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Comparative life cycle analysis for bridges made of conventional steel and stainless steel in the early design phases

Developing a parametric multi-perspective approach

Master's thesis in Circular Economy

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Abstract

Considering bridges' long service life and large scale, the decisions made in the design stage have significant impacts on resource consumption and waste generation throughout the life span. Stainless steel has recently been more often adopted as an alternative in structural components. While stainless steel has the advantage of low maintenance requirements, it is expensive and consumes more energy than conventional carbon steel during the production process. The implementation of life cycle assessment (LCA) on stainless steel bridges is rather limited at present. Also, a general LCA requires large amounts of data input and prior knowledge of LCA. It may lead to barriers when architects and structural engineers try to assess the potential environmental impacts of bridges in the early design stages. Accordingly, this study conducts a comparative case study of bridges made of conventional steel and stainless steel with a simplified design-integrated life-cycle analysis tool, which enables users to estimate environmental impacts, life cycle cost (LCC), and circularity of different design variants. A MATLAB-based tool is developed based on a parametric model consisting of three main modules, i.e., input, calculation, and output. Time-consuming procedures in LCA are simplified through default assumptions and predefined mathematical equations. Thus, quantitative outcomes of target indicators can be obtained according to limited input variables and supplementary information from an updatable database. The results show that the environmental impact factors of steel product which is needed in large quantity in bridge design have huge impacts on the overall environmental impact. Selecting stainless steel with lower impact factors is the key to improve the competitiveness of bridge designs with stainless steel. Stainless steel is a more attractive alternative in terms of LCC. The total LCC of stainless steel bridge could be lower than conventional steel bridge by avoiding periodic maintenance activities. Overall, the simultaneous assessment of LCCs, environmental impacts, and circularity provides a holistic view while assessing the sustainability of bridge construction.

Keywords: bridge, parametric model, simplified life cycle assessment, life-cycle cost, circularity, stainless steel.

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Fu-siang Syu, Gothenburg, June 2021

Notations

Roman upper case letters

ADT	Average daily traffic on a bridge
$BrCI_{(t)}$	Theoretical bridge circularity indicator
$BrCI_{(p)}$	Practical bridge circularity indicator
C_m	The unit cost of material/product
$C_{module\ A}$	The costs generated in the product and construction stage
$C_{module\ B}$	The costs generated in the use stage
$C_{M,x}$	The unit cost of maintenance activity x
$C_{P\&T,\ steel\ girder}$	The production and treatment costs of steel girders
CCI_j	The component circularity indicator of component j
D	The time required for a maintenance activity
DDF	Disassembly determining factor for a component (unitless)
F	The feature of a component that is related to a specific process
H	The operation hours of a machine
I_{prod}	The impacts generated in the product stage
I_{cons}	The impacts generated in the construction stage
I_{use}	The impacts generated in the use stage
I_{eol}	The impacts generated in the EOL stage
$I_{module\ D}$	The impacts producing the substituted primary product
IF_m	LCIA results per unit material/product (cradle to gate)
IF_{ma}	LCIA results per operating hour of a machine
IF_{p_prod}	LCIA results per unit process in the product stage
IF_{p_waste}	LCIA results per unit waste treatment process of material/product
IF_{trans}	LCIA results per ton*km of a transport type
IF_{vm}	LCIA results per unit virgin material which can be substituted by secondary material (cradle to gate)
L_{aff}	Affected roadway length
L_{eol}	The transport distance of demolition waste from the site to treatment plants or landfills
$L_{k,t}$	Transport distance of material/product k through transport type t
MCI_j	The material circularity indicator of component j
N_s	The total number of systems in the bridge
NF	The normalization factor of an LCIA method
NR	The fraction of nonreusable proportion in a component
P_{eol}	The unit price of EOL material/product
Q	The quantity of material/product in each component (kg or m^3)
$Q_{k,x}$	The quantity of material/product k needed per unit maintenance activity x (kg or m^3)

R	Recycling rate
Rv	The incomes generated at the end of the service life of a bridge
$SCI_{i(t)}$	The theoretical system circularity indicator of system i
$SCI_{i(p)}$	The practical system circularity indicator of system i
SD	System dependency (unitless)
V	The mass of virgin material/product in a component
V_n	Normal speed without delay
V_r	Reduced speed
PW	The power of a machine (kW)
W	The mass of nonreusable proportion in a component (kg)
WF	The weighting factor of an LCIA method
X	The utility of a component
Y_B	The estimated service life of a bridge
Y_C	The estimated service life of a component
Y_S	The estimated service life of a system

Roman lower case letters

d	Escalation rate
i	Discount rate
$n_{x,j}$	The year of occurrence of maintenance activity x for component j
$r_{k,j}$	The fraction of secondary material in material/product k in component j (%)
r_T	Percentage of heavy vehicle among all the ADT
w_T	The hourly cost for one truck
w_P	The hourly cost for one passenger car

Greek lower case letters

ρ	Density (kg/m^3)

Abbreviations

Abbreviation	*Explanation*
BCI	Building Circularity Indicator
BrCI	Bridge Circularity Indicator
BoQ	Bill of quantities
CAD	Computer-aided design
CCI	Component circularity indicator
CDW	Construction and demolition waste
CE	Circular economy
CED	Cumulative energy demand
CF	Characterization factor
DDF	Disassembly determining factor
EAF	Electric arc furnace
EOL	End of life
EPD	Environmental product declaration
EU	European union
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LCCA	Life cycle cost analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MCI	Material circularity indicator
MRO	Maintenance, repair, operations
PCI	Product circularity indicator
SCI	System circularity indicator
SDGs	Sustainable development goals
SP	Salvaging performance
SS	Stainless steel
TDC	Traffic delay cost
VOC	Vehicle operation cost

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Chapter 1 Introduction

The concept of sustainable development has been widely adopted to guide policies of public and private sectors nowadays. In 2015, the United Nations set the 2030 agenda for sustainable development and 17 sustainable development goals (SDGs) (United Nations, n.d.a). The SDGs address urgent and critical issues which humans face at present, such as climate change and resource depletion (United Nations, n.d.b). The Communication "Next steps for a sustainable European future" clearly indicates that the transition to a sustainable society is a primary target of the European Union (EU) (EESC, 2016). To achieve the goal, one of the main challenges for the EU is to mitigate the environmental impacts caused by buildings and constructions. In the EU, the construction and building sector accounts for around 40% of total energy final consumption, 35% of greenhouse gas emissions (GHG), and over 50% of all extracted materials (European Commission, 2011). Furthermore, the construction sector produces huge amounts of wastes, as one-third of the EU's annual waste generation (European Commission, n.d.).

In recent years, there is growing interest in the sustainability of bridges (Balogun et al., 2020). In Sweden, over 29,000 bridges are built and managed by the Swedish Transport Administration (Trafikverket) (Du, 2015). A bridge has a very long lifetime (e.g., 80 years) and requires great amounts of energy and material input from cradle to grave. Du (2015) found that the environmental impacts of a bridge highly relied on the selection of construction material. Steel is a common raw material and consumed in large quantities in bridge construction. However, its low resistance against corrosion, which leads to a great demand for maintenance, reduces its performance of sustainability. To overcome the drawbacks of steel, stainless steel has been more often adopted in buildings and structural components in recent years (Rossi, 2014). Stainless steel as a construction material has the advantages of excellent corrosion resistance, low maintenance requirements, long service life, and high recovery rate (Rossi, 2014). This may facilitate the integration of Circular Economy (CE) strategies into bridge design. However, stainless steel is very expensive and consumes more energy than conventional carbon steel during the production process (Gutowski, 2013; Rossi, 2014).

The application of a Life Cycle Assessment (LCA) in the early design stages of a building could improve the sustainability of the building (Meex et al., 2018; Tschetwertak et al., 2017). However, there are some challenges for adopting an LCA in the early design stages (Hollberg and Ruth, 2016). For instance, a complete LCA requires large amounts of input data, such as the quantities of all material and energy consumptions in each life cycle stage, while the information available in the early design stages is usually uncertain and insufficient. The parametric LCA, a computer-aided approach, is developed for incorporating LCA into the design process (Hollberg and Ruth, 2016). To enable LCA to be conducted in the early design stages, the general procedures for LCA are simplified with adequate assumptions and predefined mathematical equations. The outcomes of LCA then depend on the given key design parameters. Accordingly, users who are not familiar with the general LCA approach can evaluate the environmental performance of different design variants. Rather than obtaining accurate emissions or environmental impacts, the main purpose of a parametric LCA is to optimize and compare construction designs from an environmental point of view.

Overall, considering that a bridge is usually designed for extremely long service life, it is suggested to use LCA and Life Cycle Cost Analysis (LCCA) while evaluating different bridge designs with innovative materials (European Commission, 2013). To the best of our knowledge, few studies discussing the LCA of a stainless steel bridge are available, while some studies address the analysis of life cycle cost (LCC) of stainless steel bridges (Cadenazzi et al., 2020; Cope et al., 2013; Zilli et al., 2008).

1.1 Aim and objectives

This study aims to develop a parametric model for bridges made of stainless steel and conventional steel, which is capable of evaluating bridge design variants in the early design stages from life-cycle, environmental, economic, and circular points of view. This study is expected to provide a decision support tool for architects, engineers, or relevant stakeholders who focus on the evaluation of different design alternatives. By conducting a case study, the impact hotspots and improvement opportunities for steel bridges can be identified. The result is also able to serve as recommendations for further improving the financial feasibility and sustainability of a stainless steel bridge.

To achieve these goals, the objectives are to:

- Establish a parametric model for life cycle analysis of bridge design, which integrates LCA, LCCA, and circularity assessment.
- Develop a MATLAB-based computational tool for realizing the model.
- Apply the tool to evaluate different bridge designs, which adopt stainless steel and conventional steel. Key parameters for bridge design are then identified based on the outcome of a case study.

1.2 Research questions

This study aims to give insights into sustainable bridge design by answering the following research question:

1. How to evaluate the environmental impacts and costs of bridge design variants with life cycle thinking in the early design stages?
2. Based on the approach developed in question one, when it comes to bridge construction, is stainless steel a more environment-friendly and cost-effective solution than conventional steel from a life cycle perspective?

1.3 Limitations

The limitations of this study are outlined as below:

- *Uncertainty.* Due to the nature of the early design stages, large amounts of assumptions and various data sources will lead to uncertainties in the outcomes. Thus, all assumptions and data sources should be presented. Meanwhile, sensitivity analysis is needed as well.
- *Completeness.* This study evaluates the difference between stainless steel and carbon steel bridges in terms of life-cycle environmental impacts and costs. Thus, only the most relevant life stages and modules are included in the system boundaries. Furthermore, the parametric model only addresses environmental and economic dimensions of sustainability rather than conducting a comprehensive sustainability assessment.
- *Data availability and reliability.* The case study will focus on steel bridges in Sweden. The availability of local databases and good cost information might affect the accuracy of results. If specific data are not available, the generic data collected from multiple sources will be adopted instead.
- *Life cycle impact assessment (LCIA) methodologies.* Although numerous LCIA methods are currently available, only one LCIA method will be adopted in the case study.
- *Exposure categories for paint coating.* The maintenance schedule of a steel bridge highly depends on the environment in where it is located. In the case study, we use a general maintenance schedule for conducting LCA and LCCA. It may decrease the accuracy of the results.

1.4 Approach

This study is divided into three main parts. Firstly, a literature review is done as the basis for developing the method of this study. Following the first part, a parametric model for life cycle analysis of bridge design and a MATLAB-based computational tool for carrying out the model are formulated. Finally, two case studies, i.e., a twin-girder composite bridge design, are conducted to identify key parameters of bridge design.

- **Literature review**

The literature review covers brief introductions of LCA, LCCA, and CE, specifically their applications to bridge construction. The characteristics of stainless steel and its practical uses in bridge construction are presented as well. The information collected is mainly taken from relevant academic papers, international standards, and technical reports.

- **Parametric model**

The parametric model in the study consists of three assessment approaches, i.e., LCA, LCCA, and circularity assessment. Before the model is developed, system boundaries for LCA and LCCA should be clarified. The most relevant life cycle stages and modules considered in the model are reported. Because the data adopted in LCA and LCCA significantly affect the outcome, data sources are presented as well. The parametric model consists of three main modules. The main elements of each module are clarified. Lastly, a brief introduction of the MATLAB-based computational tool is given, including its input, output, functions, and operating environment.

- **Case studies**

Two case studies are performed for applying the parametric model. Case study 1 contains three design alternatives for a composite bridge. The main difference among alternatives is the material of the main girder, i.e., conventional carbon steel (grade S355 and grade S460) and stainless steel (grade 1.4162). Case study 2 also evaluates a composite steel-concrete bridge design. This case includes a carbon steel alternative and a stainless steel alternative while it has more information about the composition of a bridge than the first case. These case studies cover the evaluation of each bridge design in terms of environmental impacts, life cycle cost, and circularity. The main purpose is to compare the design variants to see if stainless steel is a better option in bridge construction. Furthermore, a sensitivity analysis is conducted to find the key parameters of a steel bridge design.

Chapter 2 Literature review

2.1 Life cycle assessment

2.1.1 Main steps of LCA

Life cycle assessment (LCA) is a standardized and globally adopted method for quantifying the potential environmental impacts of a service, process, or product over its entire life cycle (IES, 2010). The outcome of LCA can support decision-makers to compare the environmental performance of different alternatives and help experts to identify hotspots of environmental impacts of the target subject. Typical LCA consists of four phases, as shown in Figure 2.1:

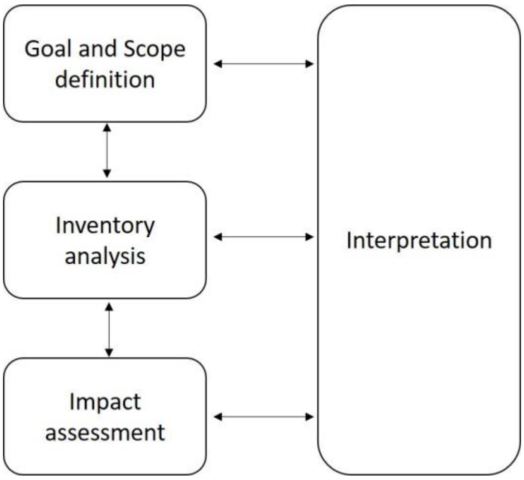

Figure 2.1: Main steps in LCA (ISO 14040:2006, 2006)

- **Goal and Scope definition:**

The first task for an LCA is to set the goal, object, scope, functional unit of assessment as well as relevant assumptions (Du, 2015). This phase affects the other three phases significantly because all the following steps are based on the decisions made in this phase. For example, the scope of an LCA should be clarified in order to collect the most relevant information in specific life cycle modules, e.g., transport, raw material extraction. A flowchart of the object's life cycle is generally used while defining the scope. The functional unit is a quantified description of a product/service which provides the reference basis for all calculations in LCA (Arzoumanidis et al., 2020). For a bridge LCA, the functional unit could be one km of a bridge which has 80 years life span with average daily traffic of 5,000 vehicles.

- **Inventory analysis:**

Life cycle inventory (LCI) analysis aims to gather all the input and output data of a product over its life cycle (SAIC, 2006). It covers the energy and raw material needed as well as all potential emissions, e.g., CO_2, NH_3, or solid wastes. According to SAIC (2006), an LCI analysis generally starts with a flow diagram of the system being evaluated to identify the relevant unit processes. The data of each unit process concerned are aggregated based on the functional unit defined in the previous phase. Du (2015) indicates that LCI data from different sources may be different because of their regional conditions, technologies applied, and system boundary applied. Several LCI databases are currently available, e.g., World steel LCI, Ecoinvent, SPINE@CPM, etc. (Du and Karoumi, 2014).

- **Impact assessment:**

The life cycle impact assessment (LCIA) focuses on the conversion from the input and output data identified in the LCI analysis to potential human health effects and environmental impacts (IES, 2010; SAIC, 2006). Impact categories can be classified into two main levels, including the problem-oriented level (midpoint) and the damage-oriented level (endpoint). The relation between these two levels could refer to Figure 2.2. The impact indicators at the midpoint level represent the effects on a specific environmental issue, e.g., air pollution or global warming (RIVM, 2018). In contrast, the endpoint level indicators aggregate the relevant midpoint impacts to reflect overall consequences, such as human health, ecosystem impact, and resource depletion.

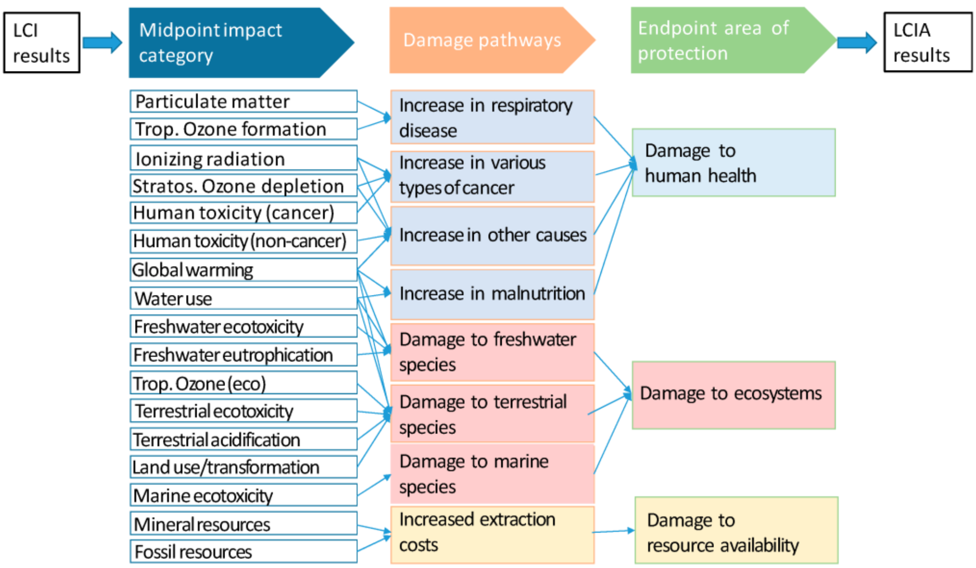

Figure 2.2: Overview of the impact categories covered in the ReCiPe 2016 method (adapted from Zsembinszki et al., 2021)

The transformation of LCI data needs to apply an LCIA method. Currently, several LCIA methods are available, such as ReCiPe, CML, IPCC (for global warming), International Reference Life Cycle Data System (ILCD), etc., which are developed by different research institutes and organizations. Du (2015) lists the main steps for conducting the LCIA:

1. Select impact categories: To decide which impact categories will be adopted.
2. Classification: To sort and allocate the LCI result parameters to different impact categories, e.g., SOx can be assigned to the indicators of acidification.
3. Characterization: To calculate the contribution of the emissions in LCI results to the impact categories by using characterization factors (CF).
4. Normalization, grouping, and weighting: To normalize the outcome of characterization based on reference values, i.e., normalization factors. The normalization factor is the total impact of a reference region for a certain impact category in a reference year. Thus, we can obtain the relative contributions of different impact categories to a reference situation, and identify the most relevant impact categories. Weighting is a procedure to decide the relative importance of impact categories while trying to aggregate all impact categories into one single score. It can be done based on monetary values, experts' opinions, etc.

- **Interpretation:**

This phase aims to draw conclusions and suggestions from the results of the inventory analysis and the impact assessment (Du, 2015). They should be consistent with the defined goal and scope. In addition, the limitations, such as uncertainties of data, shall be clarified in this phase.

2.1.2 LCA of bridges

Bridges are the important fundamental infrastructures of the transportation system. They consume huge amounts of energy and materials from cradle to grave and have much longer lifetimes than other constructions. The decisions made in the early design stages of bridge design play an extremely important role in affecting the overall life cycle environmental impacts (Balogun et al., 2020; Du et al., 2014). Du (2015) indicated that raw material quantities, construction machinery usage, maintenance schedules, and the End-of-Life (EOL) scenarios are decisive inputs in the bridge LCA. Furthermore, global warming potential (GWP) and energy consumption are the two most popular indicators when it comes to the LCA on bridges. However, Du (2015) indicates that the performance of a bridge among different indicators may act differently. A bridge should be evaluated based on the full spectrum of environmental performance. Gervásio and Da Silva (2008) found that the results of bridge LCA depend on the methodologies and weights adopted. It is needed to develop a probabilistic life cycle environmental methodology. Ek et al. (2020) developed a life cycle sustainability performance assessment method and conducted a case study of a bridge. They found that the use of suppliers' Environmental product declarations (EPDs) instead of generic data could increase the accuracy of the results because EPDs are formulated depending on suppliers' specific context.

2.2 Life cycle cost analysis of bridge

In general, stainless steel is more expensive than conventional carbon steel. The material costs of steel grade 355J2 and duplex stainless steel grade 1.4162 are around 20 SEK/kg and 65 SEK/kg separately (Wahlsten et al., 2018). While the anti-corrosion property of stainless steel could reduce the maintenance costs of bridges, the material costs of a stainless steel bridge may be much higher than a bridge made of convention steel because of the costs of stainless steel.

The total LCC is used to assess the financial feasibility of bridge design and enable stakeholders to make decisions (Mara et al., 2013; Rossi et al., 2017). LCCA considers all expected costs regarding construction at the different life stages during the whole life cycle (Gervásio and Da Silva, 2008). Costs of construction are typically classified into three categories, including construction; maintenance, repair, operations (MRO); and disposal. The costs can be further grouped according to functional elements, e.g., deck, truss (Gervásio and Da Silva, 2008).

The data of material costs and construction activity costs can be obtained from academic papers, reports by (non)official organizations and private industries, or commercial software. The MRO costs of a bridge rely on the bridge's maintenance schedule. Thus, a maintenance model is needed to estimate the demand for preventive and essential maintenance. For example, Life-365 is a commercial software aiming to estimate the maintenance schedule for reinforced concrete exposed to chlorides (Life-365, n.d.). The life-cycle costs of the design alternatives can be estimated by using the software. The disposal costs can be calculated depending on the materials or the functional elements (Gervásio and Da Silva, 2008; Mara et al., 2013). Some demolition materials, such as steel, can be resold and recycled. The income from these materials can lower the total LCC. While conducting LCCA, assumptions for future scenarios are necessary, e.g., discount rates. Literature suggests different discount rates, such as 1%, 3.5%, 3.8%, or 4%. (Cadenazzi et al., 2020; Cope et al., 2013; Gervásio and Da Silva, 2008; Mara et al., 2013). Hence, a sensitivity analysis of the discount rate may be needed for assessing the uncertainty.

The input parameters of traditional LCCA are normally fixed values (Cadenazzi et al., 2020). Recently, some LCCA studies are probabilistic analyses. To handle the uncertainty of parameters, the values of input parameters in LCCA are generated, depending on given means, standard deviation values, and distribution functions (Cadenazzi et al., 2020). Projected costs, e.g., maintenance costs, are expressed in the form of a probability distribution. Considering the main goal of this research, i.e., to compare different design variants rather than to obtain accurate LCC, the traditional deterministic analysis framework of LCCA is acceptable in this study.

2.3 Circular economy

2.3.1 Circular economy in the construction sector

Over the past few decades, the construction industry is used to operate businesses with a linear economic model, i.e., take, make, consume and discard (Benachio et al., 2020). It leads to natural resource depletion and waste problems. The construction sector consumes over 30% of extracted natural resources and causes 25% of solid waste worldwide (Benachio et al., 2020). Circular economy (CE) aims to transform the current linear pattern by closing and slowing the material loops (Leising et al., 2018). In general, CE is operated at three levels, from micro-level (individual firm, product), meso-level (industrial symbiosis, eco-industrial parks), to macro-level (global, nation, region, city) (Ghisellini, et al., 2016; Kristensen and Mosgaard, 2020; Yuan et al., 2006). In the built environment, CE on the micro-scale, meso-scale, and marco-scale addresses material/building components, entire building/construction, and eco-parks/eco-cities separately (Anastasiades et al., 2020; Pomponi and Moncaster, 2017).

Benachio et al. (2020) present the current CE practices in the construction industry. As shown in Table 2.1, these practices and researches are grouped according to different life cycle stages. They mainly focus on the CE strategies of reuse, recycling, reduce, delivering functionality, extending lifespan, minimizing recuperative maintenance, and maximizing resource efficiency. Overall, reuse seems to be the most appealing CE topic in the construction sector.

Table 2.1: Circular economy practices in the construction industry (adapted from Benachio et al., 2020)

Life Cycle Stage	Circular Economy Practices
Design phase	▪ Design and use of modular buildings ▪ Design for adaptability of existing buildings ▪ Design for Disassembly of building structures ▪ Use of a scale to analyze the level of implementation of circular economy practices in the company ▪ Use of a simulation in a BIM model to analyze the reuse potential of the materials of different types of designs early in the project ▪ Use of Life-cycle analysis to find the benefits of reusing different types of materials in the design stage ▪ Use of material stock data to help reuse of materials of a new building
Manufacturing phase (Product phase)	▪ Change of use of materials, by giving it ownership to the manufacturers to reuse the materials after the end of life of the first building ▪ Development of material passports ▪ Reuse of secondary materials in the production of building materials
Construction phase	▪ Reuse of building materials in a new construction ▪ Waste reduction ▪ Off-site construction

Operation phase	• Use of a tool to evaluate the state of materials during the lifespan and end of life of a building • Use of water management practices • Minimize recuperative maintenance with preventive maintenance
End of Life	• Analyze the potential for reuse or recycling of existing materials and if it is feasible comparing to using new materials. • Management of demolition waste • Use of a circularity tool to evaluate existing buildings and give the best possible solutions to refurbishment • Deconstruction of building structures and parts

2.3.2 Circularity assessment of bridges

One of this study's objectives is to evaluate the performance of bridge design in terms of circular economy with some quantitative indicators. In other words, we focus on the meso-level of CE. According to Anastasiades et al. (2020), so far rare studies have addressed the meso-scale, i.e., the scale of the whole bridge construction. At the present, standardized approaches for assessing the circularity of a bridge are not developed, nor are recognized circularity indicators. Furthermore, Anastasiades et al. (2020) argue that LCA and LCCA are not the most suitable approaches for measuring circularity because they do not assess the performance of reuse and recycling.

Although the consistent circularity indicators for bridges are currently not available, Coenen (2019) developed an assessment framework enabling the evaluation of the circularity of bridges. A set of indicators are established to quantify different aspects of the circularity of bridges, including design input, resource availability, adaptability, and reusability. The sub-indicators of each aspect are shown in Figure 2.3. An overall bridge circularity (between 0 and 1, a higher score means more circular) can be determined by giving weightings to the indicators. This assessment framework can work in the early design stages with the aid of assumptions and expert judgments.

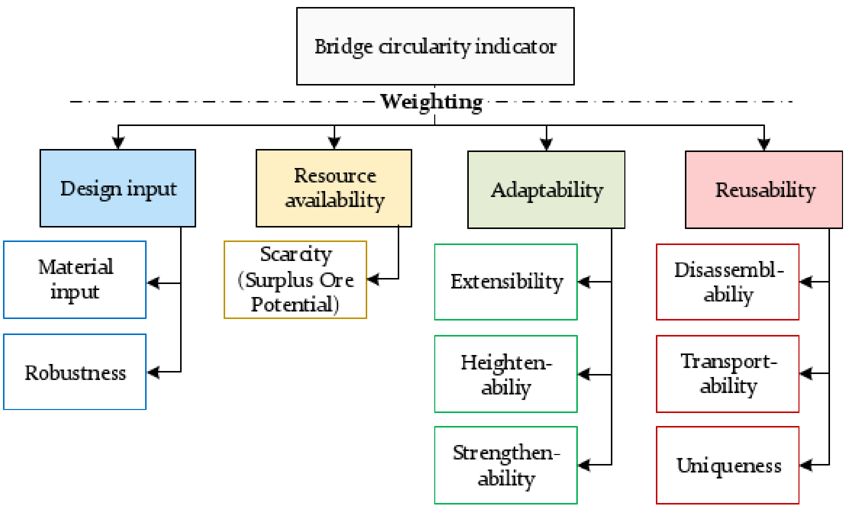

Figure 2.3: Bridge circularity indicators (Coenen, 2019)

Apart from the above approach, indicators designed for evaluating the circularity of the whole building may be applied in the assessment of bridge construction. For example, Akanbi et al. (2018) developed a mathematical modelling approach to support designers to analyze the connection between design decisions and the whole-life salvaging performance (SP). The SP represents the amounts of total recoverable, reusable, recyclable material in a building over its lifespan.

Building Circularity Indicator (BCI) can measure the circularity both on the building level and component level (Cottafava and Ritzen, 2021). BCI assessment framework consists of several indicators, including Material Circularity Indicator (MCI), Product Circularity Indicator (PCI), System Circularity Indicator (SCI), and BCI (Verberne, 2016). A building is divided into several systems, such as skin, structure, site, etc. Each system consists of various products, e.g., doors, windows, ceiling. Firstly, the material input, waste scenario, and lifespan of a product are taken into account while calculating MCI (developed by the Ellen MacArthur Foundation). The MCI is a theoretical circularity indicator that focuses on the circularity at product level. The MCI can be further transferred into the PCI by multiplying the MCI by seven identified disassembly determining factors (Verberne, 2016). The PCI can be considered as the practical circularity indicator of a product because it integrates the product disassembly possibilities. By considering the mass of all products in the same system, the SCI of each system is then calculated. Finally, the BCI of a building is determined by aggregating all SCIs and their system dependencies.

2.4 Stainless steel in bridge construction

The most common structural materials are concrete and steel (Gervasio and Da Silva, 2008). While concrete has advantages of low material costs and maintenance requirements, steel has a higher strength-to-weight ratio and ductility (Du et al., 2014; European Commission, 2013). Steel is a highly recyclable material (Gervásio and Da Silva, 2008). The electric arc furnace (EAF) process is able to use around 95% recycled steel scrap to produce structural beams, reinforcement bars, etc. While steel is a relatively sustainable alternative to other structural materials, the low resistance against corrosion reduces its performance of sustainability. To overcome the drawbacks of steel, stainless steel has been more often adopted in buildings and structural components in recent years (Rossi, 2014).

Stainless steel as a construction material has the advantages of excellent corrosion resistance, low maintenance requirements, and long service life. Austenitic-ferritic (duplex) stainless steels, which provide higher strength and lighter weight than other types of stainless steel, are profitably adopted in bridge design (Rossi, 2014). In the EOL stage, stainless steel also shows great advantages, including a high recovery rate

(90%), high recycling/reuse potential, and a low possibility to end up in a landfill (Rossi, 2014). This may facilitate the integration of circular economy strategies into bridge designs. However, some challenges need to be overcome because stainless steel has a higher price and needs more energy during the production process than conventional steel (Gutowski, 2013; Rossi, 2014). One ton of stainless steel produced solely from virgin raw materials releases 4.2 tons of CO2 equivalent (ISSF, n.d.). Thanks to the high share of scrap in the stainless steel production process, 50% on average, the emission factor can drop to 2.91 tons CO2/ton stainless steel (ISSF, n.d.). The distribution of the emission factor is shown in Figure 2.4.

The case study of this thesis focuses on steel bridges with various types of steel in the Swedish context. In Sweden, steel is the second-largest construction material of bridges (Du, 2015). According to Outokumpu (n.d.), stainless steel has been adopted in the construction and refurbishing of bridges in Sweden. Thanks to the high strength of new types of stainless steel, stainless steel is suitable for all types of bridges from pedestrian to heavy load rail bridges.

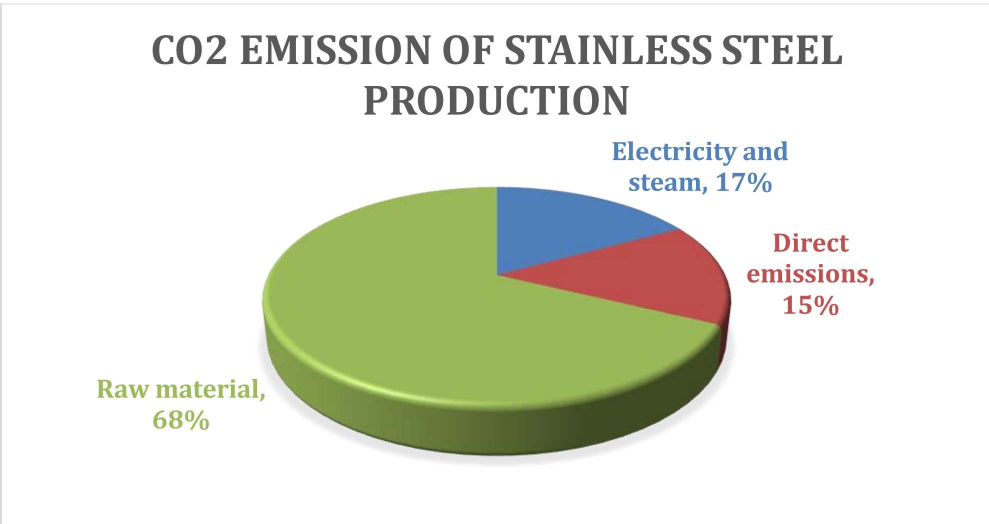

Figure 2.4: The distribution of CO2 emission of the production of stainless steel (adapted from ISSF, n.d.)

Chapter 3 Parametric model

This study develops a parametric model aiming to evaluate the environmental impacts, life cycle cost, and circularity of bridge design variants in the early design phases. In the case study of this thesis, the main difference between design variants is the material of the girders, i.e., stainless steel and conventional carbon steel. Thus, the system boundaries and relevant assumptions of the parametric model are given based on this premise.

3.1 Requirements for design-integrated LCA

Hollberg and Ruth (2016) suggest some requirements for the LCA which is applied in the architectural design process, especially for those in the early design stages. Firstly, considering the potential user's knowledge and experience in LCA, the procedures of the LCA must be simplified rather than conducting a complete LCA. The considered life stages are suggested to mainly focus on the most relevant ones. Secondly, assumptions and alternatives for handling missing data are needed because detailed information for LCA is normally unavailable in the early design stages. Thirdly, a consistent LCA model is needed. As the design process moves forward, more specific data will be available. Thus, it should allow users to replace the previous assumptions with these data in order to extend a simplified LCA to a complete LCA. Finally, the ways to present the outcome of LCA should take the users' background knowledge and purposes into account. For example, the life-cycle carbon footprints for all design variants would be beneficial for designers to make decisions.

3.2 System boundaries and data sources

System boundaries define what to include and exclude in an assessment. Due to multiple assessment approaches adopted in the parametric model, the system boundaries of each assessment approach, i.e., LCA and LCCA, would not be identical. Similarly, each assessment approach requires specific information for calculating quantitative results. Thus, the system boundaries and data sources of the parametric model are presented separately according to the assessment approaches.

3.2.1 Life Cycle Assessment

3.2.1.1 System boundary

Due to the lack of an international standard for bridge LCA, EN 15978:2011, i.e., Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, is used as a guideline to set the system boundary of the LCA in this study. The life cycle of buildings is divided into four stages, as shown in Figure 3.1. Each stage has several modules which represent the main processes and activities in the stage. An additional module, i.e., module D, represents the net benefits obtained from the reuse, recycling, and energy recovery of wastes produced during the life cycle of a building. Because this module takes place out of the general system boundary, it is optionally integrated into the analysis.

Product stage			Construction stage		Use stage					End of Life stage				Benefits and loads beyond the system boundary
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction Demolition	Transport	Waste processing	Disposal	Reuse, recovery, and recycling potential
					B6 Operational energy use									
					B7 Operation water use									

*The modules included in the analysis are marked in grey.

Figure 3.1: Life cycle stages and modules considered (adapted from EN 15978:2011)

Considering the requirements for design-integrated LCA in the previous section, only certain life cycle modules are taken into account in the parametric model. All modules (A1 to A3) in the product stage are considered. The boundary for those stages covers the 'cradle to factory gate' processes for the materials and services which are going to be used in the construction stage. While Du and Karoumi (2013) indicate that the environmental impacts derived from material transportation (A4) and construction machinery (A5) are ignorable, these two modules are included in the system boundary. For the A4 module, we consider the transport of materials and products from the factory to the bridge site, e.g., steel plates are imported from abroad by railway and transported to the bridge site by trucks. Herein, workers' commute from and to the construction site is not included. There is growing concern about GHG emissions and Cumulative Energy Demand (CED). Thus, the machinery operation required for construction processes, e.g., ground works or installation of girders, is considered in module A5. The other processes in the construction stage, such as waste management, transport within the site, cooling, or cleaning, were neglected due to a lack of information in the early design phase.

The case study in this research study the advantages of stainless steel during the use phase. Due to the property of great corrosion-resistance, there are much lower maintenance requirements for bridges made of stainless steel than bridges made of carbon steel. Hence, in the use stage, we focus on the scheduled periodic maintenance (B2) and replacement (B4) events. The production and transportation of the components and products used for them are considered. EOL treatment of replaced components is also taken into account. These activities/processes require more resources and energy, which contributes hugely to the environmental impacts of maintenance and replacement events. In addition, we assume that the analyzed bridge is always operated in a good condition, so no repair operation or refurbishment is needed. Unlike a building, a bridge is normally operated without energy and water consumption. Accordingly, module B6 and module B7 are not necessary to be considered in the system boundary.

The de-construction/demolition module (C1) was neglected in this parametric LCA model. Bridge demolition can generate large amounts of waste materials, which are needed to be transported from the site to treatment plants or landfills. Thus, module C2 is considered to evaluate the impacts derived from the transportation of wastes. Du (2015) indicates that the EOL plan for the wastes from bridge demolition is one of the key factors affecting the final LCA results. Module C3 and module C4 are then considered in the system boundaries. According to EN 15978: 2011, module C3 involves waste treatment processes, such as sorting, preparatory processes for reuse, recycling, and energy recovery. The border between this module and module D is set where the end-of-waste state of the processed material/product is reached. The boundary of module C4 covers the potential treatments needed before disposal, e.g., incineration, as well as the emissions resulting from final disposal.

The most common materials in bridge construction are concrete and steel (Du and Karoumi, 2013). Both materials have relatively high recycling rates, as 50-60% for concrete and 90-95% for steel (Manjunath and Umrigar, 2017; Hallberg and Dahllöf, 2021). Hence, the system boundaries of the parametric model consider the net environmental benefits (impact reductions) derived from the substitution of virgin materials with secondary materials (e.g., steel scrap and concrete rubble).

3.2.1.2 Data sources

According to ISO 14040 standard, the conventional LCA has four main phases. For simplifying the LCA for the construction sector, Lasvaux et al. (2013) indicate that two of the phases, i.e., life cycle inventory (LCI) and life cycle impact assessment (LCIA), are normally combined into one phase by applying Environmental Product Declarations (EPD) of building products or generic data in the analysis. These data contain LCIA results per unit product, activity, or process. There are normally multiple environmental indicators available in the results, e.g., GWP, Eutrophication potential, etc. In this study, we mainly collect this kind of aggregated data from ecoinvent database and EPDs which comply with the same international standard.

The ecoinvent database provides background information to support users in LCA. It allows users to focus on the collection of specific data about their target foreground system, e.g., how much steel is needed in specific bridge construction. Its LCI database gathers all relevant input and output data of a unit process, which is the smallest element in LCI. By interlinking several unit processes over the whole supply chain, the overall cumulative inventory of environmental flows related to a specific product or activity throughout its life cycle can be obtained. How to connect unit processes to form a product system depends on the system model selected. The latest version of the ecoinvent database (ecoinvent 3) offers three system models (Ecoinvent, n.d.). In this study, we select the cut-off system model in which recyclable materials are available without any burden to the recycling processes. For example, the environmental flows of recycling metal do not consider burdens derived from ore extraction and the primary production of the original metal product. In addition, all burdens caused by waste treatment are allocated to the waste producer when recycling or reuse of products resulting out of the treatment process occurs. This model is easier to understand the allocation in a multiple-output process than the other two models. Apart from LCI, the ecoinvent database also provides LCIA results by multiplying LCI by the characterization factors (CF) of an LCIA method. More than ten LCIA methods are available in ecoinvent, such as CML 2001, Ecoindicator 99, ReCiPe Midpoint and Endpoint, etc.

An EPD is an ISO type III declaration that provides quantified environmental information on the life cycle of a product. The calculation methodology of EPD is based on LCA. For the construction product in Europe, the European Committee for Standardisation has published EN 15804, i.e., Sustainability of construction works - Environmental product declarations – Core rules for the product category of construction products. 13 core impact indicators shall be declared according to the latest version of the standard (see Table 3.1). The life cycle stages considered in EN 15804 (product level) are consistent with EN 15978 (building level). In this study, we mainly extract the EPD information on the product stage (A1 to A3) of specific construction products used in the case study in order to increase the representativeness of LCA results.

Table 3.1: The parameters for environmental impacts in an EPD (adapted from Durão, et al., 2020)

Category	Parameter	Unit	Model/Method
Core	Climate change – total (GWP-total)	kg CO2-Eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)
	Climate change – fossil (GWP-fossil)	kg CO2-Eq.	
	Climate change – biogenic (GWP-biogenic)	kg CO2-Eq.	
	Climate change – land use and land use change (GWP luluc)	kg CO2-Eq.	
	Ozone layer depletion (ODP)	kg CFC11-Eq.	Steady-state ODPs as in WMO (1999)
	Acidification (AP)	mol H+ eq.	Accumulated exceedance model
	Eutrophication – aquatic freshwater (EP-F)	kg P eq.	EUTREND model
	Eutrophication – aquatic marine (EP-M)	marine: kg N eq.	EUTREND model
	Eutrophication—terrestrial (EP-T)	mol N eq.	Accumulated exceedance model
	Photochemical ozone formation (POCP)	kg NMVOC eq.	LOTOS-EUROS model
	Abiotic depletion potential for non-fossil resources (ADPE)	kg antimony (Sb) eq.	CML2002 model
	Abiotic depletion potential for fossil resources (ADPF)	MJ, net calorific value	CML2002 model
	Water use (WDP)	m3 water eq. of deprived water	Available WAter REmaining (AWARE) in UNEP
Optional for EPD	Human toxicity—cancer effects	CTUh	USEtox model
	Human toxicity—non-cancer effects	CTUh	
	Ionising radiation—human health effects	kg U 235 eq.	Human health effect model
	Particulate matter/respiratory inorganics	disease incidents	PM method recommended by UNEP
	Ecotoxicity for aquatic freshwater	CTUe	USEtox model
	Land use	pt (Soil quality index)	Soil quality index based on LANCA

*CTUe: comparative toxic unit for ecosystems

*CTUh: comparative toxic unit for humans

*NMVOC: non-methane volatile organic compound

Swedish Transport Administration offers an online tool for climate calculation (Trafikverket, n.d.). It enables users to evaluate climate impact and energy use of roads and railways from a life-cycle perspective. We collect data from its database for constructing the parametric model, such as the average transport distance, carbon emissions, and CED of common construction materials as well as the emission factors and fuel efficiencies of different transport methods.

3.2.2 Life Cycle Cost Assessment

3.2.2.1 System boundary

Rossi et al. (2017) suggest that the classification of life cycle modules of a building (see Figure 3.1) could be applied while conducting the life cycle cost analysis (LCCA) of a bridge. The module A series (A1 to A5) represents the stages before the use phase of a bridge. In this category, we mainly consider the material costs related to construction products needed in design variants. In order to reflect the differences between girders made of stainless steel and conventional carbon steel, we additionally consider production cost (e.g., welding and assembly of girder) and treatment cost (e.g., initial painting for carbon steel, pickling for stainless steel). The other costs (e.g., earthworks, transportation, etc.) in these modules are neglected. For the use phase (B1 to B7), the costs related to periodic maintenance of the main components of a bridge are taken into account. While maintenance events take place, the bridge users will be affected by temporary traffic restrictions. It leads to user costs which consist of traffic delay costs (TDC) and vehicle operation costs (VOC) (Wahlsten, et al., 2018). Herein, we only consider TDC as the user cost. We assume that most costs generated in the end-of-life stage (module C) do not influence the results of the comparison of design variants. Thus, all costs in the EOL stage are omitted. For the last module (D), considering the significant difference between the values of steel scrap and stainless steel scrap, we calculate the revenues coming from selling the metal scraps.

3.2.2.2 Data sources

In this study, apart from material costs, the other costs generated in module A, are mainly provided by the architects/engineers because they highly depend on material selection, the geometry of design, manufacturing and assembly methods. The costs related to maintenance operations are obtained from Trafikverket (2021) and an LCCA of a steel girder bridge conducted by Rossi et al. (2017). The LCCA collects the costs of different painting operations from academic papers and expert interviews. Finally, the prices of metal scraps use the latest market price at the present.

3.3 Model structure

Parametric modeling aims to decrease the cost of change (Davis, 2013). It allows engineers or designers to take a variety of designs into account without difficulty. With the parametric approach, the geometry, characteristics, or scenarios of construction works can be described as a set of equations that consists of several defining parameters. These parameters can be easily adjusted to create new design alternatives and scenarios. With the assistance of a computer, the calculation of target indicators, e.g., CO2 emissions, life cycle costs, is automatically made. Accordingly, designers are capable of comparing and optimizing their designs based on real-time feedback.

In the present study, a parametric model for bridge design aiming to evaluate the environmental impacts, LCC, and circularity of design variants in the early design stages is developed. Referring to the concept of the parametric model developed by Hollberg and Ruth (2016), the parametric model consists of three main modules, i.e., input, calculation, and output, as shown in Figure 3.1. Through assumptions and predefined mathematical equations in the calculation module, quantitative outcomes can be calculated according to a limited number of input parameters and supplementary information from an updatable database.

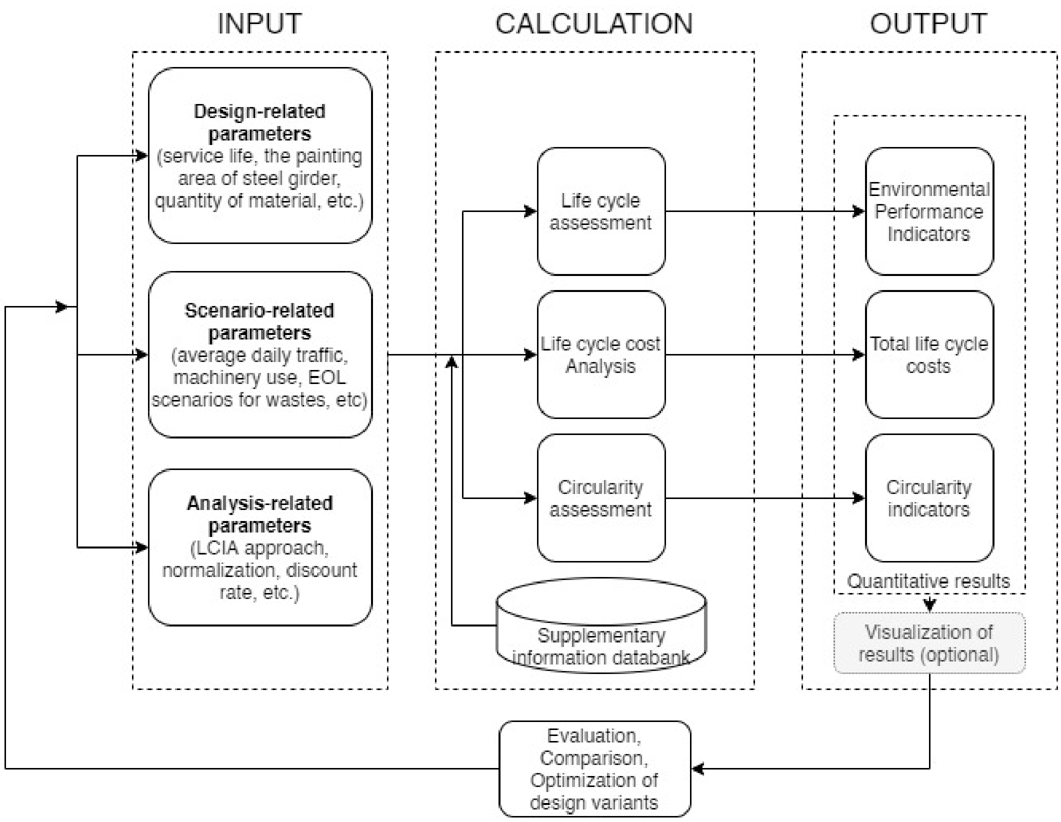

Figure 3.2: The framework of the parametric model in this study

3.3.1 Input module

Each bridge design variant shall be given a set of input parameters. This section introduces all input variables needed for the calculation module. All input parameters are divided into three categories, including design-related parameters, scenario-related parameters, and analysis-related parameters.

- **Design-related parameter**

In this category, parameters are connected with bridge design, such as composition, structure, size, material selection, design life, disassemblibility of components, etc. The materials used in a bridge are the key information for LCA. In order to analyze a bridge from a system perspective, we refer to the hierarchical arrangement of materials in a building structure defined by Durmisevic and Brouwer (2002). Herein, the composition of a bridge is divided into four levels. As shown in Table 3.2, a bridge might be broken down into two systems that consist of several functional components. The material/product inventory shall be prepared by following the hierarchical classification.

Table 3.2: An example of a hierarchical classification of materials in a bridge

Bridge level	System level	Component level	Material level
Bridge	Superstructure system	Railing	Steel
		Surfacing	Asphalt
			Bitumen
		Deck	Reinforcement bar
			Concrete
		Girder	Steel
		Bearing	Polytetrafluoroethylene
			Stainless steel
	Substructure system	Abutments	Concrete

All design-related parameters needed in the parametric model can also be categorized into four levels:

<u>*Bridge level*</u>

- Estimated service life of the bridge (Y_B, year)

<u>*System level*</u>

- Estimated service life of a system (Y_S , year)
- System dependency (SD , unitless)

Component level

- Estimated service life of component (Y_C , year)
- The Disassembly Determining Factor for component (*DDF*, unitless)
- The feature of a component which is related to a specific process (F): e.g., the initial painting area of steel girder, the welding length of steel girder, the total area of surfacing.
- The sum of production and treatment costs of steel girders ($C_{P\&T,steel\ girder}$, SEK)

Material level

- The quantity of material/product in each component (Q, kg or m^3)
- The fraction of secondary material in material/product k in component j ($r_{k,j}$, %)

In this study, we refer to the Building Circularity Indicator (BCI) developed by Verberne (2016) for evaluating the circularity of a bridge. Hence, two parameters, i.e., system dependency and disassembly determining factor (DDF), are needed. System dependency indicates the level of importance of a system in terms of circularity. It is a weighting factor between 0 and 1. For example, the circularity of system A with a shorter service life is more important than system B with longer service life. Thus, the system dependency of system A is higher than system B. Durmisevic et al. (2003) present a model for evaluating the disassembly capacity of a building. They developed 17 DDFs to reflect all possible aspects of disassemblibility. Verberne (2016) selected 7 DDFs from them to develop BCI, including DDFs for functional separation, functional dependence, technical life cycle/coordination, geometry of product edge, standardization of product edge, type of connections, and accessibility to fixings and intermediary. In this study, we only consider DDF for type of connections which represents the level of freedom between components. Table 3.3 shows the grading scale for the selected DDF. If DDF is one, it indicates the best performance on disassembly.

Table 3.3: Fuzzy variable for disassembly determining factor of type of connections (adapted from Durmisevic et al., 2003)

accessory external connection or connection system	1.0
direct connection with additional fixing devices	0.8
direct integral connection with inserts (pin)	0.6
direct integral connection	0.5
accessory internal connection	0.4
filled soft chemical connection	0.2
filled hard chemical connection	0.1
direct chemical connection	0.1

- **Scenario-related parameter**

The parameters in this category are used to construct scenarios for different activities during the period of the bridge's service life. They are divided into three groups, including transportation, machinery operation, and EOL scenarios of waste.

Transportation

This group provide the information about traffic condition of the bridge and the impact on bridge users caused by maintenance or replacement events

- Average daily traffic on the bridge (*ADT*, number of vehicles)
- Percentage of heavy vehicle among all the ADT (r_T , %)
- Affected roadway length (L_{aff}, km)
- Normal speed without delay (V_n , km/hour)
- Reduced speed (V_r , km/hour)

Machinery usage

This group provides information about the use of machines in different life stages

- The life stage where a machine is operated (construction stage or use stage)
- The power of the machine (*PW*, kW)
- The operation hours of the machine (*H*, hours)

EOL scenarios of waste

Users shall assign the treatment approach for each material in the bridge design

- The EOL scenario of material/product k (EOL_k): (e.g., recycling, reuse, disposal, incineration, etc.)
- The transport distance of demolition waste from the site to treatment plants or landfills (L_{eol}, km)

- **Analysis-related parameter**

The parameters related to LCA and LCCA allow users to easily compare the outcomes of different analysis settings and key assumptions.

LCA

- Adopted LCIA method: e.g., CML
- To integrate Module D (Benefits and loads beyond the system boundary) into the final result: Yes or No

LCCA

- Discount rate (*i*, %)
- Escalation rate (*d*, %)

3.3.2 Calculation

The calculation module needs both information from the input module and supplementary database to produce outcomes. This module consists of two main parts: (1) supplementary database; (2) mathematical equations for calculating environmental impact indicators, costs, and bridge circularity indicators.

3.3.2.1 Supplementary database

The supplementary database stores background information which does not change frequently. The data in the database is divided into four categories: resource-related, process-related, machinery-related, and LCA-related.

- **Resource-related data**

This category collects relevant data for resources needed for bridge construction and activities occurring during the life cycle of a bridge. The information of each material/product shall at least contain:

  - Density (ρ, kg/m^3): for converting between volume and mass
  - Transport distance ($L_{k,t}$, km) of material/product k through transport type t: transportation from factory gate to the bridge site. Each material/product may require multiple types of transport.
  - Material/Product cost (C_m, SEK per unit)
  - EOL Material/Product price (P_{eol}, SEK per unit): only material/product which can be resold to treatment plants needs to provide.
  - LCIA results per unit material/product (IF_m): the impacts derived from the production of material/product

If the benefit of Module D is taken into account, the LCIA results (IF_{vm}) of the production of the virgin material which can be substituted by secondary material have to be added to the database.

- **Process-related data**

This category covers the relevant information about the processes or activities which are expected to take place according to the system boundaries in this study.

  - Product stage: LCIA results per unit process in the product stage (IF_{p_prod}), specifically additional processes needed for construction products, e.g., welding of steel girder
  - Use stage: unit costs of maintenance activity x ($C_{M,x}$, SEK per unit), the quantity of material/product k needed per unit maintenance activity x ($Q_{k,x}$, kg or m^3), the time required for a maintenance activity(D, Day), maintenance plans (as shown in Table 3.4 and Table 3.5).

- EOL stage: LCIA results per unit waste treatment process of material/product (IF_{p_waste}). If there is a recycling process, recycling rate (R, %) and the virgin material which can be substituted by secondary material are needed.

Table 3.4: General maintenance plan of a bridge according to Trafikverket (Personal communication, May 2021)

Remedial action		Action time (Year)	Reference Quantity		
Structural member	Description		From	Unit	Relative %
Edge Beam	impregnation	30	Edge Beam Length	m	100
	Replacement	60	Edge Beam Length	m	100
	Impregnation	90	Edge Beam Length	m	100
Railing length	Improvement	30	Railings length	m	30
	Replacement	60	Railings length	m	100
	Improvement	90	Railings length	m	30
Bearings	Adjustment & Refreshment	30	Bearings No.	set	100
	Replacement	60	Bearings No.	set	100
	Adjustment & Refreshment	90	Bearings No.	set	100
Expansion joints	Refreshment	30	Expansion joints length	m	100
	Replacement	60	Expansion joints length	m	100
	Refreshment	90	Expansion joints length	m	100
Surfacing	Partial Improvement	5	Surfacing Area	m^2	25
	Resurfacing	10	Surfacing Area	m^2	100
	Partial Improvement	15	Surfacing Area	m^2	25
	Resurfacing	20	Surfacing Area	m^2	100
	Partial Improvement	25	Surfacing Area	m^2	25
	Resurfacing	30	Surfacing Area	m^2	100
	Partial Improvement	35	Surfacing Area	m^2	25

Table 3.5: Painting plan for a steel bridge in the environmental category C4 (adapted from Rossi et al., 2017)

	Activity	Action time (Year)	Reference unit	Unit	Relative %
Structural steelwork	Patch up	13	Initial painted surface	m^2	5
	Overcoating	19	Initial painted surface	m^2	90
	Remove & Replace	31	Initial painted surface	m^2	90
	Patch up	44	Initial painted surface	m^2	5
	Overcoating	50	Initial painted surface	m^2	90
	Remove & Replace	62	Initial painted surface	m^2	90
	Patch up	75	Initial painted surface	m^2	5
	Overcoating	81	Initial painted surface	m^2	90
	Remove & Replace	93	Initial painted surface	m^2	90
	Patch up	106	Initial painted surface	m^2	5
	Overcoating	112	Initial painted surface	m^2	90

* The service life of the target bridge in the case study is 120 years.

- **Machinery-related data**

The data regarding machinery and vehicles belong to this category.

  - LCIA results per operating hour of a machine (IF_{ma})
  - LCIA results per ton*km of a transport type (IF_{trans})
  - Hourly cost for one truck (w_T, SEK) and Hourly cost for one passenger car (w_P, SEK)

- **LCA-related data**

The LCIA results can be further normalized and weighted by using normalization and weighting factors.

  - Normalization factors (*NF*) and weighting factors (*WF*) (if available) of the LCIA approaches adopted in the parametric model.

3.3.2.2 Environmental indicator calculation

The calculation procedure of environmental impacts is shown in Figure 3.3. With the aid of a computer and equations, the parametric model automatically compiles the inventory of resources and services needed in the life cycle. Environmental impact indicators are obtained by integrating the inventory and LCIA results. Overall, the parametric model allows users to focus on the variables of their bridge designs. It leads to a decrease in the complexity of LCA.

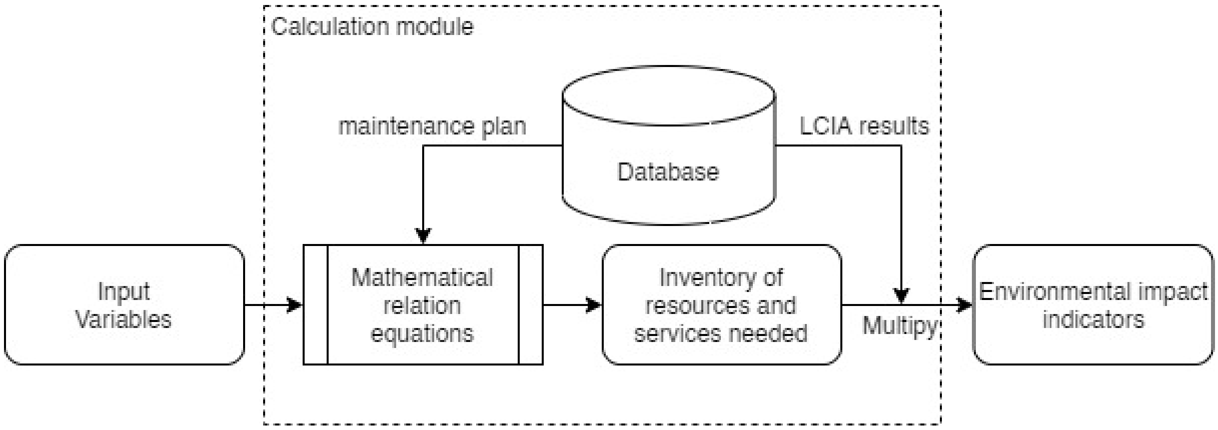

Figure 3.3: The workflow of environmental impact calculation

The environmental impact ($I_{overall}$) of a bridge throughout its entire life cycle equals the sum of impacts generated in different life stages. If the net benefit of Module D is taken into account, the impacts producing the substituted primary product are subtracted from the overall impact.

$$I_{overall} = I_{prod} + I_{cons} + I_{use} + I_{eol} - I_{module\ D} \tag{1}$$

I_{prod} is the impacts generated in the product stage
I_{cons} is the impacts generated in the construction stage
I_{use} is the impacts generated in the use stage
I_{eol} is the impacts generated in the EOL stage
$I_{module\ D}$ is the impacts producing the substituted primary product

In the product stage (A1 to A3), the impacts (I_{prod}) are divided into two groups, i.e., the production of construction products and the additional processes needed for construction products.

$$I_{prod} = \sum_k \left(\sum_j Q_{k,j} \times IF_{m,k}\right) + \sum_q \left(\sum_j F_{q,j} \times IF_{p\_prod,q}\right) \quad (2)$$

$Q_{k,j}$ is the quantity of material/product k in component j
$IF_{m,k}$ is the LCIA results per unit material/product k
$F_{q,j}$ is the feature of component j which is related to process q occurring in the product stage
$IF_{p\_prod,q}$ is the LCIA results per unit process q occurring in the product stage

In the construction stage (A4 and A5), the impacts (I_{cons}) are divided into two groups, i.e., the construction machinery use and the transportation for construction products.

$$I_{cons} = \sum_y \left(H_{y\_cons} \times IF_{ma,y}\right) + \sum_k \left(\sum_t \left(\sum_j Q_{k,j} \times L_{k,t} \times IF_{trans,t}\right)\right) \quad (3)$$

H_{y_cons} is the operation hours of machine y operated in the construction stage
$IF_{ma,y}$ is the LCIA results per operating hour of machine y
$Q_{k,j}$ is the quantity of material/product k in component j
$L_{k,t}$ is the transport distance of material/product k through transport type t
$IF_{trans,t}$ is the LCIA results per ton*km of transport type t

In the use stage (B2 and B4), the impacts (I_{use}) are divided into four groups, i.e., the machinery use, the production of materials/products for maintenance and replacement, the transportation of products and replaced components, and the treatment of replaced components.

$$I_{use} = \sum_y \left(H_{y\_use} \times IF_{ma,y}\right) \underline{\text{Machinery}} \quad (4)$$
$$+ \sum_k \left(\sum_x Q_{k,x} \times N_x \times IF_{m,k}\right) + \sum_j \left(\sum_k \left(Q_{k,j} \times N_{rp,j} \times IF_{m,k}\right)\right) \underline{\text{Production}}$$
$$+ \sum_k \left(\sum_t \left(\sum_x Q_{k,x} \times L_{k,t} \times IF_{trans,t}\right)\right) + \sum_j \left(\sum_k Q_{k,j} \times N_{rp,j}\right) \times L_{eol} \times IF_{trans.truck} \underline{\text{Transportation}}$$
$$+ \sum_j \left(\sum_k \left(Q_{k,j} \times N_{rp,j} \times IF_{p\_waste,k}\right)\right) \underline{\text{Waste Treatment}}$$

H_{y_use} is the operation hours of machine y operated in the use stage
$Q_{k,x}$ is the quantity of material/product k needed per unit maintenance activity x

$Q_{k,j}$ is the quantity of material/product k in replaced component j
N_x is the total number of times of maintenance activity x over the life cycle
$N_{rp,j}$ is the total number of times of replacement of component j over the life cycle
$IF_{ma,y}$ is the LCIA results per operating hour of machine y
$IF_{m,k}$ is the LCIA results per unit material/product k
$IF_{trans,t}$ is the LCIA results per ton*km of transport type t
$IF_{trans,truck}$ is the LCIA results per ton*km of the truck which transports wastes
$IF_{p\_waste,k}$ is the LCIA results per unit waste treatment process of material/product k
$L_{k,t}$ is the transport distance of material/product k through transport type t
L_{eol} is the transport distance of demolition waste from the site to treatment plants or landfills

In the EOL stage (C2 to C4), the impacts (I_{eol}) are divided into two main groups, i.e., the transportation and treatment of demolition wastes.

$$I_{eol} = \sum_k \left(\sum_j Q_{k,j}\right) \times L_{eol} \times IF_{trans,truck} + \sum_j \left(\sum_k \left(Q_{k,j} \times IF_{p\_waste,k}\right)\right) \quad (5)$$

$Q_{k,j}$ is the quantity of material/product k in component j
$IF_{trans,truck}$ is the LCIA results per ton*km of the truck which transports wastes
$IF_{p\_waste,k}$ is the LCIA results per unit waste treatment process of material/product k
L_{eol} is the transport distance of construction and demolition waste from the site to treatment plants or landfills

If the EOL scenario of material/product k (EOL_k) is 'recycling', the impacts caused by the recycling process shall be calculated separately as below:

$$Impact = \sum_j \left(\sum_k \left(Q_{k,j} \times R_k \times IF_{p\_recycling,k}\right)\right) + \sum_j \left(\sum_k \left(Q_{k,j} \times (1 - R_k) \times IF_{p\_disposal,k}\right)\right) \quad (6)$$

$Q_{k,j}$ is the quantity of material/product k in component j
R_k is the recycling rate of material/product k
$IF_{p\_recycling,k}$ is the LCIA results per unit recycling process of material/product k
$IF_{p\_disposal,k}$ is the LCIA results per unit disposal process of material/product k

While the EOL scenario of material/product k(EOL_k) is 'recycling', the secondary material produced from it can avoid environmental burden by substituting virgin material. The benefit is calculated as below:

$$I_{module\ D} = \sum_j \left(\sum_k \left(Q_{k,j} \times \left(R_k - r_{k,j} \right) \times IF_{vm,k} \right) \right) \quad (7)$$

$Q_{k,j}$ is the quantity of material/product k in component j

R_k is the recycling rate of material/product k

$r_{k,j}$ is the fraction of secondary material in material/product k in component j

$IF_{vm,k}$ is the LCIA results per unit virgin material which can be substituted by the secondary material made of material/product k

If more than one indicator exists in the selected LCIA method, the LCIA results are represented as vectors of the indicators in the method. Accordingly, the outcomes of environmental impact are vectors as well.

3.3.2.3 Life cycle cost calculation

According to the system boundary of LCCA in this study, only part of costs in life cycle module A and module B, as well as the revenues coming from selling the metal scraps, are taken into account while calculating life-cycle cost (LCC). Following the instruction of ISO 15686-5 (ISO 15686-5:2008, 2008), the net present value approach will be adopted to reflect the time value of money.

$$LCC = C_{module\ A} + C_{module\ B} - Rv \quad (8)$$

$C_{module\ A}$ is the costs generated in the product and construction stage

$C_{module\ B}$ is the costs generated in the use stage

Rv is the incomes generated at the end of the service life of the bridge

In the product and construction phases, we mainly consider the material costs of construction products and the production and treatment costs of steel girders.

$$C_{module\ A} = \sum_k \left(\sum_j Q_{k,j} \times C_{m,k} \right) + C_{P\&T,steel\ girder} \quad (9)$$

$C_{m,k}$ is the unit cost of material/product k

$C_{P\&T,\ steel\ girder}$ is the sum of production and treatment costs of steel girders

$Q_{k,j}$ is the quantity of material/product k in component j

For the use phase (module B), the costs consist of periodic maintenance costs and corresponding traffic delay costs (TDC). Because these costs are generated in the future, they should be converted to present value.

$$C_{module\ B} = \sum_j \left(\sum_x \left(\left(F_{x,j} * RR * C_{M,x,j} \right) \times \left(T * ADT * D_{x,j} * \left(w_T r_T + w_P (1 - r_T) \right) \right) \times \left(\frac{1+i}{1+d} \right)^{n_{x,j}} \right) \right) \quad (10)$$

Maintenance cost   Traffic delay cost   Convert to present value

$F_{x,j}$ is the feature of component j which is related to maintenance activity x

RR is the proportion of reference unit (see Table 3.4 and Table 3.5)

$C_{M,x,j}$ is the unit costs of maintenance activity x for component j

w_T is the hourly cost for one truck

w_P is the hourly cost for one passenger car

ADT is the average daily traffic on the bridge (number of vehicles)

r_T is the percentage of heavy vehicle among all the ADT

$D_{x,j}$ is the time required for maintenance activity x for component j (Days)

T is the travel time delayed for one vehicle (hours) = L_{aff} *$(1/V_r - 1/V_n)$; V_n is normal speed without delay (km/hour); V_r is reduced speed (km/hour); L_{aff} is the affected roadway length (km)

i is discount rate (%)

d is escalation rate (%)

$n_{x,j}$ is the year of occurrence of maintenance activity x for component j

The revenues coming from selling the metal scraps is calculated as below:

$$Rv = Rv_{metal\ scrap} = \sum_j \left(\sum_m \left(Q_{m,j} \times R_m \times P_{eol,m} \right) \right) \times \left(\frac{1+i}{1+d} \right)^{Y_B} \quad (11)$$

$Q_{m,j}$ is the quantity of metal m in component j

R_m is the recycling rate of metal m

$P_{eol,m}$ is the unit price of EOL metal m

i is discount rate (%)

d is escalation rate (%)

Y_B is the estimated service life of the bridge

3.3.2.4 Bridge circularity indicator calculation

We chose Building Circularity Indicator (BCI, see section 2.4.1) assessment framework developed by Verberne (2016) as the approach for evaluating the circularity of a bridge design variant. A bridge will be divided into several systems, such as superstructure and substructure. Each system consists of functional components made of different materials/products. Because the framework is a hierarchy system, we need to calculate circularity indicators from the lowest level to the highest level, i.e., in the order of component level, system level, bridge level.

At the component level, there are two indicators, i.e., material circularity indicator (MCI) and component circularity indicator (CCI). MCI takes the quantities of virgin materials and nonreusable proportion (e.g., only available for landfill, incineration) in a component as well as the utility of a component into account. MCI can be seen as the 'theoretical' circularity value of a product without considering the disassembly of the product (Verberne, 2016).

$$V_j = \sum_k \left(Q_{k,j} \times \left(1 - r_{k,j}\right)\right) \tag{12}$$

V_j is the mass of virgin material/product in component j
$Q_{k,j}$ is the mass of material/product k in component j
$r_{k,j}$ is the fraction of secondary material in material/product k in component j

$$W_j = Q_j \times NR_j \tag{13}$$

W_j is the mass of nonreusable proportion in component j
Q_j is the mass of component j
NR_j is the fraction of nonreusable proportion in component j. (Those materials/products whose EOL scenarios are incineration or disposal.)

The utility of a component is determined according to the service life of the component and the service life of the system in which the component stays.

$$X_j = \frac{Y_{c,j}}{Y_{s,i}} \tag{14}$$

X_j is the utility of component j
$Y_{c,j}$ is the estimated service life of component j
$Y_{s,i}$ is the estimated service life of the system i in which component j stays

$$MCI_j = 1 - \frac{(V_j + W_j)}{2 \times Q_j} \times \frac{a}{X_j} \tag{15}$$

MCI_j is the material circularity indicator of component j
Q_j is the mass of component j
a is a constant = 0.9 (Ellen MacArthur Foundation and Granta, 2015)

MCI should be within 0 and 1(Ellen MacArthur Foundation and Granta, 2015). If a negative value is obtained through the above equation, the MCI is given to 0.

In contrast, component circularity indicator (CCI) is the 'practical' circularity value of a component. It considers the connections and relations between materials/products. CCI can be obtained by integrating DDF.

$$CCI_j = MCI_j \times DDF_j \tag{16}$$

CCI_j is the component circularity indicator of component j
DDF_j is the disassembly determining factor for component j (See section 3.3.1)

At the system level, depending on which component level indicator is chosen, two types of system circularity indicator (SCI) are available.

$$SCI_{i(t)} = \frac{1}{Q_i} \times \sum_j MCI_j \times Q_j \tag{17}$$

$$SCI_{i(p)} = \frac{1}{Q_i} \times \sum_j CCI_j \times Q_j \tag{18}$$

$SCI_{i(t)}$ is the theoretical system circularity indicator of system i
$SCI_{i(p)}$ is the practical system circularity indicator of system i

Q_i is the total mass of system i = the sum of all components in system i
Q_j is the mass of component j which stays in system i

Finally, the bridge circularity indicator (BrCI) is calculated as below:

$$BrCI_{(t)} = \frac{1}{N_s} \times \sum_i SCI_{i(t)} \times SD_i \quad (17)$$

$$BrCI_{(p)} = \frac{1}{N_s} \times \sum_i SCI_{i(p)} \times SD_i \quad (18)$$

$BrCI_{(t)}$ is the theoretical bridge circularity indicator
$BrCI_{(p)}$ is the practical bridge circularity indicator
SD_i is the system dependency of system i (See section 3.3.1)
N_s is the total number of systems in the bridge

If the BrCI of a design variant is 0, it indicates that the design is fully linear. On the contrary, if the BrCI is 1, the design variant is fully circular.

3.3.3 Output

The results of LCA are reported depending on the selected LCIA method. For example, IMPACT 2002+, an LCIA method, covers 13 mid-point impact indicators (IES, 2010). The results of all indicators can be normalized, weighted, and finally aggregated into a single score.

$$I_{j,normalized} = \frac{I_j}{NF_j} \quad (19)$$

I_j is the obtained value of impact indicator j
$I_{j,normalized}$ is the normalized value of impact indicator j
NF_j is the normalization factor for impact indicator j which can be found in the selected LCIA method

$$Score = \sum_j (I_{j,normalized} \times WF_j) \quad (20)$$

$Score$ is the score of a bridge design
$I_{j,normalized}$ is the normalized value of impact indicator j
WF_j is the weighting factor for impact indicator j ($\sum_j WF_j = 1$)

The main purpose of the parametric model is to assist the users in evaluating the environmental impact, cost, and circularity of the design, and to compare different design variants based on the results. Thus, the three main outputs of the model are the LCA score, total LCC, and BrCI of each design variant. Apart from the results of each life cycle stage, partial results, e.g., the composition of the LCA and LCCA results of a specific stage, the MCI and CCI of a specific component, can also be outputted.

The obtained output of the model is in the form of numbers. It is possible to convert these quantitative data to the form of figures, such as pie charts, histograms, in order to gain insights into the results. Furthermore, the users can optimize their design through an iterative process. For example, by analyzing the hotspots in the life cycle, key materials or processes can be found. The design of bridge components related to these findings can be further improved. A new evaluation of the modified design with the parametric model is then conducted. Finally, the design is optimized after a few rounds of improvement.

3.4 MATLAB-based computational tool

3.4.1 Input spreadsheet

The MATLAB-based tool is built for realizing the parametric model developed in this study. The tool requires users to provide input parameters in the form of a spreadsheet. The spreadsheet consists of five sub-sheets, which are separately named bridge information, system and component information, material/product information, machinery information, analysis information. All input parameters described in section 3.3.1 are assigned to these five sheets, as shown in Table 3.6.

Table 3.6: The allocation of parameters in input spreadsheets

Sub-spreadsheet	Input parameters
Bridge information	▪ Alternative identification number ▪ Bridge service life ▪ Percentage of heavy vehicle ▪ Affected road length ▪ Normal speed without delay ▪ Reduced speed ▪ Average daily traffic ▪ Transport distance of EOL waste ▪ The total length of edge beam ▪ The total length of railing ▪ The total area of surfacing ▪ The total length of expansion joints

	▪ Total number of bearings ▪ Production and treatment cost of steel girders
System and component information	▪ Alternative identification number ▪ System title ▪ System dependency of each system ▪ System service life of each system ▪ Functional components of each system ▪ Component service life of each component ▪ Initial painting area of each component ▪ Disassembly determining factors of each component
Material/Product information	▪ Alternative identification number ▪ System title ▪ Functional Components of each system ▪ All Materials/Products in each component ▪ Quantity of each material/product ▪ Quantity unit ▪ Welding length of each steel product ▪ Fractions from secondary material ▪ EOL scenario of each material/product
Machinery information	▪ Alternative identification number ▪ Life stage in where a machine is operated ▪ Machinery type ▪ Power of each machine ▪ Operation hours of each machine
Analysis information	▪ Alternative identification number ▪ LCIA approach used for each alternative ▪ Adopted weighting factor: default/user-defined ▪ Discount rate ▪ Escalation rate

These spreadsheets will be read by MATLAB ® as tables. In order to compare various alternatives at a time, the tool allows users to input two or more sets of variables in the same spreadsheet which are then distinguished according to the alternative identification numbers.

3.4.2 Database spreadsheet

The supplementary database of the parametric model stores background information and default assumptions/settings. Because it is not possible to cover all data at a time, the database shall be able to be updated if supplements or adjustments are needed. The database is in the form of a spreadsheet as the input parameters. Four sub spreadsheets collect all data needed for the calculation of various indicators (as shown in Table 3.7).

Table 3.7: The data involved in database spreadsheets

Sub-spreadsheet	Data
Process/Activity information	▪ Life stage to where process/activity belongs ▪ Process/Activity title ▪ Unit of measurement of process/activity ▪ Unit cost of process/activity ▪ The year of occurrence of scheduled activity ▪ Frequency of repeating activity ▪ Time required for maintenance activity ▪ Operating ratio of maintenance activity ▪ Material/Product needed for maintenance activity ▪ Quantity of material/product needed ▪ Quantity unit of material/product needed ▪ Recycling rate of recycling process of waste ▪ Virgin material/product substituted by the output of recycling process ▪ LCIA results of each process/activity
Resource information	▪ Material/Product title ▪ Unit of measurement of material/product ▪ Density of material/product ▪ Unit cost of material/product ▪ Unit price of EOL waste of material/product ▪ Transport distances of material/product with different transport methods ▪ LCIA results of the production of material/product (per unit)
Transportation and machinery information	▪ Machinery/Transportation title ▪ Unit of measurement of machinery operation ▪ Fuel efficiency of transportation ▪ Unit of measurement of fuel efficiency ▪ Hourly cost for one truck ▪ Hourly cost for one passenger car ▪ LCIA results of the operation of machinery/transportation (per unit)
LCA approach information	▪ Titles of indicators of LCIA method ▪ Unit of measurement of indicators ▪ Default normalization factors of LCIA method ▪ Default weighting factors of LCIA method ▪ User-defined weighting factors of LCIA method

3.4.3 MATLAB codes

The computational tool is written in the form of a MATLAB script. It contains three main function calls, which are life cycle cost calculation, life cycle impact calculation, circularity calculation. The two excel files, i.e., input parameter and supplementary database, are read as tables. The sets of input parameters of different design variants in the input spreadsheet are separated according to the alternative identification numbers. The calculation functions use these tables as input to perform computation. The repeated calculation processes, such as present value conversion, are written as separate sub-functions.

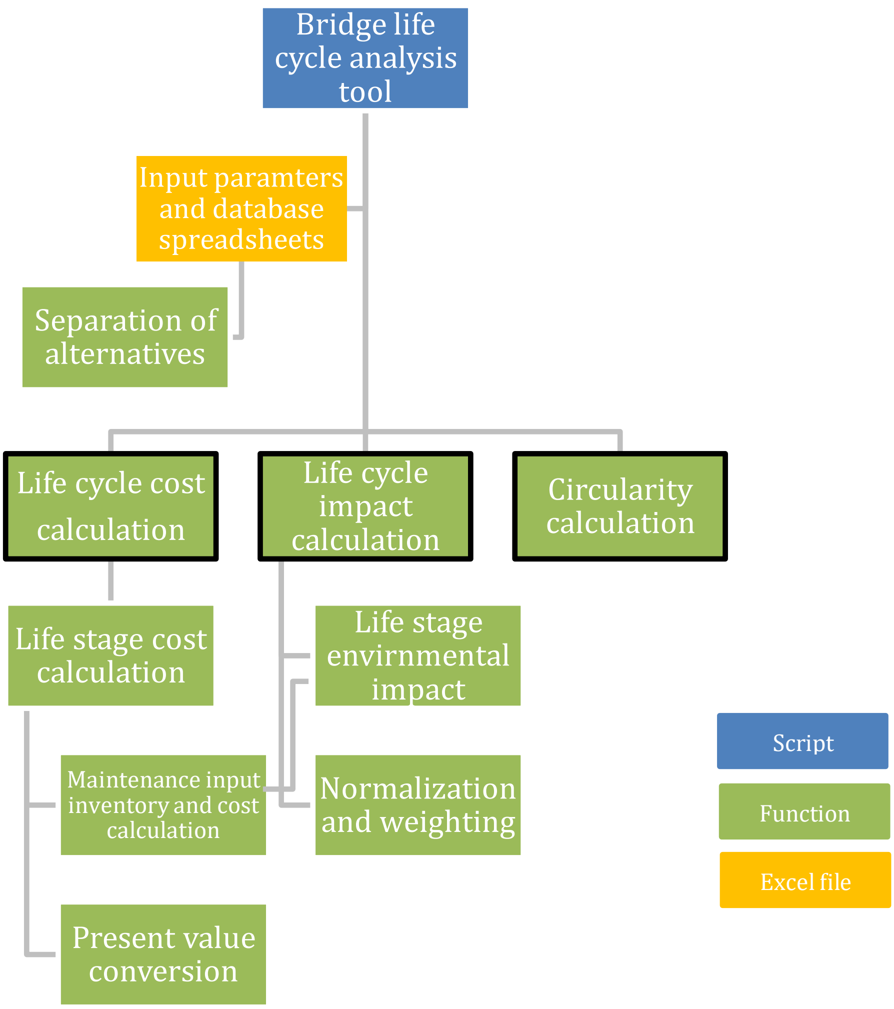

Figure 3.4: The structure of the MATLAB-based computational tool

Chapter 4 Case study

In this chapter, two bridge design cases in their early design stages demonstrate the application of the parametric model developed in this study. The two cases all focus on the application of the corrugated web and the stainless steel in a composite steel-concrete bridge. Case study 1 delivers three design alternatives with different girder materials and web designs. This case is in the very early stages, so only the information about the key components, i.e., girder and deck, of the bridge is available. Case study 2 contains two design alternatives while more information about the composition of the bridge is available than the first case study, such as the material and quantities of railing, surfacing, and formwork. The main purpose of the case studies is to study if stainless steel is a better option for bridge construction material in terms of environmental impacts, economic performance, and circularity.

4.1 Case Study 1

4.1.1 Design description

The data of case study 1 were obtained from the master thesis written by Öman and Steffner (Personal communication, May 21, 2021). The global dimensions of the bridge are shown in Table 4.1. Only two components, i.e., concrete deck and steel girder, are considered while conducting the following LCA, LCCA, and circularity assessment. The service life of the whole bridge as well as all its components are 120 years.

Table 4.1: The geometry of the bridge in case study 1 (Öman and Steffner, 2021)

Bridge type	Composite steel-concrete bridge
Bridge length	59.4 m
Height of steel girder	1.75 m
Thickness of concrete deck	0.32 m
Width of the bridge deck	9.5 m
Service life	120 years

The main difference between the three design alternatives is the design of the main girders. The design parameters of each alternative are shown in Table 4.2. The surface of steel girders in the carbon steel alternative, herein around 658 m^2 in total per bridge, has to be covered by paint to prevent corrosion. In contrast, stainless steel does not need additional protection (e.g., galvanization or painting) and maintenance (Rossi, 2014). Due to the corrugated web design, the welding length in the stainless steel (SS) alternative is longer than the other alternatives.

Table 4.2: The design parameter of the girders in case study 1 (Öman and Steffner, 2021)

Alternative	S355	S460	SS
Material of girder	Carbon Steel: grade s355	Carbon Steel: grade s460	Stainless Steel Duplex 1.4162
Density of steel	7850 kg/m^3	7850 kg/m^3	7700 kg/m^3
Geometry of girder	I-shaped	I-shaped	I-shaped
Type of web	Flat	Flat	Corrugated
Vertical stiffener	Both side	Both side	One side
Width top flange (b_{tf})*	430 mm	440 mm	440 mm
Thickness top flange (t_{tf})*	28 mm	22 mm	25 mm
Height web (h_w)*	1690 mm	1698 mm	1688 mm
Thickness tweb (t_w)*	16 mm	15 mm	6 mm
Width bottom flange (b_{bf})*	550 mm	550 mm	700 mm
Thickness bottom flange (t_{bf})*	32 mm	30 mm	37 mm
Welds: top flange to web (a_{top})*	7 mm	7 mm	5 mm
Welds: Bottom flange to web (a_{bot})*	7 mm	7 mm	5 mm
Initial painting area	658 m^2	658 m^2	-
Required welding length	238 m	238 m	270 m

* There are two types of steel beam design in an alternative, i.e., one for the spans and one for the internal support area. Herein only parameters of the beam which is located in the spans are shown

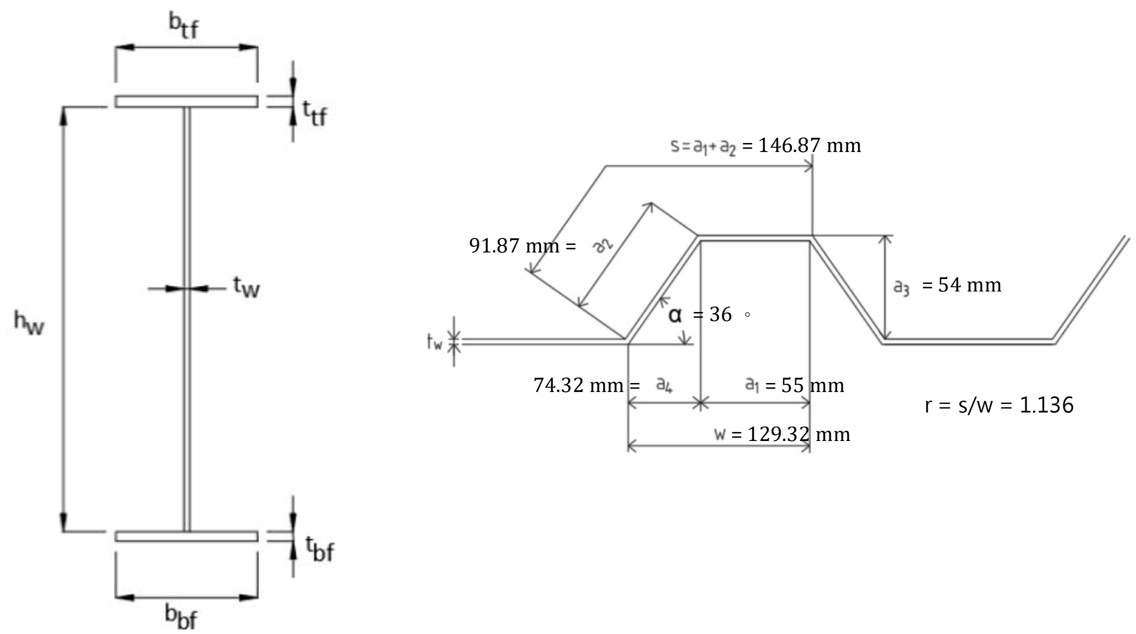

Figure 4.1: Geometric notations: cross-section of I-shaped girder (left) and top view of corrugated webs (right) (Öman and Steffner, 2021)

4.1.2 Data and assumptions

The bill of quantities (BoQ) of all three alternatives is provided by Öman and Steffner (Personal communication, May 21, 2021). As shown in Table 4.3, the total mass of the girder in the SS alternative is the lowest, as 16% lower than the S355 alternative and 6% lower than the S460 alternative.

Table 4.3: The BoQ of the alternatives in case study 1(Öman and Steffner, 2021)

Bridge level	System level	Component level	Material level	S355	S460	SS
Bridge	Superstructure system	Girder	Steel s355 (kg)	54,500	-	-
			Steel s460 (kg)	-	48,943	-
			Stainless steel Duplex 1.4162 (kg)	-	-	46,000
			Filler material for welding steel s355 (kg)	182.78	-	-
			Filler material for welding steel s460 (kg)	-	182.78	-
			Filler material for welding stainless steel (kg)	-	-	203.68
			Paint (kg)*	438.23	438.23	-
		Deck	Reinforcement bars (kg)	16,805	16,805	16,805
			Concrete (kg)	450,192	450,192	450,192

For simplification, we assumed that only one type of paint is used. The data of spreading rate (0.222 kg/ m^2) and film thickness per coat (100 µm) are from an EPD owned by Juton (2020). According to the information provided by trafikverket (Personal communication, May 12, 2021), we also assume a minimum thickness of 300 µm is needed. Accordingly, the quantity of paint can be calculated according to the initial painting area and paint requirement per square meter (0.666 kg/m^2).

In this case study, we mainly focus on the Global Warming Potential (GWP) of different designs while conducting LCA. Considering the location of the bridge site, the EPD of Hot rolled steel plates owned by SSAB, a steel company that produces steel in Sweden, Finland, and the US, is adopted to obtain the emissions factors of steel S355 and steel S460. For stainless steel, we chose an EPD of stainless steel owned by Outokumpu, a Nordic stainless steel manufacturer. The emission factors for producing one kilogram of steel are shown in Table 4.4.

Table 4.4: The adopted emission factors of steel products in case study 1

Material	GWP (kg CO_2 eq/kg steel)	Data source
Carbon steel S355	2.71	SSAB, 2020
Carbon steel S460	2.71	SSAB, 2020
Stainless steel 1.4162	2.74	Outokumpu, 2019

Steel is 100% recyclable without loss of properties (World Steel Association, 2012). Most steel products are partly made of secondary material, i.e., steel scraps. We refer to the two mentioned EPDs of steel products to assume that the steel producers in case study 1 use 20 % of scrap steel in carbon steel and 71% of stainless steel scrap in stainless steel (Outokumpu, 2019; SSAB, 2020). On the other hand, thanks to EAF, reinforcement bars can have 98% recycled content (Sustainable Concrete, n.d.). Herein, we assume the rebar used in case study 1 has 90% content coming from recycling steel scrap. Chakradhara Rao et al. (2011) suggest that it is possible to have 25% replacement of recycled coarse aggregates in the production of new concrete.

Due to the lack of comprehensive information of the bridge over its service life in the early design stages, assumptions and scenarios are needed in order to conduct life-cycle analysis. For the potential machinery use over the service life, it is omitted in this case study. According to the world steel association (2012), the recovery rate of post-consumer steel products in the construction sector was 85% in 2007. It is expected to achieve 95% in 2050. Thus, we assume all types of steel used in the design will have a 95% recovery rate at the end of the service life of the bridge, i.e., 120 years from now. Schimmoller et al. (2000) indicate that 95% of old asphalt pavement is recovered for the production of new asphalt in Sweden. Zhang et al. (2019) show that the recovery rate of construction and demolition waste (CDW) changes significantly among European countries. Thus, referring to the 2020 target of CDW recovery rate set by the European Commission, we set the EOL concrete recycling rate of 70%. Finally, the painting used during the service life of the bridge is assumed to be incinerated at the end of life. The other assumptions and adopted data are available in the appendix.

4.1.3 Results and interpretation

4.1.3.1 LCA results

Table 4.5 shows that the product stage is the main contributor to the GWP of a bridge in all three design alternatives. The transportation of construction materials from suppliers to the bridge site accounts for only around two percent (construction stage). The SS alternative does not have carbon emissions in the use stage thanks to the great anti-corrosion property of stainless steel. As shown in Figure 4.2, if the net environmental benefit coming from recycling CDW is not considered, the SS alternative apparently has the lowest GWP. On the contrary, the GWPs of the S460 and the S355 alternatives are merely 6.7% and 2.5% higher than the SS alternative respectively while taking module D into account.

Table 4.5: Distribution of the overall GWP of the design alternatives by life cycle stage

Alternative	Product stage	Construction stage	Use stage	EOL stage	Overall Life-cycle (without Module D)
S355	84.72%	2.03%	3.51%	9.74%	100.00%
S460	84.08%	2.07%	3.71%	10.14%	100.00%
SS	87.60%	2.18%	0.00%	10.22%	100.00%

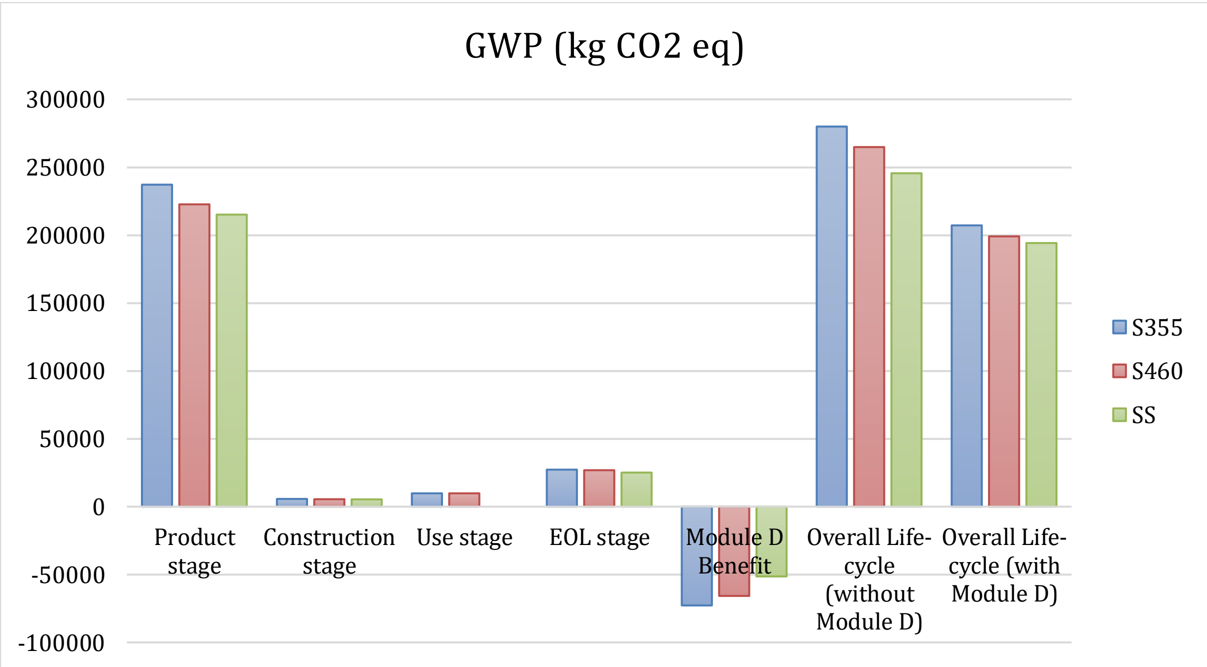

Figure 4.2: The GWPs of all alternatives in different life stages

Considering the role of the product stage in terms of environmental impacts, the distribution of the GWPs derived from the production of the chosen construction materials is analyzed. Figure 4.3 indicates that the production of steel products accounts for around 60% of the total GWP in the product stage in all three alternatives. The second largest contributor is the concrete in the deck, as more than 30% of the total GWP.

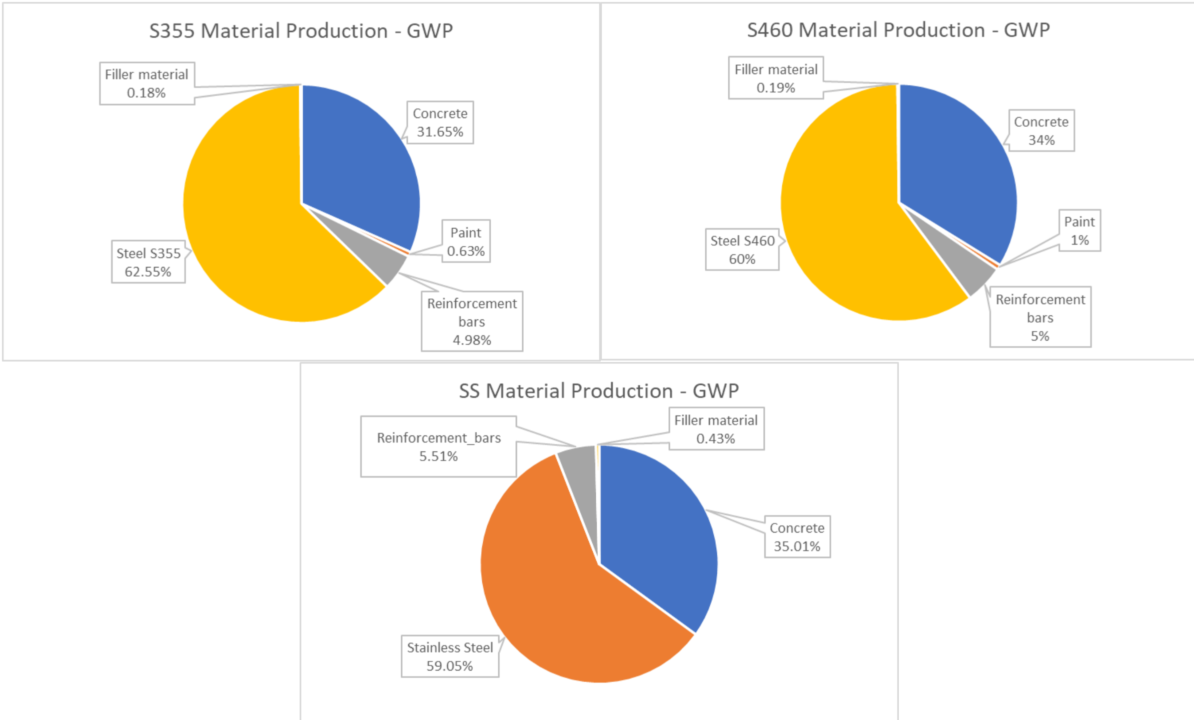

Figure 4.3: Distribution of the GWPs of the materials included in the product stage

In order to identify which material/product used in the bridge construction has the highest impact on climate change over its life cycle, we added up the GWPs derived from the production, transportation, and EOL treatments of those materials/products used in the bridge. It could assist users to do material selection in the early design stages. As shown in Figure 4.4, while concrete has the second largest GWP, the most important GWP contributor is steel products used in the girders.

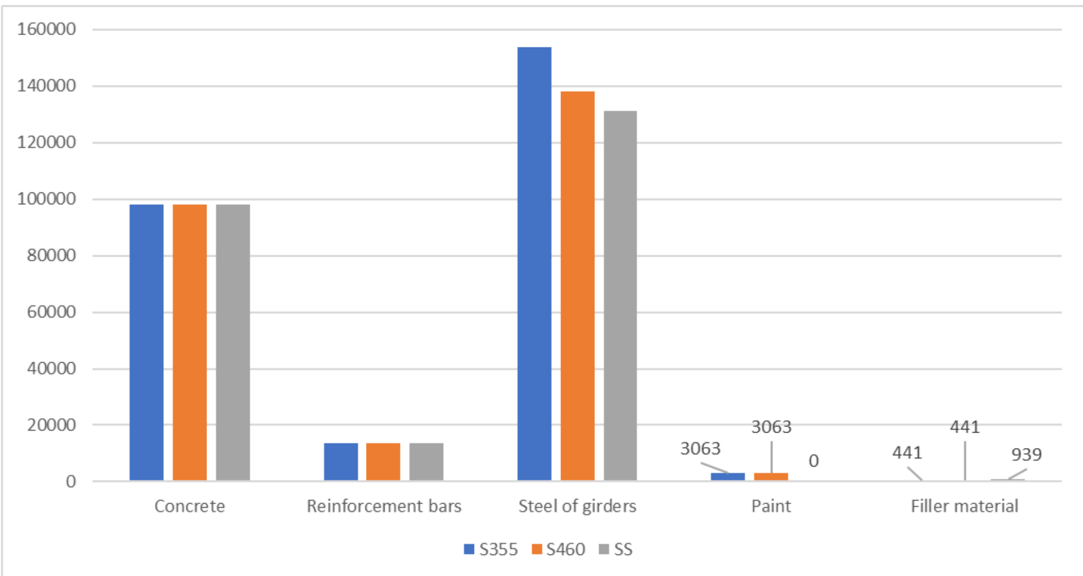

Figure 4.4: The life-cycle GWPs of the materials/products required in the bridge construction

The transportation of all dismantling wastes accounts for 57 % to 60 % of all impacts produced in the EOL stage (see Figure 4.5). In the analysis, we selected a diesel truck with an emission factor of 0.198 kg CO_2eq per ton*km to transport CWD and assumed the transport distance is 150 km. Thus, the GHG emissions from transportation can be further reduced by adopting electric trucks in the future. Furthermore, although the mass of waste paint is much smaller compared to the other materials/products in the bridge, e.g., 438 kg paint vs. 450,192 kg concrete in alternative S355, the incineration of paint is a non-negligible source of GWP in the EOL stage. It is implied that incineration is suggested to be avoided while selecting the EOL treatment approach for CWD in terms of climate change.

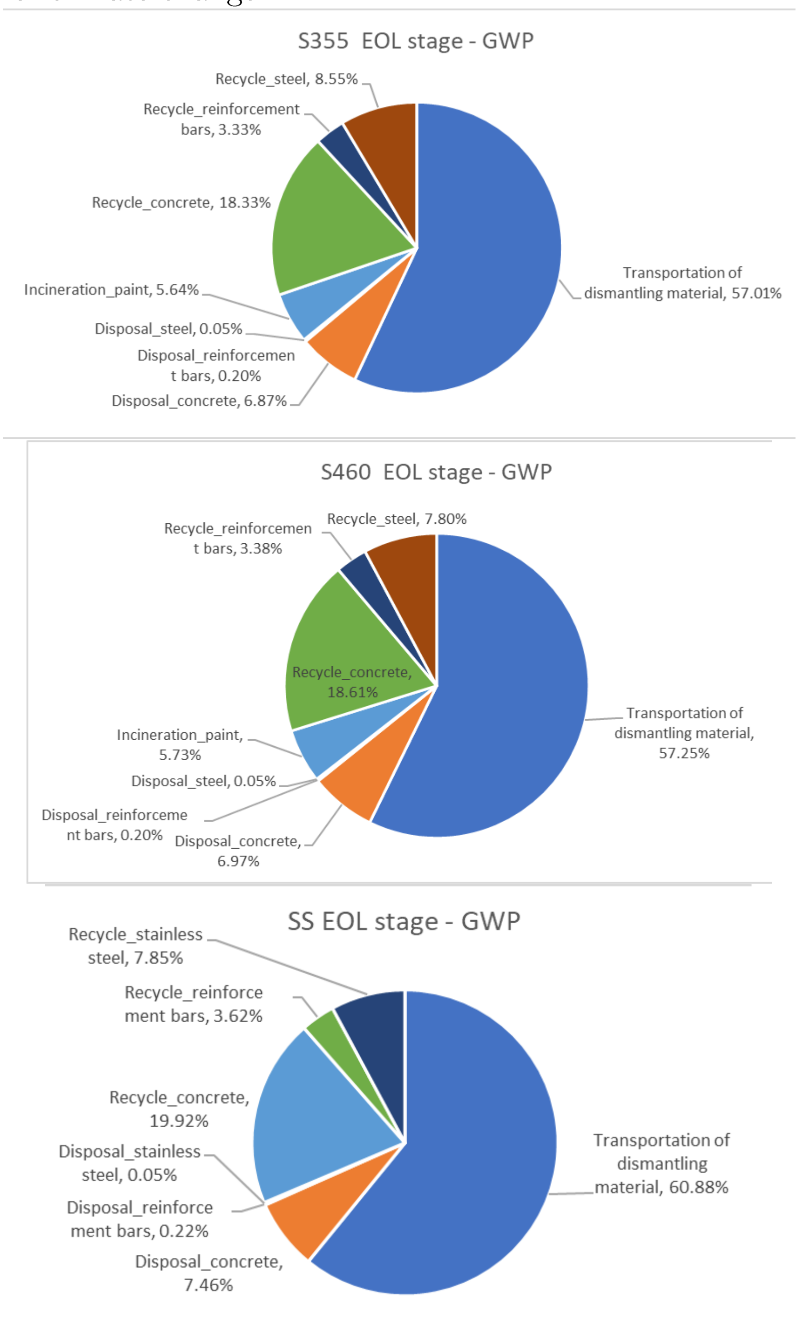

Figure 4.5: Distribution of the GWPs of the processes in the EOL stage

For reflecting the difference caused by the selection of LCIA method and data source, we chose CML 2001 as the LCIA approach and obtained all LCIA results of products and processes from the ecoinvent database. In addition, we assumed S355 steel and S460 steel contain 37% recycled steel (World steel association, n.d.). The secondary material fraction of the stainless steel in the ecoinvent is 27%. The LCIA method of CML 2001 in the ecoinvent has 15 impact categories. For calculating the aggregate score of each alternative, we selected 14 impact indicators with normalization factors (as shown in Table 4.6). After the normalization of indicators, we used the average value of all normalized values as the score of a design alternative. The results are shown in Table 4.7 and Figure 4.6.

Table 4.6: The selected CML impact indicators with normalization factors (Adapted from Ecoinvent database and openLCA Nexus)

CML 2001 impact indicators	Unit	Normalization factor
Acidification potential:average European	kg SO2-Eq	2.74E+10
Climate change:GWP 100a	kg CO2-Eq	4.81E+12
Eutrophication potential:average European	kg NOx-Eq	3.22E+10
Freshwater aquatic ecotoxicity:FAETP 100a	kg 1,4-DC.	4.72E+11
Freshwater sediment ecotoxicity:FSETP 100a	kg 1,4-DC.	4.39E+11
Human toxicity:HTP 100a	kg 1,4-DC.	7.46E+12
Ionising radiation: ionising radiation	DALYs	4.85E+4
Land use:competition	m2a	3.27E+12
Marine aquatic ecotoxicity:MAETP 100a	kg 1,4-DC.	4.63E+11
Marine sediment ecotoxicity:MSETP 100a	kg 1,4-DC.	5.92E+11
Photochemical oxidation (summer smog): MOIR	kg formed.	8.26E+09
Resources: depletion of abiotic resources	kg antimo.	8.20E+07
Stratospheric ozone depletion:ODP steady state	kg CFC-11.	8.33E+07
Terrestrial ecotoxicity:TAETP 100a	kg 1,4-DC.	2.03E+10

*1,4-DC. = 1,4-Dichlorobenzene

Table 4.7: The distribution of the final score by life cycle stage

Alternative	Product stage	Construction stage	Use stage	EOL stage	Module D	Overall Life-cycle (without Module D)	Overall Life-cycle (with Module D)
S355	1.52E-06	5.28E-08	1.12E-07	2.20E-07	-3.81E-07	1.90E-06	1.52E-06
S460	1.40E-06	4.98E-08	1.12E-07	2.13E-07	-3.45E-07	1.77E-06	1.43E-06
SS	2.62E-06	4.81E-08	0.00E+00	2.05E-07	-1.58E-06	2.87E-06	1.29E-06

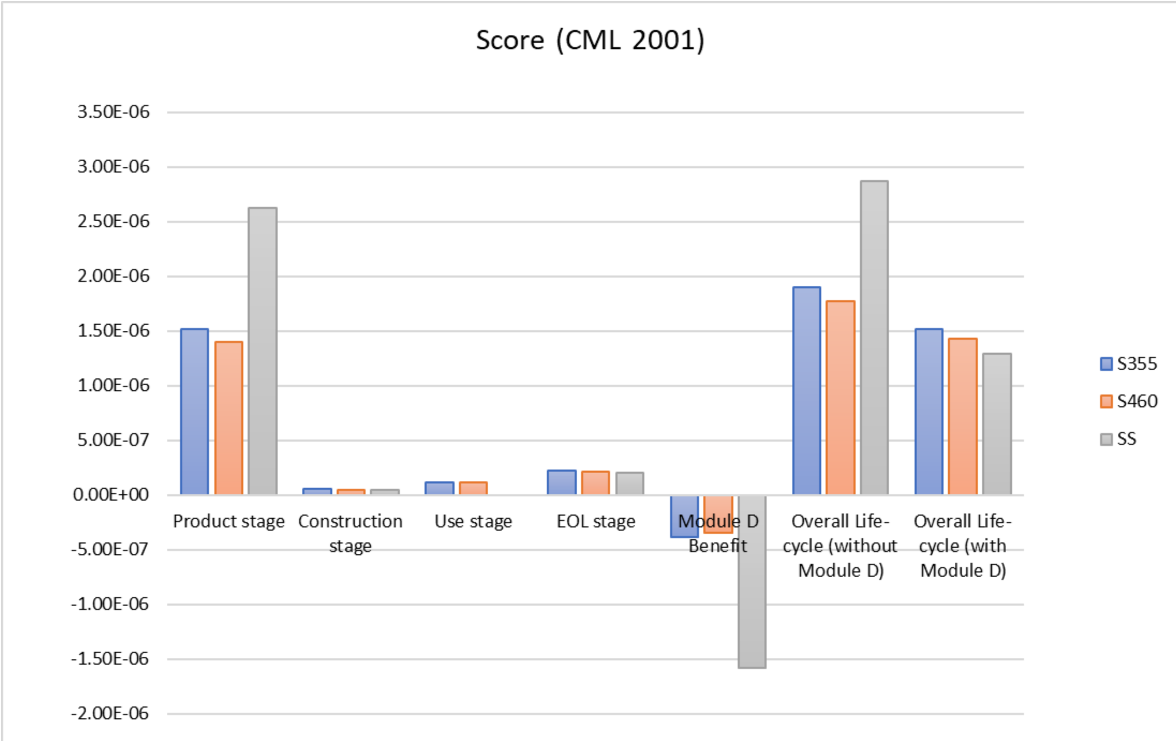

Figure 4.6: Distribution of the LCA scores of all alternatives by life cycle stage

It is observed that the SS alternative has a higher overall score than the other while without considering Module D. However, the score of the same alternative becomes the lowest when we involve the benefit of recycling stainless steel. In the analysis, we assumed that the substituted virgin materials for S355/S460 steel scrap and stainless steel scrap are pig iron and stainless steel respectively. In the ecoinvent database, the CML LCIA results of stainless steel in most impact indicators are much higher than pig iron. For example, the Human Toxicity Potential 100a of pig iron and stainless steel are 1.41 kg 1,4-DC. and 76.71 kg 1,4-DC. respectively. Furthermore, in this analysis, the stainless steel is made of a low proportion of secondary material (27%). It leads to higher recycling benefits than the first GWP analysis in the previous section (i.e., 71% of stainless steel scrap in stainless steel).

4.1.3.2 LCCA results

Figure 4.7 shows the result of LCCA. In the LCCA, the discount rate was set to 5% and the escalation rate to 2% (Rossi et al., 2017). The SS alternative has the lowest total LCC in all three design variants. Although the SS alternative has the highest material cost, the lower production and treatment costs of the main girder and no maintenance cost make stainless steel become a better option in bridge construction from an economic perspective. Thanks to the higher resell price of stainless steel scrap (4 SEK/kg SS scrap and 1.5 SEK/kg mix steel scrap), the total LCC of the stainless steel alternative is further reduced.

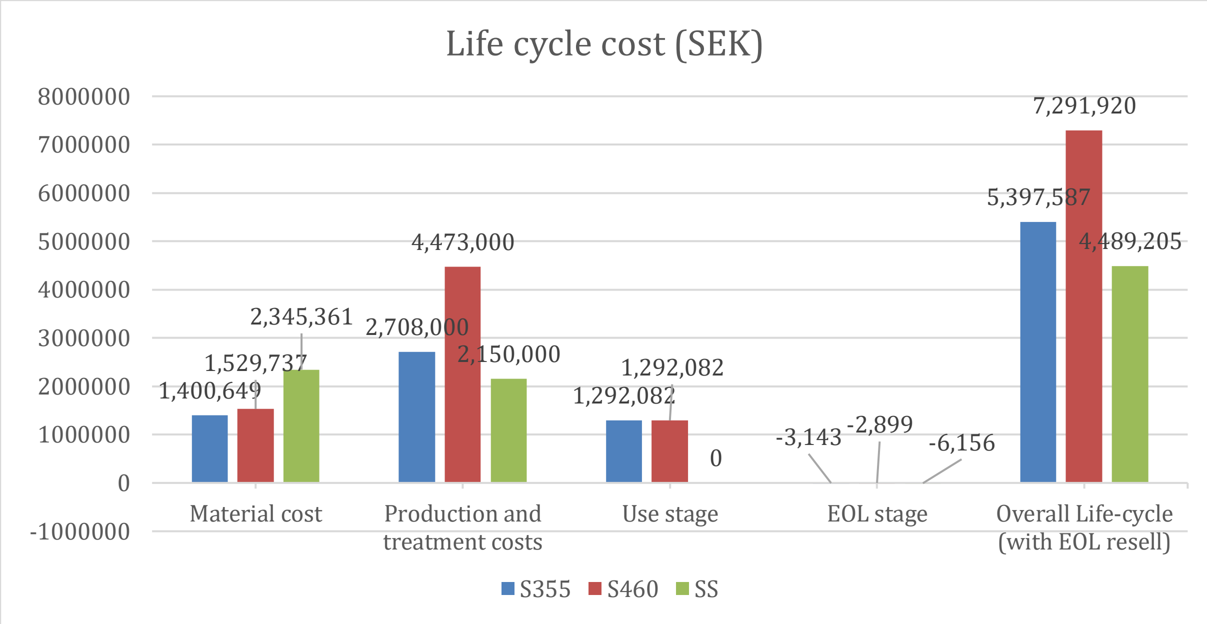

Figure 4.7: Life cycle costs of all alternatives

As shown in Figure 4.7, the production and treatment costs of the S460 alternative are higher than the other two alternatives. It is because the production cost of the S460 steel girder is much higher than the others (see Table 4.8). According to Öman and Steffner (2021), the main reasons for the higher production cost are additional energy consumption and labor for high-temperature welding preheat in the manufacturing process of the S460 steel girder.

Table 4.8: The material costs and production and treatment costs of the girders in all alternatives in case study 1 (Öman and Steffner, 2021)

Alternative	S355	S460	SS
Material cost (SEK/kg)	12	16	35*
Girder production cost (SEK)	2,158,000	3,923,000	2,015,000
Girder treatment cost (SEK)	550,000	550,000	135,000

* According to Öman and Steffner (2021), the price of stainless steel is around 30 SEK/kg. Considering the current market price, we assumed stainless steel costs 35 SEK/kg.

Figure 4.8 presents the cost distributions of all alternatives. Apart from the stainless steel alternative, carbon steel alternatives require around 20% of the life cycle cost for maintenance activities.

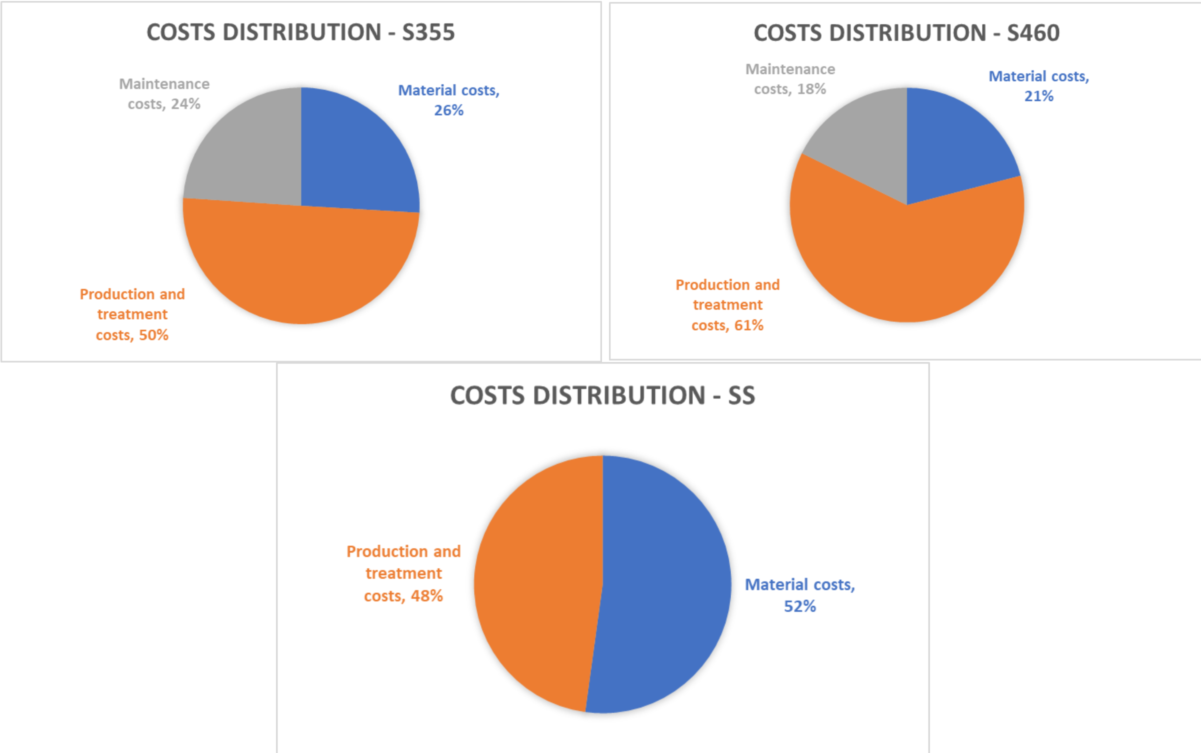

Figure 4.8: Cost distribution of all alternatives

The cost generated in the use stage can be divided into user cost (traffic delay cost) and maintenance process cost (see section 3.3.2.3). In the analysis, we made some assumptions and created a congestion scenario (see Table 4.9) to calculate the user cost. Figure 4.9 indicates that user costs account for 4% of the total cost generated in the use stage. If the time required for maintenance activities becomes 7 to 14 days, the proportion of user costs could increase up to 25%. The total costs in the use stage also get a raise of 25% as well.

Table 4.9: Parameters used for the user cost calculations (adapted Wahlsten et al., 2018)

Average Daily Traffic	5000
Percentage of trucks among all the ADT	0.1
Affected roadway length	0.5 km
Normal speed without congestion	110 km/hour
Reduced speed during congestion	50 km/hour
Time required for maintenance activities	0.5 – 2 days per activity*

* Assumptions

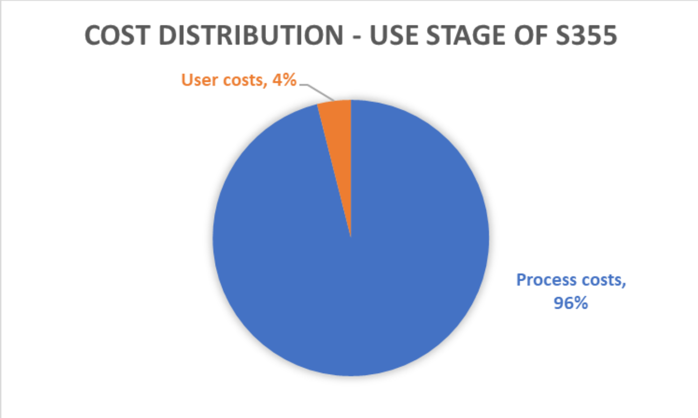

Figure 4.9: Cost distribution of the S355 alternative in the use stage

4.1.3.3 Circularity assessment results

In this case study, only the superstructure system of the bridge is covered in the analysis. We assume the system dependency of the superstructure system is 0.8. The separation between reinforcement bars and concrete in the deck usually requires an operation that destroys the original structure. Hence, the disassembly determining factors (DDF) of two main components, i.e., girder and deck, are set to 0.6 and 0.2 separately (see section 3.3.1). Table 4.10 shows the Bridge Circularity Indicators (BrCI) for each alternative. If the BrCI is 0, it means that the design is fully linear. On the contrary, if the BrCI is 1, it means that the design is fully circular. The practical value is the BrCI which considers the connection between materials/products in a component. Thus, it would be lower than the theoretical one. The stainless steel alternative adopts stainless steel which is made of 71% of stainless steel scrap. It leads to a better performance in terms of circular economy. Due to the lack of information about other components in the bridge, it is difficult to reveal the difference of circularity between alternatives.

Table 4.10: Bridge Circularity Indicators for all alternatives

Bridge Circularity Indicator	S355	S460	SS
Theoretical value	0.440	0.439	0.456
Practical value	0.109	0.107	0.116

Table 4.11: Detail information for the circularity calculation of S355 alternative

Systems	Functional Components	Total Mass (kg)	Virgin Material (kg)	EOL Waste Output (kg)	Utility Factor	MCI	PCI
superstructure	Steel girder	55,121	44,221	3,172	1	0.613	0.368
superstructure	deck	466,997	339,325	135,898	1	0.542	0.108

4.2 Case Study 2

4.2.1 Design description

The data of case study 2 were extracted from the master thesis written by Henrysson and Yman (2020). It is a redesign case in where the original bridge is a one-span composite steel-concrete bridge made of carbon steel. The general information about the original bridge is available in Table 4.12.

Table 4.12: The general information of the bridge in case study 2

Bridge number and location	Bridge 100-262-1 over Delångersbron at Forsån, Böle
Bridge type	Composite steel-concrete bridge
Bridge length	52 m
Height of steel girder	2.37 m
Width of the bridge deck	10 m

The new design addresses the material, web, and flange design of the main girders. The main differences in the parameters of the two designs are shown in Table 4.13. Stainless steel grade 1.4162 is chosen as the material of the girder in the new design (hereinafter called the SS design). Accordingly, no additional protection or maintenance is needed. Because the SS alternative adopts a corrugated web design (see section 4.1.1), its welding length is longer than the original design (hereinafter called the CS design). In case study 2, more data about the bridge design is available than in case study 1, such as the railing length and the area of pavement. In addition, in order to make the two designs comparable, the expected service life of 120 years is set for both designs. However, while the main girder and deck have 120 years of service life as the whole bridge, the railing and surfacing have to be replaced every 60 years and 10 years respectively.

Table 4.13: The design parameters of the two designs in case study 2 (Henrysson and Yman, 2020)

Alternative	CS	SS
Material of girder	Carbon Steel: grade S355 and S460	Stainless Steel Duplex 1.4162
Density of steel	7850 kg/m^3	7800 kg/m^3
Geometry of girder	I-shaped	I-shaped
Type of web	Flat	Corrugated
Initial painting area	852.9 m^2	-
Required welding length	76 m	102 m
Total railing length	102 m	102 m
Surfacing area	502.35 m^2	502.35 m^2

4.2.2 Data and assumptions

The BoQ of the two designs is shown in Table 4.14. The total mass of the girder in the SS design is 22% lower than the CS design. The quantities in the table are obtained through recalculation based on the information provided in the article by Henrysson and Yman (2020). Hence, it is not totally identical to the figuresFour components, i.e., deck, steel girder, railing, and surfacing, are taken into account in case study 2. In addition, the formwork used during the construction process is considered while conducting the LCA for this case.

Table 4.14: The BoQ of the designs in case study 2 (adapted from Henrysson and Yman, 2020)

Bridge level	System level	Component level	Material level	CS	SS
Bridge	Superstructure system	Girder	Steel s355 (kg)	36,859	-
			Steel s460 (kg)	71,738	-
			Stainless steel Duplex 1.4162 (kg)	-	84,422
			Filler material for welding steel s355 (kg)	40	-
			Steel studs	571	-
			Stainless steel studs	-	450
			Filler material for welding stainless steel (kg)	-	29
			Paint (kg)	569	-
		Deck	Reinforcement bars (kg)	6,946	6,946
			Concrete (kg)	444,201	444,201
		Railing	Steel s355 (kg)	2,600	2,600
		Surfacing	Asphalt (kg)	123,981	123,981
	Auxiliary structure	formwork	Formwork steel (kg)	27,147	27,147

In case study 2, we adopted the majority of assumptions and scenarios used in case study 1, including the discount/escalation rates, the paint requirement per square meter, the proportion of secondary materials in the selected construction materials, the recovery rates for EOL metal products and other wastes, and the waste treatment, transportation, and use scenarios (see section 4.1.2; 4.1.3.1; 4.1.3.2). This design case does not provide any data about potential machinery use over the service life as case study 1. In this case study, we also focus on the GWP of the designs. Thus, the two steel manufacturers, i.e., Outokumpu and SSAB, are selected for obtaining the emission factors (See Table 4.4) of steel products because bridge 100-262-1 is located in Sweden. The other assumptions and adopted data are available in the appendix.

4.2.3 Results and interpretation

4.2.3.1 LCA results

Table 4.15 shows that the product stage is the main contributor to the GWP of a bridge in the two designs. Compared to case study 1, the use stage in case study 2 accounts for a much higher proportion to the overall life-cycle GWP. It is because the replacements of two components, i.e., railing and surfacing, are taken into account. The production and transportation of new components and waste treatment of replaced components lead to additional carbon emissions. As shown in Figure 4.10, whether the net environmental benefit coming from recycling CDW is considered or not, the SS design has the lowest GWP. The difference between the GWPs of the two designs in the product stage mainly comes from the material saving in the new design.

Table 4.15: Distribution of the overall GWP of the designs in case study 2 by life cycle stage

Design	Product stage	Construction stage	Use stage	EOL stage	Overall Life-cycle (without Module D)
CS	69.35%	1.31%	23.77%	5.57%	100.00%
SS	67.98%	1.34%	24.97%	5.71%	100.00%

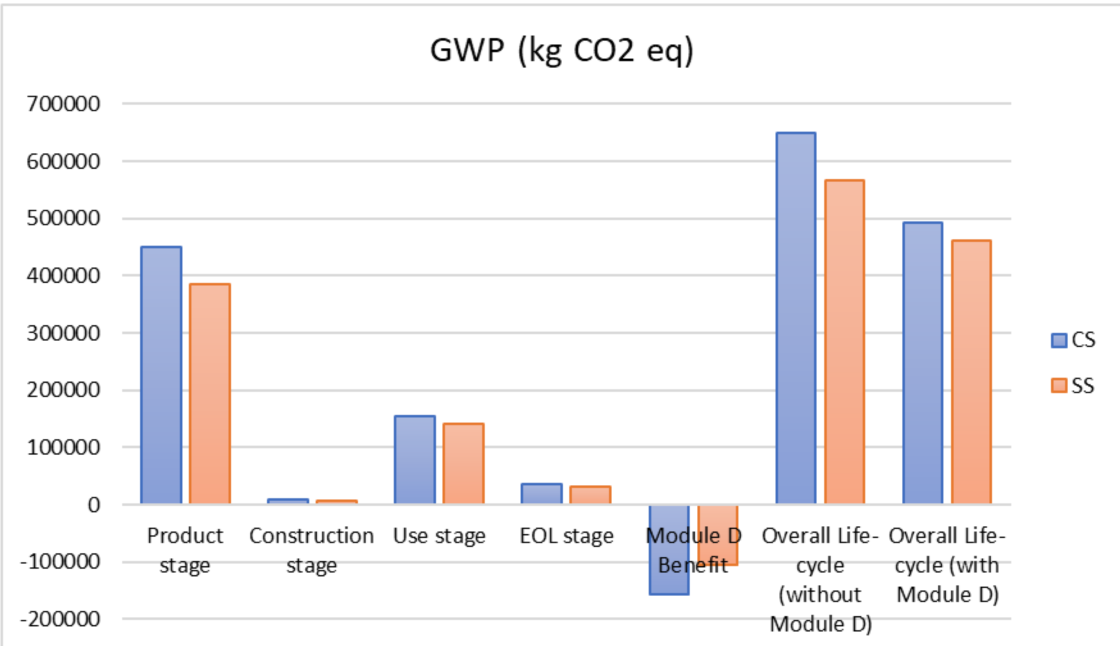

Figure 4.10: The GWPs of two designs in case study 2 in different life stages

In case study 2, we also analyzed the distribution of the GWPs derived from the production of the chosen construction materials. Figure 4.11 indicates that the production of steel products accounts for around 80% of the total GWP in the product stage in the two designs. While the concrete in both designs has the largest mass, the percentage of the GWP derived from concrete production is lower than 20%. This value could increase if more components made of concrete are taken into account, e.g., abutments.

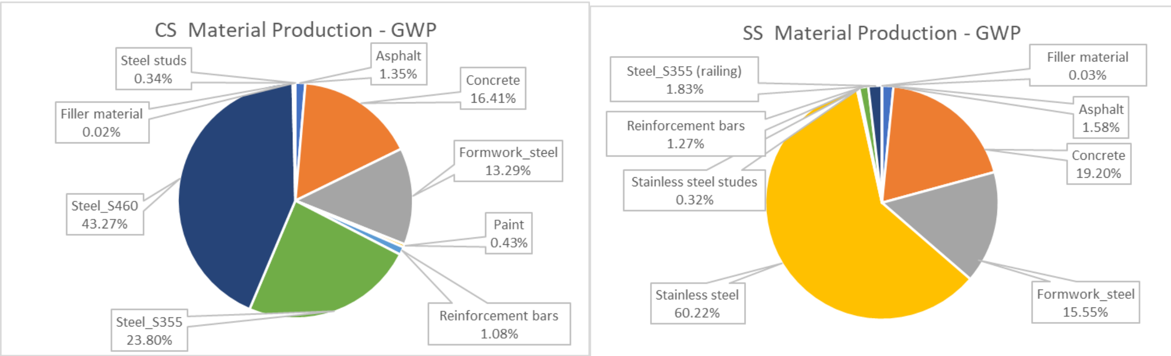

Figure 4.11: Distribution of the GWPs of the materials included in the product stage in case study 2

Following the same method adopted in case study 1, the life-cycle GWPs of the materials/products required in the bridge components are shown in Figure 4.12. Apparently, the girder steel is a GWP hotspot. Thus, designers may focus on the improvement of the steel used in girders, such as selecting steels with lower emission factor or lighter weight (lower GHG emissions from transportation).

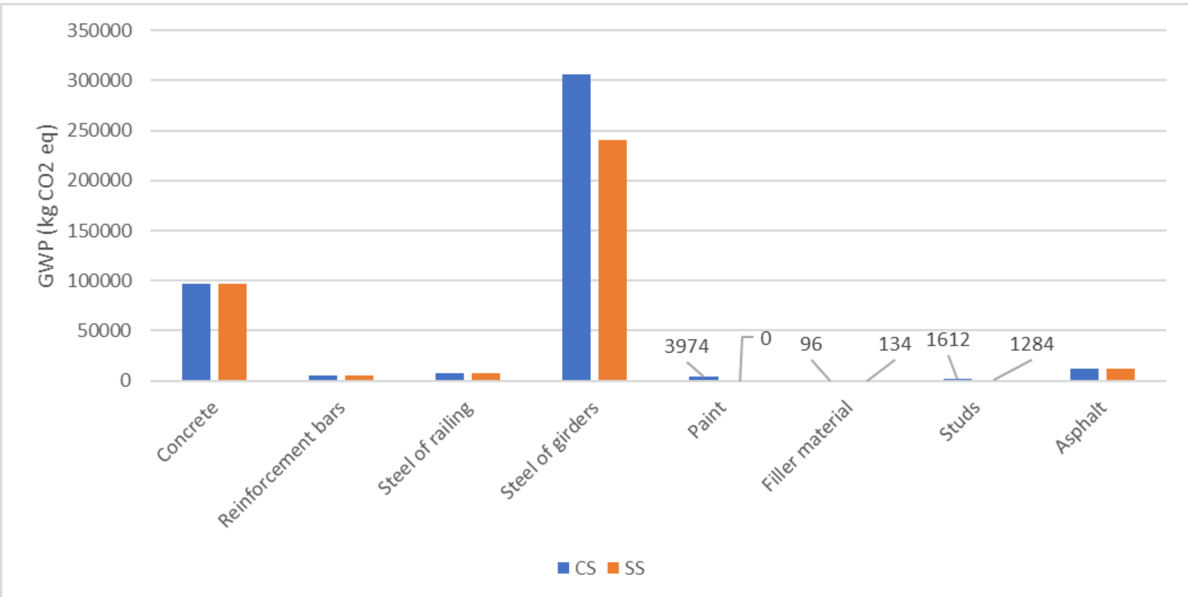

Figure 4.12: The life-cycle GWPs of the materials/products required in the bridge construction in case study 2

4.2.3.2 LCCA results

Figure 4.13 shows the result of LCCA in case study 2. The SS design has a lower total LCC than the CS design. Although the SS design has a higher material cost, the lower maintenance cost makes stainless steel more attractive in bridge construction in terms of life cycle costs. In both case studies (1 and 2), the revenues coming from selling the metal scraps do not cause any significant impact on the overall LCC. Accordingly, it may be omitted in future analyses.

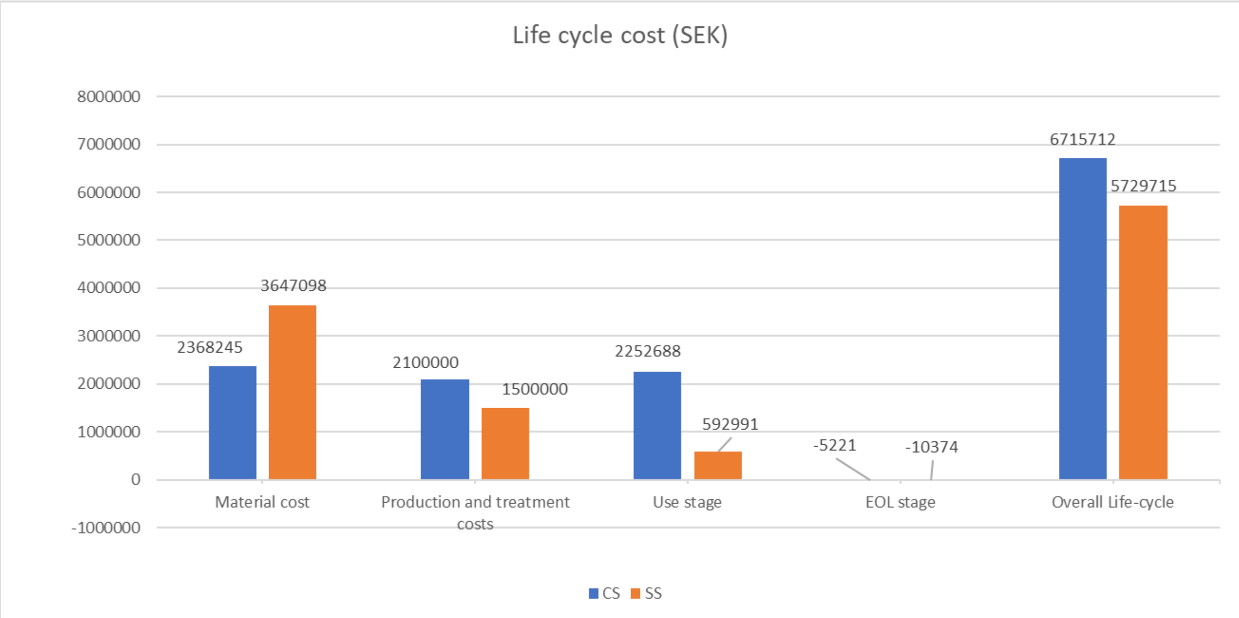

Figure 4.13: Life cycle costs of the original and new designs in case study 2

As shown in Figure 4.13, the production and treatment costs of the girder in the CS design are higher than the SS design as in case study 1. Henrysson and Yman (2020) give some reasons for explaining the situation, including the longer welding time of the carbon steel girder in the factory, the painting cost of the carbon steel girder, and the faster on-site work for the new design girder. The material costs and production and treatment costs of the girders in the two designs are shown in Table 4.16

Table 4.16: The material costs and production and treatment costs of the girders in two designs in case study 2 (Henrysson and Yman, 2020)

Cost item	CS	SS
Material cost (SEK/kg)	12	35
Girder production and treatment cost (SEK)	2,100,000	1,500,000

Figure 4.14 presents the cost distributions of the two designs. In the CS design, all three categories of costs contribute similar proportions. Compared to the costs generated in the product stage, the maintenance cost is less important in the SS design.

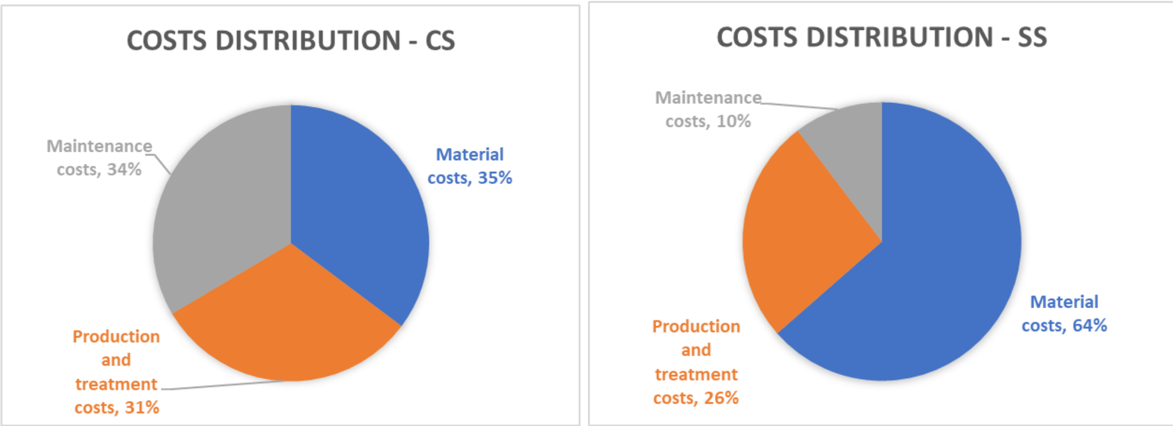

Figure 4.14: Cost distribution of the designs in case study 2

4.2.3.3 Circularity assessment results

In case study 2, only the superstructure system of the bridge is covered in the analysis. Considering the similarity between the two case studies in this thesis, we adopted similar assumptions as in case study 1, including the system dependency of superstructure (0.8), the DDFs of girder (0.6) and deck (0.2). For the railing and surfacing, we assumed that their DDFs are 0.6 and 0.1 respectively because aggregate particles in surfacing bind together through chemical reactions. Table 4.17 shows the BrCI for the two designs. According to the results, the SS design is a better option in terms of circularity. From Table 4.18, the larger quantity of virgin material use in the steel girder in the CS design results in its poor circularity performance.

Table 4.17: Bridge Circularity Indicators for all designs in case study 2

Bridge Circularity Indicator	CS	SS
Theoretical value	0.359	0.378
Practical value	0.104	0.111

Table 4.18: Detail information for the circularity calculation of the designs in case study 2

	Systems	Functional Components	Total Mass (kg)	Virgin Material (kg)	EOL Waste Output (kg)	Utility Factor	MCI	PCI
CS	superstructure	Steel girder	109,777	88,057	6,029	1	0.614	0.369
		Deck	451,147	333,845	133,608	1	0.534	0.107
		Surfacing	123,981	74,389	6,199	0.083	0	0
		Railing	2,600	2,080	130	0.5	0.235	0.141
SS	superstructure	Steel girder	84,901	24,666	4,245	1	0.847	0.508
		Deck	451,147	333,845	133,608	1	0.534	0.107
		Surfacing	123,981	74,389	6,199	0.083	0	0
		Railing	2,600	2,080	130	0.5	0.235	0.141

Chapter 5 Discussion

5.1 Key parameters of bridge design

With the assistance of the developed parametric model, users can easily create new design alternatives and scenarios to evaluate the life-cycle environmental impacts, economic performance, and circularity of bridge design. As shown in Chapter 3, lots of input variables are adopted in the parametric model. However, not all variables will have significant impacts on the outcome of the evaluation. In this section, key input variables are identified based on the results of sensitivity analysis.

For the environmental performance of bridge design, the product stage accounts for the largest proportion to the overall life-cycle impacts according to the results shown in Chapter 4. The production of materials/products needed in large quantity in bridge design is the main contributor to the impacts of bridge construction. By searching the EPDs of structural steel products produced by different manufacturers, it is found that the emission factors of these products have significant differences. For example, ArcelorMittal (Its headquarter is in Luxembourg) and Åkrene (Its headquarter is in Norway) cause the GWP of 0.524 kg CO_2 eq and 0.6 kg CO_2 eq separately while producing one kg of structural carbon steel (ArcelorMittal, 2017; Åkrene, 2021). On the other hand, the carbon steel product we adopted in case study 1, i.e., SSAB, has an emission factor of 2.71 kg CO_2 eq/kg steel produced. Thus, we conducted a sensitivity analysis of steel emission factors to find out their effects.

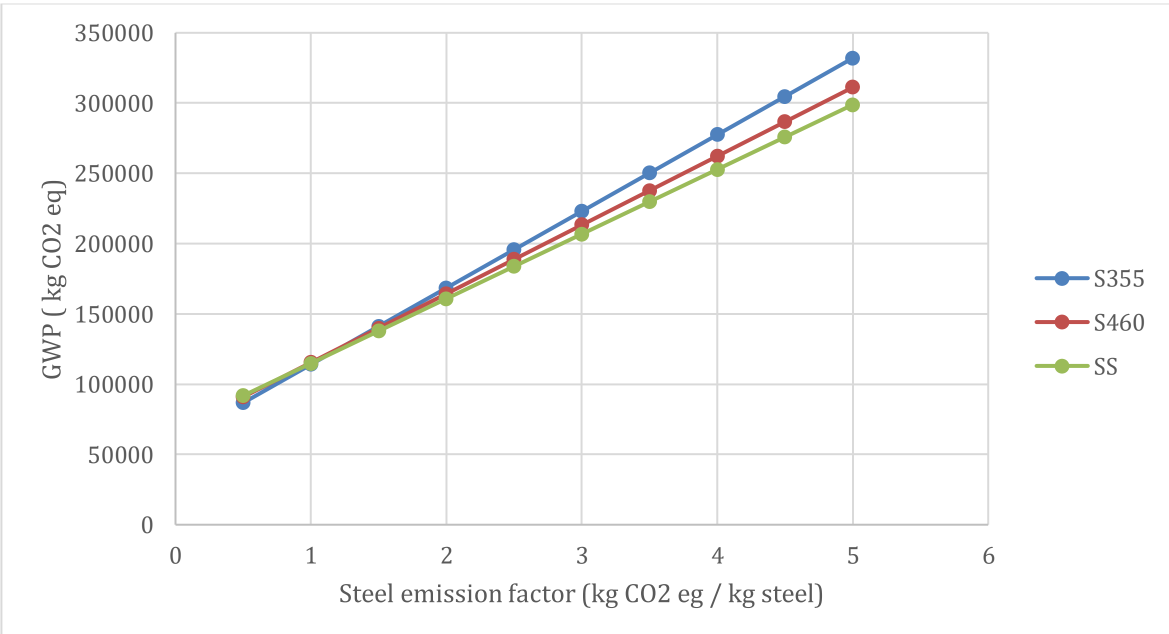

Figure 5.1: Sensitivity analysis of steel emission factors

Figure 5.1 indicates that the emission factor of steel products used in the bridge design has huge impacts on the overall environmental impact of the bridge. If the designer in our case study selects a stainless steel product with much higher emission factors, e.g., 3.5 kg CO_2 eq/kg steel, than a carbon steel product, the results of case studies will change drastically. The stainless steel alternative will not be a better option in terms of environmental performance. Thus, it is suggested that architects or engineers shall pay attention to the material/product selection while designing a bridge.

In terms of life cycle costs, material cost, production and treatment cost, and periodic maintenance cos are all important. Hence, the designs which can reduce the demands for the annual/periodic maintenance and the production and treatment processes of main components are preferred in order to reduce the total costs. For example, adopting stainless steel and designing a structure which is able to allow automatic welding could significantly decrease the life cycle costs of a bridge.

Rossi et al. (2017) indicate that the discount and escalation have significant impacts on the total life cycle costs. We conducted two sensitivity analyses, one for the discount rate and one for the escalation rate, as from 0.01 to 0.1. As shown in Figure 5.2 and Figure 5.3, the LCC of the S355 alternative decreases with the discount rate raising and increases with the escalation rate raising. However, the stainless steel alternative acts oppositely. This is because we assumed no costs (without any maintenance activity) will be generated after completing the bridge in case study 1. The only cash flow occurring in the future is the income from re-selling EOL stainless steel scraps. This revenue decreases with the discount rate raising and increases with the escalation rate raising.

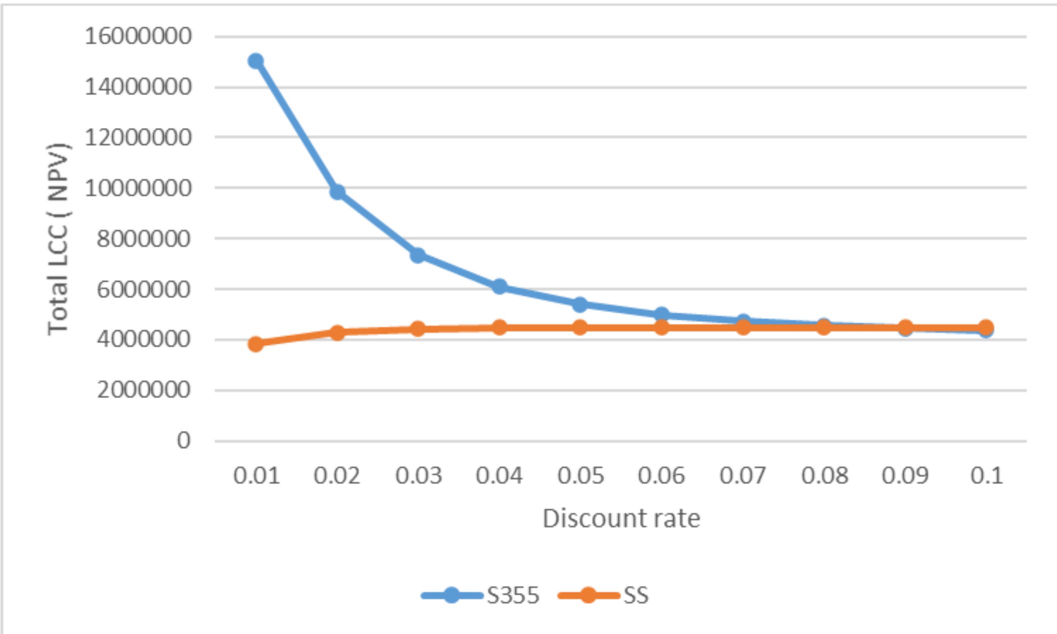

Figure 5.2: Sensitivity of the total LCC to the discount rates

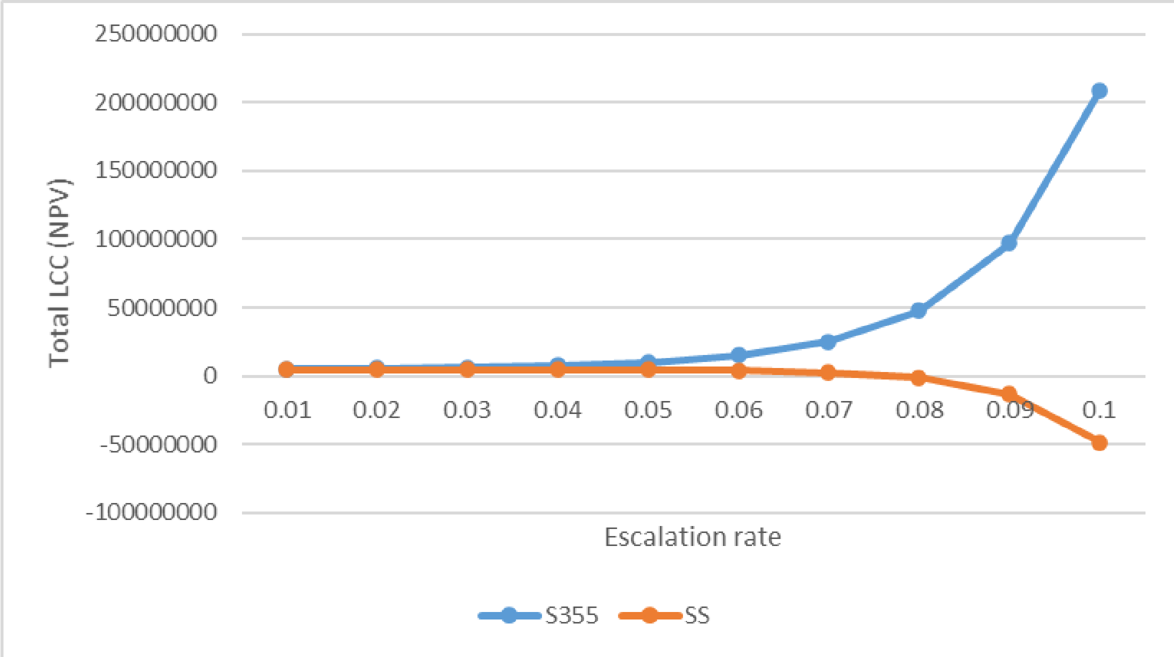

Figure 5.3: Sensitivity of the total LCC to the escalation rates

From Figure 5.2 and Figure 5.3, we can observe that the outcome of LCC comparison between different design alternatives is highly affected by the selections of discount rate and escalation rate. Thus, the uncertainties derived from these two parameters should be taken into account while conducting LCCA.

5.2 Is stainless steel a better option for bridge construction?

One of the research questions in this study is to find out whether stainless steel is a more environment-friendly and cost-effective solution than conventional steel from a life cycle perspective when it comes to bridge construction. According to the results of the case studies, stainless steel does have better economic performance than conventional carbon steel because of its advantage of low maintenance requirements. However, in terms of environmental performance (herein we focus on GWP in this study), the production of stainless steel normally causes higher GWP than conventional carbon steel. It would become the main weakness of its application on bridge construction in terms of climate change because we found around 68 to 88% of GWP coming from the product stage in the case studies. Although stainless does not need any maintenance activity, the avoided environmental burden is relatively smaller than the impacts generated during its product stage.

Chapter 6 Conclusion and further research

A bridge normally has a very long service life and a large scale. The decisions made in the bridge design stage will have significant impacts on the environmental and economic performance over the life span. In recent years, stainless steel has grabbed engineers' attention as an alternative to carbon steel. While stainless steel has the advantage of low maintenance requirements, the production of stainless steel is generally more expensive and consumes more energy than conventional steel. To the best of our knowledge, the implementation of LCA on stainless steel bridges is rather limited at present. Meantime, a general LCA requires large amounts of data input and prior knowledge of LCA. It may lead to difficulties when architects and structural engineers try to assess the potential environmental impacts of bridges in the early design stages.

Accordingly, this study conducts a comparative case study of bridges made of conventional steel and stainless steel with a simplified design-integrated life-cycle analysis tool, which enables users to estimate environmental impacts, life-cycle cost (LCC), and circularity of different design variants at the same time. Thus, a MATLAB-based tool is developed based on a parametric model consisting of three main modules, i.e., input, calculation, and output. Time-consuming procedures in LCA are simplified through default assumptions and predefined mathematical equations. Thus, quantitative outcomes of target indicators can be obtained according to the limited input variables and supplementary information from an updatable database.

The results of the case studies show that the impact factor of steel products needed in large quantity in bridge design has huge impacts on the overall environmental impact of the bridge. Selecting stainless steel with lower environmental impact factors is the key for bridge design to achieve better environmental performance. On the other hand, stainless steel is a more attractive alternative in terms of LCC. The total LCC could be lower than conventional steel bridge by avoiding maintenance activity during the use phase. Overall, the simultaneous assessment of LCCs, environmental impacts, and circularity provides a more holistic view while assessing the sustainability of bridge construction.

Due to the limitation mentioned in section 1.3, data availability and reliability may affect the accuracy of the results of the case studies. Thus, collaborations with the construction industry and steel manufacturers for more practical data is suggested. Further studies on this topic could investigate the application of other LCIA approaches to see how the results change or include more life cycle modules in the system boundary. Another interesting topic could be to collaborate with bridge designers to apply and improve the Bridge Circular Indicators developed in this study. Finally, it would be beneficial to integrate optimization process into the parametric model.

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Appendix

Input spreadsheet for case study 1 (Alternative 1: S355 Alternative 2: S460 Alternative 3: SS)

Bridge information

AlternativeNumber	BridgeServiceLife_Year	HeavyVehiclePercentage	AffectedRoadLength_km	NormalSpeed_kmPerHour	ReducedSpeed_kmPerHour	AverageDailyTraffic	TransportDistance_EOLMaterial_km	Railing_TotalLength_m	SurfacingArea_m2	ProductionTreatmentCost_SteelGirder_SEK
1	120	0.1	0.5	110	50	5000	150	0	0	2708000
2	120	0.1	0.5	110	50	5000	150	0	0	4473000
3	120	0.1	0.5	110	50	5000	150	0	0	2150000

System and component information

Alternative Number	Systems	System Dependency	System ServiceLife_Year	Functional Components	Component ServiceLife_Year	Initial Painting Area_m2	DDF_ConnectionType
1	superstructure	0.8	120	steel_girder	120	658	0.6
1	superstructure	0.8	120	deck	120	0	0.2
2	superstructure	0.8	120	steel_girder	120	658	0.6
2	superstructure	0.8	120	deck	120	0	0.2
3	superstructure	0.8	120	stainless_steel_girder	120	0	0.6
3	superstructure	0.8	120	deck	120	0	0.2

Material/Product information

Alternative Number	Systems	Functional Components	MaterialProduct Name	Material Quantity	Material Unit	Welding Length_m	FractionsFrom SecondaryMaterial	EOLScenarios
1	superstructure	steel_girder	steel_s355 2.71kgCO2_SAAB_Nordic	54500	kg	0	0.2	recycle_metal_steel
1	superstructure	steel_girder	paint	438.23	kg	0	0	incineration_paint
1	superstructure	steel_girder	welds_steel_s355	182.78	kg	238	0	recycle_metal_steel
1	superstructure	deck	concrete_plant	450192	kg	0	0.25	recycle_concrete

1	superstructure	deck	steel_reinforcement_bars	16805	kg	0	0.9	recycle_metal_reinforcement_bars
2	superstructure	steel_girder	steel_s460 2.71kgCO2_SAAB_Nordic	48943	kg	0	0.2	recycle_metal_steel
2	superstructure	steel_girder	paint	438.23	kg	0	0	incineration_paint
2	superstructure	steel_girder	welds_steel_s460	182.78	kg	238	0	recycle_metal_steel
2	superstructure	deck	concrete_plant	450192	kg	0	0.25	recycle_concrete
2	superstructure	deck	steel_reinforcement_bars	16805	kg	0	0.9	recycle_metal_reinforcement_bars
3	superstructure	stainless_steel girder	stainless_steel 2.74kgCO2_Outokumpu_Nordic	46000	kg	0	0.7135	recycle_metal_stainless_steel
3	superstructure	stainless_steel girder	welds_stainless_steel	203.68	kg	270	0	recycle_metal_stainless_steel
3	superstructure	deck	concrete_plant	450192	kg	0	0.25	recycle_concrete
3	superstructure	deck	steel_reinforcement_bars	16805	kg	0	0.9	recycle_metal_reinforcement_bars

Machinery information

Do not consider machinery use in case study 1

Analysis information

AlternativeNumber	LCIAapproach	NormalizationFactor	WeightingFactor	DiscountRate	EscalationRate	EoLBenefitConsidered
1	Climate	default	default	0.05	0.02	1
2	Climate	default	default	0.05	0.02	1
3	Climate	default	default	0.05	0.02	1

Input spreadsheet for case study 2(Alternative 1: CS Alternative 2: SS)

Bridge information

AlternativeNumber	BridgeServiceLife_Year	HeavyVehiclePercentage	AffectedRoadLength_km	NormalSpeed_kmPerHour	ReducedSpeed_kmPerHour	AverageDailyTraffic	TransportDistance_EOLMaterial_km	Railing_TotalLength_m	SurfacingArea_m2	ProductionTreatmentCost_SteelGirder_SEK
1	120	0.1	0.5	110	50	5000	150	102	502.35	2100000
2	120	0.1	0.5	110	50	5000	150	102	502.35	1500000

System and component information

Alternative Number	Systems	System Dependency	System ServiceLife_Year	Functional Components	Component ServiceLife_Year	Initial Painting Area_m2	DDF_ConnectionType
1	superstructure	0.8	120	steel_girder	120	852.9	0.6
1	superstructure	0.8	120	deck	120	0	0.2
1	superstructure	0.8	120	surfacing	10	0	0.1
1	superstructure	0.8	120	railing	60	0	0.6
2	superstructure	0.8	120	stainless_steel_girder	120	0	0.6
2	superstructure	0.8	120	deck	120	0	0.2
2	superstructure	0.8	120	surfacing	10	0	0.1
2	superstructure	0.8	120	railing	60	0	0.6

Material/Product information

Alternative Number	Systems	Functional Components	MaterialProduct Name	Material Quantity	Material Unit	Welding Length_m	FractionsFrom SecondaryMaterial	EOLScenarios
1	superstructure	steel_girder	steel_s355 2.71kgCO2_SAAB_Nordic	36859	kg	0	0.2	recycle_metal_steel
1	superstructure	steel_girder	steel_s460 2.71kgCO2_SAAB_Nordic	71738	kg	0	0.2	recycle_metal_steel
1	superstructure	steel_girder	paint	568.54	kg	0	0	incineration_paint

1	superstructure	steel_girder	welds_steel_s355	40	kg	76	0	recycle_metal_steel
1	superstructure	steel_girder	steel_studs	571	kg	0	0	recycle_metal_steel
1	superstructure	deck	concrete_plant	444201	kg	0	0.25	recycle_concrete
1	superstructure	deck	steel_reinforcement_bars	6946	kg	0	0.9	recycle_metal_reinforcement_bar s
1	superstructure	railing	steel_s355 2.71kgCO2_SAAB_Nordic	2600	kg	0	0.2	recycle_metal_steel
1	superstructure	surfacing	asphalt_6.5%_bitumen_40%_recycled	123981	kg	0	0.4	recycle_asphalt
1	auxiliary_structure	formwork	formwork_steel	27147	kg	0	0.2	
2	superstructure	stainless_stee l girder	stainless_steel 2.74kgCO2_Outokumpu_Nordic	84422	kg	0	0.7135	recycle_metal_stainless_steel
2	superstructure	stainless_stee l girder	welds_stainless_steel	29	kg	102	0	recycle_metal_stainless_steel
2	superstructure	stainless_stee l girder	stainless_steel_studs	450	kg	0	0	recycle_metal_stainless_steel
2	superstructure	deck	concrete_plant	444201	kg	0	0.25	recycle_concrete
2	superstructure	deck	steel_reinforcement_bars	6946	kg	0	0.9	recycle_metal_reinforcement_bar s
2	superstructure	surfacing	asphalt_6.5%_bitumen_40%_recycled	123981	kg	0	0.4	recycle_asphalt
2	superstructure	railing	steel_s355 2.71kgCO2_SAAB_Nordic	2600	kg	0	0.2	recycle_metal_steel
2	auxiliary_structure	formwork	formwork_steel	27147	kg	0	0.2	

Machinery information

Do not consider machinery use in case study 2

Analysis information

AlternativeNumber	LCIAapproach	NormalizationFactor	WeightingFactor	DiscountRate	EscalationRate	EoLBenefitConsidered
1	Climate	default	default	0.05	0.02	1
2	Climate	default	default	0.05	0.02	1

Database spreadsheet

Process/Activity information

LifeStage	ProcessName	ProcessUnit	GWP (kg CO2e)	CML LCIA results from Ecoinvent
product	welds_steel_s355	m	4.4*	welding, gas, steel//[RER] welding, gas, steel
product	welds_steel_s460	m	6.75*	welding, gas, steel//[RER] welding, gas, steel
product	welds_stainless_steel	m	6.09*	welding, gas, steel//[RER] welding, gas, steel

* https://link.springer.com/content/pdf/10.1007/s11367-019-01621-x.pdf (FCAW)

LifeStage	ProcessName	Process Unit	ProcessUnitCostSEK*	ActionTime year	Repeating Maintain StartingYear	Frequency year	Time requirement day_per_time	Operating Percentage	Input Name	Input Quantity	Input Unit
use	steel_girder_patchup_1st	m2	1042	13	0	0	0.5	0.05	paint	0.666	kg
use	steel_girder_overcoating_1st	m2	562	19	0	0	2	0.9	paint	0.666	kg
use	steel_girder_remove_repaint_1st	m2	2341	31	0	0	2	0.9	paint	0.666	kg
use	steel_girder_patchup_2ed	m2	1042	44	0	0	0.5	0.05	paint	0.666	kg
use	steel_girder_overcoating_2ed	m2	562	50	0	0	2	0.9	paint	0.666	kg
use	steel_girder_remove_repaint_2ed	m2	2341	62	0	0	2	0.9	paint	0.666	kg
use	steel_girder_patchup_3rd	m2	1042	75	0	0	0.5	0.05	paint	0.666	kg
use	steel_girder_overcoating_3rd	m2	562	81	0	0	2	0.9	paint	0.666	kg
use	steel_girder_remove_repaint_1rd	m2	2341	93	0	0	2	0.9	paint	0.666	kg

use	steel_girder_patchup_4th	m2	1042	106	0	0	0.5	0.05	paint	0.666	kg
use	steel_girder_overcoating_4th	m2	562	112	0	0	2	0.9	paint	0.666	kg
use	surfacing_replacement	m2	204	0	0	10	2	1	-	0	-
use	surfacing_partial_improveme nt	m2	183	0	5	10	1	0.25	-	0	-
use	railing_improvement_1st	m	1527	30	0	0	1	0.3	-	0	-
use	railing_replacement_1st	m	4072	60	0	0	2	1	-	0	-
use	railing_improvement_2ed	m	1527	90	0	0	1	0.3	-	0	-

* Data sources: Rossi, 2017; Trafikverket. 2021.

LifeStage	ProcessName	ProcessUnit	Recycling Rate	Substitute Product	GWP (kg CO2e)	CML LCIA results from Ecoinvent
eol	incineration_paint	kg			3.510096251	waste paint//[Europe without Switzerland] treatment of waste paint, hazardous waste incineration, with energy recovery + waste paint on metal//[RoW] treatment of waste paint on metal, sorting plant
eol	disposal_metal_steel	kg			0.005167336	scrap steel//[RoW] treatment of scrap steel, inert material landfill
eol	disposal_metal_stainless_steel	kg			0.005167336	scrap steel//[RoW] treatment of scrap steel, inert material landfill
eol	disposal_metal_reinforcement bars	kg			0.065211154	waste reinforcement steel//[RoW] treatment of waste reinforcement steel, collection for final disposal
eol	disposal_concrete	kg			0.013866648	waste reinforced concrete//[Europe without Switzerland] treatment of waste reinforced concrete, collection for final disposal
eol	disposal_asphalt	kg			0.012278771	waste concrete gravel//[RoW] treatment of waste concrete gravel, collection for final disposal
eol	recycle_concrete	kg	0.7	gravel	0.015857053	waste reinforced concrete//[Europe without Switzerland] treatment of waste reinforced concrete, recycling + waste reinforced concrete//[Europe without Switzerland] treatment of waste reinforced concrete, sorting plant
eol	recycle_asphalt	kg	0.95	gravel	0.013617215	waste concrete gravel//[RoW] treatment of waste concrete gravel, recycling + waste concrete gravel//[RoW] treatment of waste concrete gravel, sorting plant
eol	recycle_metal_steel	kg	0.95	pig_iron	0.044863582	iron scrap, sorted, pressed//[Europe without Switzerland] treatment of metal scrap, mixed, for recycling, unsorted, sorting
eol	recycle_metal_stainless_steel	kg	0.95	stainless_steel 0%_recycle	0.044863582	iron scrap, sorted, pressed//[Europe without Switzerland] treatment of metal scrap, mixed, for recycling, unsorted, sorting
eol	recycle_metal_reinforcement_bars	kg	0.95	pig_iron	0.05689864	waste reinforcement steel//[CH] treatment of waste reinforcement steel, recycling

Resource information

Material_Product_Name	Unit	Density kg*m-3	UnitCost SEK	EOLMaterial ResellPrice_SEK	Railway	Truck national	Truck regional	Truck local	GWP (kg CO2e)	CML LCIA results from Ecoinvent
steel_s355	kg	7850	12	1.5	1000	200	100	40	2.71	steel, low-alloyed//[RER] steel production, converter, low-alloyed
steel_s460	kg	7850	16	1.5	1000	200	100	40	2.71	steel, low-alloyed//[RER] steel production, converter, low-alloyed
stainless_steel	kg	7700	35	4	1000	200	100	40	2.74	steel, chromium steel 18/8, hot rolled//[RER] steel production, chromium steel 18/8, hot rolled
steel_reinforcement_bars	kg	7850	12	1.5	500	300	0	40	0.7	steel, low-alloyed//[Europe without Switzerland and Austria] steel production, electric, low-alloyed
welds_steel_s355	kg	7850	159	1.5	0	500	0	0	2.3	steel, low-alloyed//[RER] steel production, converter, low-alloyed
welds_steel_s460	kg	7850	159	1.5	0	500	0	0	2.3	steel, low-alloyed//[RER] steel production, converter, low-alloyed
welds_stainless_steel	kg	7700	410	4	0	500	0	0	4.5	steel, chromium steel 18/8, hot rolled//[RER] steel production, chromium steel 18/8, hot rolled
stainless_steel_studs	kg	7700	50	4	0	500	0	0	2.74	steel, chromium steel 18/8, hot rolled//[RER] steel production, chromium steel 18/8, hot rolled
steel_studs	kg	7850	50	1.5	0	500	0	0	2.71	steel, low-alloyed//[RER] steel production, converter, low-alloyed
formwork_steel	kg	7850	0	0	0	0	50	0	2.2	steel, low-alloyed//[RER] steel production, converter, low-alloyed
concrete_plant	kg	2523	1	0	0	0	0	35	0.166	concrete, 40MPa//[RoW] concrete production, 40MPa, ready-mix, with Portland cement
paint	kg	1400	150	0	0	400	0	40	3.41	electrostatic paint//[GLO] paint production, for electrostatic painting for aluminium
asphalt_6.5% bitumen_40%_recycled	kg	2243	0.8	0	0	0	50	0	0.049	0.95 gravel + 0.05 bitumen
gravel	kg	2500	-	0	0	0	30	0	0.0114	gravel, round//[RoW] market for gravel, round
pig_iron	kg	7850	-	1.5	0	1000	0	0	1.6835	pig iron//[RER] pig iron production
stainless_steel 0%_recycle	kg	7700	-	4	1000	200	100	40	4.2991	steel, chromium steel 18/8, hot rolled//[RER] steel production, chromium steel 18/8, hot rolled

Transportation and machinery information

MachineryName	Unit	GWP (kg CO2e) *	CML LCIA results from Ecoinvent
Railway	tkm	0.001	transport, freight train//[Europe without Switzerland] market for transport, freight train
Truck_national	tkm	0.079365079	transport, freight, lorry >32 metric ton, EURO6//[RER] market for transport, freight, lorry >32 metric ton, EURO6
Truck_local	tkm	0.198412698	transport, freight, lorry 16-32 metric ton, EURO5//[RER] market for transport, freight, lorry 16-32 metric ton, EURO5
Truck_regional	tkm	0.119047619	transport, freight, lorry >32 metric ton, EURO3//[RER] market for transport, freight, lorry >32 metric ton, EURO3

* Data source: Trafikverket, n.d.

MachineryName	HourlyTimeValue_SEKPerHour
passenger_vehicle	540
heavy_vehicle	145

LCA approach information

CML_Indicator	CML_Indicator_Unit	CML_NF_default
CML 2001 (superseded):acidification potential:average European	kg SO2-Eq	2.74E+10
CML 2001 (superseded):acidification potential:generic	kg SO2-Eq	2.73E+10
CML 2001 (superseded):climate change:GWP 500a	kg CO2-Eq	4.05E+12
CML 2001 (superseded):climate change:lower limit of net GWP	kg CO2-Eq	4.48E+12
CML 2001 (superseded):climate change:GWP 100a	kg CO2-Eq	4.81E+12
CML 2001 (superseded):climate change:GWP 20a	kg CO2-Eq	6.10E+12
CML 2001 (superseded):climate change:upper limit of net GWP	kg CO2-Eq	4.93E+12
CML 2001 (superseded):eutrophication potential:average European	kg NOx-Eq	3.22E+10
CML 2001 (superseded):eutrophication potential:generic	kg PO4-Eq	1.25E+10
CML 2001 (superseded):freshwater aquatic ecotoxicity:FAETP infinite	kg 1,4-DC.	5.05E+11
CML 2001 (superseded):freshwater aquatic ecotoxicity:FAETP 100a	kg 1,4-DC.	4.72E+11
CML 2001 (superseded):freshwater aquatic ecotoxicity:FAETP 20a	kg 1,4-DC.	4.69E+11

CML 2001 (superseded):freshwater aquatic ecotoxicity:FAETP 500a	kg 1,4-DC.	4.81E+11
CML 2001 (superseded):freshwater sediment ecotoxicity:FSETP infinite	kg 1,4-DC.	5.18E+11
CML 2001 (superseded):freshwater sediment ecotoxicity:FSETP 20a	kg 1,4-DC.	4.31E+11
CML 2001 (superseded):freshwater sediment ecotoxicity:FSETP 500a	kg 1,4-DC.	4.81E+11
CML 2001 (superseded):freshwater sediment ecotoxicity:FSETP 100a	kg 1,4-DC.	4.39E+11
CML 2001 (superseded):human toxicity:HTP 500a	kg 1,4-DC.	7.52E+12
CML 2001 (superseded):human toxicity:HTP 20a	kg 1,4-DC.	7.46E+12
CML 2001 (superseded):human toxicity:HTP 100a	kg 1,4-DC.	7.46E+12
CML 2001 (superseded):human toxicity:HTP infinite	kg 1,4-DC.	7.58E+12
CML 2001 (superseded):ionising radiation:ionising radiation	DALYs	48543.68932
CML 2001 (superseded):land use:competition	m2a	3.27E+12
CML 2001 (superseded):malodours air:malodours air	m3 air	0.00E+00
CML 2001 (superseded):marine aquatic ecotoxicity:MAETP 100a	kg 1,4-DC.	4.63E+11
CML 2001 (superseded):marine aquatic ecotoxicity:MAETP 20a	kg 1,4-DC.	1.16E+11
CML 2001 (superseded):marine aquatic ecotoxicity:MAETP 500a	kg 1,4-DC.	2.33E+12
CML 2001 (superseded):marine aquatic ecotoxicity:MAETP infinite	kg 1,4-DC.	1.14E+14
CML 2001 (superseded):marine sediment ecotoxicity:MSETP 500a	kg 1,4-DC.	4.63E+11
CML 2001 (superseded):marine sediment ecotoxicity:MSETP 20a	kg 1,4-DC.	2.17E+11
CML 2001 (superseded):marine sediment ecotoxicity:MSETP infinite	kg 1,4-DC.	1.14E+14
CML 2001 (superseded):marine sediment ecotoxicity:MSETP 100a	kg 1,4-DC.	5.92E+11
CML 2001 (superseded):photochemical oxidation (summer smog):EBIR	kg formed.	0.00E+00
CML 2001 (superseded):photochemical oxidation (summer smog):MIR	kg formed.	0.00E+00
CML 2001 (superseded):photochemical oxidation (summer smog):high NOx POCP	kg ethyle.	0.00E+00
CML 2001 (superseded):photochemical oxidation (summer smog):low NOx POCP	kg ethyle.	6.33E+09
CML 2001 (superseded):photochemical oxidation (summer smog):MOIR	kg formed.	8.26E+09
CML 2001 (superseded):resources:depletion of abiotic resources	kg antimo.	8.20E+07
CML 2001 (superseded):stratospheric ozone depletion:ODP 25a	kg CFC-11.	1.14E+08
CML 2001 (superseded):stratospheric ozone depletion:ODP 5a	kg CFC-11.	3.12E+08
CML 2001 (superseded):stratospheric ozone depletion:ODP 40a	kg CFC-11.	9.52E+07

CML 2001 (superseded):stratospheric ozone depletion:ODP 15a	kg CFC-11.	1.46E+08
CML 2001 (superseded):stratospheric ozone depletion:ODP 20a	kg CFC-11.	1.26E+08
CML 2001 (superseded):stratospheric ozone depletion:ODP steady state	kg CFC-11.	8.33E+07
CML 2001 (superseded):stratospheric ozone depletion:ODP 30a	kg CFC-11.	1.05E+08
CML 2001 (superseded):stratospheric ozone depletion:ODP 10a	kg CFC-11.	1.87E+08
CML 2001 (superseded):terrestrial ecotoxicity:TAETP infinite	kg 1,4-DC.	4.72E+10
CML 2001 (superseded):terrestrial ecotoxicity:TAETP 100a	kg 1,4-DC.	2.03E+10
CML 2001 (superseded):terrestrial ecotoxicity:TAETP 500a	kg 1,4-DC.	2.44E+10
CML 2001 (superseded):terrestrial ecotoxicity:TAETP 20a	kg 1,4-DC.	1.92E+10

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