenance work

Maintenance		Rate of work
To	Type	
Bearings	Repair	1,5 day/un
Bearings	Replacement	2 day/un
Concrete deck	Refurbishment	0,08 days/m²
Concrete edge beams	Replacement	0,225 days/m
Edge beams	Refurbishment	0,225 days/m
Expansion joints	Repair	0,75 m/h
Expansion joints	Maintenance	40 m/day
Expansion joints	Replacement	3,5 m/day
Gutters	Replacement	0,1 days/m
Railings	Refurbishment	4 m²/h
Railings	Replacement	1,75 m/h
Road surface	Repair	0,02 days/m²
Road surface	Replacement	0,02 days/m²
Safety barriers	Replacement	1,3 m²/h
Steel girders	Refurbishment	0,02 days/m²
Steel girders	Repair	0,02 days/m²
Water proofing layer	Replacement	0,02 days/m²