

# Life Cycle Assessment and Life Cycle Cost for Composite Bridges

Stainless Steel Corrugated Web Girders vs. Carbon Steel Flat Web Girders

Master's thesis in the Master's Programme Structural Engineering and Building Technology

ASHUR NISSAN  
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DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY  
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MASTER'S THESIS 2022

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## Abstract

Bridge constructions account for numerous material and energy consumptions. Hence, it is crucial to evaluate bridges' environmental impact and total life cycle cost in the early design stages. Data assumptions are made throughout the inventory stage due to the lack of significant required data; therefore, the sensitivity of the LCA and LCC outcomes should be considered. Steel is strongly used in bridge constructions due to its high strength and efficient recycling rates. However, steel has low resistance against corrosion which requires applying additional coating layers throughout its life cycle and returns in additional expenses. Accordingly, the bridge industry has been increasingly interested in providing more sustainable solutions. Stainless steel has been widely used in bridge designs thanks to its high corrosion resistance. Therefore, stainless steel bridges do not require regular maintenance activities. Nevertheless, stainless steel has high material initial costs. Thus bridge designers have developed different bridge design concepts to lower the total weight of stainless steel required in bridges made of this material. One of these design concepts is the application of corrugated webs in stainless steel bridges. In this master's thesis, a parametric model in Python has been developed to evaluate the environmental impact of global warming potential and the total life cycle cost of different bridge design concepts. In particular, two design concepts have been introduced and compared, carbon steel S355 with flat web and Duplex stainless steel with corrugated webs. The results showed that the stainless steel design concept has a lower total environmental impact contributing to the global warming potential. Considering the total life cycle cost, the results indicated that the economic feasibility of using stainless steel with corrugated webs is highly dependent on the fluctuating prices of stainless steel. Additionally, the outcome stated that when the average daily traffic was relatively high, the stainless steel design concept became more economically feasible than the carbon steel design concept. This study concluded the following parameters as critical for LCC: the average daily traffic, the material initial costs, the discount, and the escalation rate. The developed tool has been used in another master thesis to optimize steel bridges based on LCA and LCC.

Keywords: life cycle assessment, life cycle cost, optimization, corrugated webs, global warming potential, bridge industry, initial costs, average daily traffic.



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# List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADT	Average Daily Traffic
EAs	Evolutionary algorithms
EPD	Environmental Product Declaration
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCCA	Life Cycle Cost Analysis
NPV	Net Present Value
SS	Stainless Steel
TDC	Traffic Delay Cost



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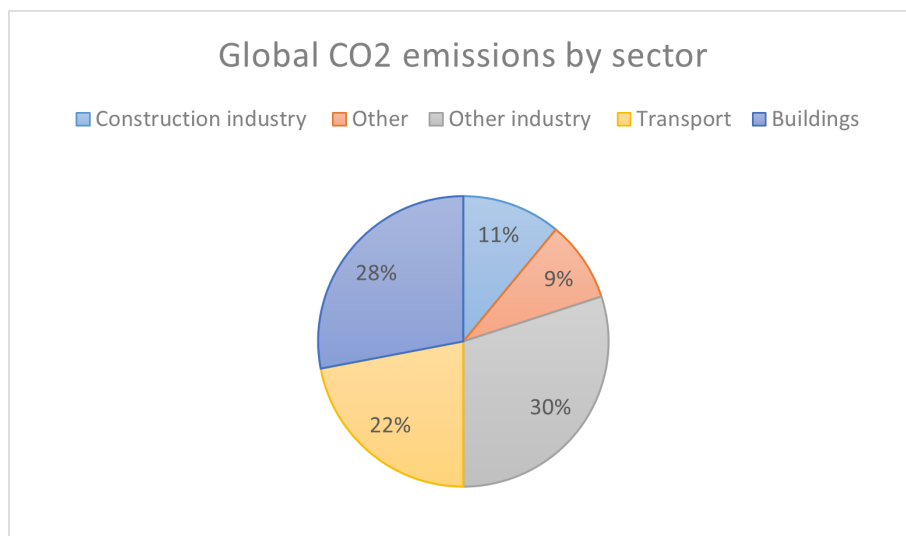
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# 1

## Introduction

In recent years, the bridge industry has become increasingly interested in sustainable development, particularly in terms of economic and environmental implications (Mara et al., 2013). Accordingly, a comprehensive approach that includes all costs and environmental burdens is needed. Therefore, the world Commission on Environment and Development (UNCED 1987) developed the Brundtland report 1987. The report defined many essential principles to reduce the environmental impacts and stated sustainable development as a development that satisfies the current needs without impairing the capacity of future generations to meet their needs (UN, 1987). As the environmental impacts caused by buildings and bridge constructions have become more extensive, new studies and strategies have been developed to find more efficient solutions in the construction industry (Rydh et al., 2002). Therefore, the life cycle assessment LCA has been introduced to provide a more detailed overview of the environmental impacts since the burden-shifting can be avoided (Rydh et al., 2002) because the life cycle assessment considers different life stages throughout a material's whole life cycle. Figure 1.1 shows that the construction industry stands for 11% of global energy-related CO<sub>2</sub> emissions (UN, 2017). United Nations regarded the sustainable development goals SDGs as objectives for 2030 (UN, 2012) and therefore today's society enhances the implementation of sustainable solutions in infrastructure design (Muñoz et al., 2020).



**Figure 1.1:** Global CO<sub>2</sub> emissions by sector adapted from (UN, 2017)

The international standards ISO 14040 and 14044 describe life cycle assessment

(LCA) as a technique for analyzing environmental aspects and impacts of a product system. A mathematical method for forming and supporting decisions is life cycle costing LCC (ISO 14040). Steel is a building material that suits well for prefabrication. The essential components used in the production are highly standardized, and the dimensional accuracy is high (Al-Emeani et al., 2011). Steel is enormously used in bridge constructions due to its efficient reuse and recycling. However, steel has low resistance against corrosion during its life span (Rossi, 2014), and therefore it is of interest to perform a life cycle assessment for constructions made of this material to conduct the environmental impacts in terms of CO<sub>2</sub> emissions and make wiser decisions in the early design process of steel constructions and infrastructures. Stainless steel has recently been widely used in construction due to its high resistance against corrosion, long service life performance, and cost-effective properties (Rossi, 2014). Furthermore, from a sustainable point of view, stainless steel is characterized by cost-effectiveness, where there is no need for maintenance, painting, or protection throughout its life cycle development (Rossi, 2014). Furthermore, bridge designs can be optimized based on the life cycle performance in terms of LCA and LCC. Researchers have developed different methods of structure optimization algorithms in this context. These methods enable designers to achieve optimal solutions by changing the variables that define the structure (Muñoz et al., 2020).

### 1.1 Aim and objectives

This master's thesis aims to develop a computational tool in Python, to evaluate the environmental impacts and the life cycle costs of bridge constructions. Based on the life cycle assessment and life cycle costs, a comparison between carbon steel and stainless steel will be provided. The computational tool will be used in a genetic algorithm optimization method to optimize bridge designs considering the environmental and economic perspectives.

The developed tool will serve as decision support for architects and bridge planners to evaluate various bridge designs from the environmental and economic points of view. Accordingly, the objectives of this study are:

- To develop a parametric model in terms of mathematical equations which integrate the life cycle assessment, and the life cycle costs of bridge constructions.
- To apply the model to conduct LCA and LCC for different bridge design concepts and provide a comparison between bridges made of carbon steel and stainless-steel girders.
- To implement the developed model in a genetic algorithm optimization as described in a parallel master thesis written by Hallgren and Johansson (2022) to optimize bridge design parameters based on the estimated LCA and LCC.

### 1.2 Method

First, a literature review of the life cycle assessment methodology and history will be provided to comprehensively understand the life cycle assessment LCA and life cycle costing LCC. The literature review includes a brief overview of the application

of LCA in bridge designs, the application of stainless steel in bridge constructions, and a brief overview of the genetic algorithm approach.

Second, a parametric model will be developed to identify the system boundary of the life cycle assessment, the life cycle cost, and the most critical parameters that will be included in the calculations. In order to develop this model, primary environmental data from different data sources and environmental product declarations will be collected and presented in a database that will serve as a basis for the parametric tool. Furthermore, interviewing experts and bridge planners will provide a life cycle cost model and price estimations.

Third, a parametric tool will be developed in Python to calculate the total environmental impacts of global warming potential and the total life cycle cost for bridge constructions. The performance of the parametric tool will be analyzed following the scope definition of the study.

Lastly, the computational tool will be implemented in a case study for different bridge design concepts. The adapted tool will be used in a genetic algorithm optimization collaboration with the master thesis written by Hallgren and Johansson (2022) to optimize bridge designs based on the life cycle performance LCA and the life cycle cost LCC. In this collaboration, the genetic algorithm will have the potential to find the optimal solutions inside an ample space of solutions.

### **1.2.1 Ecoinvent database**

Ecoinvent database is regarded as a life cycle inventory support that provides major environmental impact information for different products and materials (Ecoinvent, n.d.). This database integrates many life cycle impact assessment methods and provides background information in terms of emission factors, manufacturing processes, and flows (Ecoinvent, n.d.). The ecoinvent database will be imported into the OpenLCA software (Cilleruelo, 2021) to be used through the life cycle inventory of this study.

### **1.2.2 Environmental product declarations EPDs**

Environmental product declarations are based on life cycle assessment calculations (Liebsch, 2021). EPDs provide quantitative information about a material's life cycle in terms of environmental impact throughout the whole life cycle. In this study, different EPDs will be used in order to collect environmental data for different materials used in bridge construction.

## **1.3 Research questions**

This study aims to outline the following research questions:

1. How does the application of corrugated webs influence the environmental impact and the total life cycle cost in bridge constructions made of stainless steel?
2. What are the critical parameters for LCA and LCC of the considered design concepts?

### 1.4 Limitations

The limitations of this study are divided into two categories:

- Design-related limitations: The parametric model of this study only considers the superstructure of bridge construction. As a result, the life cycle assessment and life cycle costs are evaluated considering two structural components of the bridge's superstructure, i.e., the bridge girders and the concrete deck.
- LCA and LCC-related limitations: Due to the early design stages in which the LCA will be performed, many assumptions will be made in the case of missing data throughout the whole process, leading to uncertainties in the output. These uncertainties can significantly influence the reliability of the results. A commercial database called Ecoinvent will be used to collect environmental data for each material used in the case studies. The case studies focus on steel bridges located in Sweden. In this context, it is essential to mention that the environmental data of material production largely depend on geographical location. Hence, it is preferable to get realistic data from the factory than the global average data from global databases. This might be seen as a data availability limitation. Although several life cycle impact assessment methods LCIA exist, only one impact method will be integrated into the parametric tool for this study. Therefore, a completeness check might be performed based on the collected data.

The environmental impact, which will be calculated in the parametric model, only considers the climate change impact category, evaluating the contribution of the bridge life cycle to the global warming potential GWP.

### 1.5 Outline of the thesis

The thesis is structured into seven main parts, the literature review, the parametric modeling, the application of the parametric tool in a case study, the results, the discussions, and the conclusion. Chapter one provides background on life cycle thinking. In this chapter, the objectives of the study, the method, the research questions, and the limitations are presented. Chapter two provides a literature review of the life cycle assessment history, the life cycle cost, and the application of LCA in bridge constructions. Here, the main phases of LCA according to ISO 14040 standards, the application of stainless steel in bridge constructions, and an overview of the genetic algorithm are presented.

In chapter three, the parametric model of this study is developed, where the system boundaries and data sources are separately provided for LCA and LCC. The calculation procedure is also presented as equations and descriptions for all parameters and life cycle stages included in this study. Chapter four describes the case study to be applied in the parametric tool. This chapter includes all input parameters provided by Hallgren and Johansson (2022) and the data assumptions needed to compile LCA and LCC results. Chapter 5 presents the results and provides interpretations of the results. Whereas, in Chapter 6, the discussions are presented, and sensitivity analyses are performed and illustrated in graphs. Lastly, Chapter 7

presents the conclusion and further research recommendations.



# 2

## Literature review

### 2.1 Life cycle assessment methodology LCA

In the construction sector, the Life cycle assessment method LCA has not been widely used because it is defined as a complex method that requires a massive amount of collected input data and a long time to perform (Hollberg & Ruth, 2016). Accordingly, a simplified LCA approach is used in the early design phases, allowing designers and planners to evaluate and conduct the environmental impact of construction design.

#### 2.1.1 Life cycle assessment history and definition

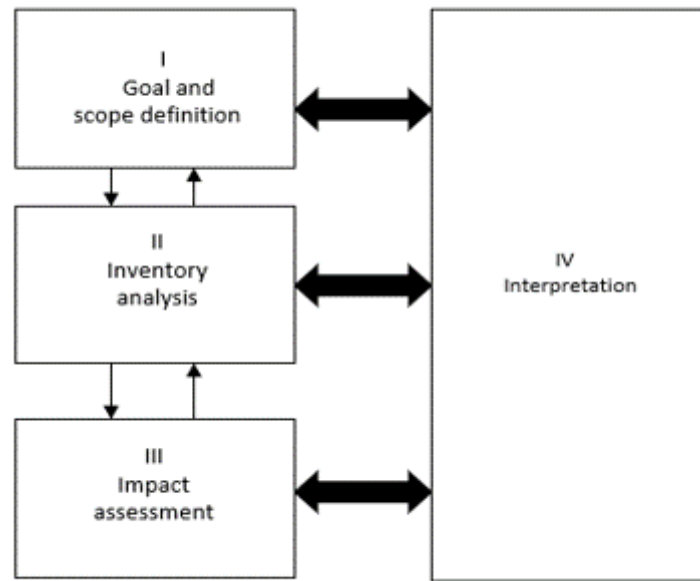
The first life cycle assessment was approached around 1970 and adopted to Resource and Environmental Profile Analysis. This approach analyzed the consumption and emissions of a product system (Grahl & Klöpffer, 2014). Furthermore, in the 1980s, the concept was developed to cover the environmental, social, and economic aspects of sustainability, where the social aspects of the system were investigated.

Life Cycle Assessment LCA was defined first by the Society of Environmental Toxicology and Chemistry (SETAC, 1991). This analysis is a holistic approach, starting from the cradle to the grave, aiming to quantify the environmental aspects of a product system or process during its life cycle (Das,2020). Additionally, LCA contributes to environmental impacts to be transferred from one media to another and from one life cycle phase to the next. The availability of this data due to LCA enhances decision-making toward an environmental strategy in construction design (Das,2020).

The international standard ISO 14040 defined LCA as a method for evaluating the environmental impacts throughout a product's life cycle, from material extraction through manufacturing, usage, and disposal. (ISO 14040, 1997)

#### 2.1.2 Phases of life cycle assessment

In this section, the framework of the life cycle assessment LCA is presented according to ISO 14040. According to ISO 14040, the life cycle assessment can be divided into four main phases: Goal and scope definition, Inventory analysis, Impact assessment, and interpretation.



**Figure 2.1:** The framework of LCA. (Adapted from ISO 14040:2009, P16).

### 2.1.2.1 Goal and scope definition

The goal and scope of the assessment must be clearly defined in the first phase of LCA by providing a holistic approach to the study's aim, why it is performed, and who is the target group. LCA has an iterative nature, making it crucial to document any change in goal and scope during the process (Grahl & Klöpffer, 2014). Moreover, the functions of the studied product systems must be well described and illustrated in flow charts, and the intended applications of the results shall be determined in the goal definition phase because this may affect later phases of an LCA study (Hauschild et al., 2018). On the other hand, the scope definition provides information about production systems that are planned to be assessed and how they will be evaluated (Hauschild et al., 2018).

Another relevant definition is the functional unit that describes the function of the studied product system in a life cycle assessment (Grahl & Klöpffer, 2014). In addition, the functional unit is used as a basis to which materials and energy flows can refer (Du, 2015). Accordingly, it is essential to define the functional unit elaborately because it influences an LCA study's procedure (Hauschild et al., 2018).

### 2.1.2.2 Inventory analysis

The process of collecting data and modeling the flow charts through, from, and into the product system is done during the life cycle inventory analysis LCI phase of an LCA study (Hauschild et al., 2018). The inventory analysis initiates by identifying the process units for the life cycle inventory model, collecting data, preparing the basis for uncertainty management, and reporting the results of LCI (SAIC, 2006). Based on the functional unit of the product system, all the relevant emissions are quantified when reporting the results during the inventory analysis phase (Du, 2015).

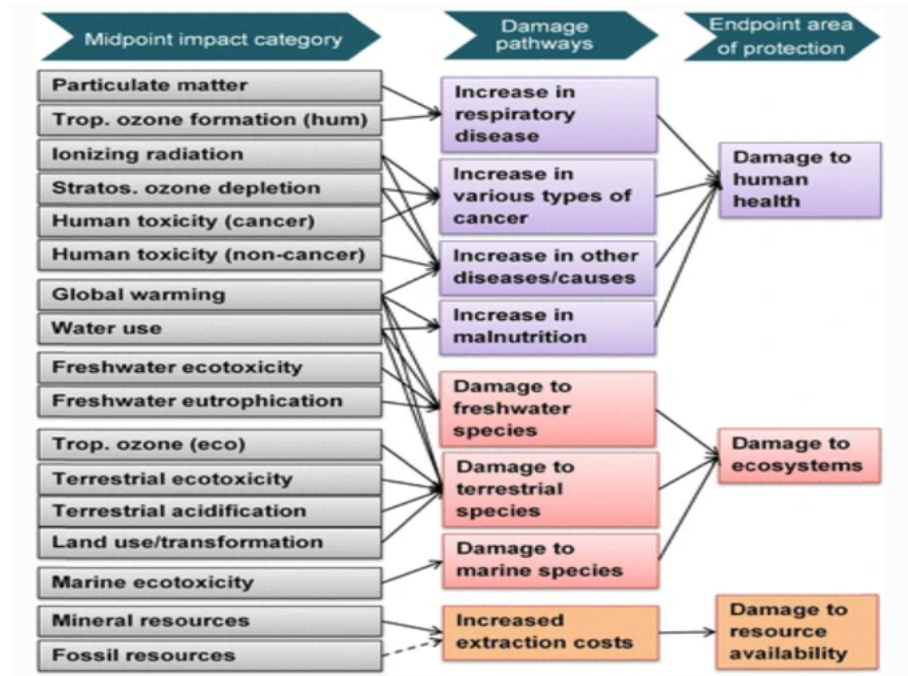


The inventory analysis is a follow-up process to the goal and scope definition and aims to create a systems model in the form of flow charts with certain system boundaries (Baumann & Tillman, 2004).

### 2.1.2.3 Impact assessment

The life cycle impact assessment LCIA phase aims to estimate the magnitude of emissions and resource use to an environmental impact associated with a category indicator (Hauschild et al., 2018). Thus, characterization factors, which represent the environmental impact per unit of stressor, convert emissions and resource extractions into a specific number of environmental impact scores (Huijbregts et al., 2016).

This phase considers two mainstream levels, the midpoint and endpoint levels (Huijbregts et al., 2016). The midpoint level (problem-oriented) aims to translate the emission list obtained from LCI into more common groups of impact categories such as global warming and abiotic depletion (Du, 2015). In comparison, the endpoint level (damage-oriented) is based on more significant overall effects, such as the impact of a product's manufacturing on human health (Du, 2015). Figure 2.2 shows the relationship between the midpoints characterized by the environmental impact categories (derived from LCI) and the endpoints characterized by the three regions of protection, damage to human health, damage to ecosystems, and damage to resource availability according to the ReCiPe 2016 method.



**Figure 2.2:** Overview of the impact categories that are covered in the ReCiPe 2016 Method (Adapted from Huijbregts et al., 2016).

The ISO 14040 Standards proposed different steps in the life cycle impact assessment

LCIA. The different steps were divided into mandatory and optional steps as follows: Mandatory steps of LCIA:

- The selection of impact categories aims to find the most suitable category indicators. This might be done by choosing an existing LCIA method (Hauschild et al., 2018). In addition, these categories should be translated into more specific impact levels, such as global warming, resource depletion, and acidification (Baumann & Tillman, 2004).
- Classification, where results of LCI are planned to be assigned to the most relevant impact category. For instance, the CO<sub>2</sub> emissions into the air are classified to climate change (Hauschild et al., 2018).
- Characterization means adding up the effects of all relevant components and using characterization factors to evaluate the contribution of the involved chemicals. For example, the effects of emissions from ammonia and nitrogen oxide on acidification (Du, 2015).

Optional steps of LCIA:

- Normalization, weighting, and grouping:

Normalization enables comparison in terms of providing a sense of the relative magnitudes of the potential environmental impact (Hauschild et al., 2018). Normalization can also be helpful in controlling consistency and communicating results (Hauschild et al., 2018). Weighting refers to procedures for conducting a single index based on the subjective assessment of various environmental impacts (Itsubo, 2015).

### 2.1.2.4 Interpretation

Interpretation is the final phase of a life cycle assessment LCA and aims to conclude from the results of life cycle inventory LCI and life cycle impact assessment LCIA (Klöpffer & Grahl, 2014). This phase refers to the goal and scope definition made in the first phase of LCA. In the standards ISO 14040 (2006), the interpretation is described as the phase in which outcomes, from the life cycle inventory and the impact assessment phase, are consistent with the goal and scope definition. The results of LCA should provide some recommendations and conclusions based on the limitations throughout the LCA study.

## 2.2 Application of LCA in bridge designs

Widman (1998) studied and compared the environmental impact of two roadway bridges, a steel box girder with eight spans of concrete decking, and a steel I girder bridge with a single concrete deck. The findings stressed that manufacturing cement and steel is the primary source of CO<sub>2</sub> emissions, and it was stated that steel bridge provides an excellent environmental choice. The study showed that transporting materials and products contributes to a large amount of CO and NO<sub>x</sub> emissions. Furthermore, the passenger traffic during the use phase has been noticed as the most polluting unit.

However, Steele et al. (2002) studied three phases in a life cycle assessment study for brick arch bridges. The phases are the bridge construction phase, the service

life phase, and the structure strengthening. The outcomes of this study stated that environmental impact reduction should not come at the cost of structural robustness and lifetime and that recycling and reuse of materials should be the main priority for all waste disposals.

Bridges are considered complex structures, so assumptions and simplifications are needed to be provided through the design phase and life cycle analysis. Many factors affect the quality of results, such as life cycle assessment scenarios, the selected life cycle impact assessment method, the LCI database, and the definition of goal and scope (Du & Karoumi, 2012). Itoh and Kitagawa (2003) concluded the use phase is the most dominant phase through the bridge life cycle, whereas Du and Karoumi (2012) stated that the manufacturing of material is the most critical phase during the bridge life cycle.

The life cycle assessment of bridges can be divided into four phases: manufacturing of materials, construction phase, use, and maintenance phase, and end-of-life EOL phase (Du, 2015). In addition, many reviewed studies within implementing LCA tools in bridge constructions evaluated the CO<sub>2</sub> emissions and energy consumption to assess the global warming potential GWP in terms of CO<sub>2</sub> emissions (Du & Karoumi, 2012). Therefore, it is essential to perform LCA studies with a holistic approach considering the entire life cycle (Muñoz et al., 2020).

## 2.3 Life cycle cost analysis LCC

The life cycle cost analysis LCCA is a methodology for systematically evaluating the life cycle cost during a set assessment period (Muñoz et al., 2016). Plenty of bridge management systems include LCC as a fundamental tool for determining the best strategy based on the remaining life span (Muñoz & Quijano, 2013). Additionally, to determine the total life cycle costs for bridge construction, the costs are discounted to their present value PV (Gervásio & Da Silva, 2008).

The life cycle cost analysis should cover the initial costs, material costs, and expected maintenance costs over the bridge's life span (European Commission, 2013). In this context, different economic evaluation methods could be implemented on the total life cycle costs, such as the payback method, EAC, the IRR method, and net present value NPV (European Commission, 2013).

Stainless steel is an expensive material due to its purchasing costs (ISSF, n.d.). While considering the whole life cycle cost, stainless steel has lower costs than carbon steel since stainless steel does not need any operations related to maintenance and repaint. The material cost of duplex stainless steel, grade 1.4162, is about 65 SEK for 1 kg stainless steel (Wahlsten et al., 2018).

LCC analysis is a suitable method to evaluate the economic feasibility of bridges; LCC adds all costs from purchasing to demolition (Mara et al., 2013). The user costs related to the traffic disturbances during the use phase of the bridge influence the total life cycle costs when the average daily traffic is relatively high (Cope et al., 2013). In the life cycle cost analysis, a deterministic analysis is performed in order to enable designers to give each input parameter a constant value (Cadenazzi et al., 2020). One of the objectives of this study is to provide a comparison between two bridge design concepts. Therefore, the traditional deterministic approach can be

used in LCC. This analysis considers the uncertainty of input parameters through sensitivity analyses (Cadenazzi et al., 2020).

### 2.4 The application of stainless steel in bridge design

The most used structural materials in bridge constructions are steel and concrete (Gervasio & Da Silva, 2008). As a result, the production phase of these materials is one of the biggest contributors to environmental burdens. However, the steel industry addresses steel as an environmentally friendly material due to its high recycling rate (Gervasio & Da Silva, 2008). The electric arc furnace method (EAF) produces steel plates, structural beams, and reinforcement bars. EAF process uses around 95 recycled steel (Gervasio & Da Silva, 2008). On the other hand, carbon steel has low resistance against corrosion and must be protected by painting, especially in constructions exposed to moisture, which increases the maintenance costs (Aghayere et al., 2020).

Stainless steel has higher resistance against corrosion (Stålbyggnadsinstitutet, 2017). It is characterized by cost-effectiveness since there is no need for maintenance activities (Rossi, 2014). Duplex stainless steel has a mixed structure consisting of two categories, austenite, and ferrite, which increases the strength of this material (Stålbyggnadsinstitutet, 2017). According to Rossi (2014), duplex stainless steel has been widely used in bridge constructions due to its high strength, providing lighter structures. Duplex stainless steel has higher formability and is highly valuable in weight-sensitive constructions, such as bridges (Stålbyggnadsinstitutet, 2017).

Backhouse and Schedin (2019) stated that over 60 years of service life for a stainless-steel bridge, the benefits, and savings in reduced maintenance costs could be between 30-40 % compared to a carbon steel bridge. The maintenance savings for a stainless-steel bridge will be considerably higher if the bridge has a longer service life (Backhouse & Schedin, 2019). Moreover, duplex stainless steel is suitable for various bridges, from railway bridges to heavy-load roadway bridges (Outokumpu, n.d.).

### 2.5 Genetic algorithms for optimization of structural designs

Multiple performance objectives must be considered simultaneously in real-world optimization problems (Deb, 2001). Often, there is a conflict between the objectives, and development in one can only be achieved at the price of the other. As a result, no one practical option will deliver the optimum results across all criteria. The optimizer's goal is to assist the decision-maker in learning about the trade-offs between objectives and finding a satisfactory solution (Deb, 2001).

Evolutionary algorithms (EAs) allow simultaneous and different solutions in one single optimization run (Deb, 2003). Evolutionary algorithms are an effective method

for finding optimal solutions to complicated optimization problems (Yildiz, 2013). Numerous evolutionary algorithms, such as the genetic algorithm NSGA- II, cuckoo search algorithm, particle swarm optimization algorithm, and artificial immune algorithm, have been widely used to obtain optimal designs (Yildiz, 2013).

### **2.5.1 Structural optimization**

Structural design optimization has been a complex subject in engineering design to produce more efficient and lighter structures. The design optimization aims to identify the structure's best form. (Yildiz, 2013). Design objectives are structural criteria used in structural optimization to evaluate a design's merit, such as minimal construction cost, minimum life-cycle cost, minimum weight, and maximum stiffness. Building code standards, which mandate the structure's safety and serviceability, are frequently used as design constraints. Furthermore, some non-behavioral restrictions, such as the type and size of available structural elements, may limit the acceptable designs. Design variables may describe the structure's shape, topology, and geometry, or they may define the size or properties of structural elements. (Sahab et al., 2013).

The optimization of bridge designs will be performed based on the life cycle assessment and life cycle costing in order to provide optimal bridge design solutions. This optimization will be performed in collaboration with the Master's thesis by Hallgren and Johansson (2022).



# 3

## The parametric tool for LCA and LCC

In this chapter, an overview of the parametric model will be defined. Firstly, an overview of the system boundary and the data sources are provided. Secondly, the parametric modeling and the equations used for the LCA and LCC evaluation will be presented. This chapter provides an overview of the parametric tool with all input parameters used in this study for LCA and LCC.

### 3.1 The goal and scope of the life cycle assessment

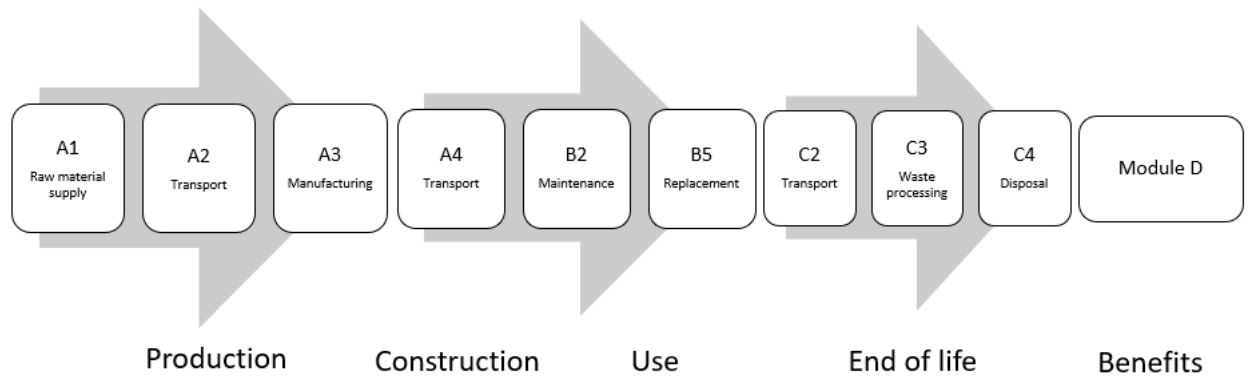
The goal of the life cycle assessment is to provide a comparison between different bridge design concepts. For example, the functional unit might be chosen to ensure regular traffic over an obstacle for a given bridge length for the desired service life. The scope of the life cycle assessment is defined in Section 3.2.

### 3.2 System boundaries and data collection

The outcome of this parametric modeling is to develop the computational tool in Python to evaluate the environmental impact and the life cycle cost of different bridge designs and enable the comparison between different bridge constructions based on the material used in the structural components. A comparison process between a carbon steel girder and a stainless-steel girder with a flat and corrugated web will be performed, considering the environmental impacts and the life cycle cost. This tool will be used in genetic algorithm optimization to optimize bridge design parameters.

#### 3.2.1 Life cycle assessment LCA

The first stage in developing the tool to calculate the environmental impact is defining what to include and exclude in the assessment. This is defined by choosing the system boundary for the life cycle assessment LCA and outlining the most important phases throughout a bridge's whole life cycle.



**Figure 3.1:** The life cycle stages included in the system boundary for a bridge construction (Own illustration adapted from EN 15978:201)

#### 3.2.1.1 The system boundary

Following the European standard EN 15978:201, a building's life cycle stages approach can be used as a guideline for a bridge's life cycle assessment to define the system boundary. Figure 3.1 shows the life cycle stages included in this study. In the production stage, modules A1 to A3 were chosen to start from the extraction of raw materials, A1, through transporting these materials to factory, A2, and manufacturing, A3. This stage might represent a whole life cycle of material production with several supplementary activities, such as material transportation, initial energy consumption, and waste treatment (Du and Karoumi, 2014). Herein, the raw material extraction, transportation, and manufacturing are considered. The material manufacture phase should consider the bridge type, for example, an I-girder steel bridge or box girder steel bridge. The construction phase considers the energy consumption of construction machines, material transportation, and the operational and supporting systems. In this study, transporting materials and products from the factory to bridge site, A4, is considered. The installation processes, including the machinery work A5, are neglected. In this stage, it could be a lack of information considering the operational types of machinery due to missing and unavailable data. Hence, the authority should require the companies to provide a project-level-based database to better promote sustainability development for bridges (Du and Karoumi, 2014).

The use phase considers the regular use and maintenance activities of the bridge. Due to the nature of bridge structures and their long-life span, a regular maintenance plan should be scheduled and operated throughout the use phase. Accordingly, energy consumption and traffic delay scenarios will contribute to a significant environmental burden (Du and Karoumi, 2014).

Therefore, in this study, the maintenance procedure, B2, and the replacement process, B5, included in this schedule (repainting) are taken into consideration. Moreover, the maintenance activities are highly affected by the bridge type. For instance, a fixed-slab bridge has a more manageable maintenance plan than a ballast bridge (Du and Karoumi, 2014). The materials used in bridge construction play an impor-



tant role in considering the effectiveness and duration of the maintenance plan. For instance, stainless-steel bridges can be operated without any need for maintenance thanks to stainless steel's high corrosion resistance property.

Maintenance activities might require specific material production processes for replacement activities. For example, bridges constructed of carbon steel need to be repainted and patched up during the maintenance plan, which in turn requires the production of an amount of paint, which must be transported to the bridge site. Hence, the transportation of this produced material should also be considered in the use phase. The end-of-life phase considers the energy consumption from the deconstruction demolition, the transportation from the bridge site to landfills, waste treatment, and recycling processes (Du and Karoumi, 2014). In this research, the transportation of waste, C2, is included. Continued, the waste processing treatment, C3, is also considered including waste sorting and material incineration. The disposal processing is also included in this study in module, C4. The end-of-life phase expects that the waste treatment procedure and the end-of-life scenario will benefit the environment in terms of recycling and reuse of materials.

Since the primary material in bridge components is steel in the girders, concrete deck, and steel reinforcement bars, the metals from these materials have high recycling rates, up to 100 %, without any loss of initial properties (Fenton and Reston, 1998). Fenton and Reston (1998) stated the steel recycling rates, from the structural plates and beams, to be up to 88%. Accordingly, in this study, module D is included in the calculations to show the environmental benefits of recycling steel and producing steel scraps. End-of-life scenarios must be carefully chosen since the recycling and reuse considerations are decisive in reducing the total environmental burdens for a bridge's whole life cycle assessment (Du and Karoumi, 2014).

### **3.2.1.2 Data sources for the life cycle inventory**

Data collection is continuously performed using the Ecoinvent database and different environmental product declarations EPDs to provide information on the environmental impacts per unit for each process included in the life cycle study. In this study, the database used is the Ecoinvent 3.8 cut-off system model with the latest version to generate as accurate results as possible for the life cycle inventory. The Ecoinvent cut-off system model assumes that the leading producer of a material does not receive any credits for providing recyclable materials (Ecoinvent, n.d.). More particularly, this means that recyclable materials are burden free to recycling processes, whereas secondary materials stand for the impact of recycling processes (Ecoinvent, n.d.). Additionally, the cut-off model allocates the incineration to the waste treatment, where the total burden is entirely assigned to the waste producer. Ecoinvent includes different impact assessment methods which focus on one single environmental impact or several impact categories, such as "Ozone layer depletion," "Climate change," "Acidification," and "Photochemical oxidation." ReCiPe and CML 2001 are two impact assessment methods that provide several impact categories both at the midpoint and endpoint level (Ecoinvent, n.d.).

Data collection should be as specific as possible. Therefore, data will be collected from the Swedish Transport Administration's online climate database, such as CO<sub>2</sub> emissions and transport distances for different transport types, to make LCA re-

sults more representative. Furthermore, different EPDs will be used throughout the life cycle inventory to provide CO<sub>2</sub> emission factors for different material production processes. For instance, CO<sub>2</sub> emissions for hot rolled steel and steel plate production will be collected in kg CO<sub>2</sub> equivalent per the production of 1 kg steel materials. In this study and the parametric tool, the CML 2001 method will be used to evaluate the environmental impacts for each life stage in terms of global warming potential GWP 100 years.

#### 3.2.1.3 CML 2001 impact assessment method

CML 2001 impact assessment method aims to reduce uncertainties by limiting the quantitative modeling to early stages in the cause-effect chain (Bernardi et al., 2020). The results of this method can be grouped in midpoint categories following common mechanisms, such as climate change. Table 3.1 presents the most common midpoint impact categories evaluated using CML 2001 method.

**Table 3.1:** The most common midpoint impact categories from CML 2001 method (Adapted from Bernardi, et al.,2020)

Impact category	Abbreviation	Unit
Global warming potential	GWP	(kg CO <sub>2</sub> eq.)
Acidification potential	AP	(kg SO <sub>2</sub> eq.)
Eutrophication potential	EP	(kg PO <sub>4</sub> eq.)
Human toxicity potential	HTP	(kg DCB eq.)
Ozone layer depletion potential	ODP	(kg R11 eq.)
Photochemical ozone depletion creation	POCP	(kg Ethene eq.)
Abiotic depletion(elements)	ADP el.	(kg Sb eq.)

#### 3.2.2 The life cycle costing assessment LCC

The parametric tool will also include the life cycle cost calculations to make the comparisons between stainless steel and carbon steel bridges more detailed and to include the economic perspective in this study. As a basis for this study, the system boundary for life cycle cost assessment should be defined to define what to include and exclude in the calculations considering a bridge's whole life cycle.

##### 3.2.2.1 The system boundary

The production and construction stages A1 to A5 in Figure 3.1, include the total investment cost. This cost includes the material and production costs, including welding and assembly costs, corrugation costs, painting costs, grinding of bridge edges, and concrete casting costs. For the welding costs, the prices are based on the connection type, fillet, butt, or bolted. Assembly of the girder and treatment costs are also included in the construction stage. The erection costs will be included depending on the number of splices needed for the main girders and cross beams. For the use stage, the costs are associated with the maintenance schedule activities.

Adelino et al. (2017) stated in their study that it is essential for LCC to include user costs during the use phase when regular traffic is disrupted because of the restrictions imposed by the maintenance plan. Accordingly, in this study, the user costs are included in the form of traffic delay costs TDC. Since one of the objectives of this study is to compare bridges made of stainless steel and carbon steel, the results obtained from LCC will differ because stainless steel bridges can be operated with no need for periodic maintenance activities. However, in this study, all costs associated with the end-of-life phase are neglected. Module D is included in LCA, considering steel and stainless steel recycling rates. Hence, the revenues generated by reselling steel scraps and stainless-steel scraps in LCC calculations are taken into consideration.

### **3.2.2.2 Data collection**

For the production and construction costs, including treatment activities, most of the costs are covered by planners and engineers in the construction industry since they rely highly on the design geometry, production, and assembly processes used in the production and construction stages. For the use phase, the costs are related to the maintenance plan operations provided by Rossi et al. (2017). To increase the accuracy of LCC results, the reference prices should represent the price available in today's market, and therefore, these costs are provided by interviewing experts in the construction industry. The costs will be collected as follows: material costs for each material used in the bridge design. For example, the steel material costs will be provided in SEK/kg based on the steel grade and profile. The welding costs will be based on the welding type, i.e., fillet and butt welds. Moreover, painting costs will be provided in SEK per painting area. The life cycle cost calculations integrated into the parametric tool are based on a calculation model and price estimations provided by Lecor Stålteknik and Bräderna Jansson (Personal communication, May 6, 2022).

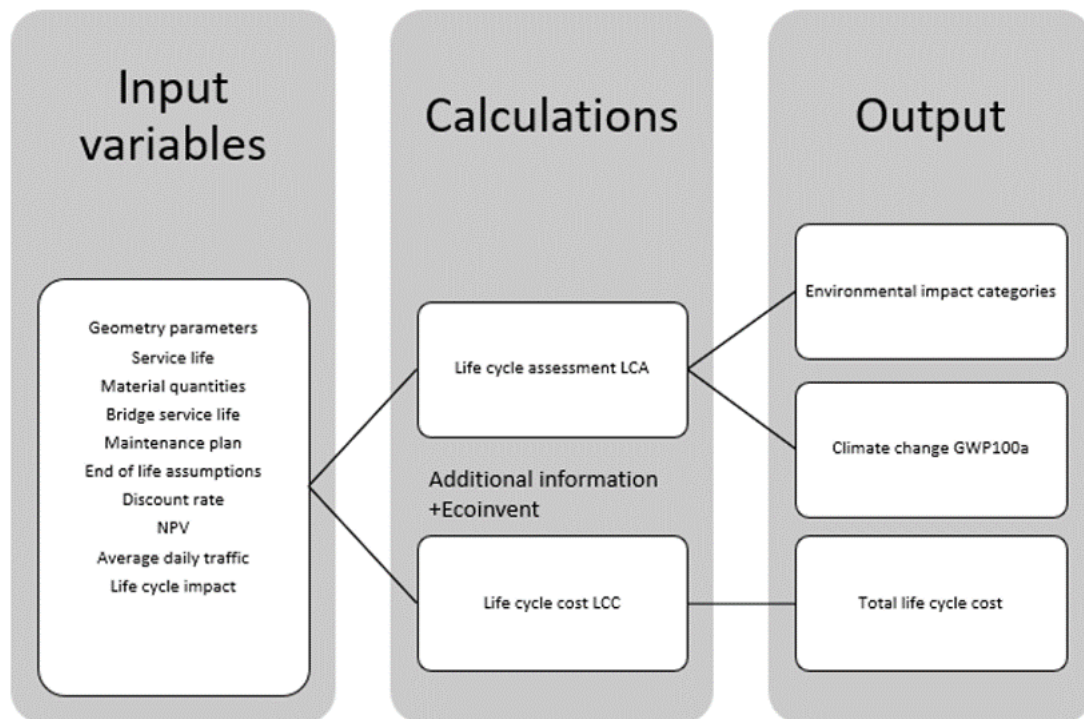
## **3.3 Requirements for LCA application in structural design**

According to Hollberg and Ruth (2016), the LCA model approach should be simplified and easy to understand without any previous knowledge of LCA to aid designers in decision-making. In this context, Hollberg and Ruth (2016) proposed some requirements for the life cycle assessment method. First, this method should be simplified and feasible. Second, since LCA is performed in the early design stages, adequate assumptions are made about missing data. Third, the LCA method should integrate models that can easily be updated and refined. Lastly, the results of this approach should be reported understandably without any need for detailed knowledge of LCA (Hollberg and Ruth, 2016).

### 3.4 The parametric model

Hollberg and Ruth (2016) suggested a parametric model for the life cycle assessment. This parametric modeling aids designers with design variations and decreases change costs in the early design phases (Davis, 2013). The parametric model developed by Hollberg and Ruth (2016) is based on numerous defined equations containing different design parameters, which can be defined as critical factors affecting the life cycle assessment calculations.

This study considers a parametric model adapted from Hollberg and Ruth (2016). Hence, the parametric model is divided into three modules, as shown in Figure 3.2. Input variables, calculations, and output. The input variables are included in the calculations in the form of mathematical equations. For example, the material quantities are included in the calculation of the environmental impacts by multiplying the quantity of each material with the environmental data obtained from external sources, i.e., Ecoinvent, to evaluate the contribution of each material supply to the total environmental impact. In summary, supplementary information and data are needed to be collected herein from Ecoinvent 3.8 and different EPDs to transfer the input variables, with the aid of equations, to outputs in the form of environmental impacts and total costs.

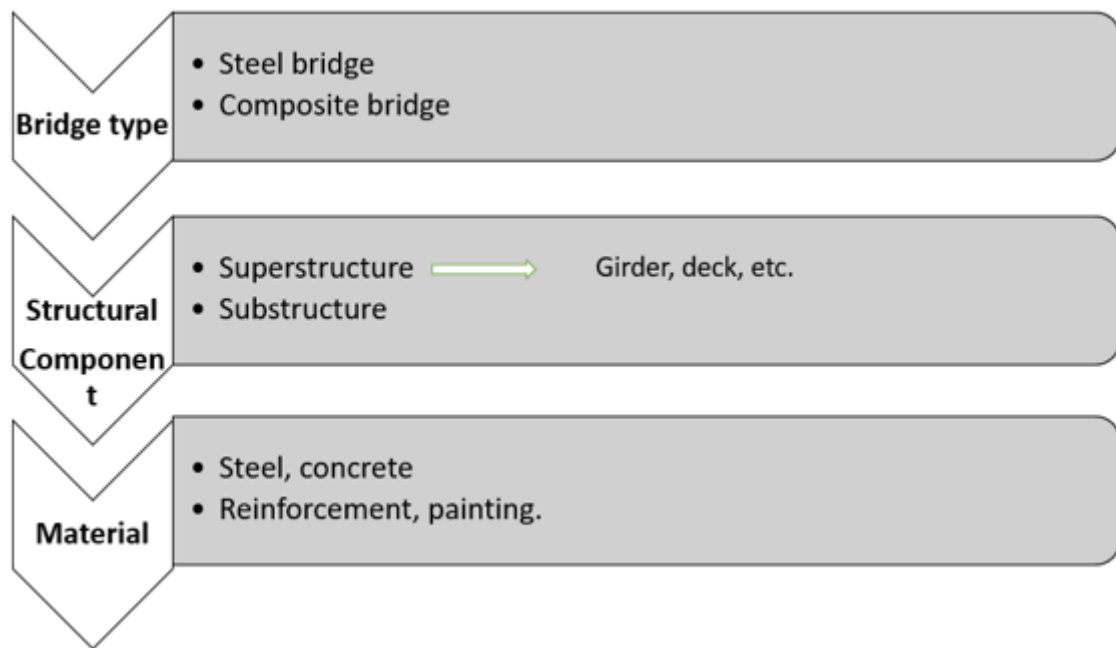


**Figure 3.2:** Concept of the parametric model used in this study (Own illustration)

#### 3.4.1 Input variables

In this section, an overview of the input variables used in the calculation is provided. These input variables are parametrically defined in the calculations to allow any

changes to the designs. First, the bridge type is defined, and the service life of the bridge is set as an input. Since the life cycle assessment in this tool is estimated for a bridge's whole life cycle, the parametric tool will assess it based on the bridge level, considering the bridge system level, element level, and material level. Du and Karoumi (2014) classified the main parameters to be considered for the life cycle assessment of railway bridges based on the bridge level. Figure 3.3 shows the main parts included in bridge construction to be considered in the parametric modelling of this study.



**Figure 3.3:** The main parts of a bridge based on the bridge level

Consequently, the input variables included in the parametric model for the life cycle assessment LCA and life cycle cost LCC are defined as follows:

- The service life of the bridge [years] is included in the parametric tool as an input parameter, which enhances the comparison between a service life of 120 to 80 years, for example, through the evaluation phase of this study.
- The painting area of the girder for carbon steel bridge girders and the pickling area for stainless steel girders.
- The quantity of material in each structural component. For example, how much steel in kg is needed for the steel girder production. This parameter is a key factor for the life cycle assessment.
- The welding length [m] to highlight the difference between the welding length required in the case of corrugated webs and flat webs.
- The affected road length [km], the average daily traffic [vehicles], the reduced and normal speed, and the percentage of heavy vehicles [%] are all defined as input for the calculation of the user costs associated with the maintenance activities.

### 3. The parametric tool for LCA and LCC

- The reference price of each material in a structural component, and the reference price of welds based on the connection type and the cross-sectional area of the welds.
- Discount rate and escalation rate [%].

#### 3.4.2 Calculations

In this section, the mathematical equations used to calculate the environmental impact and life cycle cost will be presented. First, additional information from Ecoinvent and other sources are needed as shown in Figure 3.2. This additional data will be collected based on the input variables defined in Section 3.4.1.

##### 3.4.2.1 Additional data

- Life cycle impact assessment results per unit material from Ecoinvent 3.8 database. This information will be collected based on material production.
- The transportation distance [km] for different life stages, materials, and transportation types. According to the Swedish Transport Administration (Trafikverket, n.d.), each material/element requires multiple types of transportation.
- End of life scenarios are also provided by the Swedish Transport Administration for bridge construction. For instance, potential recycling and reuse of each material in the bridge construction.
- A maintenance plan, including the periodic painting activities, is used in the parametric model for the use phase, referring to a painting plan for a steel bridge adapted from Rossi et al., (2017). Considering the maintenance plan, the painting activities, such as patch up, overcoating and remove and replace will be integrated in the parametric tool as shown in table 3.2.

**Table 3.2:** Painting plan for a steel girder adapted from Rossi et al., (2017). The service life is estimated to be 120 years

Activity	Action time (Year)	Reference	Reference unit	Painted area Relative %
Patch up	13	Initial painting area	m <sup>2</sup>	5%
Overcoating	19	Initial painting area	m <sup>2</sup>	90%
Remove and replace	31	Initial painting area	m <sup>2</sup>	90%
Patch up	44	Initial painting area	m <sup>2</sup>	5%
Overcoating	50	Initial painting area	m <sup>2</sup>	90%
Remove and replace	62	Initial painting area	m <sup>2</sup>	90%
Patch up	75	Initial painting area	m <sup>2</sup>	5%
Overcoating	81	Initial painting area	m <sup>2</sup>	90%
Remove and replace	93	Initial painting area	m <sup>2</sup>	90%
Patch up	106	Initial painting area	m <sup>2</sup>	5%
Overcoating	112	Initial painting area	m <sup>2</sup>	90%
Remove and replace	Stop	-	-	-

##### 3.4.2.2 Environmental impact calculations

In this study, the environmental impact of a bridge's life cycle is calculated based on the following equations used in the parametric model. The equations are pro-

vided for each life stage included in this study based on Figure 3.1. The total environmental impact is the sum of the environmental impacts obtained from each stage, production, construction, end of life, and benefits from reuse. Additionally, the environmental impact in the parametric tool is calculated in terms of climate change GWP, represented by CO2 emissions, in kg CO2-equivalent and the impact assessment method used for this evaluation is CML 2001 (see Section 3.1). In the production stage A1 to A3, the environmental impact is calculated using the following equations:

$$Imp_{production} = Imp_{material} + Imp_{addition} \quad (3.1)$$

$$Imp_{material} = \sum_m (\sum_j Q_{m,j} * IF_{m,m}) \quad (3.2)$$

$$Imp_{addition} = \sum_p (\sum_j F_{p,j} * IF_p) \quad (3.3)$$

**Table 3.3:** The parameters included in the production impact calculation

Notation	Description	Unit
$Imp_{production}$	The impact of the production stage	kg CO2- eq
$Imp_{material}$	The impact generated from material supply	kg CO2- eq
$Imp_{addition}$	The impact of additional processes needed in the production phase	kg CO2- eq
$Q_{(m,j)}$	The quantity of material m in component j	kg
$IF_{m,m}$	The impact assessment results per unit material m	kg CO2- eq / kg
$F_{p,j}$	The process p needed for component j in the production phase	-
$IF_p$	The impact assessment results per unit process p needed in the production phase	kg CO2- eq/m or kg CO2- eq/kg

For the construction stages A4 and A5, the environmental impact is calculated considering the transportation module A4 from the factory to the construction site. The machinery work is excluded in this stage due to the lack of information related to the machinery used and the operation hours during the construction phase. The environmental impact in this stage is calculated using the following equation:

$$Imp_{construction} = \sum_m (\sum_t (\sum_j Q_{m,j} * L_{m,t} * IF_{transport,t})) \quad (3.4)$$

**Table 3.4:** The parameters included in the construction impact calculation

Notation	Description	Unit
$Imp_{construction}$	The impact of the construction stage	kg CO2-eq
$Q_{m,j}$	The quantity of material m in component j	kg
$L_{m,t}$	The transport distance of material m by transport type t	km
$IF_{transport,t}$	The impact assessment results per ton*km of the transportation type t	kg CO2-eq / (t*km)

For the use phase, B2 and B5 modules are included in the parametric tool. The maintenance plan considers the production of paint needed to maintain the bridge during the use phase (See Table 3.2). The transportation of the paint produced is also included in the calculation of the impact of the use phase by using the following equations:

$$Imp_{use} = Imp_{repaint} + Imp_{transport} \quad (3.5)$$

$$Imp_{repaint} = \sum_m (\sum_y Q_{m,j} * n_y * IF_{m,m}) \quad (3.6)$$

$$Imp_{transport} = \sum_m (\sum_t (\sum_y Q_{m,y} * L_{m,t} * IF_{transport,t})) \quad (3.7)$$

**Table 3.5:** The parameters included in the use phase impact calculation

Notation	Description	Unit
$Imp_{use}$	The impact of the use phase	kg CO2-eq
$Imp_{repaint}$	The impact of the production of paint needed for the maintenance plan	kg CO2-eq
$Imp_{transport}$	The impact of transportation of produced material in the maintenance activities	kg CO2-eq
$Q_{m,j}$	The quantity of material m needed per maintenance activity y	kg
$n_y$	The number of times of maintenance activity y over the life cycle of the bridge	Number
$IF_{m,m}$	The impact assessment results per unit material m	kg CO2-eq/kg
$L_{m,t}$	The transportation distance of material m through the transport type t	km
$IF_{transport,t}$	The impact assessment results per ton*km of transportation t	kg CO2-eq

The impact of the traffic disturbances is omitted in the life cycle assessment. However, this impact is included in terms of traffic delay costs in the life cycle cost analysis. For the end-of-life phase, the recycling of the materials, the transportation of wastes to landfills, waste processing, and disposal. C2, C3, and, C4, are considered. The following equations are used to calculate the environmental impact in this phase:

$$Imp_{eol} = Imp_{recycling} + Imp_{disposal} + Imp_{transport,eol} \quad (3.8)$$

$$Imp_{recycling} = \sum_j (\sum_m (Q_{m,j} * r * IF_{recycling,m})) \quad (3.9)$$

$$Imp_{disposal} = \sum_j (\sum_m (Q_{m,j} * (1 - r) * IF_{disposal,m})) \quad (3.10)$$

$$Imp_{transport,eol} = \sum_m (\sum_j Q_{m,j}) * L_{eol} * IF_{transport,specific} \quad (3.11)$$

**Table 3.6:** The parameters included in the end of life phase impact calculation

Notation	Description	Unit
$Imp_{eol}$	The impact of the end-of-life phase	kg CO2 eq
$Imp_{recycling}$	The impact of the recycling processes	kg CO2 eq
$Imp_{disposal}$	The impact of disposal processes	kg CO2 eq
$Imp_{transport,eol}$	The impact of transportation in the end-of-life phase	kg CO2 eq
$Q_{m,j}$	The quantity of material m needed per maintenance activity y	kg
$r$	The recycling rate	%
$IF_{recycling,m}$	The impact assessment results per recycling process of material m	kg CO2 eq/kg
$IF_{disposal,m}$	The impact assessment results per disposal material m	kg CO2 eq/kg
$L_{eol}$	The transport distance from construction site to landfills	km

Since module D is included in the system boundary according to Figure 3.1, the benefits from avoided environmental burdens are calculated using the following equation:

$$Imp_{moduleD} = \sum_j (\sum_m (Q_{m,j} * (r - f) * IF_{v,m})) \quad (3.12)$$



**Table 3.7:** The parameters included in the benefits impact calculation

Notation	Description	Unit
$Imp_{moduleD}$	The impact of the module D	kg CO2 eq
$Q_{m,j}$	The quantity of material m needed per maintenance activity y	kg
r	The recycling rate	%
f	The fraction of secondary material in material m in component j	%
$IF_{v,m}$	The impact assessment results per unit virgin material obtained by the secondary material	kg CO2 eq/kg

### 3.4.2.3 Life cycle cost calculations

In the parametric tool, the LCC calculations consider the system boundary for LCC in section 3.2.2.1. In this section, the equations used for life cycle cost calculations will be presented for each stage. Since the costs should be presented in the time value of money, the net present value method NPV will be used. The total costs are evaluated based to the following equation:

$$Cost_{total} = C_{material} + C_{production} + C_{erection} + C_{use} - C_{revenues} \quad (3.13)$$

The equations used to calculate the material costs, production costs and erection costs are adapted after a life cycle cost model and a price estimation list provided by Mohammad al-Emrani (Personal Communication, May 6, 2022) In the production stage, the material supply cost is taken into account and the following equation is used to calculate the material costs:

$$C_{material} = \sum_j (\sum_m F_{m,j} * C_m) \quad (3.14)$$

**Table 3.8:** The parameters included in the material cost calculation.

Notation	Description	Unit
$Cost_{total}$	The total life cycle costs	SEK
$C_{material}$	The material costs	SEK
$F_{m,j}$	The reference input variable for material m in component j. For example, volume of concrete in the concrete deck	kg, m <sup>3</sup> orm <sup>3</sup>
$C_m$	The reference cost based on the reference input variable	SEK/m <sup>2</sup> SEK/kg SEK/m <sup>3</sup>

For the production costs, the following costs have been considered in the parametric tool:

- The welding cost for each connection type, considering the welding length, the welding area and the weld passes required for a weld area.
- The assembly of weld costs.
- The grinding of all free plate edges.
- The pickling costs, only for stainless steel girders.
- Corrugation costs, which depend on the length of the girders.
- The painting costs, considering the total painting area and whether if the painting is done on site or in the workshop.
- Cutting of plate costs, considering the total weight of the steel needed in the bridge construction.

$$C_{welding} = (A_w + 30) * L * c_w / (19 * l) \quad (3.15)$$

$$C_{assembly} = p * C_{welding} \quad (3.16)$$

$$C_{grinding} = l_{edges} * c_{grinding} \quad (3.17)$$

$$C_{pickling} = A_{steel} * c_{pickling} \quad (3.18)$$

$$C_{corrugation} = l_{girders} * c_{corrugation} \quad (3.19)$$

$$C_{painting} = A_{paint} * c_{paint} \quad (3.20)$$

$$C_{cutting} = weight_{steel} * c_{cutting} \quad (3.21)$$

Where:

$C_{welding}$  is the welding cost in SEK.

$A_w$  is the welding area for fillet or butt weld [mm<sup>2</sup>]

$L$  is the welding length in meters.  $c_w$  is the welding cost per hour SEK/h

$l$  is the length that a welder runs per one hour (one pass) in meters.

$C_{assembly}$  is the assembly of welds cost SEK

$p$  is the additional percentage of the total welding costs [%]

$C_{grinding}$  is the grinding cost SEK

$l_{edges}$  is the length of all free plate edges in meters.

$c_{grinding}$  is the grinding unit cost SEK/m

$C_{pickling}$  is the total cost of pickling SEK

$A_{steel}$  is the entire steel area [m<sup>2</sup>]

$c_{pickling}$  is the pickling unit cost SEK/m<sup>2</sup>

$C_{corrugation}$  is the corrugation cost SEK.

$l_{girders}$  is the length of the girders in meters.

$c_{corrugation}$  is the corrugation unit cost SEK/m.

$C_{painting}$  is the total painting cost SEK.

$A_{paint}$  is the painting area [m<sup>2</sup>]

$c_{paint}$  is unit cost of painting SEK/m<sup>2</sup>

$C_{cutting}$  is the cutting of plate costs SEK

In addition, the cost of shear studs is included in LCC by using the following equation:

$$C_{studs} = n * c_{studs} \quad (3.22)$$

Where  $n$  is the total number of shear studs and  $c_{studs}$  is the unit cost of shear studs in SEK/piece. In the construction phase, the erection costs are included for the main girders and the cross beams. The erection costs will be calculated for the main girders and end cross beams. In addition, the erection costs for the intermediate cross beams will be included in the calculation:

$$C_{erection} = n_{sp} * c_{erectionwelded} + n_{cb} * c_{erectionbolted} \quad (3.23)$$

Where  $n_{sp}$  is the number of splices and  $c_{erectionwelded}$  is the unit cost of the process of welding the main girders and the end cross beams per splice corresponding to 16 manhours work.  $n_{cb}$  is the number of intermediate cross beams (bolted) and  $c_{erectionbolted}$  is the unit cost of the process per cross beam (two joints).

The costs in the use phase are associated with each maintenance activity according to the maintenance plan used in the study (See Table 3.2). For the costs associated with the painting activities, the unit costs for each activity are provided and adapted after the painting plan provided by Rossi, et al., (2017).

$$C_{use} = C_{process} + C_{user} \quad (3.24)$$

$$C_{process} = \sum_j \left( \sum_a (A_{a,j} * P * C_{a,j}) \right) * (1 + i/1 + d)^n \quad (3.25)$$

**Table 3.9:** The parameters used in the maintenance cost calculation

Notation	Description	Unit
$C_{use}$	The costs of the use phase	SEK
$C_{process}$	The process costs associated with the painting plan	SEK
$A_{a,j}$	The process for component j needed for the maintenance activity a. In this study, it refers to the initial painting area	m <sup>2</sup>
P	The operating percentage for each maintenance activity	%
$C_{a,j}$	The unit cost of maintenance activity a, for component j	In this study SEK/m <sup>2</sup>
i	The escalation rate	%
d	The discount rate	%

The user costs consider the traffic disturbances due to the maintenance periodic schedule and account for the traffic delay costs. The travel time delayed should be calculated considering the affected road length, the normal and reduced speed due to the disturbances. The following equation calculates the travel time delayed for one vehicle as follows:

$$Time = L_{aff} * (1/v_r - 1/v_n) \quad (3.26)$$

$$C_{user} = \sum_j \left( \sum_a (Time * ADT * T_{a,j} * (h_t * p_t + h_p * (1 - p_t))) \right) * (1 + i/1 + d)^n \quad (3.27)$$

**Table 3.10:** Parameters included in the user cost calculation

Notation	Description	Unit
$C_{user}$	The user costs	SEK
Time	Travel time delayed	hour
$L_{aff}$	Affected road length	km
$v_r$ and $v_n$	Reduced and normal speed	km/h
ADT	Average daily traffic	Number of vehicles /year
$T_{a,j}$	Time needed for maintenance activity a, for component j	days
$h_t$	Cost for heavy truck per hour	SEK/h
$p_t$	Heavy vehicle percent among the average number of daily traffic	%
$h_p$	Cost for passenger car per hour	SEK/h

The average daily traffic ADT relies highly on the location of the bridge. According to Trafikverket (Personal Communication, May 20, 2022) this value can be estimated to 100,000 vehicles per year for bridges located in middle of Stockholm, for

bridges located in Gothenburg the ADT value corresponds to a lower flow with 50,000. Whereas, for bridges located in small cities, the average daily traffic is much less and could be estimated to approximately 5,000.

To make LCC results more representative, the revenues obtained from selling the metal scraps are included in the LCC calculation in this study. Here, the unit price of end-of-life scenario for each material is included.

$$C_{revenues} = \sum_j (\sum_m (q_{m,j} * r_m * P_{eol})) * (1 + i/1 + d)^Y \quad (3.28)$$

**Table 3.11:** The parameters included at the end of life revenues calculation.

Notation	Description	Unit
$C_{revenues}$	The revenues obtained from selling the scraps	SEK
$q_{m,j}$	The quantity of material m in component j	kg
$r_m$	The recycling rate of material m	%
$P_{eol}$	The unit price of end-of-life material m	SEK/kg
$i$	The escalation rate	%
$d$	The discount rate	%
$Y$	The service life of the bridge	Years

#### 3.4.3 Output

The outputs of the parametric tool considering the life cycle assessment LCA are the environmental impacts generated in each life stage and the total environmental impact. In this study, the parametric tool provides the results based on CO2 emission factors extracted from different environmental product declarations EPDs and stored in the database. The environmental impacts are represented by the climate change impact category in the form of global warming potential (kg CO2-eq). The results are shown in the form of graphs and bar charts in order to provide the users with insights into the outcome and make the comparisons between flat web carbon steel and corrugated web stainless-steel bridges, based on the environmental performance and total cost, more realistic. The global warming potential is evaluated in kg CO2 eq for each life stage and bridge design, with and without the benefits generated from reusing the metal scraps in module D (See equation 3.12). In this study, normalization and weighting of the results have not been applied since the tool's primary purpose is to calculate the environmental impact in terms of GWP and the total life cycle cost in SEK. According to ISO 14040, the LCA approach's normalization and weighting stages are optional.

The parametric tool calculates the life cycle costs for each life stage in SEK, as well as the total costs, and it accounts for the time value of money by using the net present value of user costs and revenues (See equations 3.27 and 3.28). The LCC results are reported in the form of bar charts for different design variants considered in the case study.

To analyze the results, a dominance analysis can be performed to investigate what

parts of the life cycle contribute the most to the environmental impacts, and sensitivity analyses can be performed to examine the influence of the critical parameters on LCA and LCC. The users of this tool can find the hotspots in LCA based on the obtained graphs in each life cycle stage, which supports the decision-making when improving the bridge designs. When the design is adapted and modified, the parametric tool allows users to input the new design variants and perform a new evaluation of the life cycle assessment.

Moreover, the emission factors for CO<sub>2</sub> emissions play an essential role in calculating the environmental impacts of each life stage. Therefore, the database used in the parametric tool contains different emission factors collected from different environmental product declarations, EPDs, and emission factors extracted from Ecoinvent 3.8. This increases the representativity of LCA results and enhances the sensitivity analysis performed when analyzing the outputs. In Appendix C, a detailed overview of the emission factors of CO<sub>2</sub> emissions for each life stage is provided considering numerous EPDs, Ecoinvent and "Trafikverket".

In addition, in this study, the parametric tool developed in Python will be used in a genetic algorithm optimization approach in the master thesis written by Hallgren and Johansson (2022) to optimize the bridge design based on the life cycle assessment and life cycle costs.

### 3.5 The computational tool developed in Python

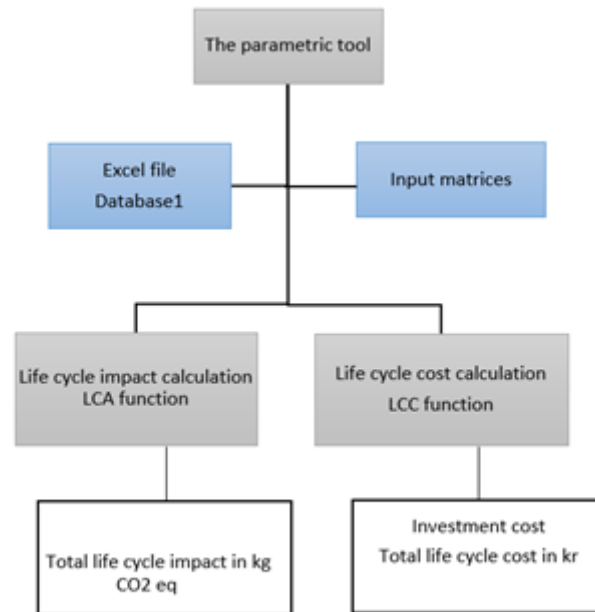
The parametric model defined in Section 3.4 for LCA and LCC will be implemented in the parametric tool in Python. This tool requires users to input different design variants in the form of matrices in Python to evaluate the life cycle impact and the life cycle cost for different bridge designs. The input variables, such as material quantities, connection types, weld thicknesses, welding length, bridge service life, painting area, pickling area, and corrugation length, are all assigned to matrices representing the input for LCA and LCC calculations. The environmental data for each material, the reference price, the fraction from secondary material, the maintenance activities, end-of-life processes, and transportation distances are all assigned to spreadsheets in the database.

The parametric tool is written in the form of Python functions. The calculations are based on two functions, one of which is developed to calculate the total environmental impact with and without benefits from reusing materials (See Appendix A). The other function is developed to calculate the life cycle costs generated in each stage. This function accounts for the total costs and includes the time value of money in terms of NPV (See Appendix B). These two functions will be called in the main script for the tool, where users can input different design parameters and change the concept of the design. For example, users can change the design concept of the main girder from flat webs to corrugated webs, and they can also change the material of the main girder from carbon steel to stainless steel. The functions will be used in the master thesis written by Hallgren and Johansson (2022) for optimizing bridge designs based on the life cycle performance and life cycle cost. Figure 3.4 shows a simplified workflow of the parametric tool.

#### 3.5.1 Input parameters

The input parameters are assigned to matrices as the following:

- Optimization target: This input determines whether the optimization will be performed based on the life cycle impact LCA, total life cycle cost, or investment cost.
- Quantities: This matrix includes the material names and quantities for a design alternative. For instance, the quantity of steel in kg needed in the main girders and cross beams.
- Connections: For one design alternative, the connection types are assigned to this input matrix in the form of connection types, different types of welds, fillet, butt and bolted, the thicknesses and lengths are also given in this matrix.
- Service life: the service life of the bridge is set as an input in the LCA and LCC function.
- Painting: Includes the painting area of the carbon steel girder and the working place, workshop or on site.
- Corrugation: Includes the corrugation length for the corrugated webs.
- Pickling area for stainless steel girders and grinding length for the carbon steel girders.



**Figure 3.4:** The simplified workflow of the parametric tool developed in this study.

#### 3.5.2 Database

The database used in the parametric tool is developed in the form of a spreadsheet. This database collects background information on the environmental impacts for different processes in each life stage. The parameters included here are essential to compile the LCA and LCC calculations in the parametric tool. This spreadsheet consists of four sub sheets.

- **Process information:** Each process in the life stage is defined here, with the process unit associated with each life stage. The unit cost for each process, the maintenance plan activities, the frequency of each activity per year, operating ratios of maintenance activities, recycling rates, fraction rates and life cycle impact results of each process included in each life stage in the form of kg CO<sub>2</sub> emissions eq, are presented in this sheet.
- **Material production information:** In this sheet, all materials used in a bridge construction are presented in terms of unit, density, material unit cost, price of reselling materials, the transportation distances are presented for all materials with different transportation types. The environmental impacts of material production are also presented here in terms of kg CO<sub>2</sub> equivalent per kg. This sheet collects background information from different EPDs and from Ecoinvent database.
- **Steel girder production information:** Different connection types for the structural components are presented in this sheet, based on the connection types between webs, flanges, plate thickness, web thickness, flange thickness is defined here. Furthermore, the reference price is defined in this sheet.
- **Transportation information:** Different transportation types and the environmental impact of the transportation extracted from Ecoinvent are defined in this sheet.

#### **3.5.3 The optimization of steel bridge designs based on LCA and LCC**

The optimization provides optimal bridge design solutions based on the life cycle impact calculation and the life cycle cost analysis. This optimization will be performed in the form of iterations to find optimal solutions of bridge design in large solutions range. Therefore, the computational tool is written in the form of Python functions for LCA and LCC to allow users using them as objective functions in a genetic algorithm approach.





# 4

## Case study

This chapter will present a case study for applying the parametric tool developed in this study to real-world bridge designs. The case study's purpose is to enable comparisons between bridge designs made of carbon steel and stainless steel with varied web designs and to define important LCA and LCC parameters. This chapter provides an overview of the optimization technique, a description of the bridge design, and data assumptions to offer insight into the assumptions needed to compile the life cycle impact and life cycle cost estimates over the bridge's service life. The optimal solutions governed by a genetic algorithm technique produced in cooperation with Hallgren and Johansson's (2022) master thesis written in order to optimize structural bridge design based on life cycle performance LCA and life cycle costing LCC are described in this chapter.

### 4.1 Workflow of the optimal input parameters

The LCA and LCC functions are utilized to optimize steel bridge design using the parametric tool created in this study. To begin, the functions are called in the optimization program constructed in partnership with Hallgren and Johansson's master thesis (2022). Second, optimization is carried out depending on life cycle cost. Thirdly, the optimal solutions are governed, and new design parameters are derived from the optimization. Finally, the best design options will be assessed from an environmental and economic standpoint by employing the parametric tool to answer the following questions:

- How does the implementation of corrugated webs affect the environmental impact and the life cycle cost for bridges made of stainless steel?
- What are the critical parameters for LCA and LCC for the considered design concepts?

### 4.2 Bridge over Delångersbron at Forsån, Böle

This case study looked at a single-span steel-concrete composite bridge (SCCB). The bridge is located in Böle, Sweden, and the case study investigates two design concepts of this bridge in which the web of the main girders is redesigned with corrugated webs instead of flat webs, and the material used for the main girder in the redesign is stainless steel, in order to see how using a bridge design with corrugated webs affects the life cycle performance and cost of stainless-steel bridges.

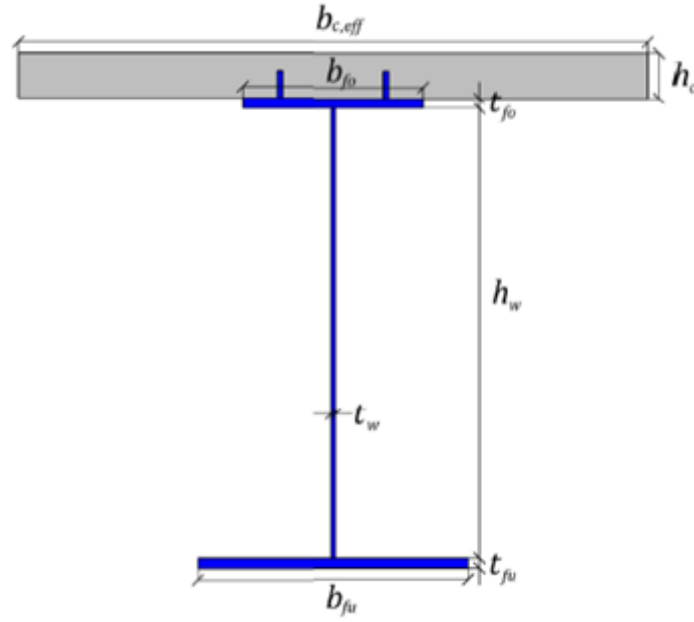
A comparison will be made between carbon steel girders with flat web and stainless-steel girders with corrugated web, considering environmental LCA and economic LCC factors. This comparison will be made based on the optimized design concepts of flat web carbon steel and corrugated web stainless steel.



**Figure 4.1:** Bridge over Delångersbron taken from BatMan (Henrysson and Yman, 2020)

### 4.2.1 Bridge design description and input parameters

The input parameters for this case study are governed by the master thesis performed by Hallgren and Johansson (Personal communication, May 21. 2022). The geometry and main dimensions of the structural design of the bridge are shown in Table 4.1. In this structural design, the focus relies mainly on two structural components of the bridge design. These are the bridge main girders and the concrete deck. In addition, the main girders are divided into several segments based on the bridge length. Each segment has a specific cross section and therefore the optimization program will consider these different cross sections and choose the optimal dimensions aiming to reduce the total life cycle cost. Figure 4.2 shows the cross-section parameters of one I girder. The structural system is braced by crossbeams, which are connected to the twin girders by vertical stiffeners.



**Figure 4.2:** Cross-sectional parameters of one I girder provided by Hallgren and Johansson (Personal Communication, May 21, 2022).

**Table 4.1:** The geometry of the bridge investigated in the case study (The original dimensions)

Bridge location and number	100-262-1
	Delångersbron, Forsån Böle
Bridge type	Steel-concrete composite bridge SCCB
The service life of the bridge	120 years
The height of the bridge girder	2.37 m
Bridge length	52 m
Span length	51 m
Width of the deck	10 m

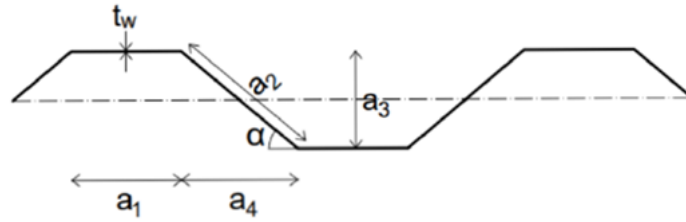
Two different design alternatives will be investigated in this case study. The basic bridge girder design concept differs between these two alternatives. Carbon steel grade S355 with flat webs was utilized for the first design alternative, whereas Duplex stainless steel SS grade 1.4162 with corrugated webs was used for the second design alternative. Furthermore, because the surface area of the carbon steel S355 girder should be covered with paint, the painting area will be included in the design requirements. Painting and maintenance operations are not required for the stainless-steel girder SS during the bridge's service lifetime. However, in order to increase the durability of stainless-steel corrosion resistance, pickling and removal of additional metal layers might be needed to be applied on the surface area of stainless-steel girders (Stainless Structurals, 2020). The optimization algorithm chooses the design dimensions for each segment based on the life cycle cost LCC analysis, in

order to lower the overall life cycle cost. Hallgren and Johansson (2022) provide the optimal design parameters of the bridge girder in table 4.2 for carbon steel S355 girders with flat webs.

**Table 4.2:** Design dimensions in mm for S355 flat web provided by Hallgren and Johansson (Personal communication, May 21, 2022).

Segment	1	2	3	4	5
$h_w$	1890	1890	1890	1890	1890
$t_w$	20	20	20	20	20
$b_{fo}$	500	500	500	500	500
$t_{fo}$	16	25	35	45	55
$b_{fu}$	1300	1300	1300	1300	1300
$t_{fu}$	16	30	45	55	55

Hallgren and Johansson (Personal Communication, May 21, 2022) offer the design parameters of the main girder for each segment for stainless steel girders with corrugated webs, which are displayed in Table 4.3. The corrugation parameters of the corrugated web design are shown in Figure 4.3.



**Figure 4.3:** Corrugation parameters provided by Hallgren and Johansson (Personal communication, May 21, 2022).

**Table 4.3:** Design dimensions in mm for SS corrugated web provided by Hallgren and Johansson (Personal communication, May 21, 2022).

Segment	1	2	3	4	5
$h_w$	1890	1890	1890	1890	1890
$t_w$	10	10	10	110	10
$b_{fo}$	450	450	450	450	450
$t_{fo}$	25	35	45	50	60
$b_{fu}$	1450	1450	1450	1450	1450
$t_{fu}$	25	35	40	45	50

#### 4.2.2 Bill of quantities and input parameters

Hallgren and Johansson (2022) provide all quantities and input parameters needed to assess the environmental impacts and life cycle costs for this study (Personal

communication, May 21, 2022). These input parameters represent the optimal design solutions found by the optimization algorithm performed based on the life cycle cost LCC analysis. The input parameters for the two bridge design concepts, carbon steel S355 with flat webs and stainless-steel SS with corrugated webs, are shown in Table 4.4 and Table 4.5.

**Table 4.4:** Quantities and input parameters for the bridge design with carbon steel S355 girders and flat webs provided by Hallgren and Johansson (Personal Communication, May 21, 2022).

Carbon steel S355 Flat webs	Structural component	Material	Input
	Steel girder	Steel S355 plate	89 728.5480 kg
	Steel girder	Steel S355 hot-rolled	1225.8400 kg
	Steel girder	Filler material for welding S355	19.1646 kg
	Steel girder	Total welding length	481.4600 m
	Steel girder	Painting area	899.9744 m <sup>2</sup>
	Concrete deck	Concrete volume	163.2 m <sup>3</sup>
		Steel reinforcement bars	2624.4237 kg

**Table 4.5:** Quantities and input parameters for the bridge design concept with stainless steel girders and corrugated webs provided by Hallgren and Johansson (Personal Communication, May 21, 2022).

Stainless steel SS Corrugated webs	Structural component	Material	Input
	Steel girder	Stainless steel SS Duplex grade 1.4162 plate	80 511.29487 kg
	Steel girder	Stainless steel SS hot-rolled	1560.16 kg
	Steel girder	Filler material for welding SS	23.5872 kg
	Steel girder	Total welding length	531.0773 m
	Steel girder	Painting area	0 m <sup>2</sup>
	Steel girder	Pickling area	1027.0268 m <sup>2</sup>
	Steel girder	Corrugation length	52.66 m
Concrete deck		Concrete volume	163.2 m <sup>3</sup>
		Steel reinforcement bars	2624.4237 kg

As shown in Tables 4.4 and 4.5, the design concept with corrugated webs requires less steel in the main girders. The amount of steel required in the main girders is decreased by 10% when the design concept is implemented with corrugated webs.

### 4.2.3 Data assumptions

Due to a lack of key information and thorough knowledge about the bridge construction during its service life, the following assumptions were taken into account in this case study and for all design alternatives. According to an environmental product declaration made on 1 kg of Hardtop XP paint manufactured by Jotun A/S (2020), the spreading rate is roughly 0.222 kg/m<sup>2</sup> for a dry film thickness of 100 m in line with ISO 14025, ISO 21930, and EN 15804. The painted corrosion protection system used on steel bridges, according to Trafikverket (2021), needs a minimum thickness of 300 m. For this study, it was assumed that just one type of paint C5 was

used for carbon steel girders. Hence, the amount of paint required can be estimated based on the painting area.

CO<sub>2</sub> emissions factors are gathered from a variety of data sources, including EPDs and the Ecoinvent database. Because the bridge under investigation in this case study is in Sweden, the emission parameters employed in the environmental effect estimates are as follows:

- The CO<sub>2</sub> emission factor for carbon steel grade S355 is based on an environmental product declaration made by SSAB, a worldwide steel firm and leading Nordic steel supplier. For one kilogram of steel, the emission factor is calculated to be 2.63 kg CO<sub>2</sub> eq.
- The CO<sub>2</sub> emission factor for stainless steel comes from an EPD done by Outokumpu, a global leader in stainless steel manufacturing. For one kilogram of stainless steel, the emission factor is predicted to be 2.74 kg CO<sub>2</sub> eq.

Appendix C contains sources for CO<sub>2</sub> emission factors for all materials utilized in this case study. Table 4.6 shows the recycling rates for all materials utilized in the bridge design in this case study, as obtained from several data sources. According to information obtained from SSAB (2020), the recycling rate of all types of steel used in this case study is 95 percent, with the remaining 5 percent going to landfills at the end of the lifetime.

**Table 4.6:** The recycling rates for all materials used in the bridge design.

Material	Recycling rate/end of life scenario	Data source
Carbon steel S355	95 %	(SSAB, 2020)
Concrete	70 %	(Collectors,2020)
Stainless Steel Duplex 1.4162	95%	(Outokumpu, 2019)
Steel reinforcement bars	95%	(SSAB, 2020)
Paint	Incineration	Assumption

Using the premise that a percentage of 20% of steel scraps is used in the manufacturing of carbon steel in this case study (SSAB, 2020). In the case of stainless-steel manufacturing, Outokumpu (2019) conducted an EPD and found that 71.35 percent of stainless-steel scraps are utilized in the process. Steel reinforcing bars may be recycled and reused at the end of their useful lives, according to Sustainable Concrete (n.d.). As a result, for the manufacturing of reinforcing steel, a 90% fraction rate from steel scraps is assumed.

Refer to the Swedish Transport Administration's climate database for the transportation of structural materials and components and consider different transportation types and distances for different materials in the bridge design. Assuming the following transportation distances for all steel plates, main girders, and cross beams, as indicated in Table 4.7, and adopted from Trafikverket (n.d.). It is assumed that the main girders will not fit on a single truck. The bridge should be subdivided since it is longer than 15 meters, and the splices will be welded together on site.

**Table 4.7:** Different transportation distances for transporting structural steel adapted from Trafikverket(n.d.).

Railway	1000 km
Diesel truck (national transport)	200 km
Diesel truck (regional transport)	100 km
Diesel truck (local distribution)	40 km

The material costs employed in the parametric tool are based on pricing estimates from interviewing specialists and bridge planners, considering the life cycle cost. Table 4.8 shows the prices of steel materials in today's market. Appendix B contains further pricing and estimates.

**Table 4.8:** Material unit costs are provided by Al-Emrani (Personal communication, May 6, 2022).

Profile	S355 [SEK/kg]	Duplex [SEK/kg]
Plate	20	60
Hot rolled	25	75
Hollow sections	30	90





# 5

## Results and analysis

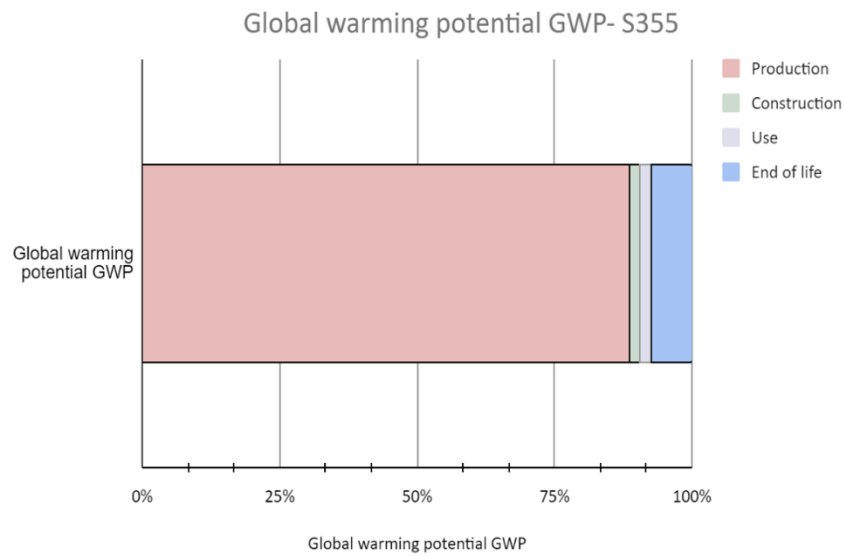
In this chapter, tables, figures, and bar charts are used to display the LCA and LCC results for the design alternatives as described in Chapter 4. The findings are interpreted to show how the new corrugated webs concept in stainless steel bridge girders influences environmental impacts and life cycle total costs.

### 5.1 Life cycle assessment results

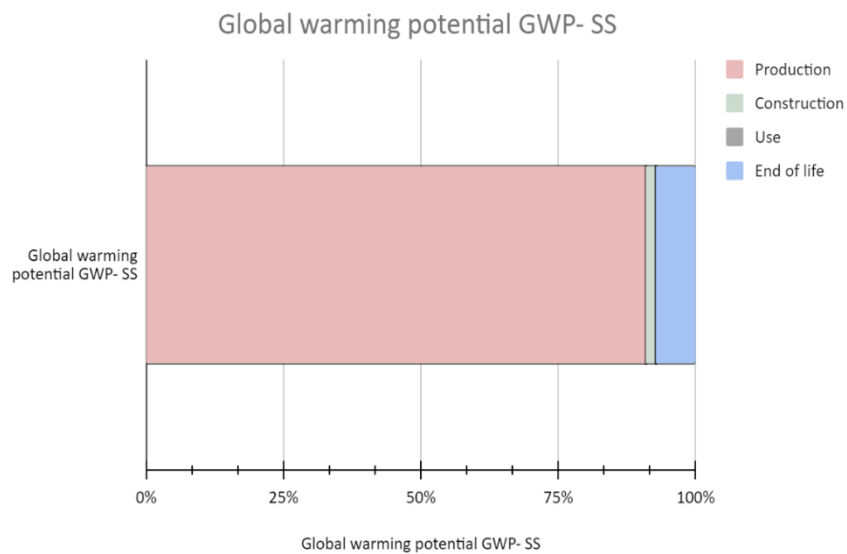
The LCA results take into consideration how much each stage of the life cycle contributes to the global warming potential in terms of kg of CO<sub>2</sub> equivalent. Table 5.1 shows how each stage in our study contributes to the overall environmental effect. The results are provided for two distinct bridge design concepts in carbon steel S355 and stainless steel. S355 carbon steel with flat webs and Duplex stainless steel with corrugated webs without accounting for the advantages of avoided environmental burdens, the overall environmental effect of the design concept using carbon steel S355 and flat webs is estimated to be 347 916 kg CO<sub>2</sub>-eq. The entire environmental impact of the design concept with stainless steel and corrugated webs is predicted to contribute 324 581 kg CO<sub>2</sub>-eq to the global warming potential GWP, according to the results. Based on the findings in Table 5.1, a dominance analysis for the two design concepts was carried out in Figure 5.1 and Figure 5.2 to see which sections of the life cycle had the most significant environmental impact.

**Table 5.1:** The contribution of each life cycle stage to GWP for S355 and SS.

Design alternative	Production	Construction	Use	End of life	Total environmental impact
S355- flat	88.80%	1.70%	2.15%	7.35%	100%
SS- corrugated	90,90%	1.80%	0.00%	7.30%	100%



**Figure 5.1:** The contribution of each life stage to the total environmental impact GWP- S355.



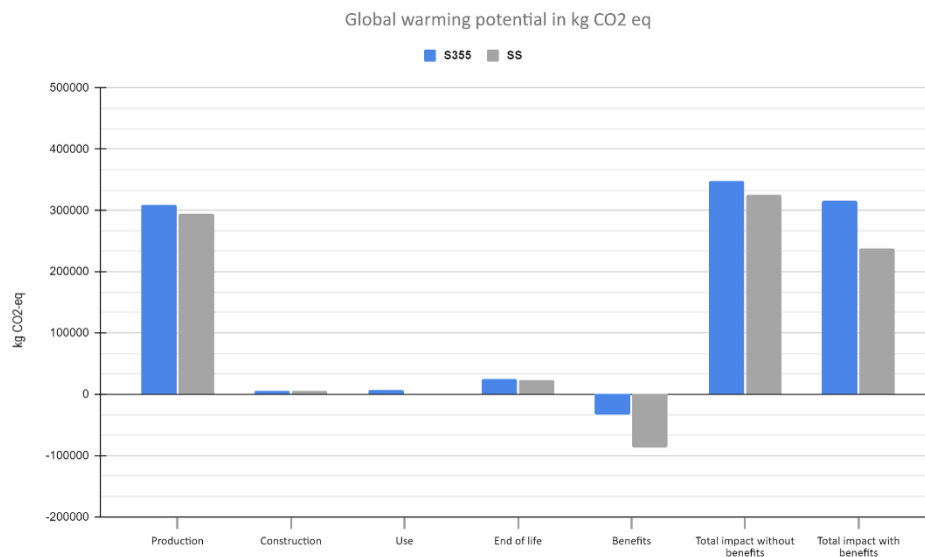
**Figure 5.2:** The contribution of each life stage to the total environmental impact GWP- SS

When examining Figures 5.1 and 5.2, it is clear that the production stage contributes the most to the total environmental impact for both of the designs considered in this case study. The production stage accounts for roughly 89% of the overall environmental impact contributing to global warming potential in the concept with carbon steel S355 girders with flat webs. In addition, the end-of-life stage accounts for 7.35% of total environmental impact. The influence of the usage stage is low for the design with stainless steel girders and corrugated webs, as shown in Figure 5.2.

This is due to stainless steel's exceptional corrosion resistance, which eliminates the need for maintenance throughout its life cycle.

Furthermore, when the benefits of reduced environmental burden are included to the total environmental impact, it is found that the total impact of the design concept with stainless steel girders is roughly 24% lower than the impact of the design concept with carbon steel girders. Figure 5.3 shows the environmental impact of each stage, as well as the total impact without benefits and the total environmental impact with benefits from reusing metal scraps in the manufacturing of stainless steel and carbon steel. Although the construction phase's contribution (about 2%) is little in comparison to the production phase's large contribution (Figure 5.3), it is important to note that the influence in the construction phase is not insignificant. The impact estimations in this phase rely heavily on the modes of transportation employed from the factory to the construction site. The estimations in this section are based on transportation distances adopted from Trafikverket(n.d.) for all structural steel types.

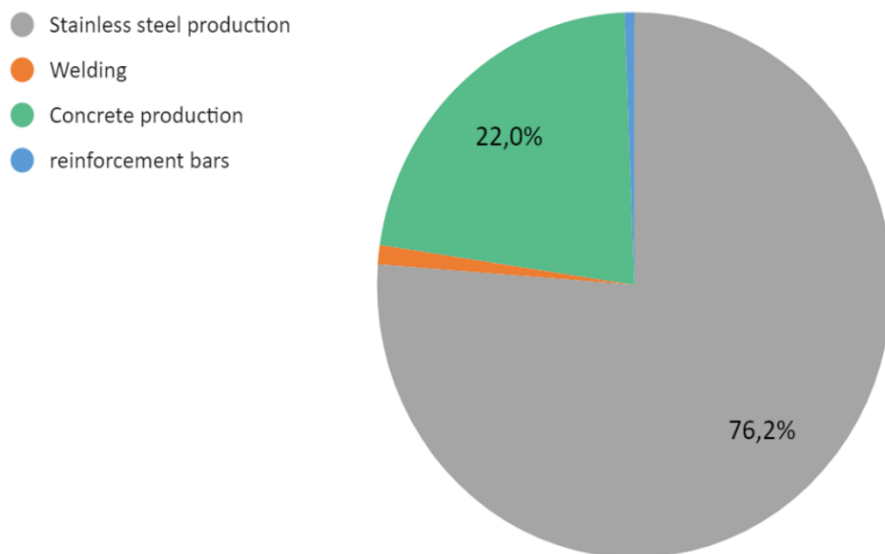
In Sweden, SSAB has adopted the use of liquefied natural gas-powered vessels to transport raw materials between Luleå and Oxelösund (Jernkontoret, 2020). This implementation could lower CO<sub>2</sub> emissions and, as a result, the construction phase's overall contribution to global warming potential. Furthermore, in the case of carbon steel S355 girders, the usage phase contributes 2.2 % to the total environmental impact (see Figure 5.3). This impact is related to the painting activities that are required during the bridge's maintenance phase, as well as the transportation processes that are required at this time. The impact governed is roughly 7496 kg CO<sub>2</sub>-eq for a service life of 120 years and carbon steel S355 girders, according to the findings. Unlike the design for stainless steel girders, where the use phase impact is negligible due to stainless steel's high corrosion resistance, and where no protective painting or maintenance activities are required during its life cycle (Rossi, 2014).



**Figure 5.3:** The contribution of each life stage to global warming potential without and with benefits.

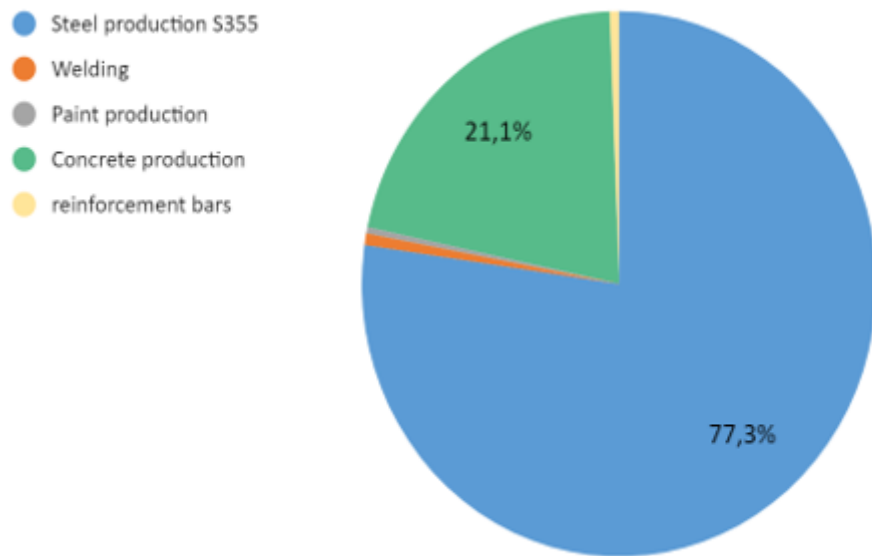
The benefits shown in Figure 5.3 account for recycling rates and metal scraps used in manufacturing carbon steel and stainless steel. As a result, since the fraction rate from secondary materials is considered to be 20% of steel scraps, the benefits for carbon steel S355 are lower than for stainless steel SS (SSAB,2020). As a result, the net steel scrap is 20% which means that for every 1000 kg of carbon steel produced, 200 kg of carbon steel scrap is credited. In contrast, it is expected that net stainless-steel scrap is 23.7% (95%-71.35%). This implies that for every 1000 kg of stainless steel produced, 237 kg of scrap stainless steel is credited.

The production phase, as illustrated in Figure 5.3, contributes the most to the total environmental impact on climate change GWP. As a result, at this stage, the processes are investigated and linked with this contribution to find the hotspots. The steel and stainless-steel manufacturing processes are the most significant processes in the production phase of the bridge investigated in this study, according to Figures 5.4 and 5.5. With approximately 21% to 22% in the production process for the two design concepts, the next biggest contribution comes from making concrete. When the welding impact for stainless-steel girders with corrugated webs is compared to the welding impact for steel girders with flat webs, the welding impact for stainless-steel girders with corrugated webs is around 46 percent greater. This is due to the longer welding lengths necessary in the design of corrugated webs, which affects the welding process' contribution to the total environmental impact.



**Figure 5.4:** Material production process SS.

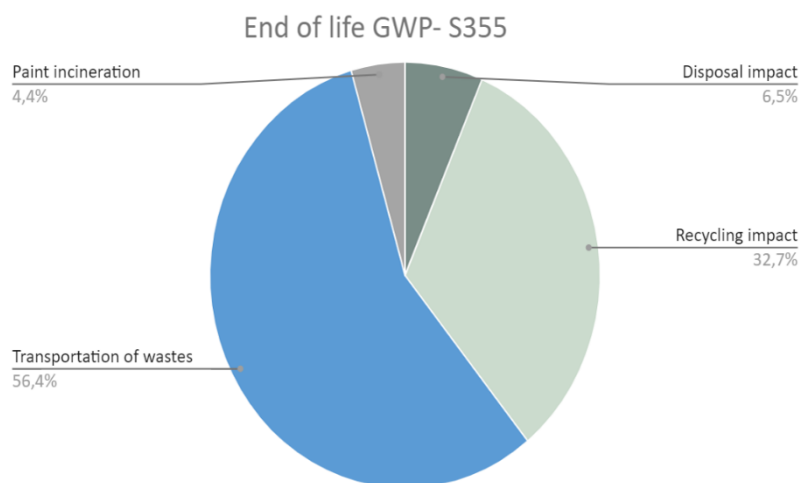
In addition, as shown in Figure 5.4, the stainless-steel girders do not require any initial painting. As a result, the paint production phase for stainless steel is avoided. In this study, paint manufacture is required and contributes about 1140 kg CO<sub>2</sub>-eq during the production stage of carbon steel S355 girders.



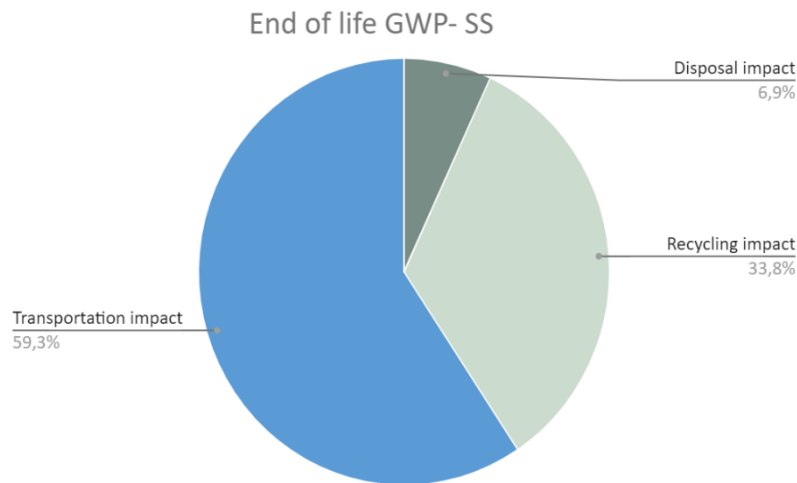
**Figure 5.5:** Material production process S355.

Considering the two design approaches, the end-of-life stage accounts for 7.3 % to 7.4% of the total environmental impact, as shown in Table 5.1. As a result, the processes contained in this stage have been investigated further to determine which components contribute the most to global warming potential.

Figures 5.6 and 5.7 depict the contribution of each end-of-life procedure to the overall environmental impact. Transportation contributes the most to the global warming potential in the end-of-life stage for the two design approaches, as shown in Figures 5.6 and 5.7. More specifically, it accounts for 56% to 59% of the entire impact. Recycling of materials used in bridge construction is the second most significant contributor, followed by material disposal. The burning of paint is part of the end-of-life phase for carbon steel girders and contributes 4.4% to the global warming potential (GWP).



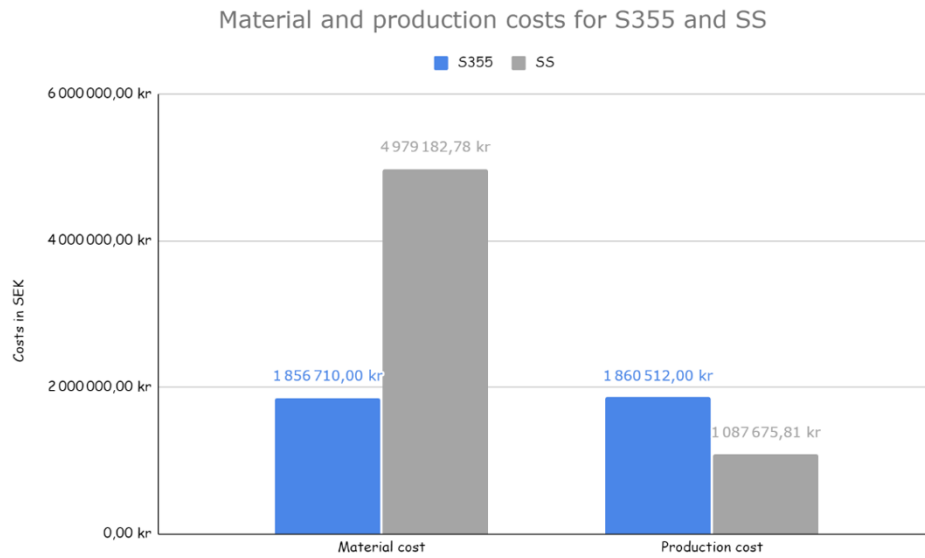
**Figure 5.6:** The contribution of the end-of-life stage to GWP-S355



**Figure 5.7:** The contribution of the end-of-life stage to GWP-SS.

## 5.2 Life cycle cost results

For the two design alternatives, carbon steel S355 girders with flat webs and stainless-steel SS girders with corrugated webs, the LCC results account for material costs, production costs, erection costs, maintenance costs, and user costs. To make the comparison more realistic, the prices for each step will be shown individually, based on the design concept and materials chosen for the main girders. The material and production expenses are addressed in Figure 5.8. The material costs for stainless-steel SS girders are substantially higher due to the high initial cost of stainless-steel plates in today's market rates, which amounts to 60 SEK/ kg, as illustrated in (Table 5.2). Because steel plates are used in significant quantities in the bridge's main girders, examine the overall costs of steel and stainless-steel plates to see how the initial costs affect the entire cost of the main girders. The quantities, initial costs, and total costs for steel and stainless-steel plates employed in this case study are shown in Table 5.2.

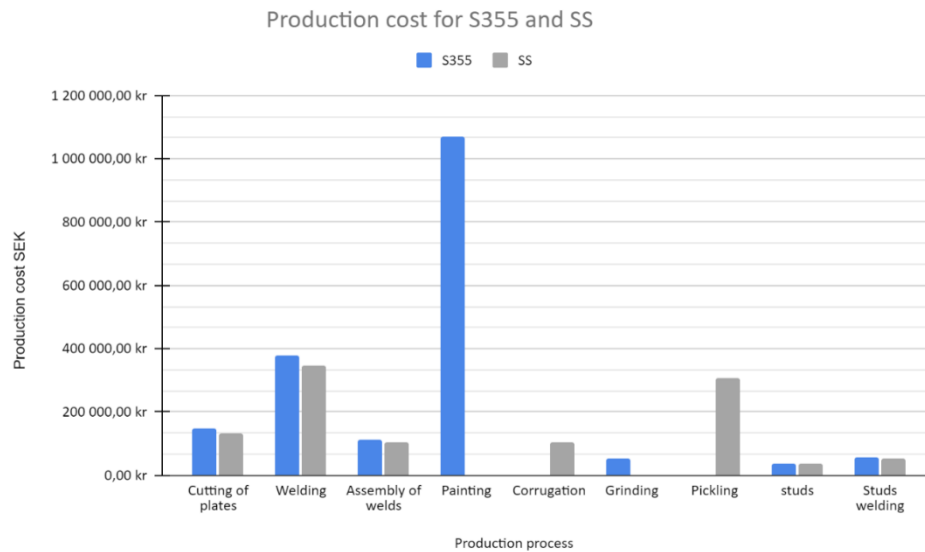


**Figure 5.8:** Material and production cost for S355 and SS.

**Table 5.2:** The difference between material costs for steel and stainless-steel plates in the bridge construction.

Material	Structural component	Material unit cost [SEK/kg]	Quantity [kg]	Material costs SEK > SEK
Carbon steel S355	Bridge girder cross beams	20	89 728.5480	1 794 571
Stainless steel SS Duplex	Bridge girder Cross beams	60	80 511.2949	4 830 678

The production cost of carbon steel S355 girders with flat webs is approximately 41% more than the production cost of stainless-steel SS girders with corrugated webs, as shown in Figure 5.8. As a consequence, it's worth looking into which elements and processes in the production phase are responsible for the production cost shown in Figure 5.8. As a result, examining each expense associated with the bridge girders' production phase. For this investigation, Figure 5.9 depicts the production cost with all parts included in the parametric tool.



**Figure 5.9:** The production cost for S355 and SS.

The main variations in the production costs of the two design approaches are shown in Figure 5.9. The major difference is the expense of painting, which is required in the fabrication of carbon steel S355 girders. Stainless steel girders, on the other hand, do not require any coating layers because stainless steel is a well-known material when it comes to corrosion resistance (Rossi, 2014). Pickling, on the other hand, may be applied to the surface of stainless-steel girders to improve corrosion resistance (Stainless Structurals, 2020). The pickling cost is considerably less than the painting cost, as shown in Figure 5.9, and this is related to the unit cost for both painting and pickling utilized in the case study. Painting costs used in this study and required for carbon steel girders are around 1000 SEK per painting area for painting in the workshop, while pickling costs are around 300 SEK per pickling area for stainless steel girders.

In addition, the welding cost of carbon steel S355 girders with flat webs has an impact on the high production cost. The welding cost in the parametric model is calculated using price estimation model (Personal communication, May 6, 2022), which takes into account the welding duration and total number of weld passes necessary for a weld area. A welder costs 550 SEK per hour and can weld approximately 4 meters (one pass) (Al-Emrani, Personal Communication, 2022). The welding cost of carbon steel S355 girders with flat webs is greater than the welding cost of stainless-steel SS with corrugated webs, according to the results. As a result, the causes behind such a finding should be investigated. The use of corrugated webs in bridge girders eliminates the need for extra stiffeners during welding, resulting in lower welding and fabrication costs (K, 2021). In the workshop, welding carbon steel girders with flat webs takes a long time, resulting in increased production and fabrication costs (Henrysson and Yman, 2020).

Another factor contributing to the high production cost of carbon steel S355 girders with flat webs, as illustrated in Figure 5.9, is the expense of cutting plates. This cost is mostly determined by the overall weight of steel plates required in the fabrication



of the main girders. Because the use of stainless-steel girders with corrugated webs decreases material consumption by 10%, the cost of cutting plates for carbon steel S355 is higher than for stainless steel SS. The expenses of erection and concrete casting for carbon steel S355 girders and stainless-steel SS girders are shown in Table 5.3.

**Table 5.3:** The erection and concrete casting costs in the construction phase.

Bridge design concept	Carbon steel S355 with flat webs	Stainless steel SS with corrugated webs
Erection costs	51 200 SEK	57 800 SEK
Concrete casting costs	408 000 SEK	408 000 SEK

The expenses of erection for stainless steel girders are 6 600 SEK more than for carbon steel girders, according to the results in Table 5.3. The reason for this is because erection expenses take into account the number of splices as well as the overall number of intermediate crossbeams. The number of crossbeams required in the design for stainless steel girders is larger than that required for carbon steel girders, resulting in higher erection costs. Because both design concepts use the same quantity of concrete to produce the concrete deck, the concrete casting cost is the same for both design concepts. In addition, the study calculates maintenance expenses, which are separated into costs related with the painting system's activities and costs incurred by users as a result of traffic interruptions during the repair period. Table 5.4 shows the expenses in the usage phase, which include both maintenance and user costs for a 120-year service life.

**Table 5.4:** The maintenance and user costs for S355 and SS (ADT =5000).

Bridge design concept	Carbon steel S355 with flat webs	Stainless steel SS with corrugated webs
Maintenance cost	1 697 507 SEK	0.0 SEK
User cost	50 908 SEK	0.0 SEK

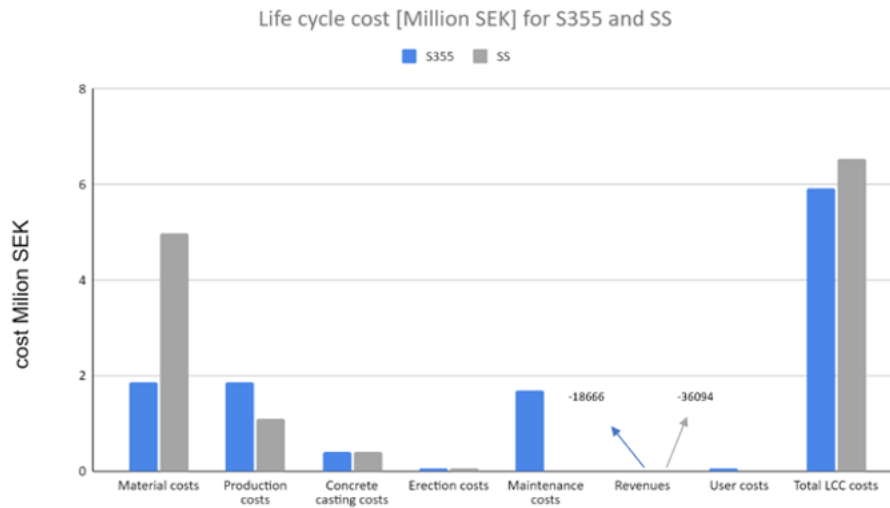
In terms of net present value (NPV), the costs in Table 5.4 account for the time value of money. The following assumptions were used in order to determine the net present value:

- The discount rate is assumed to be 5% (Rossi, et al.,2017).
- The escalation rate is assumed to be 2% (Rossi et al., 2017).
- The average daily traffic ADT is assumed to be low 5000 vehicles per year for the bridge evaluated in this case study located at Forsån, Böle (Chapter 4).

The stainless-steel girder does not require any maintenance operations, as shown in Table 5.4, hence maintenance expenses for stainless-steel bridge girders are removed. Maintenance costs account for 97% of total costs generated in the use stage for carbon steel S355 girders, while user costs account for 3% and are highly dependent on the geographical location of the bridge construction, taking into account the average daily traffic ADT and the time required for each maintenance activity, which results in time delay costs.

Additionally, the return-on-investment costs for carbon steel S355 and stainless-steel SS are calculated. The results demonstrate that at the end-of-life stage, income from

reselling steel metal scraps amount to 18 665 SEK. When profits from the sale of stainless-steel metal scraps are included in, the results show a 36 094 SEK return on investment. Outokumpu provides these costs, which are based on market values from the previous year (Personal communication, May 18, 2022). The unit price for carbon steel S355 is considered to be 7 SEK per kilogram of steel scraps, whereas the unit price for stainless steel is higher at 15 SEK per kilogram of stainless-steel scraps. However, because to the high production and material costs for the two design concepts investigated in this thesis' case study, the revenues do not have a significant impact on the overall LCC, as the results demonstrate. Figure 5.10 shows the life cycle costs for carbon steel S355 girders with flat webs and stainless-steel SS girders with corrugated webs at each life cycle stage.



**Figure 5.10:** Life cycle cost results for each stage included in this study (ADT = 5000).

As illustrated in Figure 5.10, the stainless-steel design concept's material costs account for the majority of the total life cycle cost, resulting in a high overall life cycle cost for stainless steel girders with corrugated webs. Although the bridge design concept with stainless steel girders saves around 10% in material costs, the unit costs of stainless-steel plates used in the bridge girder and cross beams are the key factor impacting the material costs in Figure 5.10. Based on the steel profile, interviewing bridge designers provides the unit prices used in the calculations. For example, stainless steel plates are expected to cost 60 SEK/kg, whereas a hot-rolled profile costs 75 SEK/kg (Personal correspondence, May 6, 2022).

# 6

## Discussion

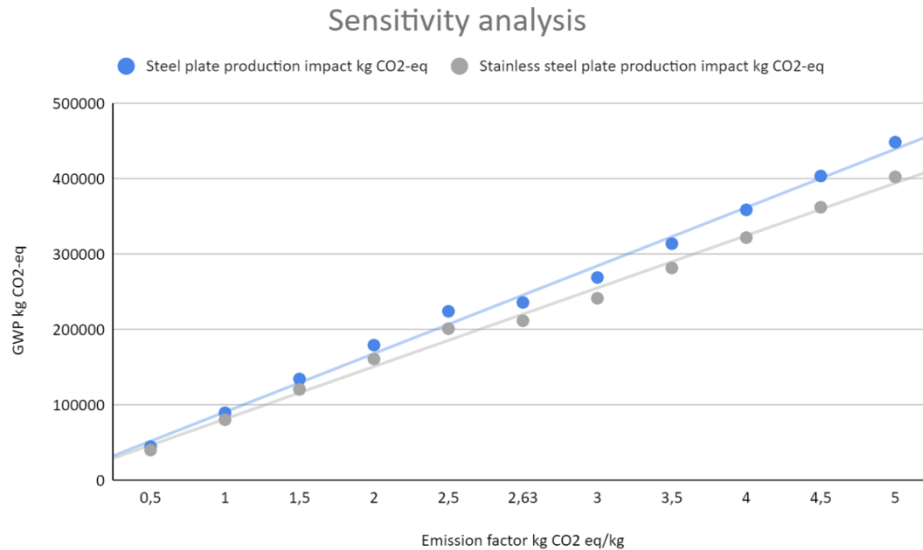
In this chapter, the results obtained in Section 5 will be discussed in order to identify the most critical contributors to the total environmental impact and total life cycle cost. Based on the parametric model developed in Section 3, and the results obtained in Section 5, the performance of the parametric tool will be analysed by conducting sensitivity analyses on the critical parts of the different life cycle stages to enhance the understanding of the influence of the parameters on the output.

### 6.1 Life cycle assessment discussion

According to the results obtained in Section 5, Figure 5.3 shows that the production phase for carbon steel S355 girders and stainless-steel girders has the highest contribution to the total environmental impact in terms of global warming potential. When investigating into the production phase, it has been showed that the material production of steel and stainless-steel acts as the most dominant process throughout the production phase of the bridge evaluated in the case study. Referring to the bill of quantities provided by Hallgren and Johansson (Personal Communication, May 16, 2022), it is observed that major of large quantities of structural steel are needed in the production of steel plates, which in turn requires a huge amount of material and energy consumption needed for the extraction of raw materials, manufacturing and assembling of the main girders and cross beams. All these processes have a significant impact contributing to the global warming potential. Itoh and Kitagawa (2003) stated in their LCA study the manufacturing of construction steel materials as the main contributor to the total environmental impact.

Furthermore, when investigating the environmental impact of the production phase, it is observed that the impact factors per unit play an important role in the evaluation of the production phase impact. For instance, the environmental impact of steel production governed in Section 5, is based on the emission factor for an EPD performed by SSAB(2020) and accounts for 2.63 kg CO<sub>2</sub>-eq per one kilogram of carbon steel. For stainless steel plate production impact, the emission factor is extracted from an EPD performed by Outokumpu(2019) and assumed to 2.74 kg CO<sub>2</sub>-eq per one kilogram of stainless steel. According to Trafikverket(n.d.) the emission factor of steel production has the value of 2.2 kg CO<sub>2</sub>-eq/ kg contributing to the global warming potential, which corresponds to the mean value of 10 EPDs from Norway and Finland. An EPD performed by Åkrene Mek. Verksted A/S (2021) stated the emission factor of steel production to 0.6 kg CO<sub>2</sub>-eq for producing one kilogram

steel. Since the emission factors presented in the current study vary depending on the manufacturer, a sensitivity analysis has been performed on the emission factors used in the calculation of the environmental impact of steel production contributing to the total global warming potential. The results of this analysis are shown in Figure 6.1 for the production of steel and stainless-steel plates. A sensitivity analysis increases the understanding of the influence of the parameters on the output of the parametric model.



**Figure 6.1:** Sensitivity analysis on the emission factors kg CO2-eq/kg.

Figure 6.1 shows that the emission factors of the production of steel and stainless-steel plates, have a significant impact on the environmental impact of the production phase and thereby on the total environmental impact of the bridge design in the case study (Chapter 4 and Chapter 5). If the emission factor of steel production used in the case study was chosen to the corresponding value from Åkrene's EPD 0.6 kg CO2-eq/kg, the production impact of steel plates would be reduced with around 70% which returns in a reduction in the contribution of the production phase to the global warming potential obtained in Chapter 5.

## 6.2 Life cycle cost discussion

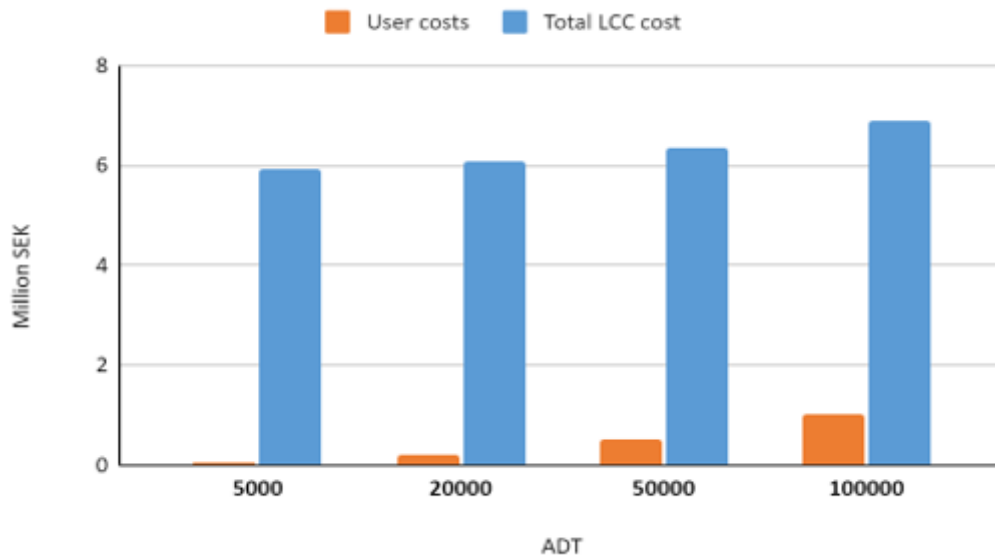
Considering the life cycle costs of bridge constructions with the high demands on their functionality throughout the long service life, it is preferable to provide solutions that require as low maintenance activities as possible in order to avoid any additional maintenance costs associated with the traffic disturbances that result in user costs in terms of time delay costs. This is more considerable for bridges with a high traffic flow. The application of stainless steel in bridge constructions reduces the maintenance costs thanks to its high corrosion resistance properties and therefore the maintenance costs in the case study for the stainless-steel design concept

are assumed to be omitted. The results obtained in Figure 5.10 indicate that the maintenance costs for carbon steel girders stands for 29% of the total life cycle cost. These costs are generated because carbon steel girders need to be coated with paint during the use phase of the bridge.

The average daily traffic ADT was assumed to 5000 as a low value according to Wahlsten et al., (2018). Accordingly, a sensitivity analysis for the average daily traffic is conducted to analyse how changing this parameter and the scenario of the traffic flow over the bridge, investigated in the case study, could affect the user costs and thereby the total life cycle costs. In Table 6.1 different average daily traffic scenarios were applied to investigate how this parameter influences the user costs associated with the maintenance plan throughout the use phase of the bridge.

**Table 6.1:** The user costs and total life cycle cost for carbon steel S355 girders for different ADT scenarios.

Scenario- Service life of 120 years	User costs for carbon steel S355 girders	Total LCC costs for carbon steel S355 girders
Current bridge (ADT = 5000)	50 980 SEK	5 906 244 SEK
Scenario 1 (ADT = 20 000)	203 921 SEK	6 059 185 SEK
Scenario 2 (ADT = 50 000)	509 802 SEK	6 365 066 SEK
Scenario 3 (ADT = 100 000)	1 019 604 SEK	6 874 868 SEK



**Figure 6.2:** Total life cycle costs and user costs for different average daily traffic scenarios (Only for carbon steel S355 bridge girders).

The results obtained in Table 6.1 and Figure 6.2 show that the average daily traffic ADT has a significant impact on the total life cycle cost. This effect is more considerable for the scenarios with high values of ADT. For example, An ADT of 100 000 increases the total life cycle cost of the carbon steel S355 girders investigated in the case study with around 16%. Which indicates that the geographical location of the bridge and the traffic flow situation should be considered when evaluating the life

cycle cost analysis.

As stated in Figure 5.8, the material costs are the main contributor to the total life cycle costs for stainless steel girders investigated in the case study. Due to the high material unit costs for stainless steel in today's market prices corresponding to 60 SEK/kg for stainless steel plates, referring to the master thesis written by Henrysson and Yman (2020) and using the material costs used and provided by Stål and Rörmontage (Henrysson and Yman, 2020) a sensitivity analysis is performed on the material costs. In table 6.2 Today's market prices and the prices in 2020 are stated for carbon steel S355 and Duplex stainless-steel.

**Table 6.2:** Material reference prices 2022 vs. 2020 for carbon steel and stainless steel.

Material unit cost	Carbon steel S355	Stainless steel Duplex
Today's market prices SEK/kg	20	60
Price in 2020 SEK/kg	9	30

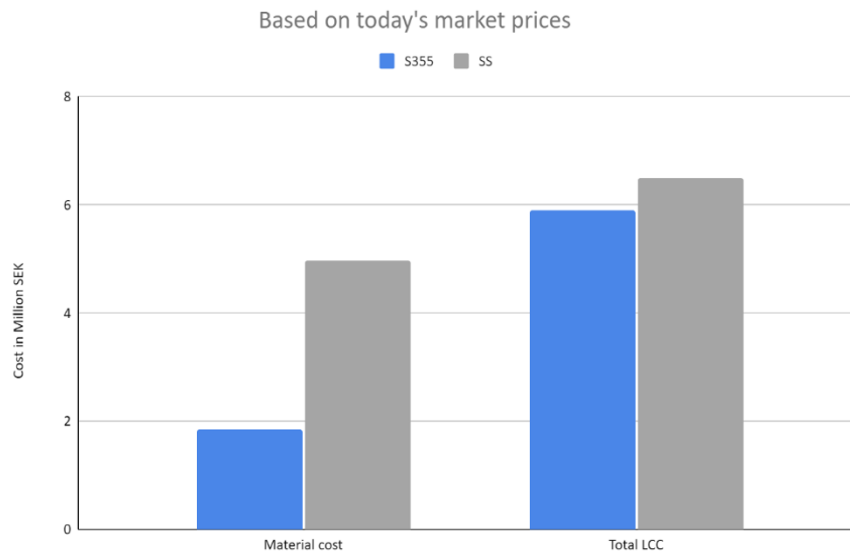
The results of this sensitivity analysis are presented in Table 6.3 and Table 6.4. It is observed that the material costs have a significant impact on the total life cycle costs for both carbon steel and stainless-steel girders. For the case conducting for the material prices in 2020 (Table 6.4), the total LCC costs have drastically decreased for the design concept with stainless-steel SS girders compared to the results in Table 6.3.

**Table 6.3:** Material costs and total LCC costs are based on today's material unit costs.

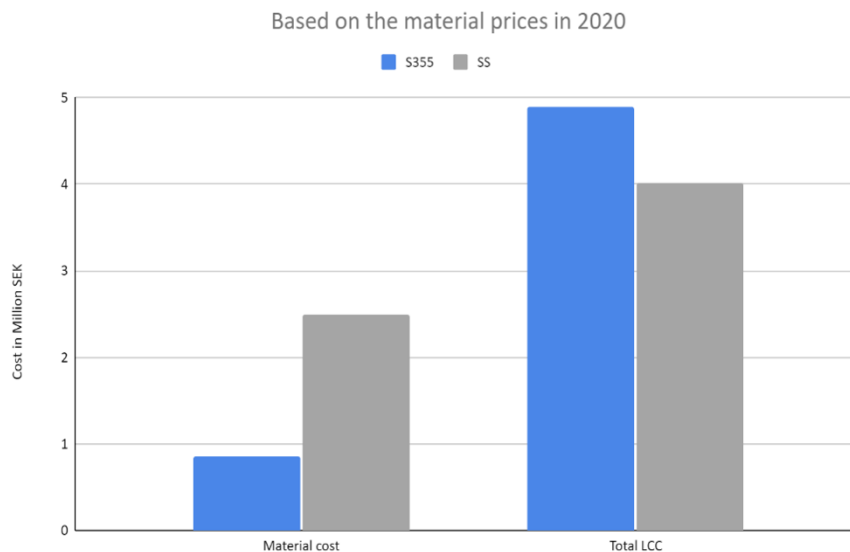
Design concept	Material costs SEK	Total LCC costs SEK
Carbon steel S355 girders	1 856 710	5 906 243
Stainless steel SS girders	4 979 183	6 496 564

**Table 6.4:** Material costs and total LCC costs are based on the material unit costs in 2020.

Design concept	Material costs SEK	Total LCC costs SEK
Carbon steel S355 girders	850 083	4 899 617
Stainless steel SS girders	2 493 637	4 011 018



**Figure 6.3:** Material costs and total LCC for S355 and SS (Based on today's market prices).

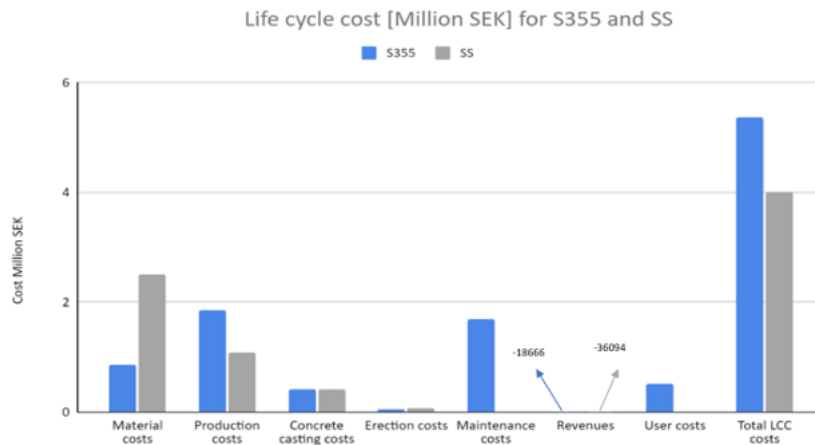


**Figure 6.4:** Material costs and total LCC for S355 and SS (Based on the prices in 2020).

Figure 6.3 and Figure 6.4 illustrate the results obtained in Table 6.3 and Table 6.4, respectively. The results stress that the initial costs of the materials have a significant influence on the total life cycle cost. Based on today's prices as shown in Figure 6.3, it is observed that the design concept with stainless steel girders has higher total life cycle cost due to the high initial cost of stainless steel in today's market (60 SEK/kg). Examining Figure 6.4, considering the material prices in 2020, it is noticed that the design concept with stainless steel girders and corrugated webs

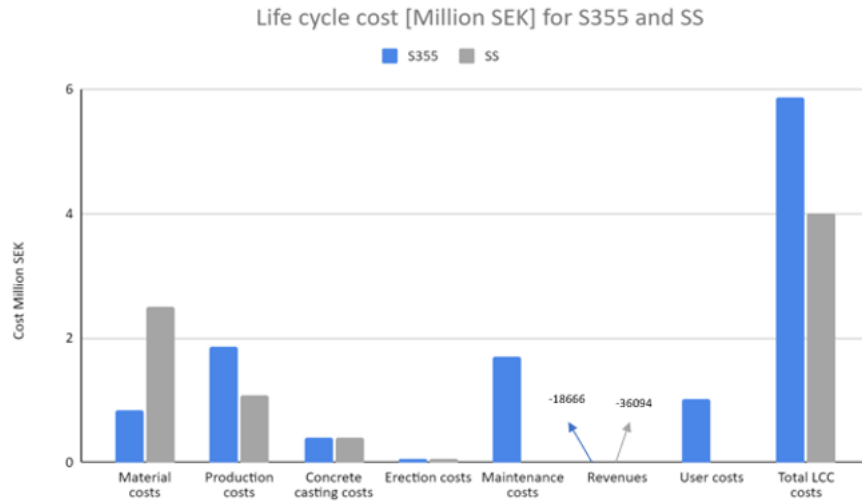
has lower total life cycle cost than the alternative of carbon steel girders. Hence, both figures state that the initial cost of the material is crucial when evaluating the life cycle cost analysis. Accordingly, it is worth to point that the economic feasibility of implementing corrugated webs in stainless steel bridge girders is highly dependent on the fluctuating prices of the stainless steel material.

Since the average daily traffic, ADT, and material costs are key parameters affecting the total life cycle cost for the design concepts, as shown in Figures 6.2, 6.3, and 6.4, referring to Figure 5.10 two different scenarios are defined. The first scenario with average daily traffic of 50 000 and considering the material costs in 2020. In contrast, the second scenario has an average daily traffic of 100 000 and considers the material costs in 2020. Figure 6.5 and Figure 6.6 shows the changed parameters' influence in scenarios one and two on the total life cycle cost for the design concepts investigated in the case study. As illustrated in Figure 6.5 and Figure 6.6, the design concept with stainless steel girders and corrugated has lower total life cycle cost than carbon steel S355 design concept. Therefore, the economic feasibility of stainless steel concept relies highly on the average daily traffic over the bridge. The ADT parameter has a significant impact on the total maintenance costs and thereby the overall life cycle cost for carbon steel S355 girders.



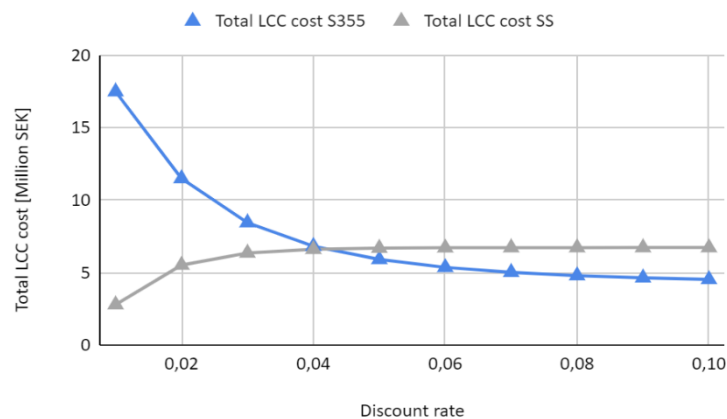
**Figure 6.5:** Total life cycle cost for S355 and SS (ADT = 50 000, considering the material prices in 2020) scenario one





**Figure 6.6:** Total life cycle cost for S355 and SS (ADT = 100 000, considering the material prices in 2020) scenario two

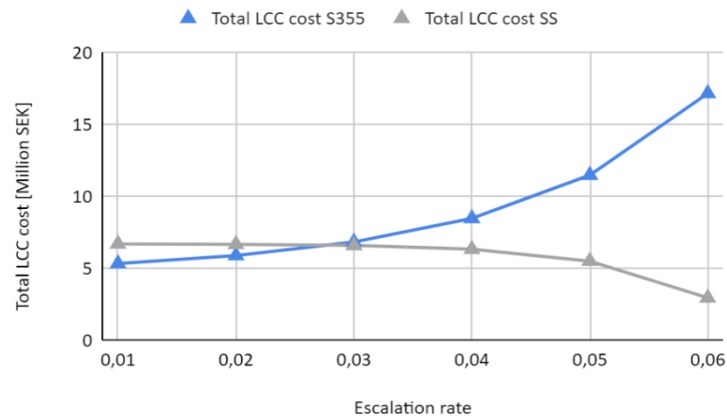
In addition, according to Lee (2015) and Rossi et al.,(2017) the initial values of the discount rate and escalation rate are chosen respectively to 5% and 2% in the calculation of the total life cycle cost in the case study. The uncertainty of these parameters should be considered in the LCC analysis and therefore a sensitivity analysis of the total life cycle cost, regarding the discount rate and escalation rate, is conducted. Within a range of 1% to 10%, the total LCC costs are evaluated and illustrated in Figure 6.7 for the carbon steel S355 and stainless-steel SS design alternatives.



**Figure 6.7:** Sensitivity of the total LCC cost to the discount rate.

The results obtained in Figure 6.7 show that the total LCC for carbon steel S355 design alternative increases when decreasing the discount rate. Moreover, the total LCC decreases with the increase of the discount rate. The design concept with stainless steel SS girders acts conversely, where it is noticed that the total LCC decreases when decreasing the discount rate and increases with the raising of the discount rate.

When analysing Figure 6.8, it is observed that the total LCC for carbon steel S355 increases when increasing the escalation rate. Whereas the stainless-steel design alternative has an opposite action, where the total LCC decrease when increasing the escalation rate. The reason behind the stainless steel's performance in Figure 6.8 is associated with the assumption that states no maintenance costs are needed throughout the use phase of stainless-steel girders where the only factor contributing here is the raising of the revenues (cashflows) coming from selling stainless-steel scraps which decreases the total LCC for the stainless-steel design alternative.



**Figure 6.8:** Sensitivity of the total LCC cost to the discount rate.

### 6.3 Critical parameters for LCA and LCC

According to the results obtained in Section 5 and the sensitivity analyses performed in Sections 6.1 and 6.2, it is observed that some parameters have a significant impact on the life cycle assessment LCA and life cycle cost LCC. For the life cycle impact of LCA, as shown in Figure 6.1, the CO<sub>2</sub> emission factors of the steel production vary a lot depending on the manufacturer and the data source, where different data sources provide different emission factors. Which in turn influences the contribution of steel production in the case study to the global warming potential. By choosing a manufacturer with a relatively low emission factor, the contribution of the production phase to the total environmental impact may be reduced. This is preferable for bridge constructions since the production stage contributes the most to the total environmental burden, as shown in the case study in Figure 5.3

On the other hand, considering the life cycle cost LCC of the bridge investigated in the case study, it is noticed that many parameters affect the total cost. One of them is the average daily traffic ADT. When examining different scenarios of ADT, low (5000) as high value (50 000). The results showed that the total LCC for the design concept with carbon steel S355 girder increased with 7%. At the same time, the total LCC for the other design concept with stainless steel girders did not change due the assumption that states no maintenance costs are governed when stainless steel is used instead of the conventional carbon steel.

In addition, another critical parameter for LCC is the material costs used in the case study. These costs represent today's market prices and are much higher for stainless steel, corresponding to 60 SEK for 1 kilogram of stainless-steel plates and 20 SEK for 1 kilogram of carbon steel plates. When analyzing lower material initial costs, the total LCC decreased drastically for both design concepts investigated in the case study (See Table 6.3 and Table 6.4).

Moreover, it has been shown that the discount and escalation rate are essential parameters for LCC. When changing these parameters in a range of 1% to 10%, the LCC performance acts differently for the different design alternatives. When decreasing the discount rate, the total LCC for the design concept with carbon steel S355 increases.

## 6.4 Uncertainties in the results

The data gaps through the life cycle inventory should be considered in order to investigate to what extent these gaps have affected the accuracy of LCA and LCC results. One of the factors that affect the representativity of LCA and LCC results is associated with the fact that only two structural components of the bridge construction were considered in the calculations, i.e., the twin girders and the concrete deck.

Additionally, considering the life cycle assessment LCA, the environmental data of the materials in the bridge design are collected from different data sources and environmental product declarations. This was performed for two reasons: the significant lack of options available in the ecoinvent database and the lack of information on the origins of materials used by the bridge designers. However, the database developed in this study contains environmental data from the global database ecoinvent, different EPDs, and the Swedish Transport Administration's database to enable users to examine the difference in the results based on the chosen data source.



# 7

## Conclusion

### 7.1 Final conclusion

In this chapter, the conclusion will be presented based on the results obtained in Chapter 5 and Chapter 6. The conclusion will address the following question: How using a corrugated web design concept may affect the environmental impact and the total life cycle cost in bridges made of stainless steel girders?

Considering the total environmental impact of the design concepts investigated in the case study accounting for the advantages of the avoided burden, it is found that the design concept with corrugated webs in stainless steel girders has a lower total environmental impact contributing to the global warming potential. This is associated with the fact that stainless steel girders do not require maintenance operations throughout the bridge's service life. This, in turn, reduces the impact in the use phase of the bridge and, thereby, the total environmental impact.

It has been found that the contribution of the bridge construction to the global warming potential is highly dependent on the life cycle impact assessment method chosen in the calculation and the database used in the life cycle inventory. In this thesis, and since the investigated bridge is located in Sweden, Swedish conditions were taken into consideration when it comes to the emission factors of the basic materials in the bridge construction. With these concerns, it is concluded that the application of corrugated webs in stainless steel girders reduces the total environmental impact of the bridge construction.

Considering the life cycle cost, it is found that the integration of corrugated webs in stainless steel girders reduces the fabrication and production cost compared to the design concept with flat webs in carbon steel girders. Additionally, the results proved that the application of stainless steel in bridge design reduces the maintenance costs due to the high corrosion-resistance property of Duplex stainless steel. Thus, no need for maintenance throughout the whole service life of the bridge.

Based on the results obtained in Chapter 5, the material costs for stainless steel are more significant than the material costs for carbon steel. This is associated with the significant raise of the initial costs of stainless steel per kilogram in today's market. The discussions, presented in Chapter 6, pointed out that the stainless steel girders with corrugated webs has lower total life cycle cost when accounting for the initial costs of carbon steel and stainless steel in 2020. Consequently, the economic fea-

sibility of implementing corrugated webs in stainless steel bridge girders is highly dependent on the fluctuating prices of the stainless steel material.

Additionally, it is found that the stainless steel design concept is more economical and efficient when the average daily traffic is relatively high by avoiding the periodic maintenance schedule and the closure of the bridge which returns in additional costs for both the bridge planners and society. Thus, the following parameters are concluded as critical for LCA and LCC in bridge constructions: the emission factors of steel products, the material initial costs, the average daily traffic, the discount and escalation rate.

### 7.2 Further research

For further research on the life cycle assessment and life cycle cost topic, conducting a more comprehensive life cycle assessment considering the bridge's substructure is suggested.

Moreover, including additional parameters in the investigation, such as the correlation between the time required for each maintenance activity and the total life cycle cost, is recommended. Investigating further carbon and stainless steel grades in the case study is also suggested.

Overall, collaborations with the steel industry and bridge designers in the early stages of LCA and LCC are highly recommended, in order to provide more realistic data, which is preferable when evaluating the life cycle assessment and life cycle cost.

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# A

## LCA function

```
1 import pandas as pd
2 import numpy as np
3
4 ##the life cycle impact assessment
5 def LCA(OptimizationTarget,Painting, Quantities, Connection, ServiceLife):
6     # Load work sheets from the Database for the bridge design
7     # Database1, the spreadsheets in Database1 are read by Pyhton.
8     Process_df = pd.read_excel('Database1.xlsx', sheet_name='ProcessInfo')
9     MaterialEnergy_df = pd.read_excel('Database1.xlsx', sheet_name='MaterialEnergy'
10 )
11     Transportation_df = pd.read_excel('Database1.xlsx',sheet_name='
12     TransportationMachinery')
13     LCA_related_df = pd.read_excel('Database1.xlsx', sheet_name='LCA_Related')
14     Datab_steel_gir_prod_df = pd.read_excel('Database1.xlsx', sheet_name='
15     Steel_girder_prod_data_process')
16     # Create a zero array
17     tota_LCA_impact_without_benefits = np.zeros(1)
18     tota_LCA_impact_with_benefits = np.zeros(1)
19     # Calculate the material supply impact
20     for row in Quantities:
21         plate_qty = row[0]
22         hotrolled_qty = row[1]
23         hollowsection_qty = row[2]
24         weld_qty = row[3]
25         paint_qty = row[4]
26         concrete_qty = row[5]
27         rebars_qty = row[6]
28     plate_impact_data = MaterialEnergy_df[MaterialEnergy_df['
29     Material_Product_EnergyName'] == Quantities[0, 0]]
30     plate_impact_unit = plate_impact_data['Climate change:GWP from EPDs']
31     plate_impact = plate_qty * plate_impact_unit.squeeze()
32     hotrolled_impact_data = MaterialEnergy_df[
33     MaterialEnergy_df['Material_Product_EnergyName'] == Quantities[0, 1]]
34     hotrolled_impact_unit = hotrolled_impact_data['Climate change:GWP from EPDs']
35     hotrolled_impact = hotrolled_qty * hotrolled_impact_unit.squeeze()
36     hollowsection_impact_data = MaterialEnergy_df[
37     MaterialEnergy_df['Material_Product_EnergyName'] == Quantities[0, 2]]
38     hollowsection_impact_unit = hollowsection_impact_data['Climate change:GWP from
39     EPDs']
40     hollowsection_impact = hollowsection_qty * hollowsection_impact_unit.squeeze()
41     weld_impact_data = MaterialEnergy_df[MaterialEnergy_df['
42     Material_Product_EnergyName'] == Quantities[0, 3]]
43     weld_impact_unit = weld_impact_data['Climate change:GWP from EPDs']
44     weld_impact = weld_qty * weld_impact_unit.squeeze()
45     paint_impact_data = MaterialEnergy_df[MaterialEnergy_df['
46     Material_Product_EnergyName'] == Quantities[0, 4]]
47     paint_impact_unit = paint_impact_data['Climate change:GWP from EPDs']
48     # the piant qty must be multiplied by a factor/0.36/ to convert it in to kg of
49     paint required.
50     paint_impact = Painting[1,0] * 0.36 * paint_impact_unit.squeeze()
51     concrete_impact_data = MaterialEnergy_df[MaterialEnergy_df['
52     Material_Product_EnergyName'] == Quantities[0, 5]]
53     concrete_impact_unit = concrete_impact_data['Climate change:GWP from EPDs']
54     # mulitply concrete qty with the density to get the kg of concrete required.
55     concrete_impact = concrete_qty * 2400 * concrete_impact_unit.squeeze()
```

```

47 rebars_impact_data = MaterialEnergy_df[
48     MaterialEnergy_df['Material_Product_EnergyName'] == Quantities[0, 6]]
49 rebars_impact_unit = rebars_impact_data['Climate change:GWP from EPDs']
50 rebars_impact = rebars_qty * rebars_impact_unit.squeeze()
51 material_supply_impact = plate_impact + hotrolled_impact + hollowsection_impact
52     + weld_impact + paint_impact + concrete_impact + rebars_impact
53 # Calculte for the welding impact
54 welding_impact_data = Process_df[Process_df['ProcessName'] == Quantities[0, 3]]
55 welding_impact_unit = welding_impact_data['Climate change:GWP from EPDs']
56 #The total welding length
57 welding_length = 0
58 for row in Connection:
59     connection_part = row[0]
60     length = row[3]
61     if connection_part == 'Fillet' or connection_part == 'Butt':
62         welding_length = welding_length + length
63 welding_impact = welding_length * welding_impact_unit.squeeze()
64 production_phase_impact = material_supply_impact + welding_impact
65 # Calculate the transportation impact
66 tran_1 = Transportation_df[Transportation_df['MachineryName'] == 'Railway']
67 tran_imp_1 = tran_1['Climate change:GWP from EPDs']
68 tran_2 = Transportation_df[Transportation_df['MachineryName'] == '
69     Truck_national']
70 tran_imp_2 = tran_2['Climate change:GWP from EPDs']
71 tran_3 = Transportation_df[Transportation_df['MachineryName'] == '
72     Truck_regional']
73 tran_imp_3 = tran_3['Climate change:GWP from EPDs']
74 tran_4 = Transportation_df[Transportation_df['MachineryName'] == 'Truck_local']
75 tran_imp_4 = tran_4['Climate change:GWP from EPDs']
76 plate_transport_data = MaterialEnergy_df[MaterialEnergy_df['
77     Material_Product_EnergyName'] == Quantities[0, 0]]
78 plate_trans_distance_1 = plate_transport_data['Railway']
79 plate_trans_distance_2 = plate_transport_data['Truck_national']
80 plate_trans_distance_3 = plate_transport_data['Truck_regional']
81 plate_trans_distance_4 = plate_transport_data['Truck_local']
82 plate_transport_impact_1 = (plate_qty * plate_trans_distance_1.squeeze() *
83     tran_imp_1.squeeze()) / 1000
84 plate_transport_impact_2 = (plate_qty * plate_trans_distance_2.squeeze() *
85     tran_imp_2.squeeze()) / 1000
86 plate_transport_impact_3 = (plate_qty * plate_trans_distance_3.squeeze() *
87     tran_imp_3.squeeze()) / 1000
88 plate_transport_impact_4 = (plate_qty * plate_trans_distance_4.squeeze() *
89     tran_imp_4.squeeze()) / 1000
90 plate_transport_total = (
91     plate_transport_impact_1 + plate_transport_impact_2 +
92     plate_transport_impact_3 + plate_transport_impact_4)
93 # hotrolled transportation
94 hotrolled_transport_impact_1 = (hotrolled_qty * plate_trans_distance_1.squeeze()
95     * tran_imp_1.squeeze()) / 1000
96 hotrolled_transport_impact_2 = (hotrolled_qty * plate_trans_distance_2.squeeze()
97     * tran_imp_2.squeeze()) / 1000
98 hotrolled_transport_impact_3 = (hotrolled_qty * plate_trans_distance_3.squeeze()
99     * tran_imp_3.squeeze()) / 1000
100 hotrolled_transport_impact_4 = (hotrolled_qty * plate_trans_distance_4.squeeze()
101     * tran_imp_4.squeeze()) / 1000
102 hotrolled_transport_total = (
103     hotrolled_transport_impact_1 + hotrolled_transport_impact_2 +
104     hotrolled_transport_impact_3 + hotrolled_transport_impact_4)
105 # concrete transportation
106 concrete_transport_data = MaterialEnergy_df[MaterialEnergy_df['
107     Material_Product_EnergyName'] == Quantities[0, 5]]
108 concrete_trans_distance = concrete_transport_data['Truck_local']
109 concrete_transport_impact = (concrete_qty * 2400 * concrete_trans_distance.
110     squeeze() * tran_imp_4.squeeze()) / 1000
111 construction_transport_impact = plate_transport_total +
112     hotrolled_transport_total + concrete_transport_impact
113 # Calculate the use phase impact (maintenance, patch up, overcoating and remove
114     and repaint)
115 y_b = ServiceLife

```

```

119 main_sche_patchup = Process_df[Process_df['ProcessName'] == '
steel_girder_patchup']
120 patchup_action_time = main_sche_patchup['ActionTime_year']
121 # print(patchup_action_time)
122 main_sche_overcoating = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
123 overcoating_action_time = main_sche_overcoating['ActionTime_year']
124 # print(overcoating_action_time)
125 main_sche_remove_repaint = Process_df[Process_df['ProcessName'] == '
steel_girder_remove_repaint']
126 remove_repaint_action_time = main_sche_remove_repaint['ActionTime_year']
127 Oper_per_patchup = Process_df[Process_df['ProcessName'] == '
steel_girder_patchup']
128 Operation_per_patchup = Oper_per_patchup['OperatingPercentage']
129 In_qty_patchup = Process_df[Process_df['ProcessName'] == 'steel_girder_patchup'
]
130 Input_qty_all = In_qty_patchup['InputQuantity']
131 Oper_per_over_remo = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
132 Operation_per_over_remo = Oper_per_over_remo['OperatingPercentage']
133 df_final = pd.concat([patchup_action_time, overcoating_action_time,
remove_repaint_action_time], axis=0)
134 store_paint_req = np.zeros(y_b)
135 k = 0
136 Paint_req = 0
137 for p in range(1, y_b):
138     action = df_final.loc[df_final.index.values[k]]
139     # print(p)
140     # print('#####')
141     # print(k)
142     if p == action and k == 0:
143         Paint_req = Painting[1,0] * Operation_per_patchup.squeeze() *
Input_qty_all.squeeze()
144         # print(Paint_req)
145         # print('%%')
146         k = k + 1
147         store_paint_req[p] = Paint_req
148     elif p == action and (k == 1 or k == 2):
149         Paint_req = Painting[1,0] * Operation_per_over_remo.squeeze() *
Input_qty_all.squeeze()
150         k = k + 1
151         store_paint_req[p] = Paint_req
152     if k == 3:
153         df_final.loc[df_final.index.values[range(0, 3)]] = df_final.loc[
df_final.index.values[range(0, 3)]] + 31
154         k = 0
155 Total_paint_req = np.sum(store_paint_req)
156 # print(Total_paint_req)
157 paint_impact_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 4]]
158 paint_impact_unit = paint_impact_data['Climate change:GWP from EPDs']
159 total_paint_impact_use_phase = Total_paint_req * paint_impact_unit.squeeze()
160 # transportation impact of produced paint in the use phase
161 paint_transport_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 4]]
162 paint_transport_distance_national = paint_transport_data['Truck_national']
163 paint_transport_distance_local = paint_transport_data['Truck_local']
164 paint_tran_impact_national = (
165     Total_paint_req *
166     paint_transport_distance_national.squeeze() * tran_imp_2.squeeze()) / 1000
167 paint_tran_impact_local = (Total_paint_req * paint_transport_distance_local.
squeeze() * tran_imp_4.squeeze()) / 1000
168 paint_tran_impact = paint_tran_impact_national + paint_tran_impact_local
169 # Total impact in use phase
170 use_phase_impact = paint_tran_impact + total_paint_impact_use_phase
171 # print(use_phase_impact)
172 # Calculate the impact of end of life stage
173 # Here we extract the disposal unit impact kg CO2 eq/kg from Database1
174 dis_imp_metal = Process_df[Process_df['ProcessName'] == 'disposal_metal_steel']
175 dis_imp_1 = dis_imp_metal['Climate change:GWP from EPDs']

```

```

155     dis_imp_reinf = Process_df[Process_df['ProcessName'] == '
disposal_metal_reinforcement_bars']
156     dis_imp_reinf_1 = dis_imp_reinf['Climate change:GWP from EPDs']
157     dis_imp_concrete = Process_df[Process_df['ProcessName'] == 'disposal_concrete']
158     dis_imp_concrete_1 = dis_imp_concrete['Climate change:GWP from EPDs']
159     # Here we extract the recycling rate and recycling unit impact kg CO2 eq/kg
from Database1
160     Recyclable_amount_metal = Process_df[Process_df['ProcessName'] == '
recycle_metal_steel']
161     # We assume the same recycling rate for steel and stainless steel according to
World steel association
162     # This recycling rate for steel, stainless
163     Metal_steel_recycling_rate = Recyclable_amount_metal['RecyclingRate']
164     # concrete recycling rate
165     Recyclable_amount_Concrete = Process_df[Process_df['ProcessName'] == '
recycle_concrete']
166     # this is the recycling rate for Concrete
167     Concrete_recycling_rate = Recyclable_amount_Concrete['RecyclingRate']
168     # Now we extract the recycling impact per unit from Database1
169     # This impact is the same for steel and stainless steel according to Ecoinvent
database.
170     recy_imp_metal = Process_df[Process_df['ProcessName'] == 'recycle_metal_steel']
171     recy_imp_1 = recy_imp_metal['Climate change:GWP from EPDs']
172     # reinforcement bars
173     recy_imp_reinf = Process_df[Process_df['ProcessName'] == '
recycle_metal_reinforcement_bars']
174     recy_imp_reinf_1 = recy_imp_reinf['Climate change:GWP from EPDs']
175     # concrete
176     recy_imp_concrete = Process_df[Process_df['ProcessName'] == 'recycle_concrete']
177     recy_imp_concrete_1 = recy_imp_concrete['Climate change:GWP from EPDs']
178     # disposal calculations
179     # disposal plate impact
180     disposal_plate = plate_qty * (1 - Metal_steel_recycling_rate.squeeze()) *
dis_imp_1.squeeze()
181     # print(disposal_plate)
182     # disposal hotrolled impact
183     disposal_hotrolled = hotrolled_qty * (1 - Metal_steel_recycling_rate.squeeze())
* dis_imp_1.squeeze()
184     # print(disposal_hotrolled)
185     # disposal hollowsection
186     disposal_hollowsection = hollowsection_qty * (1 - Metal_steel_recycling_rate.
squeeze()) * dis_imp_1.squeeze()
187     # disposal weld impact
188     disposal_weld = weld_qty * (1 - Metal_steel_recycling_rate.squeeze()) *
dis_imp_1.squeeze()
189     # disposal concrete impact
190     disposal_concrete = concrete_qty * 2400 * (1 - Concrete_recycling_rate.squeeze
()) * dis_imp_concrete_1.squeeze()
191     # disposal reinf.bars
192     disposal_rebars = rebars_qty * (1 - Metal_steel_recycling_rate.squeeze()) *
dis_imp_1.squeeze()
193     total_disposal_impact = disposal_plate + disposal_hotrolled +
disposal_hollowsection + disposal_weld + disposal_concrete + disposal_rebars
194
195     # recycling calculations
196     recycle_plate = plate_qty * Metal_steel_recycling_rate.squeeze() * recy_imp_1.
squeeze()
197     recycle_hotrolled = hotrolled_qty * Metal_steel_recycling_rate.squeeze() *
recy_imp_1.squeeze()
198     recycle_hollowsection = hollowsection_qty * Metal_steel_recycling_rate.squeeze
() * recy_imp_1.squeeze()
199     recycle_weld = weld_qty * Metal_steel_recycling_rate.squeeze() * recy_imp_1.
squeeze()
200     recycle_concrete = concrete_qty * 2400 * Concrete_recycling_rate.squeeze() *
recy_imp_concrete_1.squeeze()
201     recycle_rebars = rebars_qty * Metal_steel_recycling_rate.squeeze() *
recy_imp_reinf_1.squeeze()
202     total_recycle_impact = recycle_plate + recycle_hotrolled +
recycle_hollowsection + recycle_weld + recycle_concrete + recycle_rebars
203

```



```

204 # paint incineration
205 paint_incineration = Process_df[Process_df['ProcessName'] == '
incineration_paint']
206 paint_inc_imp = paint_incineration['Climate change:GWP from EPDs']
207 paint_incineration = Painting[1,0] * 0.36 * paint_inc_imp.squeeze()
208
209 # transportation in the end of life
210 # We assume the transport distance to 150 km local truck
211 distance_eol = 150 # km
212 total_weight = (plate_qty + hotrolled_qty + hollowsection_qty + (Painting[1,0]
* 0.36) + (
213     concrete_qty * 2400) + weld_qty + rebars_qty) / 1000
214 # print(total_weight)
215 tran_4 = Transportation_df[Transportation_df['MachineryName'] == 'Truck_local']
216 tran_imp_4 = tran_4['Climate change:GWP from EPDs']
217 transportation_eol = total_weight * distance_eol * tran_imp_4.squeeze()
218
219 # total impact in the end of life
220 total_eol_impact = total_disposal_impact + total_recycle_impact +
paint_incineration + transportation_eol
221
222 # Calculate the benefits from the avoided environmental burden considering the
reuse of
223 # metal scraps in carbon steel and stainless steel production, reuse of
concrete and reinf.bars.
224 plate_data = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName']
== Quantities[0, 0]]
225 plate_reuse_impact = plate_data['GWP for reuse ']
226 plate_fraction = plate_data['Fraction_rates']
227 hotrolled_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 1]]
228 hotrolled_reuse_impact = hotrolled_data['GWP for reuse ']
229 hotrolled_fraction = hotrolled_data['Fraction_rates']
230 hollowsection_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 2]]
231 hollowsection_reuse_impact = hollowsection_data['GWP for reuse ']
232 hollowsection_fraction = hollowsection_data['Fraction_rates']
233 weld_data = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName']
== Quantities[0, 3]]
234 weld_reuse_impact = weld_data['GWP for reuse ']
235 weld_fraction = weld_data['Fraction_rates']
236 concrete_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 5]]
237 concrete_reuse_impact = concrete_data['GWP for reuse ']
238 concrete_fraction = concrete_data['Fraction_rates']
239 rebars_data = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName']
] == Quantities[0, 6]]
240 rebars_reuse_impact = rebars_data['GWP for reuse ']
241 rebars_fraction = rebars_data['Fraction_rates']
242 # Calculate the benefits
243 benefit_plate = plate_qty * (
244     Metal_steel_recycling_rate.squeeze() - plate_fraction.squeeze()) *
plate_reuse_impact.squeeze()
245 benefit_hotrolled = hotrolled_qty * (
246     Metal_steel_recycling_rate.squeeze() - hotrolled_fraction.squeeze())
* hotrolled_reuse_impact.squeeze()
247 benefit_hollowsection = hollowsection_qty * (
248     Metal_steel_recycling_rate.squeeze() - hollowsection_fraction.
squeeze()) * hollowsection_reuse_impact.squeeze()
249 benefit_weld = weld_qty * (
250     Metal_steel_recycling_rate.squeeze() - weld_fraction.squeeze()) *
weld_reuse_impact.squeeze()
251 benefit_concrete = concrete_qty * 2400 * (
252     Concrete_recycling_rate.squeeze() - concrete_fraction.squeeze()) *
concrete_reuse_impact.squeeze()
253 benefit_rebars = rebars_qty * (
254     Metal_steel_recycling_rate.squeeze() - rebars_fraction.squeeze()) *
rebars_reuse_impact.squeeze()
255 benefit_total = -1 * (
256     benefit_plate + benefit_hotrolled + benefit_hollowsection +

```

## A. LCA function

---

```
benefit_weld + benefit_concrete + benefit_rebars)
257 # Calculate the total environmental impact
258 tota_LCA_impact_without_benefits = production_phase_impact +
construction_transport_impact + use_phase_impact + total_eol_impact
259 total_LCA_impact_with_benefits = production_phase_impact +
construction_transport_impact + use_phase_impact + total_eol_impact +
benefit_total
260 if OptimizationTarget == 'LCA':
261     return (total_LCA_impact_with_benefits)
```

# B

## LCC function

```
1 import pandas as pd
2 import numpy as np
3
4 # -----
5 # this function calculates the welding costs for each fillet or butt weld and
6 # will be called in the final LCC function.
7 def calculate_cost(thickness, length, connection_part):
8     if connection_part == 'Fillet':
9         area = thickness ** 2
10        cost = (area + 30) / 19 * (length * 550) / 4
11
12    elif connection_part == 'Butt':
13        b = 5
14        area = thickness * (b + (b / (3) ** 0.5))
15        cost = (area + 30) / 19 * (length * 550) / 4
16        if thickness > 20:
17            cost = cost + (350 * length)
18        elif thickness <= 20:
19            cost = cost + (200 * length)
20    else:
21        cost = 0
22    return cost
23
24 # -----
25 # This function calculates the investment costs and the total LCC costs based
26 # on the matrices that are input for this function.
27 # LCC costs include material costs, welding costs, painting costs,
28 # corrugation costs, grinding costs, pickling costs, concrete casting costs,
29 # maintenance costs and revenues.
30
31 def LCC(OptimizationTarget, Quantities, Connection, Painting, lenghtCorr,
32        ServiceLife, pickling_area, grinding_len, Nsp, Ncb, ADT):
33     # Load work sheets from the Database for the bridge design
34     # Database1, the spreadsheets in Database1 are read by Pyhton.
35     Process_df = pd.read_excel('Database1.xlsx', sheet_name='ProcessInfo')
36     MaterialEnergy_df = pd.read_excel('Database1.xlsx', sheet_name='MaterialEnergy')
37     Transportation_df = pd.read_excel('Database1.xlsx', sheet_name='
38     TransportationMachinery')
39     #LCA_related_df = pd.read_excel('Database1.xlsx', sheet_name='LCA_Related')
40     Datab_steel_gir_prod_df = pd.read_excel('Database1.xlsx', sheet_name='
41     Steel_girder_prod_data_process')
42     # Create a zero array
43     invest_cost = np.zeros(1)
44     total_LCC = np.zeros(1)
45     # Calculate the material costs
46     for row in Quantities:
47         plate_qty = row[0]
48         hotrolled_qty = row[1]
49         hollowsection_qty = row[2]
50         weld_qty = row[3]
51         paint_qty = row[4]
52         concrete_qty = row[5]
53         rebars_qty = row[6]
54     in_row_plate = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName
```

```

    ']' == Quantities[0,0]]
53 unit_cost_plate = in_row_plate['UnitCost_SEK']
54 plate_cost = plate_qty * unit_cost_plate.squeeze() # plate cost
55 in_row_hot_rolled = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0,1]]
56 unit_cost_hotrolled = in_row_hot_rolled['UnitCost_SEK']
57 hotrolled_cost = hotrolled_qty * unit_cost_hotrolled.squeeze() # hotrolled
cost
58 in_row_hollow = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0,2]]
59 unit_cost_hollow = in_row_hollow['UnitCost_SEK']
60 hollow_cost = hollowsection_qty * unit_cost_hollow.squeeze() # hollow cost
61 in_row_weld = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName'
]] == Quantities[0,3]]
62 unit_cost_weld = in_row_weld['UnitCost_SEK']
63 #weld_cost = weld_qty * unit_cost_weld.squeeze() # weld cost
64 in_row_paint = MaterialEnergy_df[MaterialEnergy_df['Material_Product_EnergyName
']] == Quantities[0,4]]
65 unit_cost_paint = in_row_paint['UnitCost_SEK']
66 #paint_cost_mtrl = paint_qty * 0.36 * unit_cost_paint.squeeze() # paint cost
67 in_row_concrete = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0,5]]
68 unit_cost_concrete = in_row_concrete['UnitCost_SEK']
69 #concrete_cost = concrete_qty * 2400 * unit_cost_concrete.squeeze() # concrete
cost
70 in_row_rebars = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0,6]]
71 unit_cost_rebars = in_row_rebars['UnitCost_SEK']
72 rebars_cost = rebars_qty * unit_cost_rebars.squeeze() # reinforcement bars
cost
73 Material_costs = plate_cost.squeeze() + hotrolled_cost.squeeze() + hollow_cost.
squeeze() + rebars_cost.squeeze()
74 #calculate cost of cutting of plates
75 cutting_cost = 1.65 * plate_qty
76 # Calculate the welding costs for the fillet and butt welds
77 total_cost_weld = 0
78 for row in Connection:
79     # print(row)
80     connection_part = row[0]
81     thickness = row[2]
82     length = row[3]
83     cost = calculate_cost(thickness, length, connection_part)
84     total_cost_weld = total_cost_weld + cost
85     assembly_costs = 0.3 * total_cost_weld
86 # Calculate the painting costs
87 data_paint = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['Connection_parts'
]] == 'painting']
88 paint_place = data_paint['Working_place']
89 paint_price = data_paint['Reference_price']
90 paint_p = np.array(paint_price)
91 paint_cost = 0
92 total_paint_cost = 0
93 for row in Painting:
94     paint_a = row[0]
95     paint_place = row[1]
96     if paint_place == 'Workshop':
97         paint_cost = paint_a * paint_p[0]
98     elif paint_place == 'On site':
99         paint_cost = paint_a * paint_p[1]
100     else:
101         continue
102     total_paint_cost += paint_cost
103 # Calculate the corrugation costs
104 data_corrug = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['Connection_parts
']].str.match('corrugation')
105 corrug_unit_cost = data_corrug['Reference_price']
106 corrugation_cost = corrug_unit_cost.squeeze() * lenghtCorr
107 # Calculate the grinding costs
108 data_grinding = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['
Connection_parts']].str.match('grinding ')

```

```

109 grinding_unit_cost = data_grinding['Reference_price']
110 grinding_cost = grinding_unit_cost.squeeze() * grinding_len
111 # Calculate the pickling costs
112 data_pickling = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['
Connection_parts'].str.match('pickling ')]
113 pickling_unitcost = data_pickling['Reference_price']
114 pickling_cost = pickling_area * pickling_unitcost.squeeze()
115
116 # Calculate the costs of shear studs
117 data_studs = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['Connection_parts'
].str.match('shear_studs')]
118 studs_unit_cost = data_studs['Reference_price']
119 # calculate shear studs costs
120 for row in Connection:
121     length = row[3]
122     connection_part = row[0]
123     if connection_part == 'ShearStuds':
124         n = length #number of shear studs
125         studs_cost = n * studs_unit_cost.squeeze()
126         # cost of welding shear studs
127         data_studs_welding = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['
Connection_parts'].str.match('weld_stud')]
128         welding_stud_unitcost = data_studs_welding['Reference_price']
129         studs_weld_cost = n * welding_stud_unitcost.squeeze()
130         # total shear studs costs
131         total_studs_cost = studs_cost + studs_weld_cost
132         # Calculate the concrete casting costs
133         data_casting = Datab_steel_gir_prod_df[Datab_steel_gir_prod_df['
Connection_parts'].str.match('casting')]
134         casting_unit_cost = data_casting['Reference_price']
135         casting_cost = casting_unit_cost.squeeze() * concrete_qty
136         #Calculate the erection costs
137         erection_cost = (Nsp * 9000) + (Ncb*2200)
138         invest_cost = Material_costs + total_cost_weld + assembly_costs +
total_paint_cost + corrugation_cost + grinding_cost + pickling_cost +
total_studs_cost + casting_cost + erection_cost+cutting_cost
139
140 # Calculate the maintainance costs
141 d = 0.05 # discount rate
142 e = 0.02 # escalation rate
143 User_cost_data = MaterialEnergy_df[MaterialEnergy_df['
Material_Product_EnergyName'] == Quantities[0, 0]]
144 L_aff = User_cost_data['AffectedRoadLength_km'] #Affected road length
145 V_reduced = User_cost_data['ReducedSpeed_kmPerHour'] #Reduced speed
146 V_normal = User_cost_data['NormalSpeed_kmPerHour'] #normal speed
147 heavy_v_p = User_cost_data['HeavyVehiclePercentage'] #Heavy vehicle
percentage
148 y_b = ServiceLife # the service life
149 Process_df = pd.read_excel('Database1.xlsx', sheet_name='ProcessInfo')
150 main_s_patchup = Process_df[Process_df['ProcessName'] == 'steel_girder_patchup'
]
151 Patchup_action_time = main_s_patchup['ActionTime_year']
152 #print(Patchup_action_time)
153 Time_req_for_main_patchup = Process_df[Process_df['ProcessName'] == '
steel_girder_patchup']
154 Patchup_time_req = Time_req_for_main_patchup['Time_requirement_day_per_time']
155 Operational_per_patchup = Process_df[Process_df['ProcessName'] == '
steel_girder_patchup']
156 Patchup_oper_per = Operational_per_patchup['OperatingPercentage']
157 main_s_overcoating = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
158 Overcoating_action_time = main_s_overcoating['ActionTime_year']
159 #print(Overcoating_action_time)
160 Time_req_for_main_overcoating = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
161 Overcoating_time_req = Time_req_for_main_overcoating['
Time_requirement_day_per_time']
162 Operational_per_overcoating = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
163 Overcoating_oper_per = Operational_per_overcoating['OperatingPercentage']

```

## B. LCC function

```

164 main_s_remove_repaint = Process_df[Process_df['ProcessName'] == '
steel_girder_remove_repaint']
165 Remove_repaint_action_time = main_s_remove_repaint['ActionTime_year']
166 #print(Remove_repaint_action_time)
167 Time_req_for_main_remove_repaint = Process_df[Process_df['ProcessName'] == '
steel_girder_remove_repaint']
168 Rem_repaint_time_req = Time_req_for_main_remove_repaint['
Time_requirement_day_per_time']
169 Operational_per_remo_repaint = Process_df[Process_df['ProcessName'] == '
steel_girder_remove_repaint']
170 Remo_repaint_oper = Operational_per_remo_repaint['OperatingPercentage']
171 cost_s_patchup = Process_df[Process_df['ProcessName'] == 'steel_girder_patchup'
]
172 Patchup_cost = cost_s_patchup['ProcessUnitCost_SEK']
173 cost_s_overcoating = Process_df[Process_df['ProcessName'] == '
steel_girder_overcoating']
174 Overcoating_cost = cost_s_overcoating['ProcessUnitCost_SEK']
175 cost_s_remove_repaint = Process_df[Process_df['ProcessName'] == '
steel_girder_remove_repaint']
176 Remove_repaint_cost = cost_s_remove_repaint['ProcessUnitCost_SEK']
177 Heavy_vehicle_time_va = Transportation_df[Transportation_df['MachineryName'] ==
'heavy_vehicle']
178 Heavy_veh_time_price = Heavy_vehicle_time_va['HourlyTimeValue_SEKPerHour']
179 Passeng_vehicle_time_val = Transportation_df[Transportation_df['MachineryName']
== 'passenger_vehicle']
180 Passeng_veh_time_price = Passeng_vehicle_time_val['HourlyTimeValue_SEKPerHour']
181 df_final = pd.concat([Patchup_action_time, Overcoating_action_time,
Remove_repaint_action_time], axis=0)
182 # print(df_final)
183 k = 0
184 Cost_for_maintain = np.zeros(y_b)
185 Cost_for_users = np.zeros(y_b)
186
187 for p in range(1, y_b):
188     action = df_final.loc[df_final.index.values[k]]
189     if p == action and k == 0:
190         Paint_req_patch = Painting[1,0] * Patchup_oper_per.squeeze()
191         NPV_Cost_Paint = (Paint_req_patch * Patchup_cost) * ((1 + e) / (1 + d))
192     ** p
193     NPV_Cost_users = ((L_aff * ((1 / V_reduced) - (1 / V_normal))) * ADT *
Patchup_time_req.squeeze() * (
194         (Heavy_veh_time_price.squeeze() * heavy_v_p) + (
Passeng_veh_time_price.squeeze() * (1 - heavy_v_p)))) *
((1 + e) / (1 + d)) ** p
195
196     # print(NPV_Cost_Paint)
197     k = k + 1
198     Cost_for_maintain[p] = NPV_Cost_Paint
199     Cost_for_users[p] = NPV_Cost_users
200     elif p == action and (k == 1 or k == 2):
201         Paint_req_over = Painting[1,0] * Overcoating_oper_per.squeeze()
202         Paint_req_rem_repaint = Painting[1,0] * Remo_repaint_oper.squeeze()
203         if k == 1:
204             NPV_Cost_Paint = (Paint_req_over * Overcoating_cost) * ((1 + e) /
(1 + d)) ** p
205             NPV_Cost_users = ((L_aff * (
206                 (1 / V_reduced) - (1 / V_normal))) * ADT *
Overcoating_time_req.squeeze() * (
207                 (Heavy_veh_time_price.squeeze() *
heavy_v_p) + (
208                     Passeng_veh_time_price.squeeze()
* (1 - heavy_v_p)))) * (
209                 (1 + e) / (1 + d)) ** p
210
211         elif k == 2:
212             NPV_Cost_Paint = (Paint_req_rem_repaint * Remove_repaint_cost) *
((1 + e) / (1 + d)) ** p
213             NPV_Cost_users = ((L_aff * (
214                 (1 / V_reduced) - (1 / V_normal))) * ADT *
Rem_repaint_time_req.squeeze() * (

```

```

215             (Heavy_veh_time_price.squeeze() *
216             heavy_v_p) + (
217             Passeng_veh_time_price.squeeze()
218             * (1 - heavy_v_p)))) * (
219             (1 + e) / (1 + d)) ** p
220
221     k = k + 1
222     Cost_for_maintain[p] = NPV_Cost_Paint
223     Cost_for_users[p] = NPV_Cost_users
224     if k == 3:
225         df_final.loc[df_final.index.values[range(0, 3)]] = df_final.loc[
226         df_final.index.values[range(0, 3)]] + 31
227         k = 0
228         NPV_total_maintain_cost = np.sum(Cost_for_maintain)
229         NPV_total_user_cost = np.sum(Cost_for_users)
230         NPV_Use_stage = NPV_total_maintain_cost + NPV_total_user_cost
231         # Calculate the revenues costs that comes from reselling metal scraps
232         #d = 0.01 # discount rate
233         #e = 0.02 # escalation rate
234         y_b = ServiceLife # the service life
235         Recyclable_amount_metal_steel = Process_df[Process_df['ProcessName'] == '
236         recycle_metal_steel']
237         Metal_steel_recycling_rate = Recyclable_amount_metal_steel['RecyclingRate']
238         resell_plate_data = MaterialEnergy_df[MaterialEnergy_df['
239         Material_Product_EnergyName'] == Quantities[0,0]]
240         resell_plate = resell_plate_data['EOLMaterial_ResellPrice_SEK']
241         resell_plate_cost = -1 * Metal_steel_recycling_rate.squeeze() * plate_qty *
242         resell_plate.squeeze() * (
243         (1 + e) / (1 + d)) ** y_b
244
245         resell_weld_data = MaterialEnergy_df[MaterialEnergy_df['
246         Material_Product_EnergyName'] == Quantities[0,3]]
247         resell_weld = resell_weld_data['EOLMaterial_ResellPrice_SEK']
248         resell_weld_cost = -1 * Metal_steel_recycling_rate.squeeze() * weld_qty *
249         resell_weld.squeeze() * (
250         (1 + e) / (1 + d)) ** y_b
251
252         resell_hotrolled_data = MaterialEnergy_df[MaterialEnergy_df['
253         Material_Product_EnergyName'] == Quantities[0,1]]
254         resell_hotrolled = resell_hotrolled_data['EOLMaterial_ResellPrice_SEK']
255         resell_hotrolled_cost = -1 * Metal_steel_recycling_rate.squeeze() *
256         hotrolled_qty * resell_hotrolled.squeeze() * (
257         (1 + e) / (1 + d)) ** y_b
258
259         resell_hollowsection_data = MaterialEnergy_df[MaterialEnergy_df['
260         Material_Product_EnergyName'] == Quantities[0,2]]
261         resell_hollowsection = resell_hollowsection_data['EOLMaterial_ResellPrice_SEK']
262         resell_hollowsection_cost = -1 * Metal_steel_recycling_rate.squeeze() *
263         hollowsection_qty * resell_hollowsection.squeeze() * (
264         (1 + e) / (1 + d)) ** y_b
265
266     Total_revenue_reselling = np.sum(
267     resell_plate_cost + resell_weld_cost + resell_hotrolled_cost +
268     resell_hollowsection_cost)
269     total_LCC = NPV_Use_stage + Total_revenue_reselling + invest_cost
270     if OptimizationTarget == 'Invest':
271         return (invest_cost)
272     elif OptimizationTarget == 'LCC':
273         return (total_LCC)
274
275     #
276     invest_cost,
277     NPV_total_maintain_cost,
278     Total_revenue_reselling,
279     Material_costs,
280     total_cost_weld,
281     assembly_costs,
282     total_paint_cost,
283     corrugation_cost,
284     grinding_cost,
285     pickling_cost,
286     total_studs_cost,

```

## B. LCC function

---

```
272 #         casting_cost ,
273 #         erection_cost ,
274 #         cutting_cost)
275 #
```

---



C

**Environmental data**

Table C.1: Environmental data for the materials used in a bridge design.

Material	GWP from different EPDs	Data source	CML 2001 (superseded): climate change: GWP 100a	Data provider in Ecoinvent 3.8_cuttoff_system
	kg CO2-eq/kg		kg CO2-eq/kg	
steel_s355_plate	2,63	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low
steel_s355_hot_rolled	2,16	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,12782	Ecoinvent Steel production, low-alloyed-hot rolled RER
steel_s355_hollow_section	2,63	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low

**Table C.1:** Environmental data for the materials used in a bridge design.

Material	GWP from different EPDs	Data source	CML 2001 (superseded): climate change: GWP 100a	Data provider in Ecoinvent 3.8_cutoff_system
steel_s460_plate	2,63	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low
steel_s460_hot_rolled	2,16	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,12782	Ecoinvent Steel production, low-alloyed-hot rolled RER
steel_s460_hollow_section	2,63	SSAB 2020 <a href="https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]">https://www.ssab.com/download-center?dcFilter=environmentalpr&amp;dcSearch#sort=%40customorder%20descending&amp;f:document=[3f0a0e364ca54f74a30faff866bd87ff]</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low
stainless_steel_hot_rolled	2,74	Outokumpu 2019 <a href="https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations">https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations</a>	5,02593	Ecoinvent Chromium steel 18/8, hot rolled, RER steel production, hot rolled

**Table C.1:** Environmental data for the materials used in a bridge design.

Material	GWP from different EPDs	Data source	CML 2001 (superseded): climate change: GWP 100a	Data provider in Ecoinvent 3.8_cutoff_system
stainless_steel_hollow_section	2,74	Outokumpu 2019 <a href="https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations">https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations</a>	5,02593	Ecoinvent Chromium steel 18/8, hot rolled, RER steel production, hot rolled
stainless_steel_plate	2,74	Outokumpu 2019 <a href="https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations">https://www.outokumpu.com/en/sustainability/sustainable-solutions/environmental-product-declarations</a>	4,52358	Ecoinvent Chromium steel 18/8, hot rolled, steel production, hot rolled
steel_reinforcement_bars	0,7	<a href="https://klimatkalkyl-pub.ea.trafikverket.se/Klimatkalkyl/Modell">https://klimatkalkyl-pub.ea.trafikverket.se/Klimatkalkyl/Modell</a>	0,54224	Ecoinvent steel, low-alloyed // [Europe without Switzerland and Austria] steel production, electric, low-alloyed.

**Table C.1:** Environmental data for the materials used in a bridge design.

Material	GWP from different EPDs	Data source	CML 2001 (superseded): climate change: GWP 100a	Data provider in Ecoinvent 3.8_cutoff_system
welds_steel_s355	2,4	<a href="https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406">https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low
welds_steel_s460	2,4	<a href="https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406">https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406</a>	2,0665	Ecoinvent Steel-low-alloyed, Steel production RER, converter, low

**Table C.1:** Environmental data for the materials used in a bridge design.

Material	GWP from different EPDs	Data source	CML 2001 (superseded): climate change: GWP 100a	Data provider in Ecoinvent 3.8_cuttoff_system
welds_ stainless_ steel	4,5	<a href="https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406">https://reader.elsevier.com/reader/sd/pii/S0959652615008549?token=FA9383A03384550004F0CA4012F0780A2B984868A63F655417B0D148BB5D4038C999C0D1D0AF6894DA4527ECABF370BE&amp;originRegion=eu-west-1&amp;originCreation=20220405154406</a>	5,02593	Ecoinvent Chromium steel 18/8, hot rolled, RER steel production, hot rolled
concrete	0,166	<a href="https://klimatkalkyl-pub.ea.trafikverket.se/Klimatkalkyl/Model">https://klimatkalkyl-pub.ea.trafikverket.se/Klimatkalkyl/Model</a>	0,1663	Ecoinvent Concrete production40 Mpa ready mix with portland cement Row.
paint	3,52	<a href="https://www.epd-norge.no/getfile.php/1316585-1608215319/EPDer/Byggevare/Maling/NEPD-2596-1317_Hardtop-XP-Jotun-UAE-Ltd-LLC-.pdf">https://www.epd-norge.no/getfile.php/1316585-1608215319/EPDer/Byggevare/Maling/NEPD-2596-1317_Hardtop-XP-Jotun-UAE-Ltd-LLC-.pdf</a>	3,72718	Paint production for electrostatic painting for aluminium GLO

**Table C.2:** Production and construction phase and processes with their environmental impact.

Life cycle stage	Process name	GWP from different EPDs kg CO <sub>2</sub> -eq/m	Data source	CML 2001 (superseded):climate change :GWP 100a (kg CO <sub>2</sub> -eq/m)	Data provider in Ecoinvent 3.8_cutoff_system
Production	Welding S355	4,4	<a href="https://link.springer.com/content/pdf/10.1007/s11367-019-01621-x.pdf">https://link.springer.com/content/pdf/10.1007/s11367-019-01621-x.pdf</a> FCAW carbon steel	0,18458	Database-Ecoinvent Welding, gas, steel RER
Production	Welding SS duplex	6,09	<a href="https://link.springer.com/content/pdf/10.1007/s11367-019-01621-x.pdf">https://link.springer.com/content/pdf/10.1007/s11367-019-01621-x.pdf</a> FCAW carbon steel	0,18458	Database-Ecoinvent Welding, gas, steel RER
Life cycle stage	Process name	Transportation type	GWP from Trafikverket kg CO <sub>2</sub> -eq/ t*km	CML 2001 (superseded): climate change: GWP 100a kg CO <sub>2</sub> -eq/t*km	Data provider in Ecoinvent 3.8_cutoff_system
Construction	Transportation	Railway	0,001	0,05617	Ecoinvent, Transport, freight train , deisel, Europe without Switzerland.

Table C.2: Production and construction phase and processes with their environmental impact.

Life cycle stage	Process name	GWP from different EPDs kg CO2-eq/m	Data source	CML 2001 (superseded):climate change :GWP 100a (kg CO2-eq/m)	Data provider in Ecoinvent 3.8_cutoff_system
Construction	Transportation	Diesel truck national	0,079	0,0863	Ecoinvent transport, freight lorry >32 metric ton, EURO 6 RER
Construction	Transportation	Diesel truck regional	0,119	0,09075	Ecoinvent transport, freight, lorry >32 metric ton, EURO 3 RER
Construction	Transportation	Diesel truck local	0,198	0,16502	Ecoinvent transport, freight, lorry 16-32 metric ton, EURO5 RER



**Table C.3:** Use and end-of-life phase processes and their environmental impact.

Life cycle stage	Process	Reference unit	Action of the activity/ year	Data source
Use phase	Steel girder patch up	m2	13	Rossi et al.,(2017)
Use phase	Steel girder overcoating	m2	19	The painting plan is used from: Rossi, B., Marquart,S., & Rossi, G. (2017). Comparative life cycle cost assessment of painted and hot-dip galvanized bridges. Journal of Environmental Management, 197, 41–49. <a href="https://doi.org/10.1016/j.jenvman.2017.03.022">https://doi.org/10.1016/j.jenvman.2017.03.022</a>
Use phase	Steel girder remove and replace	m2	31	Rossi et al.,(2017)
Life cycle stage	Process	GWP from Ecoinvent / kg CO2-eq/kg	Data provider	

**Table C.3:** Use and end-of-life phase processes and their environmental impact.

Life cycle stage	Process	Reference unit	Action of the activity/ year	Data source
end of life	Paint incineration	2,41154	Ecoinvent Treatment of hazardous waste, hazardous waste incineration with energy recovery. Europe without Switzerland.	
end of life	Steel disposal	0,00519	Ecoinvent Treatment of scrap steel, inert material landfill Row	
end of life	Stainless steel disposal	0,00519	Ecoinvent Treatment of scrap steel, inert material landfill Row	
end of life	Reinforcement bars disposal	0,06552	Ecoinvent Treatment of waste reinforcement steel, collection for final disposal Row	
end of life	Concrete disposal	0,01231	Ecoinvent Treatment of waste concrete gravel, collection from final disposal Row	

**Table C.3:** Use and end-of-life phase processes and their environmental impact.

Life cycle stage	Process	Reference unit	Action of the activity/ year	Data source
end of life	Steel recycling	0,045	Treatment of metal scrap mixed for recycling, unsorted, sorting, iron scrap sorted pressed Europe without Switzerland	
end of life	Stainless steel recycling	0,045	Treatment of metal scrap mixed for recycling, unsorted, sorting, iron scrap sorted pressed Europe without Switzerland	
end of life	Concrete recycling	0,00961	Ecoinvent Treatment of waste concrete gravel, sorting plant Row	
end of life	Reinforcement bars recycling	0,05719	Ecoinvent Treatment of waste reinforcement steel, recycling Row	



# D

## Material and production cost estimations

**Table D.1:** Material and production cost estimations used in the case study.

Material costs		
Steel/profile	S355-S460 [kr/kg]	Stainless steel Duplex [kr/kg]
Plate	20	60
Hot-rolled	25	75
Hollow sections	30	90
Production costs	Reference unit	Cost
Cutting of plates	kr/ton	1650
Shear studs	kr/piece	30
Welding shear studs	kr/piece	45
Grinding	kr/m	125
Corrugation	kr/m	2000
Painting (workshop)	kr/m <sup>2</sup>	1000
Painting (on site)	kr/m <sup>2</sup>	3000
Pickling	kr/m <sup>2</sup>	300

### 2.2 Welding

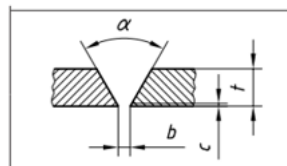
No. Of weld passes required for a weld area,  $ns = (Aw+30)/19$

$Aw$  = area of the fillet or butt weld (for butt weld,  $\alpha = 60$ ,  $b = 5$ )

A welder runs 4 m weld (one pass) per hour and has a cost of 550 kr/hour

Cost for weld =  $ns \times L \times 550$  kr/4 (L is the length of the weld with  $Aw$ , in meters)

$$W_{cost} = \frac{Aw+30}{19} \cdot \frac{L \cdot 550}{4}$$



**Figure D.1:** The welding cost calculation used in the case study.

## D. Material and production cost estimations

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**Table D.2:** Construction and maintenance costs used in the LCC calculation in the case study. The service life of the bridge is 120 years.

Concrete casting cost	2500	kr/m <sup>3</sup>		
Erection costs				
Main girders and cross beams	9000	kr/splice		
Intermediate cross-beams	2200	kr/cross beam		
Maintenance costs	Reference unit	Action time (year)	Cost per unit	Operating precentage of painting
Patch up	m <sup>2</sup>	13	1042	0,05
Overcoating	m <sup>2</sup>	19	562	0,9
Remove and replace	m <sup>2</sup>	31	2341	0,9
Patch up	m <sup>2</sup>	44	1042	0,05
Overcoating	m <sup>2</sup>	50	562	0,9
Remove and replace	m <sup>2</sup>	62	2341	0,9
Patch up	m <sup>2</sup>	75	1042	0,05
Overcoating	m <sup>2</sup>	81	562	0,9
Remove and replace	m <sup>2</sup>	93	2341	0,9
Patch up	m <sup>2</sup>	106	1042	0,05
Overcoating	m <sup>2</sup>	112	562	0,9

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