NTNU – Trondheim
Norwegian University of
Science and Technology

Life Cycle Assessment of a Norwegian Bridge

Thomas Charles Edouard Dequidt

Civil and Environmental Engineering
Submission date: June 2012
Supervisor: Amund Bruland, BAT

Norwegian University of Science and Technology
Department of Civil and Transport Engineering

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF CIVIL AND TRANSPORT ENGINEERING

Report Title: Life Cycle Assessment of a Norwegian Bridge	Date: 09/06/2012 Number of pages (incl. appendices): 157			
	Master Thesis	x	Project Work	
Name: Thomas Dequidt				
Professor in charge/supervisor: Amund Bruland				
Other external professional contacts/supervisors:				

Abstract:

Life cycle assessment (LCA) methodology aims at evaluating the environmental impacts of a product or system from a holistic approach. In this methodology, all life cycle phases of the product are identified and assessed, from the raw material acquisition to the end-of-life phase.

This master thesis is dealing with the LCA of a Norwegian bridge. First, a literature review is realized by going through 14 bridge LCA references. Then, a detailed description of bridge LCA methodology is performed. Finally, an LCA study is applied on *Tverlandsbrua*, a Norwegian bridge project, in order to assess the overall global warming impact of the bridge life cycle.

The conclusions of the literature review are very different according to the goals and scopes of the studies. Concrete and timber bridges are often more environmentally performing than steel or composite concrete-steel bridges. Material production is generally the life cycle phase leading to most impacts, followed by the maintenance & repair phase. Improvements in material design and use of recycled materials are important to bring down the overall emissions.

The LCA methodology description has been through all elements specified in the ISO standards. The methodology has been adapted to the needs of the case study but the goal and scope definition has been kept wide enough to allow comparisons with future bridge assessments. Input data (energy, material flows, etc.) are as much as possible gathered from the client and subcontractors of the project, but sometimes assumed. Output data (greenhouse gases emissions) are either directly collected from environmental reports or calculated by an LCA software.

The overall global warming impact of Tverlandsbrua is 6665 kgCO_2-eq per functional unit (FU), all life cycle phases considered. The FU, i.e. the unit to which the emissions are referred, is defined as 1 square meter effective bridge deck area through a lifetime of 100 years. When the operation phase (mainly consisting of traffic-related emissions) is not considered, the emissions are brought down to 1358 kgCO_2-eq per FU. Concrete, steel and asphalt life cycles are identified as the main component contributors. Uncertainty and sensitivity analyses, discussions and recommendations for further studies are performed in order to give clues for more environmentally performing solutions.

Keywords:

1. Life cycle assessment
2. Bridge
3. Carbon footprint
4. Norwegian

Preface

At a time when our civilization is at a level of technology and knowledge that has never been reached before, tremendous issues are threatening the human being. According to the Intergovernmental Panel of Climate Change, global greenhouse gases (GHG) emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. The atmospheric concentrations of CO_2 and CH_4 in 2005 exceeded by far the natural range over the last 650,000 years. [1] This clearly shows that we contribute somehow to environmental changes. Hence, it is our duty to change our behaviour before it is too late.

In such a context, the Norwegian Ministry of Transport and Communications realizes every 4 years a National Transport Plan considering measures to reduce climate change. In its latest report, the Ministry states that new measures in the transport sector will result in a reduction in emissions between 2.5 and 4.0 million tons CO_2 equivalents in relation to expected emissions in 2020. [2] This task is partly entrusted to the Norwegian Public Roads Administration, *Statens vegvesen*, in order to reduce emissions from road transportation and infrastructures.

As a master exchange student in relation with the department of Civil and Transport Engineering of the Norwegian University of Science and Technology of Trondheim (NTNU), the purpose of my Master Thesis is to assess the climate change (or global warming) impact of the life cycle of a Norwegian road bridge, applying a robust methodology: life cycle assesment (LCA). This work is realized in cooperation with *Statens vegvesen* and the contractors and subcontractors of a Norwegian road bridge project. A comprehensive description of this methodology as well as a large literature review of previous bridge life cycle assessment studies help me ensure the reliability and accuracy of my results.

I would like to thank my NTNU supervisor Amund Bruland, the Norwegian Public Roads Administration, Reinertsen AS and all the subcontractors related to this bridge project for their precious help in this thesis. From Reinertsen AS, I especially thank Nina Oxas, Tom Kvalø, Ole Grindhagen and Øystein Wiggen for their patience and investment in my work.

Norwegian University of Science and Technology.

Trondheim, June 2012.

Thomas Dequidt.

Abbreviations

AADT : Annual average daily traffic.

ADP : Abiotic depletion potential.

AoP : Area of protection.

AP : Acidification potential.

ASCE : American Society of Civil Engineers.

AUV : Underwater concrete.

BOF : Basic oxygen furnace.

CH_4 : Methane.

CO : Carbon monoxide.

CO_2 : Carbon dioxide.

CO_2-eq : Carbon dioxide equivalent.

EAF : Electric arc furnace.

ECC : Engineered cementitious composites.

EOL : End-of-life.

EPD : Environmental performance declaration.

EVA : Ethylvinylacetate.

FRP : Fiber-reinforced polymer.

FU : Functional unit.

GHG : Greenhouse gas.

GJ : Gigajoules

GWP : Global warming potential.

GWP100 : Global warming potential, 100-year baseline.

HPC : High performance concrete.

ICE : Institution of Civil Engineers.

IndEcol : Industrial Ecology.

IOA : Input-output analysis.

IPCC : Intergovernmental Panel on Climate Change.

ISO : International Organization for Standardization.

LCA : Life cycle assessment.

LCCA : Life cycle cost analysis.

LCI : Life cycle inventory.

LCIA : Life cycle impact assessment.

MEEDDM : Ministère de l'Ecologie, de l'Energie, du Developpement Durable et de la Mer.

NO_x : Nitrogen oxides.

NPC : Normal performance concrete.

N_2O : Dinitrogen monoxide or Nitrous oxide.

PC : Prestressed concrete.

PVC : Polyvinyl chloride.

SCM : Supplementary cementitious materials.

SLCA : Social life cycle assessment.

SO_2 : Sulfur dioxide.

TFS : Transoceanic freight ship.

tkm : Tonne-kilometre.

TNT : Trinitrotoluene.

TRI : Toxics release inventory.

UHPC : Ultra high performance concrete.

vkm : Vehicle-kilometre.

VOC : Volatile organic compounds.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Definition and background

Life cycle assessment (LCA) is a methodology which aims at evaluating the environmental impacts of a product or a system during its whole life. In order to do this, each phase of the product life must be taken into consideration. For an industrial common product, these phases are raw material acquisition, transportation, production, use, maintenance & repair and end-of-life treatment (such as reuse, recycling, burning, landfilling, etc.). In a life cycle assessment analysis, a product or system is evaluated throughout the identification of all input and output flows that are responsible for the overall impact. Input flows can be material, water and energy consumptions for example, and output flows can be identified as material waste, emissions into the water and the air, etc. Once all those inventory flows have been identified and quantified, the results can be interpreted. Interpretation of results can be used to compare two different systems in order to choose the more environmentally performing, or to show which stage of a product life is the most polluting in order to improve its overall environmental performance. Figure 1.1 describes the global chart of life cycle assessment.

The LCA methodology has its origins in 1970's. One of the earliest, if not the earliest, LCA study performed was made for a major US soft drink producer in 1969. They wanted to understand the environmental aspects of alternatives to the then prevailing glass bottle. In this study the importance of having a holistic approach was demonstrated. In was understood that it was not sufficient to only include production of glass and plastic. Other elements in the life cycle were also needed to obtain a fair comparison of the two alternatives. This study provided motivation for the soft drink producer to further explore the utility of plastic bottles. [8]

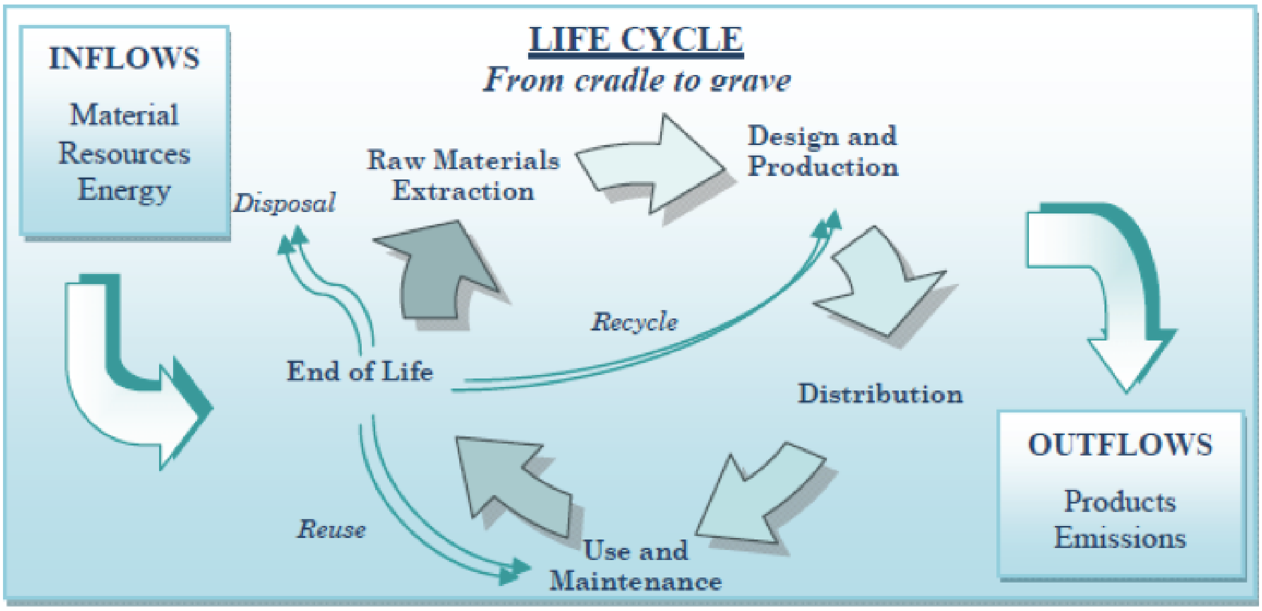

Figure 1.1: Life cycle assessment : "From cradle to grave". [3]

Today, LCA is used to assess all types of products and product systems. The importance of including the various life-cycle phases varies. For example, an assessment of a coal fired power plant will generally find that the majority of the environmental load is associated with the operation phase. The quite opposite will be the case for solar power. In that case, the production phase will cause the majority of the impacts. [8]

The ISO 14040 standards are the first standards dealing with LCA methodology and were introduced in 1997. The ISO 14040 standards are included in the ISO 14000 family dealing with environmental management. ISO 14000 standards provide environmental management guidelines, tools and methodologies for organizations, such as environmental management systems (ISO 14001 & 14004) or environmental performance evaluation (ISO 14031). ISO 14040 provides the general methodology and describes the principles for a life cycle assessment study and for life cycle inventory (LCI). However, it does not describe a particular technique for the individual phases of the study.

In 1997, the International Organization for Standardization published the first edition of the ISO 14040:1997. After that, the standards 14041:1998, 14042:2000 and 14043:2000 were published. ISO 14041 describes the inventory phase, ISO 14042 the impact assessment phase and finally the ISO 14043 provides guidance to make the interpretation of the whole life cycle assessment. The subsequent second edition of the ISO 14040 (ISO 14040:2006, Life Cycle Assessment: Principle and Framework [4]) and the ISO 14044:2006 (Life Cycle Assessment: Requirements and Guidelines [5]) replace all of them, and are currently used.

The standards ISO 14047, ISO 14048, ISO 14049 that will complement the ISO standard series 14040 are currently in process to be published. The standard ISO 14047 will contain illustrative examples of how to apply the ISO 14042 (LCIA); in the same way, ISO 14049 will provide examples to apply the ISO 14041 (LCI); finally, the ISO 14048 will involve the data documentation format for developing an LCA.

The main important aspect of the ISO 14040 standards is that they divide LCA methodology in four fundamental and complementary parts: goal and scope of the study, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation, as shown in figure 1.2. [4]

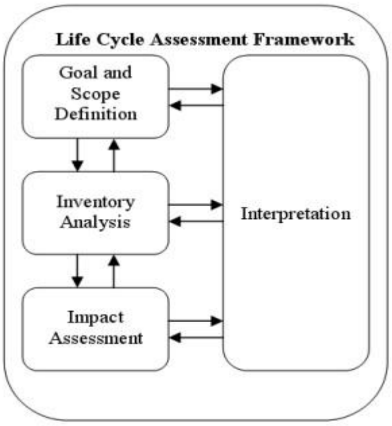

Figure 1.2: The four parts of Life Cycle Assessment methodology. [4]

1.2 Goal and scope of the study

The first stage of LCA is goal and scope definition. In this section shall be included the details of the goal of the study, its hypotheses and its boundaries. This part is fundamental because it drafts the global flowchart of the analysis and must hence be comprehensive and well-built. The most important factor in this stage is to know precisely what are the decision makers expectations so that the LCA analysis can be as accurate as possible. For example, one goal of LCA may be to compare the environmental performances of two different products, services or processes. Other studies, however, may aim at determining the stages of the life cycle that contribute the most to certain impacts. Hence, different aims influence the way the analysis should be performed. [5]

The goal and scope of an LCA analysis must provide the context in which the study is made, including the system boundaries and the approximations that need to be taken. The model and process layout are defined here. It must also provide a detailed description of the studied product including the processes, materials or products needed and the units considered in the model. Time scale and functional units also have to be established during this stage. [4]

The functional unit is the unit to which the entire system data will be referred to, both for input and output flows. The reference unit also allows to make comparisons between different LCA analyses. This unit can provide physical or functional criteria. A physical type of unit may be the characteristics of the product studied, for example resist a certain carrying load.

On the other hand, a functional type unit would provide information about the quantities of material required to fulfill an objective, for example 50 years of product full service. The level of precision of the functional unit depends on the aim of the study and its intended applications. If the analysis is very specific, the functional unit should be very precise. On the other hand, if the results are to be compared with other more general ones, the functional unit definition should be vague enough to ensure the comparisons, especially if these results constitute a basis for further studies.

The scope definition must include the data requirements and the assumptions that are going to be made, mentioning the limitations of the study. The boundaries chosen in the study are defined by the processes that are going to be included. Normally the analysis excludes stages, processes or materials of product life that are not going to be significant or that cannot provide sufficient accurate data. All these factors will condition the accuracy of the results and have to be considered in the interpretation phase. [4]

1.3 Life Cycle Inventory (LCI)

The second stage of LCA is the life cycle inventory (LCI). In this stage, the life cycle inventories are made by quantifying the different material and energy flows included during the lifetime of a product or system. This is the most complex and comprehensive phase of an LCA analysis. In order to identify and quantify these inventory flows, each main process of the product or system should be subdivided as much as possible in order to obtain unit processes, hence defining unit inventory flows, considering the system boundaries established in the goal and scope definition stage. Once again, the importance of a clear and well-built goal and scope definition is crucial [4].

There are different approaches to calculate a life cycle inventory and to estimate the contribution of each material or process to the impacts on the environment. There are different theories, for instance, in considering the contribution of recycled or reused materials as a negative factor, in order to show that they are decreasing the environmental impacts of the product.

There are many databases where the data required to calculate the output flows can be found. These databases include data for specific processes, technologies and materials. It is important to choose an accurate source of data to build the LCI, because it will influence the quality of the results. Some companies make their own inventory databases and have their own values or parameters. These values may change due to variations in measurements, types of materials involved, etc.

Finally, it is also possible to gather data directly from site investigations, in factories or plants for example. This source of data can provide very precise and accurate information, but one must bear in mind that it is often very difficult to obtain it, mainly because this type of information is usually kept private.

1.4 Life Cycle Impact Assessment (LCIA)

The impact assessment is the third stage of LCA. During this phase, the potential environmental impacts are estimated and classified, characterized, normalized and weighted in order to be interpreted for the next and final stage of the LCA analysis. [4]

The results obtained in the previous LCI phase are analyzed by calculating the contributions of each sub-process to the impact categories stated in the goal and scope definition. The output data are first aggregated by impact category, and these impact categories can be aggregated as well in order to obtain a single environmental value for the entire product analyzed. The methodology used in the impact assessment phase of an LCA is not well defined yet in the standards, and there are many different ways available to carry it out. To perform an LCIA, several impact categories exist and there are as well many methodologies available to aggregate those impact categories. The choice of these parameters depends on which impacts are included in the study, and this is generally specified by the decision makers. Nevertheless, the global methodology is quite similar for all these elements and not all of them are mandatory.

According to the latest ISO 14040:2006 [4] and ISO 14044:2006 [5] standards, an LCIA should include the selection of impact categories, category indicators and characterization models, classification as well as characterization. Other elements such as normalization, grouping and weighting are not mandatory. A more detailed explanation of each element will be performed later in this report.

1.5 Interpretation phase

In the interpretation phase, all the results obtained from the inventory and impact assessment phases of the LCA are compiled and evaluated in order to get a final conclusion. In this phase, the significant aspects of the life cycle can be identified and the alternatives are evaluated or some activities can be adjusted if required. It is all part of an iterative procedure that leads to achieve the goal of the study and make improvements in the LCA study. [4]

The interpretation must be consistent with the goal and scope definition, and reflects the main purposes of the study. Data quality and source must be verified so that the accuracy of the results and reliability of the study can be ensured, bearing in mind the boundaries, uncertainties and limitations of the study. The final conclusions must be consistent with all the previous phases and consider the subjectivity implied in the elections made in the middle steps of the LCA. The interpretation phase may also include recommendations for future analyses or researches. Other complementary analyses might be used, such as sensitivity analysis, uncertainty analysis, variation analysis, contribution analysis, dominance analysis or comparative analysis; but are not mandatory. [4] Finally, other tools can be useful to help in the decision-making process, and many other aspects aside from the environmental issues can be included in the interpretation. For example, the consideration of cultural, social or economic aspects could be important as well.

This presentation of the theoretical LCA framework aimed at familiarizing the reader with common LCA vocabulary and global methodology. Each stage of the LCA analysis will be further detailed in this report, adapting the LCA requirements to a Norwegian bridge project owned by the National Public Roads Administration (*Statens vegvesen*).

Chapter 2

Previous researches

As a basis for a comparison with the case study results, a literature review of previous bridge LCA analyses has been performed. 14 references are hence presented in this section, dating from 1998 to 2011. The first part consists in a description of the different studies performed. In a second part, the main findings are gathered in order to draw a preliminary list of elements that are important to focus on when performing an LCA analysis. A comparison between the different studies regarding the major environmental burdens, that are carbon emissions and energy use, is also performed.

2.1 Literature review

C. Zhang et al. in 2011. [9]

Environmental Evaluation of FRP in UK Highway Bridge Deck Replacement Applications Based on a Comparative LCA Study is taken from the journal *Advanced Materials Research*. An LCA analysis is performed to compare the environmental impacts of two bridge deck replacement alternatives: a fiber-reinforced polymer (FRP) deck and a conventional prestressed concrete deck. The impacts are evaluated in terms of carbon emissions. Initial demolition, construction and future maintenance are assessed. Construction equipment use, end-of-life demolition and materials recovery are not considered. Three sources of carbon emission are considered: embodied carbon of materials, transportation and traffic disruption. The life cycle design is 120 years.

It is found that for the whole service life, the prestressed concrete option is more environmentally friendly than the FRP one, even if emissions due to FRP are smaller at initial construction. During maintenance, FRP decks are less advantageous due to higher embodied carbon in the surfacing material. The demolition phase contributes in very small proportions. The impact of non-structural elements (surfacing, water-proofing and bearing replacement) is found quite important. The importance of local material sources and disposal sites to minimize impacts from transportation is also highlighted. Improvements in the manufacturing of FRP concrete could lead to less impacts in the future.

J. Hammervold et al. in 2011. [10]

Environmental Life-Cycle Assessment of Bridges is taken from the *Journal of Bridge Engineering* and published by the ASCE Association. This report presents a detailed comparative environmental life cycle assessment (LCA) case study of three bridges built in Norway. In order to encompass a wide scale of bridge designs, the analysis dealt with a steel box girder bridge, a concrete box girder bridge and a wooden arch bridge. The material production, transportation, construction, operation (excluding traffic disruption), maintenance, repair and end-of-life phases are included. 6 impact categories are considered, as well as normalization and weighting.

The study shows that the production of materials for the main load carrying systems (i.e. the bridge superstructure) and the abutments account for the main share of the environmental impacts as these parts require large quantities of materials. The three main impact categories are global warming potential (GWP), abiotic depletion potential (ADP) and acidification potential (AP). A comparison of the three bridges shows that the concrete bridge alternative performs best environmentally on the whole, but when it comes to global warming, the wooden bridge is better than the other two.

L. G. San Martin in 2011. [3]

LCA of a Spanish railway bridge is a Master Thesis realized by a KTH student (Stockholm, Sweden), dealing with the Life Cycle Assessment of a steel arch railway bridge with prestressed concrete decking. All stages are taken into account: material stage (raw material extraction, production and distribution), construction (including diesel, electricity and water), use and maintenance (repair and replacing) and the end of life. In the end of life scenario, 70% of concrete and 90% of steel are recycled and the wood is land-filled. 6 impact categories are considered, as well as normalization and weighting.

The results show that the main contributor to the environmental impacts is the material production phase, accounting for 64% of the total results. Concrete and steel production share the biggest part of the overall impacts, followed by timber production. These processes account for great amounts of CO_2 emissions. The main contributing elements are the temporal structure, the substructure and the superstructure, decreasingly.

Z. Lounis et al. in 2010. [11]

Towards sustainable design of highway bridges, published by the National Research Council of Canada, uses LCA methodology to compare two bridge deck designs: a high performance concrete (HPC) bridge deck and a conventional concrete bridge deck. This paper discusses some performance indicators, such as safety, serviceability, costs, traffic disruption, greenhouse gas emissions, which can be used for life cycle design of highway bridges. Environmental impacts, in terms of greenhouse gas emissions and waste production are estimated for all activities occurring during the life cycle of both concrete deck alternatives. The three major elements that illustrate the differences between the two alternatives are cement production, additional transportation needed for the SCMs included in the HPC mix and CO_2 emitted by cars/trucks delayed by the maintenance, repair and replacement activities. Economic and social impacts are also evaluated, but will not be discussed here.

It is found that additional transportation and differences between emissions due to traffic disruption are not very significant, but cement production shows striking differences. The CO_2 emissions due to cement production are almost three times less important for HPC than for a conventional concrete. Furthermore, the shorter service life of the normal concrete deck, which leads to an increase in traffic disruption due to earlier replacement, also contributes to the higher CO_2 emissions of the NPC deck.

Bouhaya et al. in 2009. [12]

Simplified environmental study on innovative bridge structure is taken from the journal *Environmental Science & Technology.* 3 scenarios of a composite wood-ultra high performance concrete (UHPC) bridge are studied regarding energy use and GHG emissions. Those 3 scenarios differ according to the end-of-life scenarios of the wooden girders. The first one is landfilling, the second one is burning and the third one is reuse of the wood. Material production, transportation, construction, maintenance and end-of-life phases are included. The functional unit considered is a 25 m span bridge deck.

Calculations show that the main part of the energy comes from the material. Thanks to the CO_2 uptakes of the wood during its lifetime, the overall GHG emissions are negative for the scenarios with land filling and reuse of wood. However, the consumption of primary energy is lower for the scenario in which wood is burned instead of natural gas.

Gervásio and da Silva in 2008. [13]

Comparative life-cycle analysis of steel-concrete composite bridges is taken from the journal *Structure and Infrastructure Engineering*, published by Taylor & Francis. A prestressed concrete girder bridge and a steel-concrete composite I-girder bridge are compared. Both Life

Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) methods are applied, representing an integrated methodology for a life-cycle and sustainability analysis. In the LCA, only different grades of steel and concrete inputs to the bridge and the construction phase are included (due to lack of data). 3 types of concrete mixes are assessed.

For total environmental performance the composite bridge is found the best alternative, after normalization and weighting of the results. However, when looking at Global Warming only, both bridges have roughly the same overall performance. The results of the Life Cycle Cost Analysis are not discussed here.

Collings in 2006. [14]

An environmental comparison of bridge forms is taken from the journal *Bridge Engineering*. Two studies are presented. One (*the initial study*) is about three alternative bridge designs related to the same site (a major creek crossing in the Middle East), the second (*the primary study*) is about three alternative bridge forms crossing a river in the UK (river width approximate 120 m). *The initial study* comprises a concrete cantilever bridge, a concrete cable stay bridge and a steel arch bridge. CO_2 emissions are found highest for the steel bridge. Paint, waterproofing and plastics are important in spite of small amounts. *The primary study* considers three basic forms with three material choices for each alternative. This gives 9 alternatives in total; girder, arch and cable stayed bridges using steel, concrete or steel-concrete composite design material.

The results show that concrete bridges have lower embodied energy and CO_2 emissions. Moreover, the differences between steel and concrete bridges appeared insignificant for small structures (20 m). It is also found that a well-engineered longer span (120 m) bridge utilizing local materials, recycled steel and cement produced by the dry process (plus some cement replacement) can be almost as environmental friendly as a shorter-span (20 m) structure in which no consideration has been given to environmental issues. More architectural solutions, like leaning or distortion of elements, have larger environmental impact as they require more material and more complex construction (arch and cable stay bridges versus girder bridges).

Report from the MEEDDM in 2006. [15] (French reference)

Analyse du Cycle de Vie d'un pont en béton is a French report entitled *Life Cycle Assessment of a concrete bridge, example of application on a common bridge* in English. This handbook gives general guidelines to assess the environmental impacts of a bridge project. It is to be applied for prestressed concrete structures. The analysis covers the evaluation of the deck, piers and foundations, as well as the superstructure equipment. The functional unit is defined as a prestressed concrete bridge used as a highway infrastructure for a life time of 100 years. The impacts from traffic are not assessed. The loads were designed according to French recommendations (not Eurocodes). The study includes: raw material acquisition, transportation, fabrication of components, construction, maintenance and repair and recycling of the material after end of life. The material used for the site preparation and installation is also included in the analysis. 9 environmental impacts are assessed, including global warming and energy use.

The results show that the material fabrication stage accounts for the most important part of the emissions: for 6 impacts indicators, it represents between 31 and 59% of the total emissions. The surveillance, maintenance and repair stage represents the second most important field.

K. Steele et al. in 2005. [16]

Environmental sustainability for bridge management is taken from the journal *Bridge Management 5* and published by Thomas Telford Limited. An LCA analysis is performed to compare the environmental impacts of three bridge designs: a steel through deck, a reinforced concrete beam bridge and a brick arch structure. These three bridges all had similar service functionality: a span of approximately ten meters, a 40 ton design load capacity, a 120-year design life and a single lane carriage way capacity. The impacts are given in Ecopoint indicators.

It was determined that up to the point of bridge completion, the two beam structures had a lower environmental impact than the arch bridge. The single biggest cause of environmental impact during a bridge life cycle can be attributed to construction. Design efficiency is important and careful use of materials is critical to realize a low impact solution. Consideration of structure service life and construction of an adaptable bridge will minimize life cycle impact. Movement of materials to and from the construction site is identified as important as is minimization of construction waste. For existing bridge infrastructure, it is generally environmentally better to maintain, refurbish, or strengthen the structure rather than demolish it and rebuild again. Finally, the environmental burden of traffic disruption and vehicle diversions can make significant contribution to the overall environmental impact of bridge works activity.

Keoleian, Kendall et al. in 2005. [17]

Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints is taken from the *Journal of Infrastructure system*, published by the ASCE association. Two types of deck systems are compared; a steel-reinforced concrete deck with conventional steel expansion joints and a steel-reinforced concrete deck with a link slab design using a concrete alternative; engineered cementitious composites (ECC). The study includes material production, construction, use and end-of-life management related to the bridge decks. Three reconstruction options are considered; bridge deck replacement, deck resurfacing and repair and maintenance (mainly fixing of cracks and potholes) including the traffic disruption due to these activities.

The analysis shows that the ECC deck yields significantly lower environmental impacts, for all pollutants (because of less need for maintenance). Traffic disruption due to construction and repair is significant for the environmental performance for both decks. It is also found that predicting maintenance and repair schedules for each system is critical in evaluating the performance of alternative materials.

Martin in 2004. [18]

Concrete bridges in sustainable development is taken from *Proceedings of the ICE*. Two comparisons of bridge deck designs are performed in this study using LCA methodology. The decks are evaluated regarding energy use and greenhouse gases emissions, and the whole life cycle of the construction materials was considered, from raw material extraction to demolition and recycling. The first one compares a steel-concrete composite deck and a concrete deck (including girders). In the second study, three types of concrete for bridge decks are compared : lightweight, normal density and high-strength concrete (including girders).

In this first study, the concrete alternative gives lower embodied energy and GHG emissions (given as CO_2-equivalents) when considering new materials, but the composite solution gives lower GHG emissions when recycled materials are used. In the second one, no significant difference in energy consumption is found for the three alternatives. However, the high-strength concrete is supposed to have longer durability, and might thus be the preferred alternative.

Y. Itoh et al. in 2003. [19]

Using CO_2 emission quantities in bridge life cycle analysis is taken from the journal *Engineering Structures* and published by Elsevier. A modified life cycle methodology is used to evaluate and compare two types of steel bridges; a conventional and a minimized girder bridge. The conventional bridge has 7 longitudinal girders and the minimized girder bridge has only 3, and thus requires less steel. A prestressed concrete deck is required for the minimized girder, as this shall contribute to structural rigidity. The bridges are compared regarding CO_2 emissions and costs. The life cycle stages included are construction, use and replacement.

The results show that the minimized girder bridge gives both lower CO_2 emissions and costs in total, and also when looking at maintenance only the emissions are the lowest for the minimized girder bridge, mainly because the prestressed concrete deck requires far less maintenance than the reinforced concrete deck.

A. Horvath et al. in 1998. [20]

Steel versus Steel-Reinforced Concrete Bridges: Environmental Assessment, taken from the *Journal of Infrastructure Systems* and published by the ASCE association, presents an environmental assessment on two bridge alternatives; steel and steel-reinforced concrete bridges. In this study, a combination of LCA and economic input-output analysis is applied. This method is predicated on the fact that in a modern economy every sector contributes, directly or indirectly, to every other sector. Economic input-output analysis explicitly accounts for all of the direct and indirect inputs to produce a product or service by using the input-output matrices of a national economy. For example, cement production and electricity are direct inputs of concrete production, but many agricultural and service sectors are indirect, or second, third, etc., tier suppliers [8]. This makes the system border very wide as input-output includes all upstream activities in the system (all economic sectors). Three groups of environmental impacts are quantified in this study; TRI chemical emissions, hazardous waste generation and conventional air pollutants emissions. Material inputs for the two bridges, including all upstream activities for the production of these are included. For the use phase, only repainting of the steel structure is included.

The concrete design has lower overall environmental effects. Environmental effects through the lifetime of the bridge can be highly important, as SO_2, NO_x, CH_4 and VOC emissions are significantly higher for paint manufacturing than for the production of all girders for the example bridge. It is stressed that if more environmental effects were included, or if there were other designs, the results might have been different. It is also pointed out that bridges are often demolished due to obsolescence rather than reaching their end of service life. Here is suggested an argument to choose materials with the lowest environmental impact rather than the highest durability, as durability becomes irrelevant.

J. Widman in 1998. [21]

Environmental Impact Assessment of Steel Bridges, taken from the *Journal of Constructional Steel Research* published by Elsevier, deals with an LCA analysis performed on two types of bridges: a steel box girder bridge and a steel I-girder bridge with concrete decking. The inventory includes all state-of-the-art data available (at the time) on the products and processes. The studied unit is environmental impact (as kg air emission) per square meter lane.

The concrete in steel bridges contributes to almost 50% out of the environmental impact and the fact that steel bridges need less material than concrete bridges, shows that steel bridges are good environmental choices. The emissions CO_2, NO_x, SO_2 and CO correspond to more than 95% in weight out of the total airborne emissions. As environmental effects from the maintenance part are very small, it is not important to increase the longevity by using a lot of corrosion protective substances or extra amounts of material to prevent material deterioration.

2.2 Main findings

2.2.1 Preliminary results

This literature review gathered different approaches of bridge environmental assessment. Some references focused on the comparison of the life cycle environmental performance of several bridges, others simply gave recommendations regarding environmental - or even sustainable - issues related to bridge projects, and others did both. Even if different assumptions were made by the authors, some common recommendations and results can be found. Here is a (non-exhaustive) list of the main issues discussed in the articles:

Goal of the study

Among all the references, 12 perform an LCA analysis in order to compare the environmental impacts of different bridge designs and 2 realize a comprehensive general analysis of bridge LCA with a case study. This shows that LCA methodology is often used as a comparative tool in order to choose the best environmental solution, but it can also be performed in order to assess the overall environmental performance of one type of bridge, which is for example the intended goal of this thesis.

Types of bridges

45 bridges are assessed within the 14 references selected, including 22 concrete, 13 steel (including steel-concrete non-composite), 5 steel-concrete composite, 4 wood and 1 brick bridges. This shows that concrete bridges are predominant in bridge life cycle assessment and that concrete and steel represent the two principal materials used in bridge design, compared to wood or brick.

Functional unit

Only 5 authors clearly define their functional unit. Most of the time, the results are given considering the overall impact of the bridge or some of its elements, according to the goal and scope definition of the study. This choice of functional unit makes difficult the possibility of having comparisons between the results of different studies, as bridge geometry or selection of the elements assessed differ, for example. However, one reference [10] defined its functional unit as "1 square meter effective bridge surface area" (i.e. approximately the upper deck surface area), which can be a good functional unit to compare analyses dealing with different bridge geometries.

Life cycle phases considered

Due to limitations in data availability and accuracy, some authors do not include all life cycle stages in their analysis. Material production, transportation, construction and maintenance phases are always taken into consideration. 6 references consider end-of-life treatment. Traffic disruption due to maintenance activities is evaluated in 2 studies, but regular traffic is never considered. The assumptions regarding which processes are included or not in the life cycle phases differ a lot according to the references. However, a majority of the studies consider the impacts from main material processes (concrete, steel or wood production, as well as the construction and maintenance activities related) including the amount of energy required, transportation to the site, assembly at site as well as repair, maintenance and replacement activities.

Design service life

8 references consider a design service life of 100 years or more (120 years for 4 references), which is the average design service life in bridge management. The other studies do not consider the entire bridge (e.g. only a bridge deck replacement) and hence use a shortened design service life.

Emissions and impact categories considered

5 references consider more than 6 impact categories in their studies, usually accompanied with weighting and normalization of the results. 8 references use global warming potential in their studies while the others just consider CO_2 emissions or discarded air pollutants. Energy use is explicitly calculated in 6 references. This is not an impact category as defined in LCA ISO standards, but it gives representative information about the environmental performance of a bridge project.

Life cycle phases contributing to major environmental impacts

For all references, material production (sometimes included in the construction phase of the bridge) is the biggest contributor. The second most contributing phase is either maintenance and repair (3 references) or traffic disruption due to construction or maintenance and repair activities (2 references).

Bridge components contributing to major environmental impacts

Most of the time, only the bridge superstructure (and more precisely its structural elements) is considered in the analyses. Among the 2 references considering a complete bridge assessment, only one finds out that temporal form work and bridge substructure lead to more environmental impacts than the bridge superstructure. Most often, as the structural elements of the superstructure contain the most important part of total material use, and as material phase is related to the biggest share of the environmental impacts, only bridge decks and their supporting features (girders, arches, cables, etc.) are considered.

Best environmental choice in comparative studies

Among the 12 comparative studies of the literature review, 3 references highlight innovative bridge deck design (ECC link slabs, HPC concrete, minimized number of girders) over conventional bridge deck design. Regarding the studies assessing different material choices, concrete is often the best environmental solution regarding the overall impact (5 references). However, for greenhouse gases (GHG) emissions; steel, composite or wooden alternatives are sometimes preferred (3 references), especially if recycled material are used (1 reference).

Other recommendations

A few similar recommendations are given by the authors, mainly considering material and design quality, but also LCA recommendations for further studies. It is often stated that use of recycled or sustainable material is strongly recommended as it can lower efficiently burdens from material phase, as well as use of renewable energy. For LCA practitioners, it is important to consider transportation distances and traffic disruption during construction or maintenance, as they can represent an important share of the environmental impacts. Hence, as this is directly related to bridge owners, designers and contractors, local material source is important to minimize transportation related emissions, so are maintenance schedules in order to limit traffic disruption related emissions as much as possible. 2 references considering timber bridges insist on the positive impact of CO_2 uptakes during wood life cycle. Another one indicates that more architectural solutions (cable-stayed bridges, for example) often lead to more environmental impacts, as they require more material and construction features to be realized.

2.2.2 Carbon emissions and energy consumption

In this section, the main results regarding carbon emissions (in terms of $kgCO_2$ or $kgCO_2$-eq emissions) and energy consumption (in GJ) are presented. Within the 14 references selected, 33 and 28 out of the 45 bridge case studies show the total amounts of carbon emissions and energy use, respectively. The other studies simply show the shares of carbon emissions and energy use within the different life cycle phases. As stated earlier, energy use is not an impact category as indicated in the ISO standards, but this category gives a representative idea of the environmental performance of a bridge project.

As a recurrent choice in the literature, the reference unit selected to allow comparison of the results is "1 square meter effective bridge deck area through a lifetime of 100 years". The case studies are sorted according to the material design choice (concrete, steel, composite concrete-steel or wood) in order to identify the importance of this parameter in bridge design, as often stated by the authors in the literature review. Average values are also calculated, first by mixing all design materials and then by taking them individually. However, two references, Bouyaha et al. (2009) [12] and Gervasio et al. (2008) [13], covering 5 case studies, are not included in the average values as their scopes and assumptions differ a lot from those of the other studies.

As the references chosen cover a very wide range of bridge and material designs, scopes, inventories and assumptions, the purpose of this section is not to realize a comprehensive comparison of the results, but to give an average estimation of the carbon emissions and energy consumption related to typical bridge designs. Hence, no investigations have been realized about correlations between the functional unit (effective deck area), carbon emissions and energy use, since this would not have been accurate. The results of this work shall not be directly used to draw strict conclusions about carbon emissions and energy use of bridges.

All bridges

When combining all results regardless material design choice and excluding Bouyaha et al. (2009) [12] and Gervasio et al. (2008) [13], the average values for carbon emissions and energy consumption are 1830 $kgCO_2$ and 23.1 GJ per functional unit (FU), respectively. As the results for carbon emissions mix CO_2 emissions and global warming, the calculated average value is slightly overestimated, as global warming takes into account other emissions, such as methane or nitrous oxide. A sensitivity analysis should be performed to evaluate the importance of this mix-up regarding the accuracy of the results, however this will not be done here due to the absence of data for these other emissions. The carbon emission and energy consumption values range from 107 to 3720 $kgCO_2$ and from 4.65 to 51.6 GJ per FU, respectively. The bridge deck area varies from 144 to 3400 m^2, with an average value of 2495 m^2.

Concrete bridges

20 case studies deal with concrete bridges which makes concrete the most common material in bridge construction, in the framework of this literature review.

Table 2.1 displays carbon emission and energy consumption values for each case as well as average values for concrete bridges. As a first conclusion, we can state that in average and in the scope of this review, concrete bridges are more environmentally efficient, both regarding carbon emissions (1590 kgCO_2 per FU) and energy consumption (20.5 GJ per FU). One reason is that a lot of improvements are regularly achieved in concrete design regarding its environmental effectiveness. Fiber reinforced concrete (FRC), high performance concrete (HPC) and engineered cementitious composite (ECC) concrete for link slabs are examples of more durable concretes, even if FRC still needs improvements in its production to be environmentally competitive.

HPC material is the best concrete option for carbon emissions (133 kgCO_2 per FU) and a prestressed concrete simple box girder bridge scores the lowest energy consumption value for any material design (4.65 GJ per FU). The worst concrete option for both carbon emissions and energy consumption scores 3390 kgCO_2-eq per FU and 48.8 GJ per FU, respectively, and consists in a conventional reinforced concrete deck with steel expansion joints. A concrete arch bridge scores the second worst environmental burdens for both categories. Gervasio et al.(2008) [13] gives significantly lower values for both categories, as only concrete and steel production are included in the calculations of carbon emissions and energy use, respectively.

Concrete bridges						
Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Zhang et al., 2011	FRP bridge deck	144	2670	kgCO_2	-	-
Zhang et al., 2011	Prestressed deck	144	2380	kgCO_2	-	-
Hammervold et al. 2011	Box girder (whole bridge)	417	600	kgCO_2-eq	-	-
Lounis et al., 2010	HPC deck	597	133	kgCO_2	-	-
Lounis et al., 2010	Reinforced deck	597	378	kgCO_2	-	-

Continue on next page

Continued from previous page

Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Collings, 2006	Cantilevered viaduct	4300	1500	$kgCO_2$	18	GJ
Collings, 2006	Cable-stay viaduct	4300	1420	$kgCO_2$	18.4	GJ
Collings, 2006	Girder bridge	4300	2050	$kgCO_2$	25.5	GJ
Collings, 2006	Arch bridge	4300	3340	$kgCO_2$	40.9	GJ
Collings, 2006	Cable-stay bridge	4300	3110	$kgCO_2$	36.6	GJ
MEEDDM, 2006	Prestressed bridge (whole bridge)	495	1370	$kgCO_2$-eq	13.2	GJ
Keoleian et al., 2005	Reinforced deck with steel exp. joints	2560*	3390*	$kgCO_2$-eq	48.8*	GJ
Keoleian et al., 2005	Reinforced deck with ECC link slab	2560*	2280*	$kgCO_2$-eq	29.3*	GJ
Martin, 2004	Prestressed bridge	330*	621*	$kgCO_2$-eq	5.24*	GJ
Martin, 2004	Post-tensioned box girder bridge, lightweight concrete (B45)	3200*	-	-	14.5*	GJ

Continue on next page

Continued from previous page

Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Martin, 2004	Post-tensioned box girder bridge, normal concrete (B65)	3200*	-	-	13.7*	GJ
Martin, 2004	Post-tensioned box girder bridge, high-strength concrete (B85)	3200*	-	-	13.3*	GJ
Itoh et al., 2003	Prestressed simple pre-tensioned T-girder bridge	2250*	120	$kgCO_2$	4.7*	GJ
Itoh et al., 2003	Prestressed simple box girder bridge	2250*	107	$kgCO_2$	4.65*	GJ
Gervasio et al., 2008**	Prestressed box girder	10862	53.2***	$kgCO_2$	0.912***	GJ
Average	**-**	**2287***	**1590***	**$kgCO_2$**	**20.5***	**GJ**

* Estimated values.
** Not included in the average values.
*** Only concrete production is assessed for carbon emissions and steel for energy use.

Table 2.1: Concrete bridges

Steel bridges

7 case studies deal with steel bridges. Table 2.2 displays carbon emission and energy consumption values for each case as well as average values. The average values show that steel bridges contributes to significantly higher carbon emissions (2180 kg CO_2 per FU) and energy consumption (31.0 GJ per FU) than concrete bridges. Furthermore, the worst values amongst all bridges are scored by two steel arch bridges; a steel arch with prestessed concrete deck contributing the most to global warming (3720 kgCO_2-eq per FU), and another steel arch bridge holding the most important energy consumption value (51.6 GJ per FU).

These values show, in the scope of this review, that steel bridges are much less environmental effective than concrete bridges, mainly because steel requires much more energy for its production than concrete and hence emits more carbon emissions. Furthermore, less improvements have been achieved to reduce environmental burdens related to steel production, compared to concrete, whose design improvement already showed its environmental effectiveness.

Steel bridges						
Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Hammervold et al., 2011	Box girder**	321	790	kgCO_2-eq	-	-
San Martin, 2011	Arch with PC deck**	672	3720	kgCO_2-eq	-	-
Collings, 2006	Arch viaduct	4300	1430	kgCO_2	19.6	GJ
Collings, 2006	Girder bridge	4300	2340	kgCO_2	32.8	GJ
Collings, 2006	Arch bridge	4300	3610	kgCO_2	51.6	GJ
Collings, 2006	Cable stay bridge	4300	3190	kgCO_2	42.2	GJ
Itoh et al., 2003	Box girder bridge	2250*	200*	kgCO_2	8.98*	GJ
Average	**-**	**2920***	**2180***	**kgCO_2**	**31***	**GJ**
* Estimated values.						
** Whole bridge.						

Table 2.2: Steel bridges

Steel-concrete composite bridges

5 case studies deal with steel-concrete composite bridges. Table 2.3 displays carbon emission and energy consumption values for each case as well as average values. The average values for carbon emissions (2490 kgCO_2 per FU) and energy consumption (32.5 GJ per FU) are slightly higher than for steel bridges. We can notice that the steel-concrete composite arch bridge scores the highest carbon emission (3720 kgCO_2 per FU) and energy consumption (50.7 GJ per FU) values, as it was the case for concrete and steel arch bridges.

Steel-concrete composite bridges						
Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Collings, 2006	Girder bridge	4300	2290	kgCO_2	30.8	GJ
Collings, 2006	Composite arch bridge	4300	3720	kgCO_2	50.7	GJ
Collings, 2006	Cable stay bridge	4300	3190	kgCO_2	39.8	GJ
Martin, 2004	Girder bridge	330*	752*	kgCO_2-eq	8.59*	GJ
Gervasio et al., 2008**	I-girder bridge	10862	25.2***	kgCO_2	1.42***	GJ
Average	**-**	**3308***	**2490***	**kgCO_2**	**32.5***	**GJ**
* Estimated values. ** Not included in the average values. *** Only concrete production is assessed for carbon emissions and steel for energy use.						

Table 2.3: Steel-concrete composite bridges

Timber bridges

4 case studies deal with timber bridges. However, Bouyaha et al.(2009) [12] and Hammervold et al.(2011) [10] have different assumptions regarding wood in its material production phase. The former includes the carbon dioxide uptakes of wood during its lifetime and the latter simply considers wood as carbon-neutral. Hence, in the former study, the overall life cycle carbon emissions are negative whereas in the latter one, the carbon emissions are positive. These two scopes are too different to enable relevant comparisons and calculations of average values for timber bridges.

Nevertheless, table 2.4 indicates low carbon emission and energy consumption values, all case studies considered (550 kgCO_2 per FU and 11.3 GJ in the worst case, respectively). The end-of-life treatment of timber leads to very different results, as wood combustion creates more carbon emissions but saves energy, and vice-versa for wood landfilling/recycling. In any case, timber seems to be an interesting material for bridges thanks to its environmental properties. However, the deck areas taken from the case studies are relatively low, so we cannot conclude about the suitability of timber for bigger structures.

Timber bridges						
Reference	**Type of bridge**	**Effective deck area (m^2)**	**Carbon emissions (per FU)**	**Unit**	**Energy consumption (per FU)**	**Unit**
Hammervold et al. 2011	Arch (whole bridge)	229	550	kgCO_2-eq	-	-
Bouyaha et al., 2009	UHPC decking (wood landfilling)	250	-6.72	kgCO_2	11.3	GJ
Bouyaha et al., 2009	UHPC decking (wood combustion)	250	101	kgCO_2	7.44	GJ
Bouyaha et al., 2009	UHPC decking (wood recycling)	250	-71.9	kgCO_2	11.3	GJ

Table 2.4: Timber bridges

2.3 Conclusions

This literature review considered a wide range of studies with very different scopes. Generally, material production is pointed out as the most polluting life cycle phase, followed by maintenance. Transportation distances and traffic disruption may also be important factors to be considered. By sorting the different bridge case studies according to their main design material, we could see that timber and concrete offer relative environmentally performing solutions, compared to steel and steel-concrete composite alternatives. Carbon emissions and energy use values confirm the importance of material design improvement (especially for concrete and steel, as they represent the two most wide-spread materials in bridges). More architectural bridges (arch, cable-stay, etc.) are also likely to increase environmental impacts due to more complex construction methods and design materials. However, no general conclusions can be drawn about the overall impact of the bridges during their lifetime, as important differences in scopes and assumptions were considered.

Chapter 3

Bridge Life Cycle Assessment

This chapter deals with a comprehensive methodology description of bridge life cycle assessment. All four major phases (goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results) are described in detail according to ISO standards and previous bridge LCA references. This section applies the recommendations from the standards to a case study but the scope, assumptions and limitations remain wide enough to allow comparisons of the results with future bridge assessments.

The construction of the methodology is related to the needs of *Statens vegvesen*, the Norwegian Public Roads Administration. As owners of the roads and bridges in Norway, this administration was interested in an environmental assessment of their bridges. Their original wish was to obtain an environmental evaluation of one of their current bridge projects that could serve as a basis for the assessment of future bridge projects. Hence, this methodology must be sufficiently accurate and focused on the impact assessment of Norwegian bridge projects, but wide enough to include the possibility of different bridge designs, geometries, etc. However, as pointed out in chapter 2, the choices of materials or deck designs can lead to very different conclusions regarding the environmental burdens of a whole bridge. In order to deal with this issue, limitations will be stated regarding the scope and interpretation of the methodology.

3.1 Goal and scope definition

This section aims at describing the first stage of LCA methodology, i.e. goal and scope definition. In this part, the purpose of the study, its aim, its boundaries, assumptions and approximations will be stated, as well as the model and process layout. A meticulous attention will be attributed to the boundaries of the study, especially regarding foreground processes related to material manufacturing phases and energy production processes.

3.1.1 Goal of the study

According to ISO 14040:2006 standard [4], this phase shall include the intended application, the reason for carrying out the study, the intended audience (to whom this study is to be communicated and useful) and whether the results are intended to be used in comparative assertions intended to be disclosed to the public (not included in this report).

Intended application

This study is carried out in cooperation with *Statens vegvesen*. The bridge project chosen for the case study is *Tverlandsbrua*, located near Bodø, Norway. The intended goal of this study is to identify the overall environmental impact of this bridge and use the results as a basis for further bridge projects. Furthermore, the results of the case study will be compared to similar previous studies.

Reason for carrying out the study

The growing worldwide awareness of climate change and its environmental, social and economic impacts are not to be proved anymore, and this is even more obvious in the building and construction sector. In 2007, according to the Norwegian National Transport Plan 2010-2019, the transport sector was responsible for approximately 25 per cent of Norway's total greenhouse gas emissions. The last decades have shown a substantial increase in emissions from the sector, and the Government's goal is that existing and new measures in the transport sector will result in a reduction in emissions between 2.5 and 4.0 million tons CO_2-equivalents in relation to expected emissions in 2020 [2]. This plan was established by the Norwegian Ministry of Transport and Communication and *Statens vegvesen* is responsible for its application in the road transport sector. Hence, the Norwegian Public Roads Administration is carrying out studies in order to estimate the CO_2-equivalent emissions from the Norwegian roads, bridges and tunnels.

Life cycle assessment is one of the methodologies intending to assess those impacts. Contrary to other environmental management techniques, such as risk assessment, environmental performance evaluation or environmental impact assessment; LCA is historically the first holistic approach, considering a product in its entire lifetime. This life cycle approach allows to obtain very detailed and precise results, considering all the processes involved in the realization of the product or system.

Intended audience

The intended audience of this thesis regroups NTNU university, *Statens vegvesen*. As this audience might not be familiar with LCA methodology, a complete description of the methodology is performed in this thesis to help them understand life cycle assessment methodology. This study can also help LCA practitioners for future bridge LCAs.

3.1.2 Scope of the study

The definition of the scope of the study is the second part of the goal and scope definition. According to the ISO 14040:2006 standard [2], the scope of the study shall include the product or system to be studied, its functions, the functional unit, the system boundaries, allocation procedures, impact categories selected and methodology of impact assessment, data requirements, assumptions, limitations, initial data quality requirements, type of critical review (excluded here) and type and format of the report required for the study (excluded here).

Product studied

The product studied here is the *Tverlandsbrua* bridge. This bridge is located in the Nordland county, 15 km from Bodø. The deck design is a post-tensioned concrete box-girder, with a main span of 165 m and a total length of 670 m (abutment to abutment). The effective width is 23.45 m. The bridge is designed for a double traffic lane in each direction and a pedestrian/bicycle lane. The works started in early June 2011 and are to be achieved in late September 2013. The mounting method chosen by the contractor is a balanced cantilevered traveling formwork system. This system is made up of two mobile wagons supporting the bridge deck formwork. The wagons are installed at the top of the columns axis and are moved from a 5 meters maximum distance each time the in-situ cast concrete part has reached a sufficient strength.

Function

The purpose of this bridge is to link Løding, a coastal city, and Vikan by crossing the Salt fjord, hence shortening the traveling distance between both cities by 3 km and reducing the traffic jams that occur in the morning and in the afternoon. The annual average daily traffic (AADT) estimated by *Statens Vegvesen* is 8600 veh/day for the bridge opening in 2013 and is assumed to grow up until 15000 veh/day by 2113. [?]

Functional unit

According to the ISO 14040:2006 standard, the functional unit is defined as *the quantified performance of a product system for use as a reference unit* (section 3.20). In other words, it helps quantifying the product identified functions. This aims at providing a reference to which the inputs and outputs are related. The definition of the functional unit is, among other things, primordial to allow comparison of results between different systems. Moreover, if additional functions of any of the systems are not taken into account in the comparison of functional unit, then these omissions shall be explained and documented [5].

In our LCA study, the functional unit must be sufficiently precise to allow the impact assessment of the *Tverlandsbrua* bridge, but wide enough to include the possibility of the environmental assessment of future bridge projects. As described in a French report from the MEEDDM (2006) [15], the functional unit for a specific project shall include criteria about the type of product, its function and its lifetime. However, as we want to include a wide range of bridge designs, a simpler functional unit shall be defined. **The functional unit selected for this study is: "1 square meter effective bridge deck area through a lifetime of 100 years"**, which is the same as the one chosen for the CO_2-equivalent emissions assessment in the literature review.

This functional unit combines physical and temporal criteria. The choice of an effective bridge deck area is due to the inaccuracy of a one-dimension physical distance (length or width), whereas the product of both is more significant. Indeed, it would be inaccurate to compare two bridges with the same effective length but different numbers of traffic lanes, for example. The effective bridge deck area enables comparison between different bridges despite the fact that they are built at different locations with different sizes. However, this choice is somehow reductive since the bridge substructure is not clearly represented through this functional unit. Finally, a 100-year life is currently the most common lifetime attributed to new bridges, maintenance and repair phases included.

System boundaries

The system boundaries defines the unit processes to be included in the system. Ideally, the product system should be modeled in such a manner that inputs and outputs at its boundary are elementary flows. The choice of elements of the physical system to be modeled depends on the goal and scope definition of the study, its intended application and audience, the assumptions made, data and cost constraints, and the cut-off criteria, i.e. the specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from the study. The models used should be described and the assumptions underlying those choices should be identified. The cut-off criteria used within a study should be clearly understood and described [4].

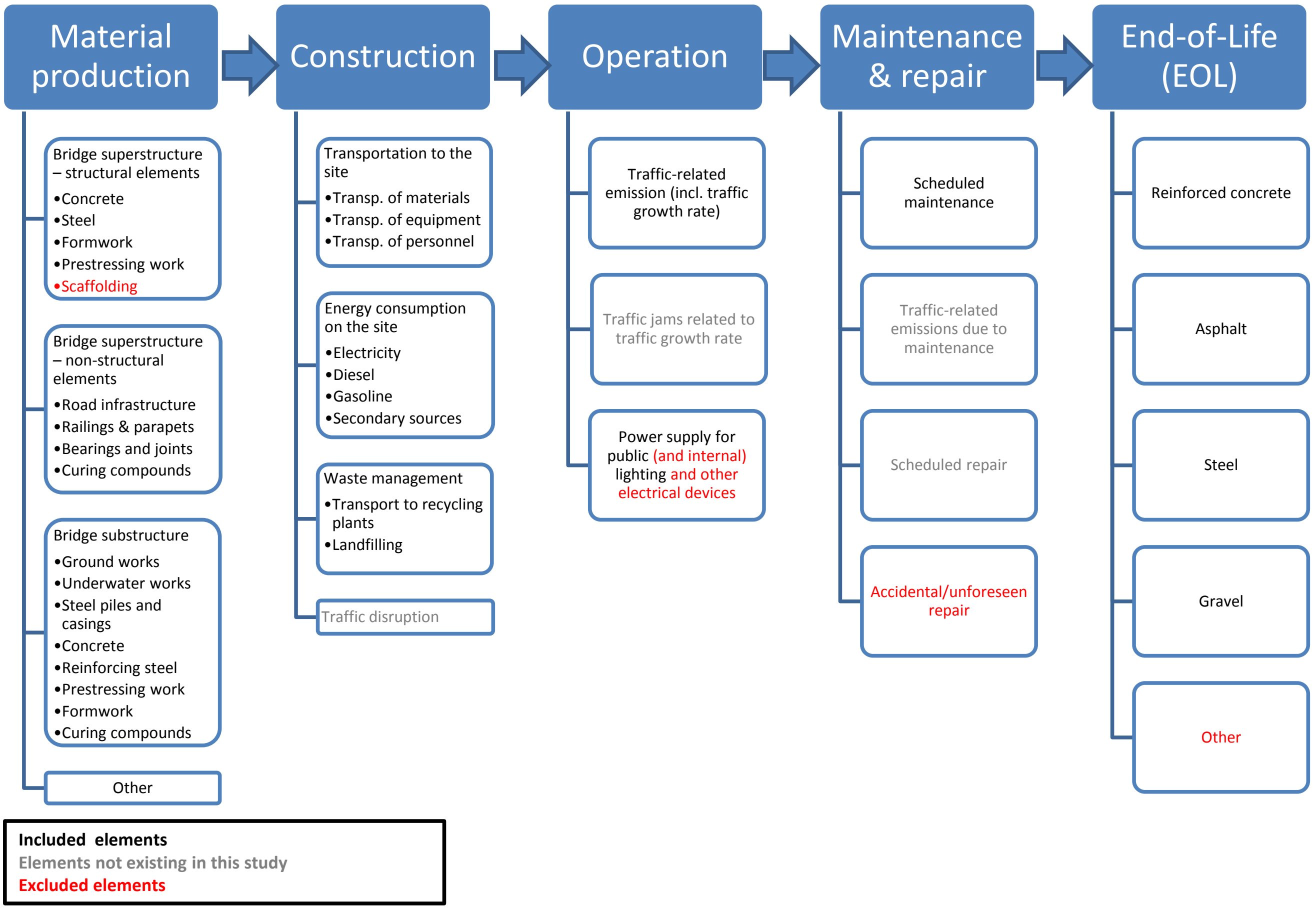

Figure 3.1: System boundary of Tverlandsbrua (only foreground processes).

Figure 3.1 describes the bridge life cycle phases and the associated processes and sub-processes. As many processes are included in this thesis, only foreground processes (i.e. data associated to the product studied) are shown in this figure. System boundaries including background processes (i.e. data taken from generic databases) are realized in the case study, where the production and construction life cycle phases are deeply analyzed. The red-colored elements are excluded from the analysis, whereas the grey-colored ones are not present in this project. A more detailed description of the life cycle phases is performed below.

Material production phase: the production phase includes concrete, reinforcing steel, formwork, prestressing equipment (strands, anchors, ducts, grouting paste), asphalt & waterproofing, railings & parapets, bearings & joints, curing & surfacing measures, bored piles steel casings, steel pipe piles and products for ground & underwater works. The production of the rented equipment (such as scaffolding, machines, cantilever traveling formwork system, etc.) is not always considered in this analysis as this equipment is likely to be reused in other projects and the wearing down of the infrastructures related to a specific project is difficult to assess. However, some product or equipment processes from the generic database include infrastructure use, and this will be stated whenever such processes are selected.

Construction phase: the construction phase includes burdens from transportation of material, equipment and personnel to the bridge construction site, energy consumption on the site from machinery equipment use, short displacements by boat and waste management on the site. As the bridge is part of a new road project crossing the Saltfjorden, representing an overall 2.1 km length, no traffic disruption is accounted for the bridge construction. The corresponding traffic disruption would be attributed to the carbon footprint assessment of the roads from each part of the bridge ends.

Operation phase: the operation phase includes emissions from traffic and power supply for public lighting. According to *Statens vegvesen*, the annual average daily traffic (AADT) expected for the opening of this bridge is 8600 veh/day. With a yearly traffic growth rate of 0.558% expected within the next 100 years, the AADT expected in 100 years is 15000 veh/day, which is still well below the actual bridge capacity. Hence, no important traffic jams are considered during the bridge life cycle in the analysis.

Repair and maintenance phase: according to *Statens vegvesen* handbook n°136 - Inspection for bridges [22] two inspections are frequently performed: a simple visual inspection every year and a main inspection every 5 years (including cable and underwater inspections). The repair and maintenance phase also includes a new asphalt course every 3 years. The bridge is designed for a 100-year life cycle without any important reconstruction work (bridge deck renewal, etc.), hence no important structural repairs are scheduled during the bridge life cycle. Accidental events (earthquakes, violent storms, collisions, etc.) can occur and affect the structural properties badly enough to require structural repairs. However, as no relevant data related to the probability of occurrence of such events and the subsequent repairs can be found, this is not taken into consideration in the analysis.

End-of-life (EOL): the EOL phase considers the bridge deconstruction and EOL of reinforced concrete, asphalt, steel from prestressing works and railings & parapets and gravel used for backfilling against the abutments and as ballast in the caisson. Those four components represent all together 98.6% of the overall bridge weight. The end-of-life treatment of other materials is not considered.

Allocation procedures

Allocation procedures are used to partition the environmental load of a process when several products or functions share the same process. For example, when waste is burnt at the incineration factory, the fraction and type of emissions associated to each component is unknown unless the exact composition of the bulk mass is known. Allocation procedures are then used in order to attribute accurately the burdens from incineration to each component.

According to the ISO 14044:2006 standard [5], the inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure. The allocation procedure shall be divided in three steps.

Step 1: wherever possible, allocation should be avoided by dividing the unit process in sub-processes and collecting the input and output data related to each sub-process or expanding the product system to include the additional functions related to the co-products.

Step 2: where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.

Step 3: when physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them, for example their economic value.

Allocation procedures in this analysis are avoided as much as possible. For example, this is avoided for all materials considered in the production phase, as a detailed material composition is available. However, regarding the energy consumption at site from machinery and other equipment use (cranes, barracks, loaders, excavators, etc.), as only a bulk amount is available over the entire bridge construction period, the energy is allocated according to the proportional weight of each component category. For example, the amount of energy required for formwork handling on the site is calculated by multiplying the share of the formwork weight in the overall bridge weight by the total amount of electricity consumed by the crane. The same allocation procedure is used for diesel and gasoline consumption on the site and transport of the crane and personnel to the site.

Impact categories selected and methodology of impact assessment

As stated previously, life cycle impact assessment (LCIA) is the third stage of LCA methodology. It is composed of mandatory and optional elements. Among those mandatory elements, the selection of impact categories and, subsequently, the methodology of impact assessment are of utmost importance. Those elements must be consistent with the goal and scope definition and the interpretation phases of the LCA analysis. However, the selection of impact categories and the methodology of impact assessment are not specified in the ISO standards 14040:2006 and 14044:2006. The choice is left to the LCA practitioner, according to the intended purpose of the study.

In our case study, *Statens vegvesen* is interested in the carbon footprint assessment of their bridges. The carbon footprint is defined as the total emissions of greenhouse gases, for a defined unit. The greenhouses gases emissions, responsible for the greenhouse effect, are calculated as carbon dioxide equivalent (CO_2-eq). The related impact category is global warming (or climate change). In order to calculate the amount of CO_2-eq emitted, a characterization model is used: the global warming potential (GWP). This characterization model determines the relative contribution of each greenhouse gas (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc.) over a period of time. Usually, a 100-year baseline is chosen: this is called the 100-year global warming potential (GWP100). The methodology of impact assessment is the step coming right after the selection of the impact categories. However, this is not considered here since only one impact category is selected here, but a short explanation of the possible methodologies of impact assessment will be performed in the description of the life cycle impact assessment (LCIA) phase.

Data and initial data quality requirements

The collection or calculation of data can be one of the most energy and time consuming part of an LCA analysis. Whether the data are collected or calculated, the choice of the level of data quality is already a complicated task. How precise must be the data in order to give sufficiently accurate results? This is not an easy question to answer, but the ISO 14044:2006 [5] standard give some recommendations for the collection of data.

- The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundary. The collected data, whether measured, calculated or estimated, are utilized to qualify the inputs and outputs of a unit process.
- When data have been collected from public sources, the sources shall be referenced. For those data that may be significant for the conclusions of the study, details about the relevant data collection process, the time when data have been collected, and further information about data quality indicators shall be referenced. If such data do not meet the data quality requirements, this shall be stated.
- Among other things, the major headings of the classified data may be energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products, waste, releases to air, water and soils as well as other environmental aspects.

Data used for this study are mainly directly collected from the different actors involved in the project, hence constituting a trustful basis for the life cycle inventory (LCI) phase. The bill of quantities of the entire project is provided by the client, *Statens vegvesen* [23]. Input data from material and energy consumption for the production and construction phases are provided by the contractor and the different subcontractors, while data related to operation and repair &

maintenance and end-of-life phases are provided by the client. Only data for the end-of-life phase are based on own assumptions. Output data are generally calculated using the LCA software *Arda v.15-education*, that includes the generic database *EcoInvent v2.2*. A few output data are collected from environmental performance declarations (EPDs) or similar.

Assumptions and limitations

Assumptions and limitations account for an important part of the goal and scope definition. They allow the study to support the reliability of its scientific results when some aspects are deliberately omitted or neglected. A list of assumptions and limitations are stated below, divided in two categories: general assumptions and limitations, that are valid for the assessment of future bridge projects using this thesis as guideline, and specific assumptions and limitations, that are related to this project.

General assumptions and limitations:

Preparatory works: consultancy, administrative documentation or all works required before the first day of work on the bridge construction site are not considered in this analysis since the data inventory would be very energy and time consuming and uncertain. Moreover, burdens from this phase are supposed negligible compared to the complete bridge life cycle.

Economic and social assessment: this study only deals with the carbon footprint assessment of Norwegian bridges, and no guidelines are given in this report regarding economic and social aspects. However, key sustainability elements are underlined in a previous report, TBA 4530 - Construction Engineering & Project Management, Specialization Report [24], dealing with LCA methodology for bridges.

Carbonation mechanism: carbonation is a very complex mechanism to model. Depending on the concrete composition, porosity, weather conditions and many other parameters, the results over a 100-year life can vary tremendously. Hence, this carbon-saving mechanism is not included in this analysis.

CO_2 uptakes from wood: as wood absorbs CO_2 particulates during its life, using it as a construction material can significantly reduce the overall carbon footprint of a project. However, this is once again a complex mechanism to model and this will not be included in this analysis.

Specific assumptions and limitations:

Material data limitations: as defined in the system boundaries, some components are considered marginal and are not included in the production and construction phases. The contribution from the production of temporary equipment (scaffolding, machines, etc.) is sometimes not considered. For the repair & maintenance phase, accidental/unforeseen structural repairs are not considered. For the end-of-life treatment phases, only reinforced concrete, asphalt, steel and gravel are considered. The benefits from the recycling processes (of concrete, reinforcing steel, wood, etc.) are not considered in this analysis as those recycled products will be used in other projects.

Energy consumption assumptions: for the construction phase, a global assumption of energy use is realized for material handling on the site as it is almost impossible to determine the amount of energy required to mount each element independently. Moreover, as the contracting company provides power supply, diesel and gasoline for almost all its subcontractors, only a raw sum is provided.

Energy consumption limitations: as stated in the system boundaries, the production phase does not consider the contribution from the manufacturing processes of several products. For the construction phase, the power supply of the barracks and other processes requiring small energy supply are omitted.

3.2 Life cycle inventory (LCI)

This section deals with the second major step of LCA methodology. During the LCI phase, input and output flows are listed and the type and source of data are specified.

3.2.1 General requirements

The ISO 14040:2006 [4] standard gives the framework and general principles required to perform an LCI:

- The process of conducting an inventory analysis is iterative. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goals of the study will still be met. Sometimes issues may be identified that require revisions to the goal or scope of the study.
- Two main processes are identified for the data acquisition: data collection and data calculation. Requirements about the quality of these data is specified in the section of Goal and Scope definition named “Data and initial data quality requirements”.
- The calculation of energy flows should take into account the different fuels and electricity sources used, the efficiency of conversion and distribution of energy flow, as well as the inputs and outputs associated with the generation and use of that energy flow.

- Consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems. The allocation method is described in the Goal and Scope section named "Allocation procedures".

Figure 3.2 shows simplified procedures for inventory analysis, according to the ISO standard 14044:2006. [8]

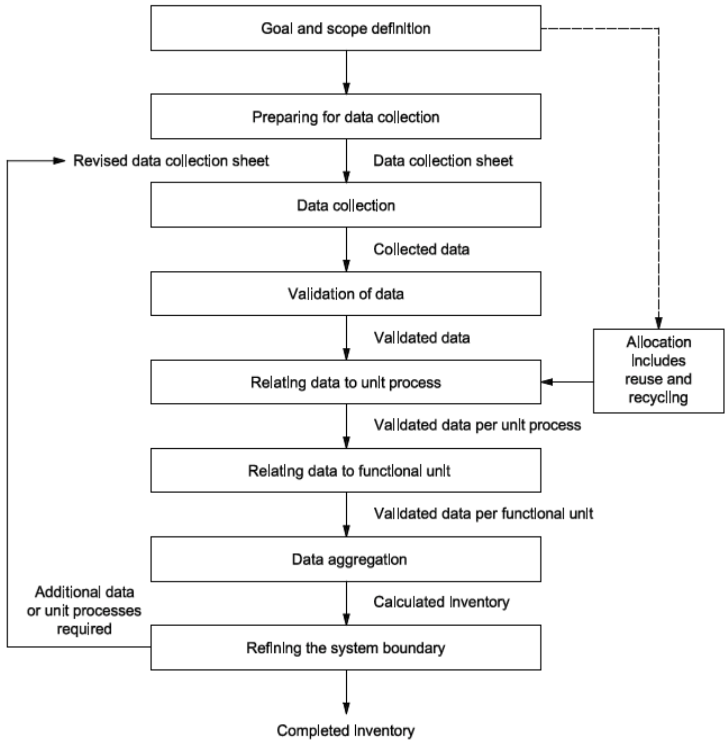

Figure 3.2: Simplified procedures for inventory analysis. [5]

The LCI of bridges (and construction in general) is a quite complicated task, because contrary to industrial products (such as plastic bottles), the life cycle phases do not follow a linear production line. Each bridge is a unique type of product and the quantification of input flows can be highly uncertain, especially during the construction phase. No guarantee is given regarding the respect of initial material and energy consumption during the entire construction period. Hence, additional input flows should be considered in order to foresee future needs at the bridge site, but those are complex to model before the actual end of the construction period. In order to counterbalance this high uncertainty, collection and calculation of data should be performed as accurately as possible, and changes in data collection procedures should be considered as more is learnt about the system. This is not a straight forward decision process.

The decision-making process of input data source for the production and construction phases is represented in figure 3.3. Input data collected for the carbon footprint assessment of Tverlandsbrua are directly provided by the client, contractor and subcontractors, hence ensuring good quality data. However, when the product reference is provided but a part of the information is missing, a worksheet of the referenced product is searched in order to obtain missing data. When such worksheets can not be found, similar worksheet products are researched. If no similar worksheet products are available, generic data from the software database are used. If in the meanwhile new information is sent by the client, contractor or subcontractors, the new information is analyzed throughout the same decision-making process.

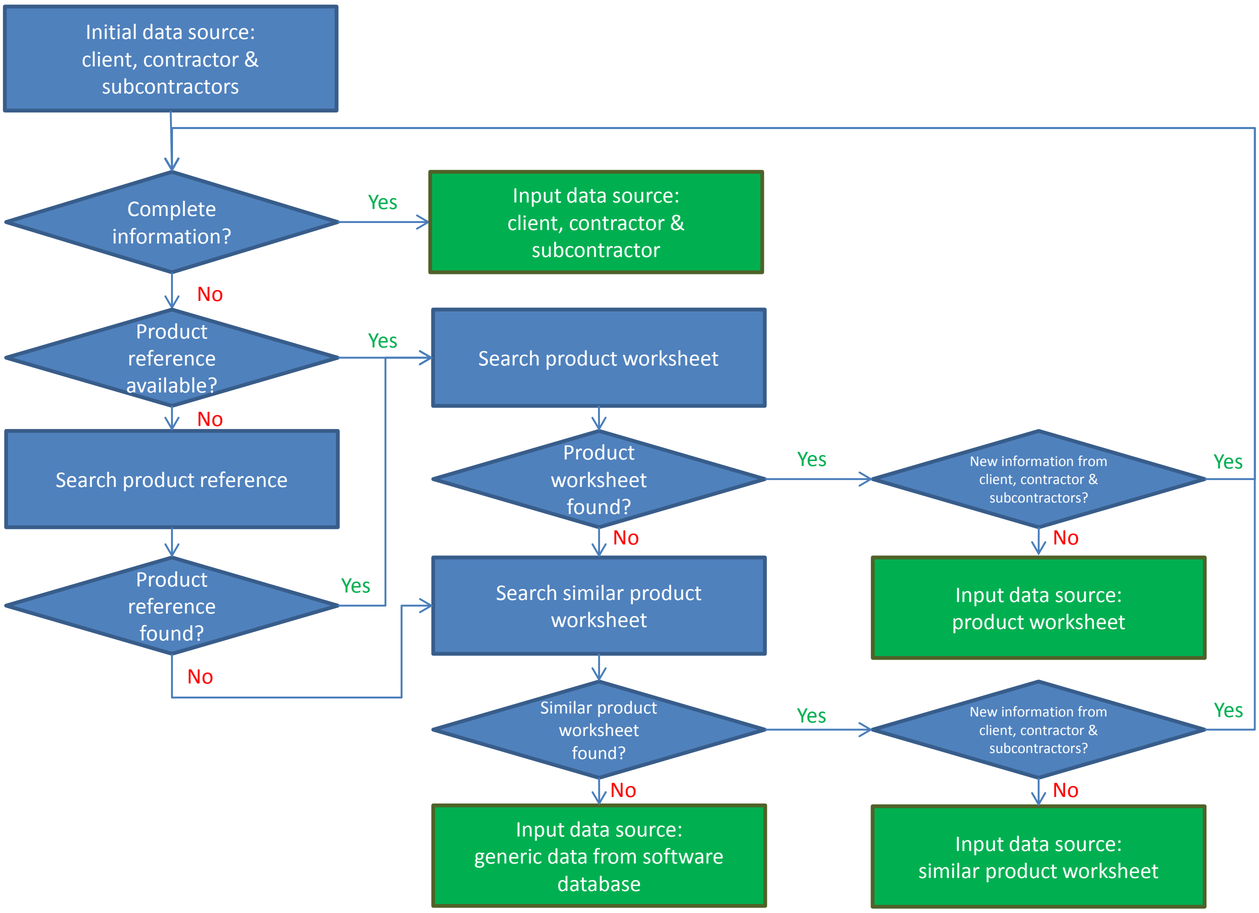

Figure 3.3: Decision-making process for input data source selection for the production and construction phases.

When input data are finally collected, their level of quality is checked to be in accordance with the goal and scope definition phase. If not, revisions have to be made. Due to time limitations, if missing data are not provided before this master thesis report has to be handed-in (11th of June), the closest generic data from the software database are selected. Finally, once all input data sources are identified, the closest process available in the software database is attributed to the input data in order to calculate the output data.

For the operation, repair & maintenance and end-of-life phases, the input data source is much easier to find, as there are less processes considered than in the production and construction phases. Indeed, for the operation phase, the AADT and growth traffic rate are given by the client, the public lighting energy consumption is provided by the client and a communication system company. For the maintenance & repair phase, inspection and surface course renewal schedules are provided by the client and the type of asphalt is the same as for the production phase. Finally, for the end-of-life phase, energy consumption from deconstruction and end-of-life treatment of disposal materials are calculated using generic data from the software database.

Finally, output flow sources are easy to determine in this study, as only carbon footprint is assessed. Hence, only greenhouse gases emissions are calculated.

3.2.2 Collection and calculation of data

Once unit process flows have been listed, they must be quantified, by collection or calculation. As discussed previously, gathering data can be a very energy and time consuming work. As far as possible, data should be collected from generic or specific databases, and calculation or estimation of data should be done as a last option. Indeed, data calculation often constitutes an important source of uncertainty and inaccuracy in the data quality and sometimes, even good data calculation does not lead to more precise results than those obtained with the same data collected from a database.

The LCA software used for our calculations is *Arda v.15-education*. This software has been created for the students of the NTNU Industrial Ecology(IndEcol) program, Trondheim, Norway, in order to perform life cycle assessment exercises. This software, even if produced for educational and not professional goals, is very powerful. It integrates the *EcoInvent v2.2* database as well as the ReCiPe methodology for life cycle impact assessment. The latter will be discussed in the next chapter, dealing with life cycle impact assessment.

The latest version of *EcoInvent v2.2* database is from 2009 and compiles a comprehensive range of process categories such as energy supply, fuels, heat production, electricity generation, wood, building materials or transport (more than 4000 unit processes in total). This database also includes capital requirements associated with the various processes, i.e. the part of the impacts associated with the construction and refurbishment of production facilities. However, this database can be somewhat fragmented in its construction. That is, when you look at the input structure of a given process you might find that the *cooking recipe* and emissions are split across several different sub-processes, which can be sometimes confusing. Nevertheless, this database is by far the most recent, comprehensive and best quality general LCA database available today in several LCA software packages [8].

For a few production and construction processes, carbon emissions from private databases are provided by the manufacturers. 70% of reinforcing steel comes from *Badische Stahlwerke GMBH* in Germany and 30% From *Celsa* in Mo I Rana, Norway, and the steel pipe piles come from *Ruukki* in Finland. All manufacturers realized environmental reports or environmental performance declaration (EPD) spreadsheeets including the greenhouse gases emissions related to their products.

A last remark is added to this LCI methodology, related to traditional LCA studies. When describing a system by dividing in its different processes, inputs, outputs and added values, one can argue that this production chain is often not linear.

To exemplify this, we can take the example of the production of a transportation vehicle. The production requires steel, but the production of this steel requires the input of transportation services and thereby vehicles, requiring steel for their production, etc. This type of inter-process dependency between industries clearly shows that a hierarchical perspective of a production system is inappropriate [8].

To take into account this interdependence, Nobel Laureate in Economics Wassily Leontief provided the basis for this through the invention and development of input-output analysis (IOA). Nowadays, statistical offices around the world develop national accounts which allow for the development of input-output tables. Other methodologies have been developed to mix traditional LCA analysis and IOA, named hybrid LCA analysis [8]. IOA and hybrid LCA analysis will not be here further developed due to lack of time, but this is an interesting aspect to be looked at in further studies.

3.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment is the third stage of LCA methodology. During this stage, the data from the inventory flows listed during the LCI phase are aggregated to obtain more comparable values. The type and level of aggregation depends on the methodology and the goal and scope requirements. However, the ISO 14040:2006 [4] and 14044:2006 [5] standards give recommendations to perform an LCIA and to differentiate the mandatory tasks from the optional ones. According to the ISO standard 14040:2006, an LCIA study should at least contain the selection of impact categories, category indicators and characterization models, the classification of the LCI results and the characterization of the LCI results. Other elements such as normalization, grouping and weighting are not mandatory, as shown in figure 3.4. [4]

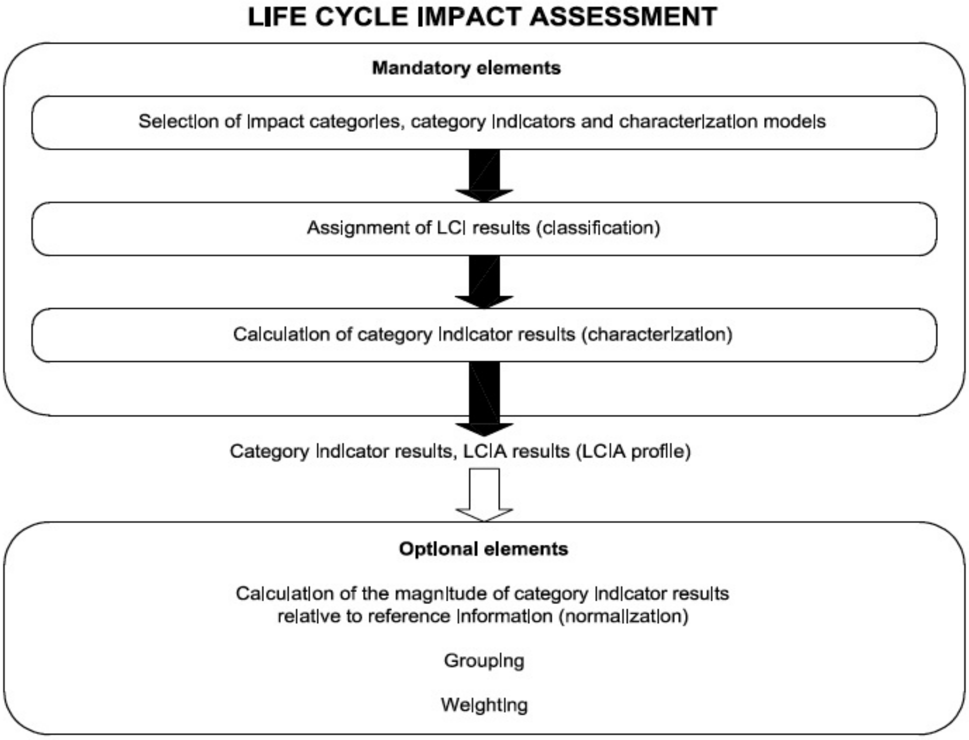

Figure 3.4: Elements of the LCIA phase. [4]

3.3.1 Selection of impact categories, category indicators and characterization models

As showed in the description of the LCI phase, many input and output data constitute the inventory flows. The results of an LCA study cannot just display a list of disaggregated output data, as this would represent a huge number of values and would be neither comfortable to read nor representative of the global environmental impact. This would also make difficult the comparison between results from different studies and hence complicate the results interpretation. A first step of the LCIA is then to aggregate values in a same category of impact and obtain one representative value per category.

The impact category is the category to which the LCI data will belong, the category indicator is the indicator related to the impact category and the characterization model describes in which context (political choices, intergovernmental summits, etc.) the impact category and the category indicators are defined. Furthermore, there are two types of impact categories: midpoint and endpoint. The midpoint approach models assess the impact categories regarding to the baseline impact categories and its impact to the environment, while the endpoint approach evaluates the damage caused to the areas of protection (AoPs), defined as the resources use, human health and ecological impact [8]. The choice of midpoint or endpoint indicators depends on the scope of the study, since midpoint indicators are easy to calculate but hard to interpret (in terms of effects on the planet), whereas endpoint indicators are hard to calculate but easy to understand. In order to allocate an impact category, a category indicator and a characterization model to all output data from the LCI analysis, different methodologies have been developed but the standards do not advice one specific methodology for the moment. The LCA practitioner is then free to use the software adapted to his needs, according to the impact categories he his interested in as well as the classification and characterization models.

However, some guidelines and recommendations are given in the ISO 14044:2006 [5] standard:

- Whenever impact categories, category indicators and characterization models are selected in an LCA, the related information and sources shall be referenced. This also applies when new impact categories, category indicators or characterization models are defined. Examples of impact categories are given in ISO/TR 14047.
- The selection of the impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.
- LCI results other than mass and energy flow data included in the LCA (for example, land use) shall be identified and their relationship to corresponding category indicators shall be determined.

In this analysis, only climate change, a midpoint impact category, is looked at, as it is the only impact category related to greenhouse gases emissions. The only sources of greenhouse gases emissions are related to mass and energy flows, hence land use is not considered in this analysis (this would be relevant in the impact category abiotic depletion, for example, if this was to be considered). Figure 3.5 displays the category indicator, characterization model and other information related to the climate change impact category. [5]

Term	Example
Impact category	Climate change
LCI results	Amount of a greenhouse gas per functional unit
Characterization model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change
Category indicator	Infrared radiative forcing (W/m^2)
Characterization factor	Global warming potential (GWP_{100}) for each greenhouse gas (kg CO_2-equivalents/kg gas)
Category indicator result	Kilograms of CO_2-equivalents per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radiative forcing is a proxy for potential effects on the climate, depending on the integrated atmospheric heat adsorption caused by emissions and the distribution over time of the heat absorption

Figure 3.5: Climate change impact category. [5]

3.3.2 Classification (assignment) of LCI results

In this step of the LCIA, the different flows included in the inventory are assigned to each impact category. According to ISO 14044:2006 [5] standard, the following basic recommendations are given:

- assignments of LCI results that are exclusive to one impact category.
- identification of LCI results that relate to more than one impact category, including distinction between parallel mechanisms (for example, SO_2 is apportioned between the impact categories of human health and acidification) and assignment to serial mechanisms (for example, NO_x can be classified to contribute to both ground-level ozone formation and acidification).

In this analysis, all output data (greenhouse gases emissions) are allocated to one single impact category, climate change. The Intergovernmental Panel on Climate Change listed the greenhouse gases that are relevant to the category indicator infrared radiative forcing (related to the impact category Climate Change). Some of these greenhouse gases are also allocated to the category indicator ozone depletion (related to the impact category stratospheric ozone depletion), but this is not a problem since those gases a part of a serial mechanism (i.e., they contribute the same way to both impact category, without being apportioned between them).

3.3.3 Characterization (calculation) of LCI results

The category indicator results are calculated for each impact categories using characterization factors. These factors are coefficients that are multiplied by each output data related to the impact category selected in order to aggregate all corresponding data in one single score. The characterization factor values represent the relative importance of each output data compared to a reference output data. The calculation of the characterization factors also depends on the characterization model selected.

In this analysis, as only climate change impact category is selected, the characterization factor associated is the global warming potential (GWP100) for each greenhouse gas. As a recommendation from the IPCC, the baseline chosen for the calculations is 100 years, even if other baselines are available (20 and 500 years). GWP100 characterization factors for each greenhouse gases and other substances are presented in appendix B.

3.3.4 ReCiPe life cycle impact assessment methodology

Many impact assessment methodologies are implemented in the different LCA softwares and databases available in the world. As an LCA study can be performed many different ways, those methodologies aim at simplifying LCA calculations and helping the LCA practitioner to be coherent throughout his entire analysis. In the LCA software used for this analysis, *Arda v.15-education*, the ReCiPe LCIA methodology is used. This methodology includes as well the GWP100 characterization factors for greenhouse gases as described by the IPCC, which is the main reference for the life cycle impact assessment phase in this analysis. Other elements that are not considered in this analysis, such as midpoint and endpoint indicators, normalization, grouping and weighting, are included in the ReCiPe methodology.

3.3.5 Optional elements: normalization, grouping, weighting and data quality analysis

Depending on the goal and scope definition of the study, additional elements can be added to the LCIA phase. Those elements often help the decision makers throughout the calculation of a unique value indicating the level of environmental impacts of a project when different impact categories are selected in the analysis. With such a method, all impact category results are aggregated in one single indicator. However, those optional elements are neither well identified nor controlled by any standard. Hence, the choice of the factors is often subjective and can lead to misinterpretations of the LCIA results. According to the ISO 14044:2006 [5] standard, the different optional elements are defined as following:

- Normalization: calculating the magnitude of category indicator results relative to reference information.
- Grouping: Sorting and possibly ranking of the impact categories.
- Weighting: Converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available.
- Data quality analysis: better understanding the reliability of the collection of indicator results, the LCIA profile.

Normalization, grouping and weighting are not relevant in this analysis since only one impact category is assessed, and hence they will not be further discussed. However, if other bridge environmental assessments taking into account several impact categories are performed in the future, these optional elements should be looked at. Regarding data quality analysis, uncertainty and sensitivity analyses are performed. The uncertainty analysis deals with data that are not completely reliable and the consequences of variations in amount or source of input data towards the overall impact. The sensitivity analysis tries to evaluate to consequences of variations in the amount or source of input data related to the processes that account for important shares of the overall impact.

3.4 Interpretation phase

The interpretation phase is the last stage of an LCA study. This section links the three previous phases and gives coherence to the entire study. Indeed, as we can see in figure 1.2, the interpretation phase is not simply coming after the LCIA phase, but is an inherent part of each phase. More precisely, this phase considers the findings from the inventory analysis and the life cycle impact assessment together, and establishes a consistency with the goal and scope definition. Moreover, according to the ISO [4] 14040:2006 standard, the interpretation phase should reflect that the LCIA results are based on a relative approach, that they indicate potential environmental effects, and that they do not predict actual impacts on category endpoints (human health, forest damages, etc.), the exceeding of thresholds or safety margins or risks.

According to the ISO 14044:2006 [5] standard, the interpretation should comprise the following elements:

- Identification of the significant issues based on the results of the LCI and LCIA phases of LCA.
- An evaluation that considers completeness, sensitivity and consistency checks (not considered here).

- Conclusions, limitations and recommendations.

The relationships between those elements and the other phases of LCA are shown in Figure 3.6. [5]

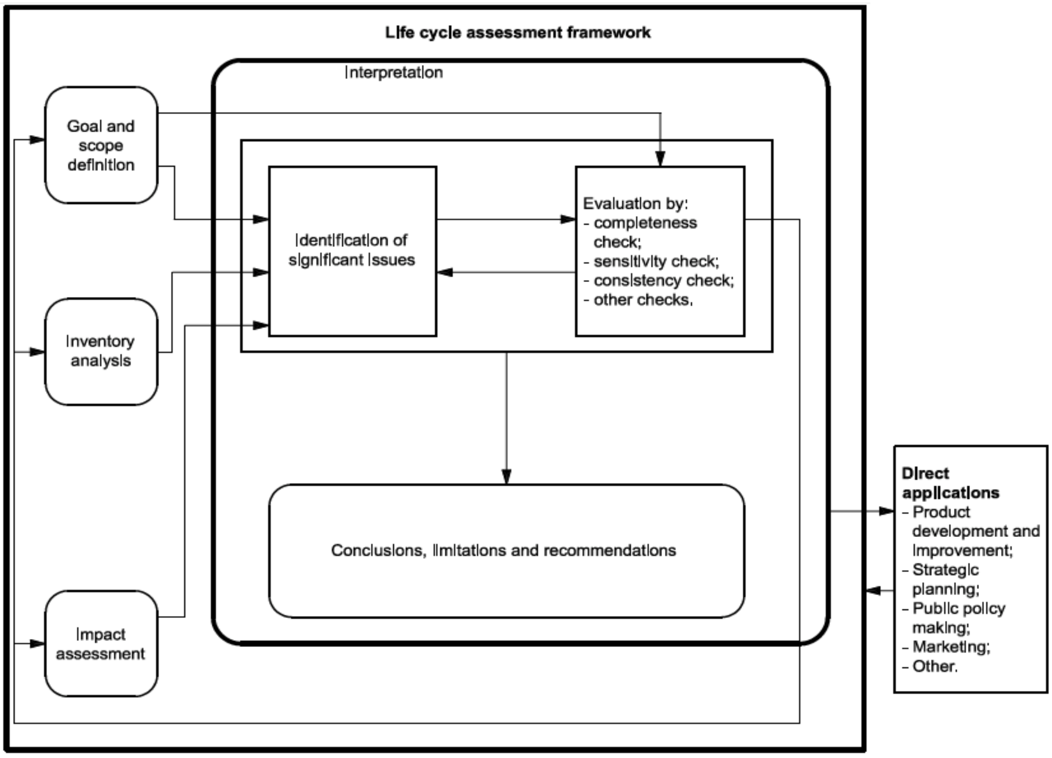

Figure 3.6: Relationships between elements within the interpretation phase with the other phases of LCA. [5]

3.4.1 Identification of significant issues

This element aims at identifying the significant issues of the LCA study through the structuring of the LCI and LCIA results in accordance with the goal and scope definition. Examples of significant issues can be inventory data (energy, emissions, etc.), impact categories (global warming, acidification, etc.) or significant contributions from life cycle stages (raw material acquisition, production, etc.). The purpose of this interaction between LCA phases is to include the implications of the methods used, assumptions made, etc. in the preceding phases, such as allocation rules, cut-off criteria, etc. [5] The results from the uncertainty and sensitivity analyses are also presented here.

3.4.2 Conclusions, limitations and recommendations

The aim of this section is to draw conclusions, identify limitations and give recommendations for the intended audience of the LCA.

Conclusions should be done in such a way that the significant issues are identified, the methodology and results are evaluated (uncertainty and sensitivity analyses) and that the conclusions are consistent with the requirements of the goal and scope definition, including the identification of the limitations [5].

Recommendations shall be based on the final conclusions of the study, and shall reflect a logical and reasonable consequence of the conclusions. Whenever appropriate to the goal and scope of the study, specific recommendations to decision-makers should be explained.

Chapter 4

Case study: Tverlandsbrua

In this section, an LCA study is performed on a bridge case study. First, a description of the bridge is realized. Then, for each life cycle phase, a detailed inventory list of data is performed stating the sources and methods of data collection or calculation, bearing in mind the system boundaries and assumptions stated in the goal and scope definition. Finally, the results from the LCA software *Arda v.15-education* are presented, as well as the interpretation of these results and the realization of uncertainty and sensitivity analyses.

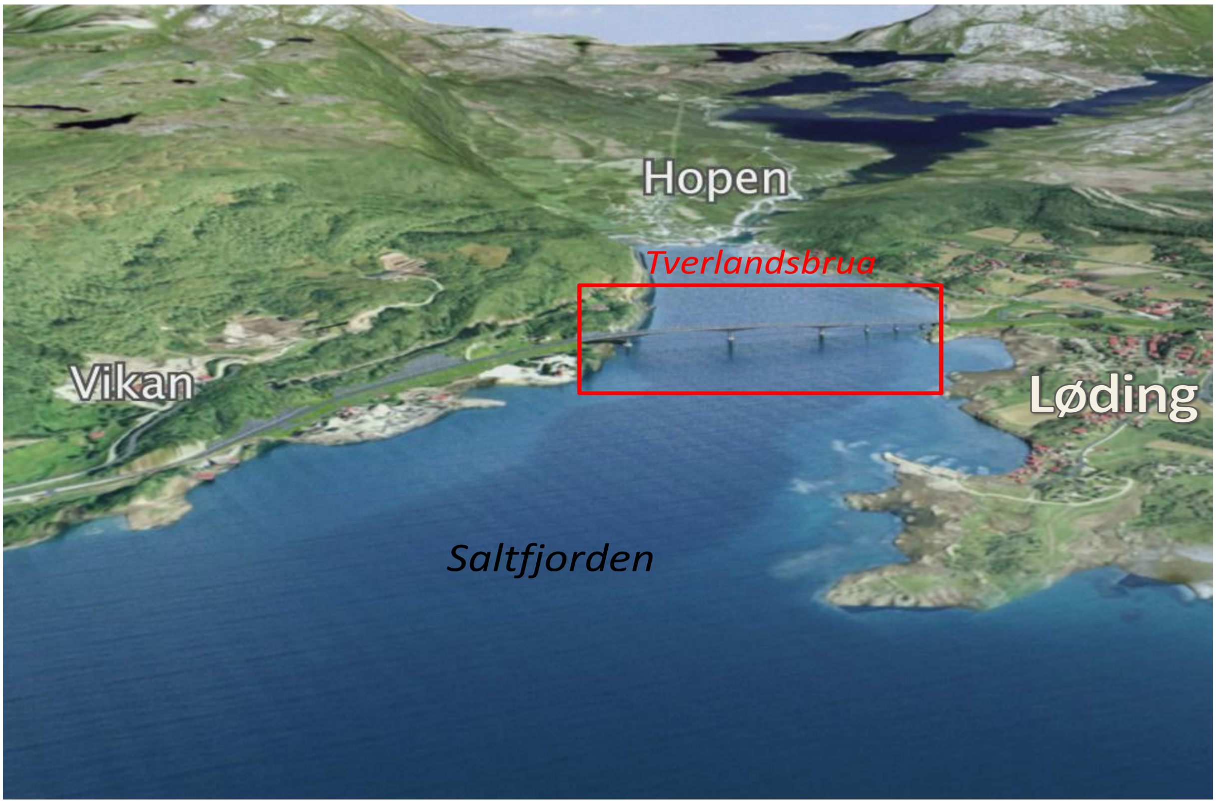

Figure 4.1: Localization of Tverlandsbrua project. [6]

4.1 Bridge description

As stated earlier, Tverlandbrua is located in Nordland county, 15 km from Bodø, Norway. The bridge will cross Saltfjorden, and hence is built in a marine environment. The bridge is designed for a double traffic lane in each direction and a pedestrian/bicycle lane. The works started in early June 2011 and are to be achieved in late September 2013 and are part of the 2.010 km road project *Rv.80 Løding-Vikan*, owned by *Statens vegvesen*. All technical drawings are provided by *Statens vegvesen* and realized by the consultancy company *Aas-Jakobsen*.

4.1.1 Bridge superstructure

Longitudinal profile

The deck design is a post-tensioned concrete box-girder, with a main span of 165 m and a total length of 670 m (abutment to abutment). The deck is divided in 7 spans, as shown in figure 4.2. Two different construction methods are used for the cast in-situ concrete box-girder. A part of the bridge superstructure is mounted using a balanced cantilevered traveling formwork system, totalizing 522 m divided in 4 spans. This system is made up of two mobile wagons supporting the bridge deck formwork. The wagons are installed at the top of the column axis 2, 3 and 4 (see figure 4.2) and are moved from a 5 meters maximum distance each time the in-situ cast concrete part has reached a sufficient strength (see example on figure 4.3).

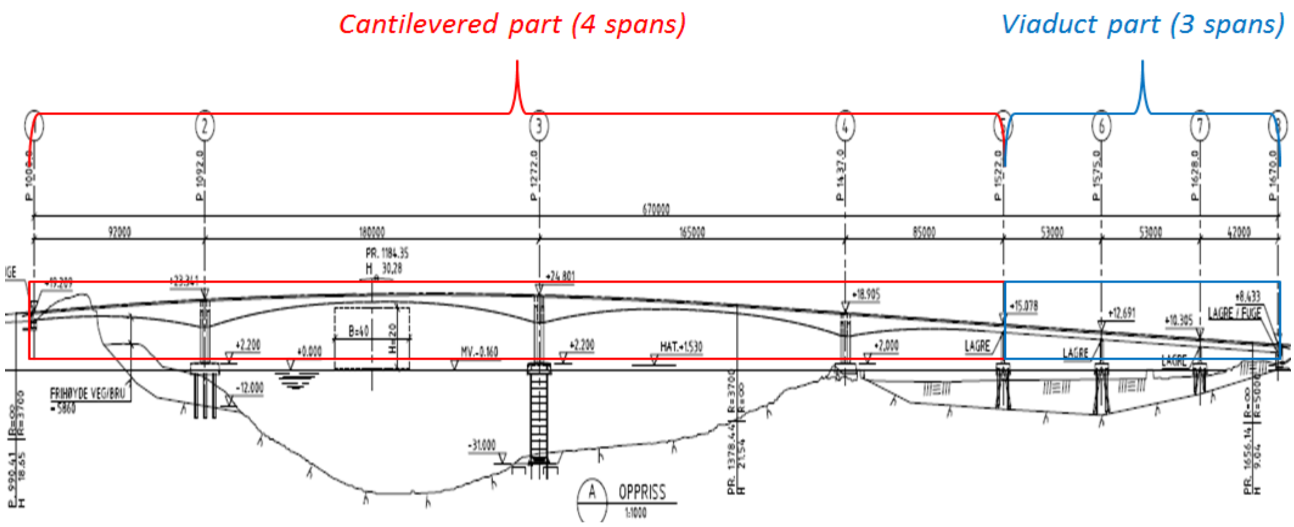

Figure 4.2: Tverlandsbrua: construction methods. [7]

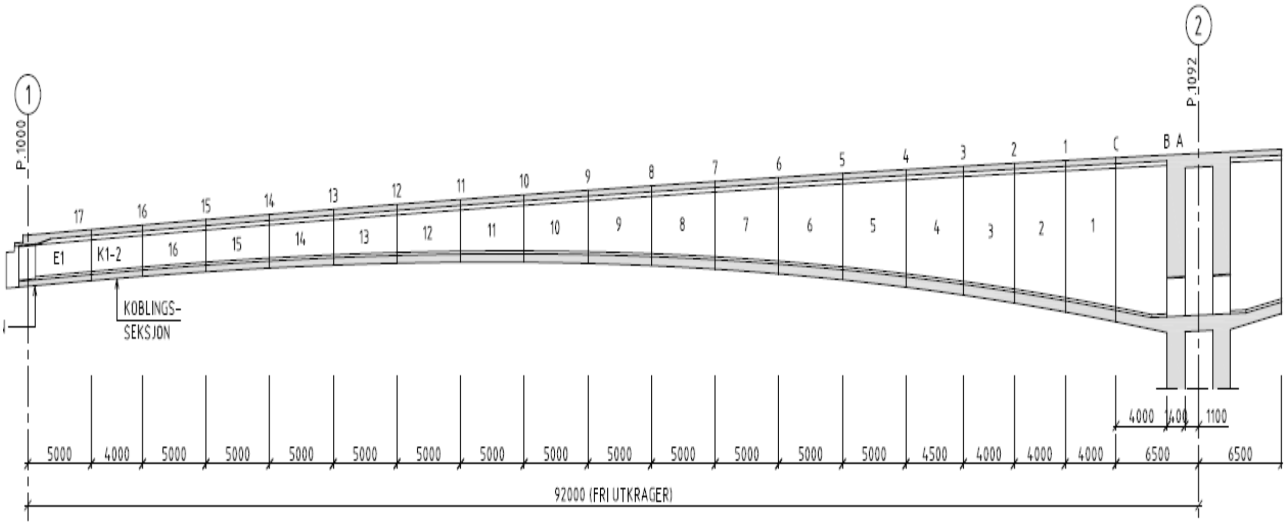

Figure 4.3: Tverlandsbrua: cantilevered construction of span 1 (starting from part 1). [7]

The other part of the structure is built as a viaduct cast in a formwork supported by a simple scaffolding, totalizing 148 meters divided in 3 spans. As the construction of the viaduct goes on, the formwork and scaffolding system are moved from the abutment (axis 8) to the column axis 5, where they reach the cantilevered constructed part. A temporary underwater structure is built to support the scaffolding, as shown in figure 4.4.

Figure 4.4: Tverlandsbrua: viaduct part.

The spans of the viaduct located between axis 8-7 and 7-6 are built first. Then, a first cantilevered part is built from both parts of axis 4 simultaneously with the last span of the viaduct part (between axis 6-5), until the cantilevered and viaduct parts meet at axis 5. Finally, the cantilevered parts from axis 2 and 3 are built one after another (see figure 4.5). Post-tensioning is then applied in both longitudinal and transverse directions.

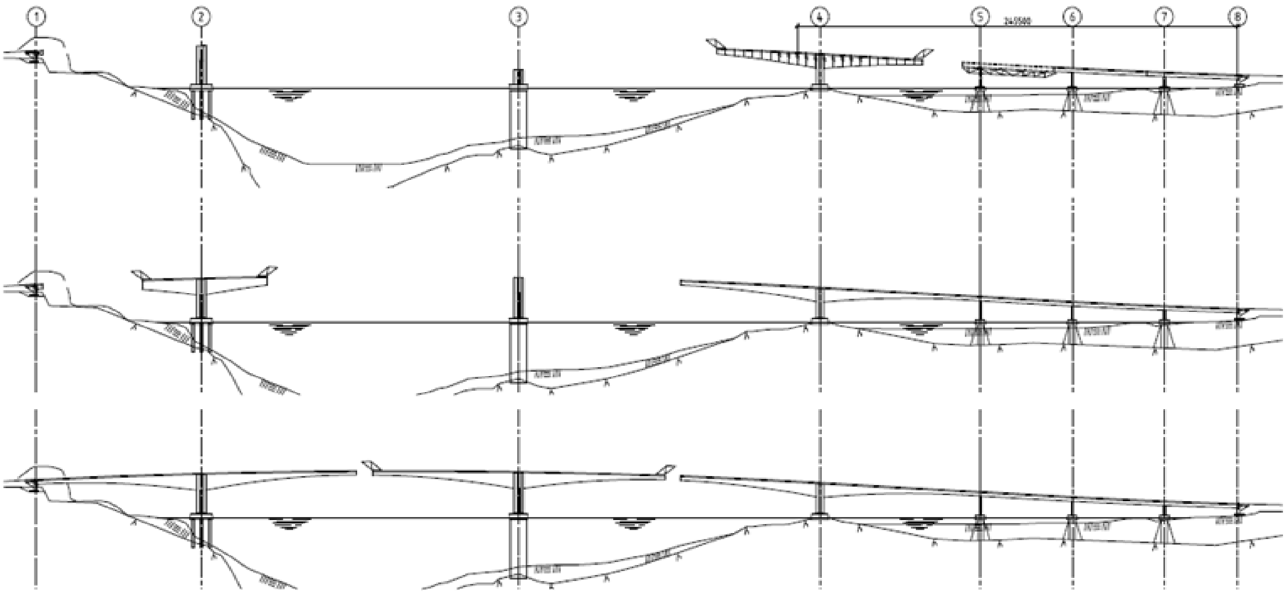

Figure 4.5: Tverlandsbrua: overall construction methodology. [7]

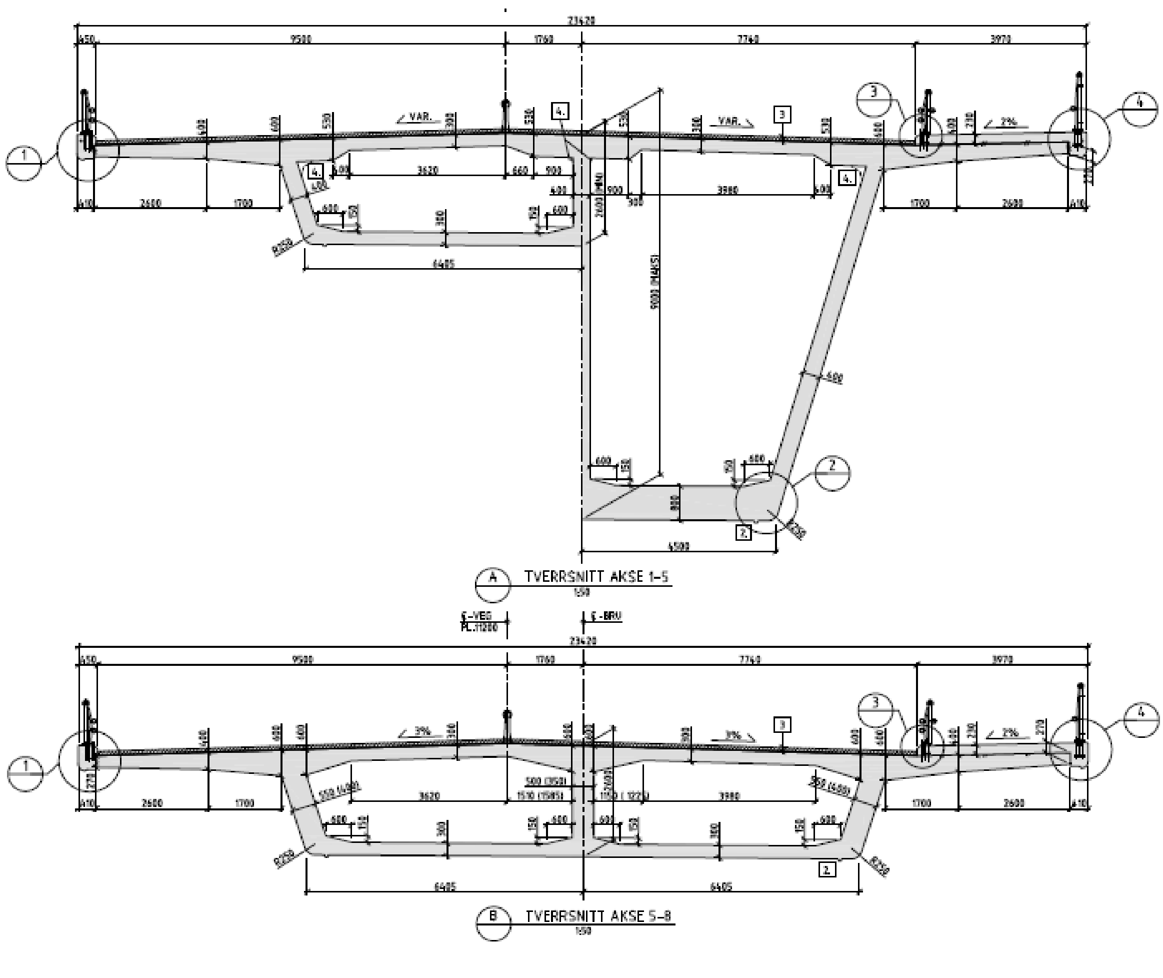

Figure 4.6: Tverlandsbrua: box-girder varying (upper drawing) and constant (lower drawing) heights. [7]

Cross-sections

The total deck width is 23.5 m (sometimes a bit less, 23.42 m) divided in 2 double traffic lanes, 9.5 m each, a walkway/bicycle lane of 4 m (railings included) and 0.5 m for the other external railing. The concrete box-girder of the viaduct part (from axis 5 to 8) has a constant height (2.6 m) and bottom chord width (14 m), whereas the cantilevered part (from axis 1 to 5) has a varying height (from 2.6 to 9 m), as shown in figure 4.6.

4.1.2 Bridge substructure

Abutments and columns

The abutments, located at axis 1 and 8, are designed as cantilever abutments resting on a rock support foundation (no piles). These abutments are quite massive (600 m^3 concrete for both abutments) with a large stem transmitting horizontal forces to a wide footing, acting itself as a cantilever beam to prevent from instability issues due to horizontal and vertical forces (see figure 4.7).

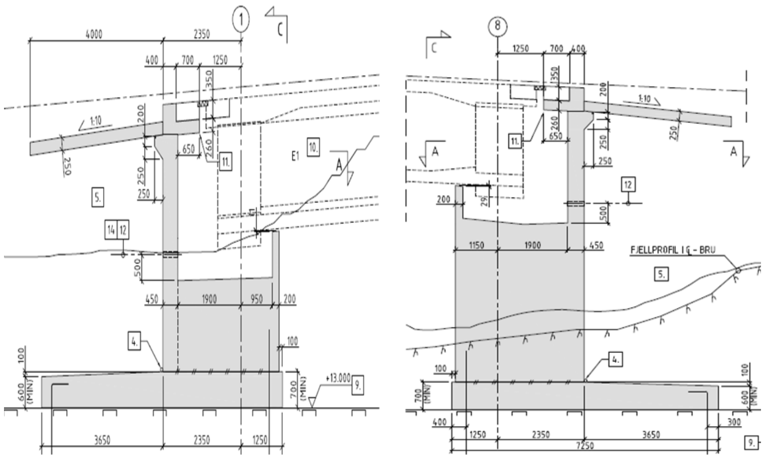

Figure 4.7: Tverlandsbrua: abutments, axis 1 (left) and axis 8 (right). [7]

Two types of designs are realized for the columns. The columns supporting the cantilevered constructed part are designed as twin solid walls slightly tapered, while the columns supporting the viaduct part act as twin simple columns on top of which rests a bridge bearing, as shown in figure 4.8.

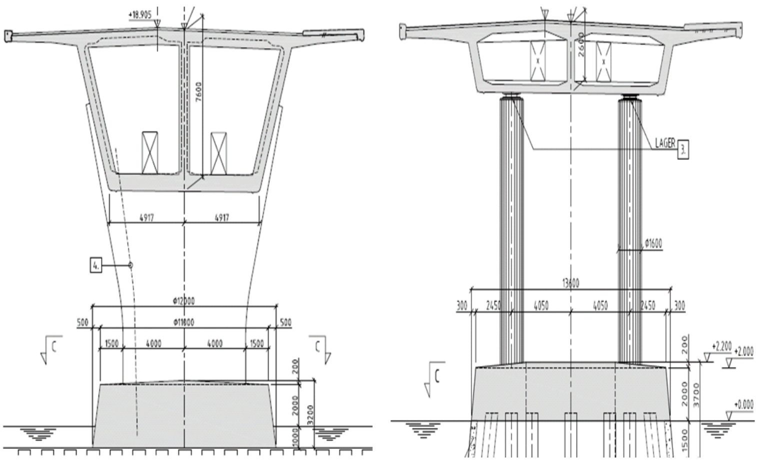

Figure 4.8: Tverlandsbrua: twin solid walls for the cantilevered part (left) and twin simple columns for the viaduct part (right). [7]

Foundations and piles

Four types of foundations are realized in this project.

In axis 2, a concrete foundation is realized with bored piles. The foundation looks like a cylinder tapered at the top, with an average diameter of 15.6 m and a height of 3.9 m, on which rest the twin solid walls. At the periphery of the foundation, concrete skirts are realized and reinforced with prestressing tendons in order to prevent boats from being sucked up under the foundation in case waves get an amplitude so important that the sea level becomes lower than the bottom of the foundation. In addition, 12 piles are bored in the rock mass, cast with concrete and anchored to the rock mass using prestressing tendons, as shown in figure 4.9.

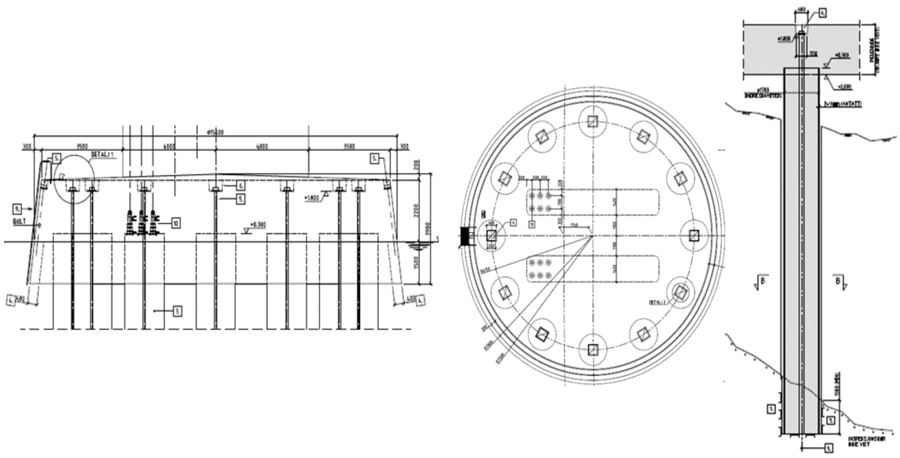

Figure 4.9: Tverlandsbrua: axis 2: foundation cross-section (left), foundation plan view (middle) and bored piles (right). [7]

In axis 3, a sinked caisson is realized. The construction of this caisson was made in several step. The caisson started to be cast on the shore of the fjord. As the total height of the caisson is 27.75 m, the concrete work was realized in 2.5 m height parts. When the first part was realized, the caisson was brought to the sea and ballasted with rock in order to sink it partially and maintain it stable in the water. Then, the other parts were cast off-shore and as the caisson was sinking a little bit more after each cast part due to its own weight, more ballast was added in order to stabilize it. When the caisson was finished and still partially sinked, three boats towed the caisson to its intended position (axis 3). There, the caisson was ballasted until it sank completely and reached a concrete platform at the bottom of the sea in which the bottom of the caisson was inserted. Once the caisson was finally installed, a concrete foundation similar to the one from axis 2 was realized. Prestressing cables going through the foundation, caisson and bottom platform maintain the overall structure anchored in the bed rock. Figure 4.10 shows the sinked caisson.

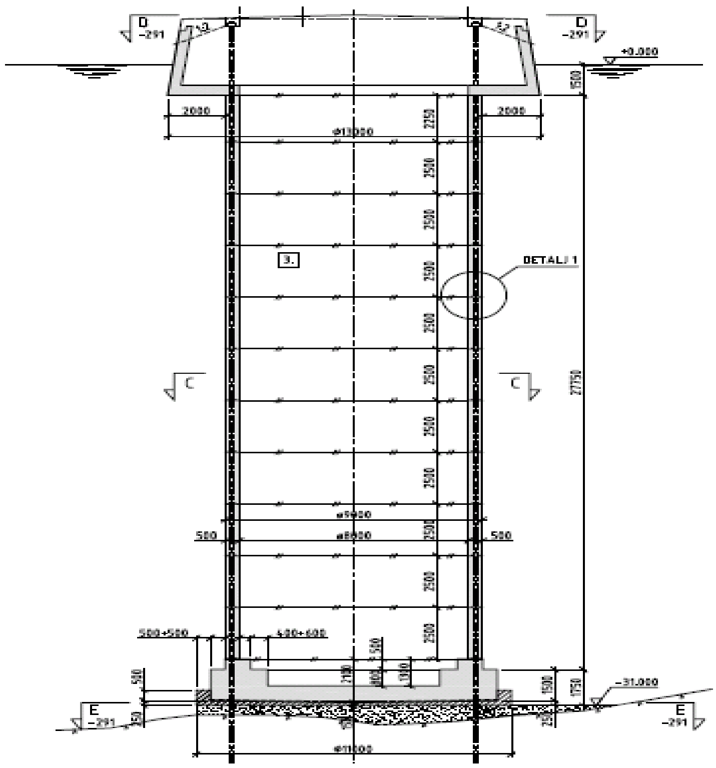

Figure 4.10: Tverlandsbrua: sinked caisson. [7]

In axis 4, a concrete foundation is simply anchored in the bed rock using prestressing tendons, as shown in figure 4.11.

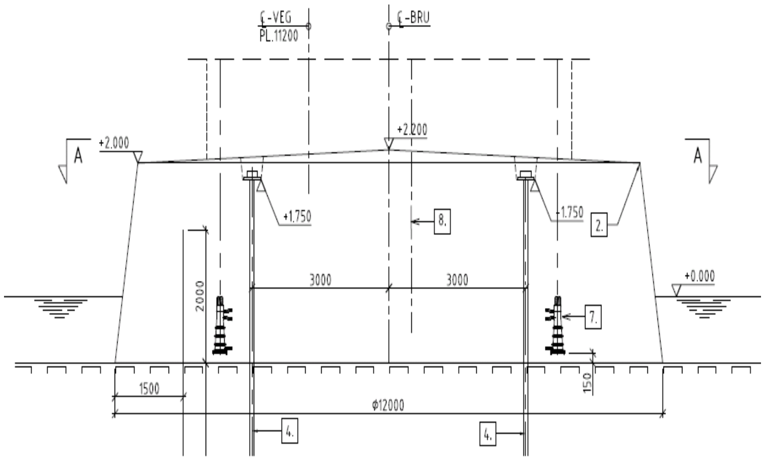

Figure 4.11: Tverlandsbrua: foundation axis 4. [7]

Finally, in axis 5, 6 and 7, a concrete foundation is realized with steel pipe piles. A larger foundation, oblong-shaped, is built for those 3 axis, each supported by 14 steel pipe piles. The steel piles are first dig in the soil using a piling rig. The bottom of the piles are designed with a rock shoe in order to prevent the bottom from slipping on the bed rock. Once the steel pipe piles are installed, they are reinforced and filled with concrete and connected to the concrete foundations. The twin simple columns are then cast on the foundation, as shown in figure 4.12.

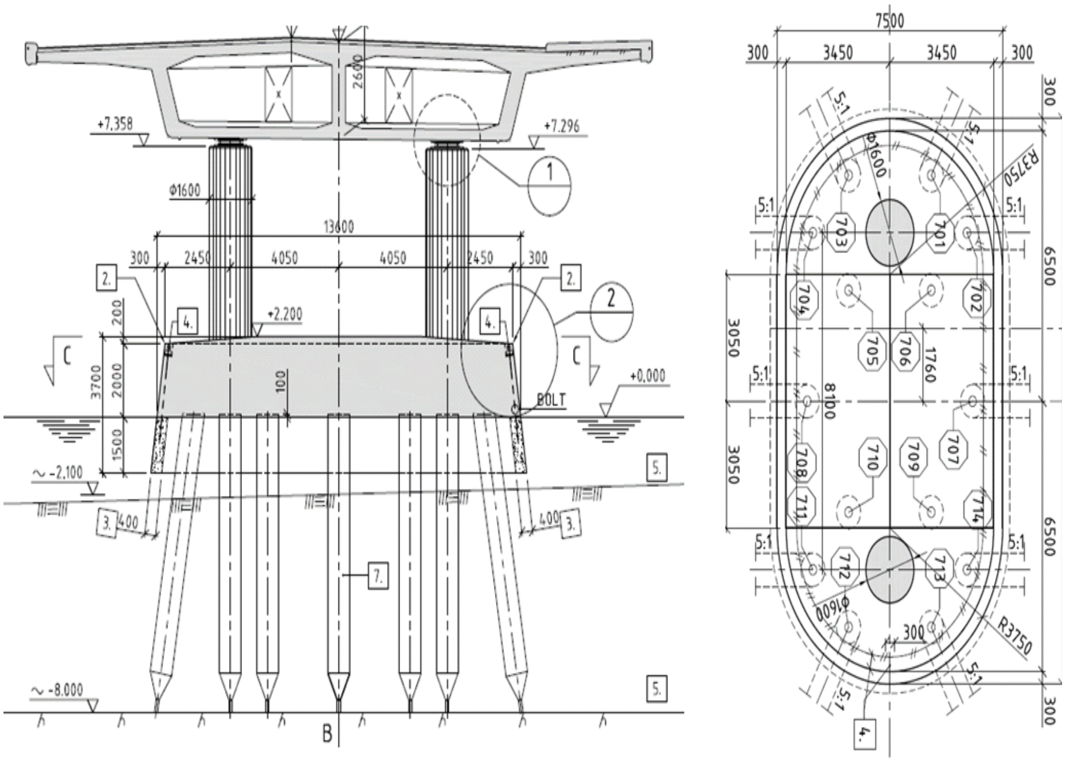

Figure 4.12: Tverlandsbrua: axis 5: foundation cross-section (left) and foundation plan view (right). [7]

4.2 Tverlandsbrua life cycle inventory

In this section, the data inventory of the five life cycle phases of the bridge are detailed. Sources of data and assumptions for data collection and calculation are stated. The list of the bridge contractors is presented in appendix C and represented the main source of input data. The complete input data inventory is presented in appendix E.

4.2.1 Material production phase

The material production phase is divided in three main processes: superstructure, substructure and other.

The system boundaries of the superstructure is shown in figure 4.13. For this analysis, it was interesting to divide the superstructure in two categories, the structural part (concrete deck box-girder) and the non-structural part (road infrastructure and equipment), in order to identify the main sources of emissions in a bridge life cycle. This division will also be considered in the other life cycle phases.

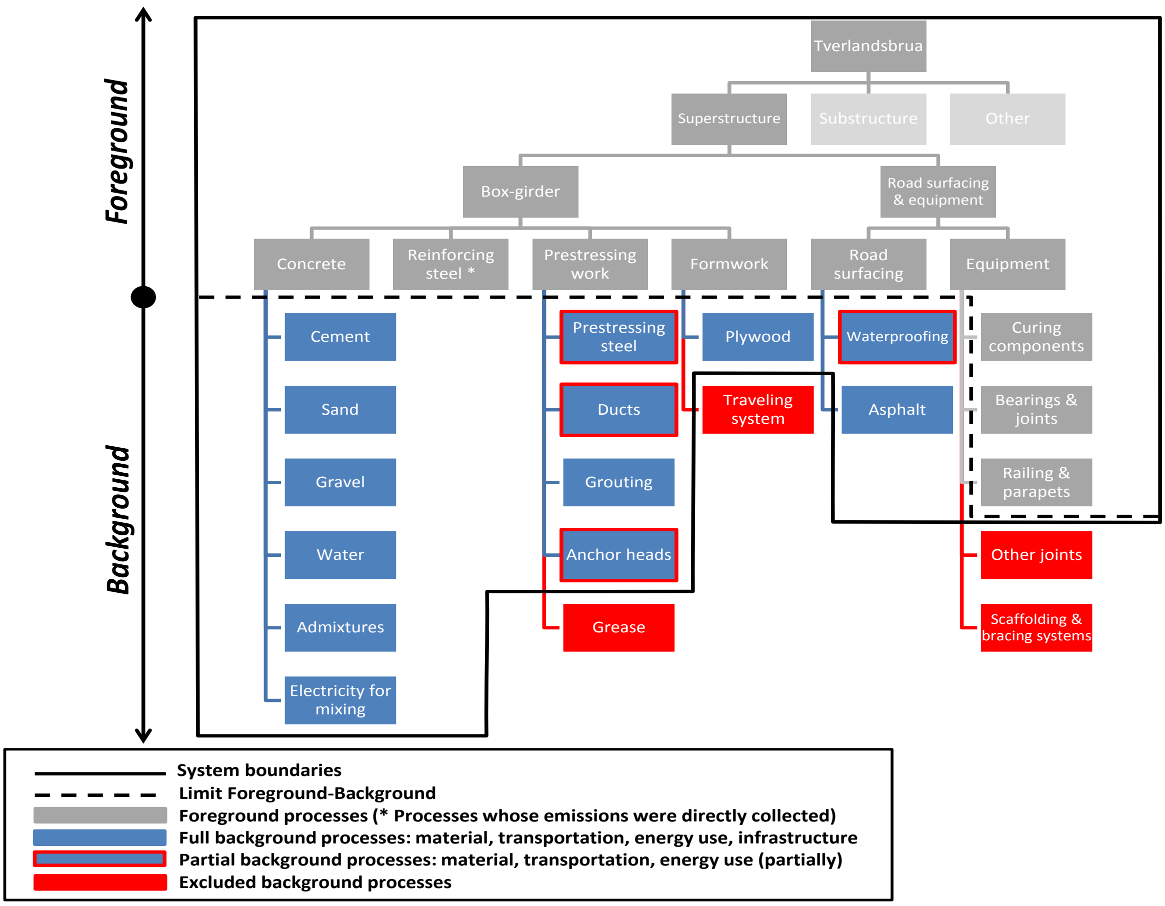

Figure 4.13: System boundary of the superstructure production phase.

The system boundaries of the substructure is shown in figure 4.14. The bridge substructure is composed of the abutments, columns, caisson, foundations and piles. Ground and underwater works are also included in this part.

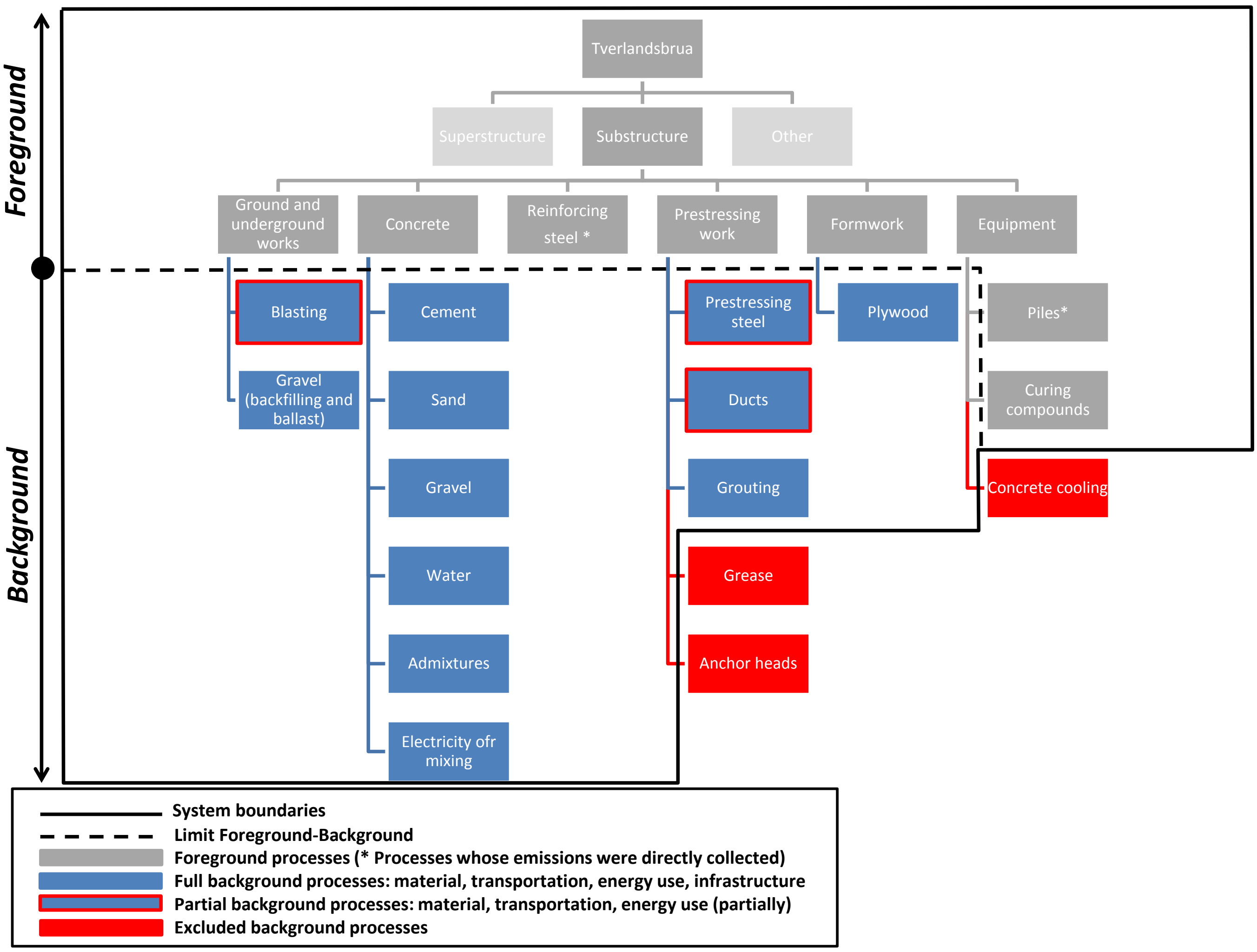

Figure 4.14: System boundary of the substructure production phase.

The last category includes elements that can not be clearly attributed to the superstructure or substructure or whose data quality is bad. As this category contains many small processes, a list of the elements considered is performed further in the report.

The input data are almost always provided by subcontractors. Whenever possible, a complete assessment of these elements is performed (i.e. including transportation of components, energy use from manufacturing processes, etc.). When such data are not available, they try to be assessed through generic processes from the *Ecoinvent v2.2* database included in the software. As far as possible, European average data are selected from the database as they constitute the most reliable origin. When such generic data are not found, some processes are omitted. The importance of these omissions will be considered in the discussion part.

Concrete

5 types of concrete are used in this project: B35 SV-30, AUV B45-SV30 (underwater concrete), B45 SV-30 (Dmax=16 mm), B55 SV-30 (Dmax=16 mm) and B55 SV-30 (Dmax=22mm). According to the concrete supplier, the B55 SV-30 concrete shares are 20% Dmax=16mm and 80% Dmax=22mm. The durability class is MF40 for all concretes, except for AUV concrete that has a M40 durability class. The composition is basically the same for all concretes, only the amount of components change. The components are:

Cement: two types of cement are used: *Norcem Industrisement* and *Norcem Standard FA*. The former is a Portland cement CEM I 42,5 R, containing 90% clinker, 5% additional milling substances and 5% gypsum. The latter is a CEM II/A-V 42,5 R cement containing 80% Portland cement and 20% fly ash. The cement selected from the database is taken at plant and the process includes the manufacturing processes mixing and grinding, internal processes (transport, etc.) and infrastructure (specific machines and plant) [25]. The *Norcem Industrisement* is transported to the concrete factory by truck (about 197 km) and then by freight ship (about 28 nautic miles). The *Norcem Standard FA* cement is transported from Kjøpsvik by freight ship (about 96 nautic miles).

Fly ash is contained in the CEM II/A-V 42,5 R cement (*Norcem Standard FA*). It is mainly composed of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). However, as fly ash is a by-product of the coal-fired power plants, it is considered as waste without burdens. The fly ash transportation is included in the transportation of the *Norcem Standard FA* cement.

Silica fume , or microsilica, is another cement admixture. It is mainly composed of silicon dioxide (SiO_2). The product used in this case is *Fesil Microsilica*. However, as silica fume is a by-product of the production of elemental silicon or ferro silicon alloys, it is considered as waste without burdens. The silica fume is transported by truck from Mo I Rana (237 km).

Sand constitutes the filler part of the concrete that has a diameter range of 0-8 mm. The sand selected from the database is taken at mine. The sand is transported by freight ship from Glømmen (220 nm) and Vika (78 nm).

Gravel constitutes the filler part of the concrete that has a diameter range of 8-22 mm. The gravel selected from the database is taken at mine. The gravel is transported by freight ship from Tomma (78 nm).

Cold water is used for mixing concrete. The water selected from the database is cold tap water. No transportation is considered for water as it is directly taken at the concrete factory.

Superplasticizing admixture are used to have a better concrete workability. The admixture used in this case is *Dynamon SX-N*. Superplasticizers are mainly based on acrylic polymers. Acrylic filler is selected from the database. The superplasticizing admixtures are transported by truck on a distance of 1100 km.

Air-entraining admixture are used for concrete frost protection by producing smaller and more evenly distributed air bubbles. The air-entraining admixture used in this case is *Mapeair 50*. According to a document from the Cement Admixtures Association [26], one of the synthetic air-admixture components used for air-entraining are diethanolamines. Hence, diethanolamine is selected from the database. The air-entraining admixtures are transported by truck on a distance of 1100 km.

Set-retarding admixture are used to control the setting of concrete. They are mainly based on sodium gluconate. The product used in this case is *Mapetard R*. Sodium carbonate is selected from the database. The set-retarding admixtures are transported by truck on a distance of 1100 km.

Anti-washout admixtures are used in underwater casting to prevent concrete from separating in water. The product used in this case is *Rescon T*. Anti-washout admixtures can be cellulo- or acrylo-based polymers. Carboxymethyl cellulose powder is selected from the database. The anti-washout admixtures are transported by truck on a distance of 1100 km.

Energy use for concrete mixing: once all the components are brought to the concrete factory, they must be mixed together. The calculation of the required energy is based on average values from the total production of the concrete plant in 2011. An electricity mix from Norway is selected from the database. 99.1% of this electricity is generated by hydro power plants [27].

Table 4.1 shows the total amount of concrete, composition and energy required for mixing concrete per type of concrete. The amount of concrete is obtained from the bill of quantities realized by *Statens Vegvesen* [23], and the concrete composition is provided by the concrete supplier of the project. Concrete used for piles and ballast concrete are also included here. The total amount of concrete is 18172.7 m^3. A sensitivity analysis is performed later in this report, comparing the different concretes used in this project with a reference concrete and a low-carbon concrete.

	B35 SV-30 (Dmax= 22 mm)	AUV B45 SV-30 (Dmax= 22 mm)	B45 SV-30 (Dmax= 22 mm)	B55 SV-30 (Dmax= 16 mm)	B55 SV-30 (Dmax= 22 mm)
Total amount (m^3)	600	351	4227	2615	10379.7
Density (kg/m^3)	2356	2364	2359	2408	2406
Energy use (kWh/m^3)	5.089	5.089	5.089	5.089	5.089
0/8 mm (Glommen) (%)	24.54	28.65	28.71	33.86	34.48
0/8 mm (Vika) (%)	10.72	7.12	7.14	0.00	0.00
8/16 mm (Tomma) (%)	12.99	12.95	12.98	39.46	13.80
16/22 mm (Tomma) (%)	25.23	24.38	24.43	0.00	25.31
Norcem Standard FA (%)	18.02	18.33	18.37	14.19	13.99
Norcem Industrisement (%)	0.00	0.00	0.00	3.79	3.73
Fesil Microsilica (%)	0.75	0.76	0.77	1.45	1.43
Cold water (%)	7.54	7.31	7.32	7.01	7.02
Dynamon SX-N (%)	0.11	0.13	0.13	0.19	0.19
Mapetard R (%)	0.00	0.06	0.06	0.00	0.00
Mapeair 50 (%)	0.09	0.10	0.10	0.05	0.05
Rescon T (%)	0.00	0.21	0.00	0.00	0.00

Table 4.1: Total amount, energy consumption and composition of each type of concrete.

Table 4.2 shows the amount of concrete per type of element and concrete. As previously presented in figures 4.13 and 4.14, the concrete is divided in two function categories, the bridge superstructure and substructure. The choice of the element subcategories is based on *Statens Vegvesen* element codification from the bill of quantities [23].

Element category	B35 SV-30 (Dmax= 22 mm)	AUV B45 SV-30 (Dmax= 22 mm)	B45 SV-30 (Dmax= 22 mm)	B55 SV-30 (Dmax= 16 mm)	B55 SV-30 (Dmax= 22 mm)	Total
Total (m^3)	600	351	4227	2615	10379.7	18172.7
Total (%)	3.30	1.93	23.26	14.39	57.12	100.00
Superstructure (m^3)	-	-	878	2615	10380	13873
Superstructure (%)	-	-	4.83	14.39	57.12	76.34
Substructure (m^3)	600	351	3349	-	-	4300
Substructure (%)	3.30	1.93	18.432	-	-	23.66
Bridge superstructure						
D31 - capital axis 2,3,4 (m^3)	-	-	-	343.4	1373.6	1717
D32 - cantilevered part axis 2,3,4 (m^3)	-	-	-	1743	6972	8715
D33 - viaduct part axis 5,6,7,8 (m^3)	-	-	-	486	1944	2430
D34 - end section axis 1 (m^3)	-	-	-	42.6*	90.4	133
D95 - edge kites and sidewalks (m^3)	-	-	878	-	-	878
Bridge substructure						
B21 - bored piles axis 2 (m^3)	-	170	225.7**	-	-	395.7

Continue on next page

Continued from previous page

Element category	B35 SV-30 (Dmax= 22 mm)	AUV B45 SV-30 (Dmax= 22 mm)	B45 SV-30 (Dmax= 22 mm)	B55 SV-30 (Dmax= 16 mm)	B55 SV-30 (Dmax= 22 mm)	**Total**
B22 - steel pipe piles axis 5,6,7 (m^3)	-	-	205	-	-	205
C11 - abutments axis 1,8 (m^3)	600	-	-	-	-	600
C21 - foundations axis 2,4,5,6,7 (m^3)	-	-	1250	-	-	1250
C22 - caisson axis 3 (m^3)	-	181	765***	-	-	946
C31 - columns axis 2,3,4 (m^3)	-	-	811	-	-	811
C32 - columns axis 5,6,7 (m^3)	-	-	92	-	-	92

* Including 20 m^3 of ballast concrete
** Including 10 m^3 for excess consumption
*** Including 250 m^3 of ballast concrete

Table 4.2: Amount of concrete per element category

Reinforcing steel

The B500NC reinforcing steel used in this project comes from two main manufacturers: 70% from *Badische Stahlwerke GMBH* in Germany and 30% from *Celsa* in Mo i Rana. The shares of reinforcing steel production between both suppliers are provided by the subcontractor of the bridge but are likely to vary according the the stocks availability. SUch variations are considered in an uncertainty analysis later in this report.

An environmental report from *Badische Stahlwerke GMBH* [28] gives the average CO_2 emissions of a ton of finished reinforcing steel (i.e. at the factory gate) in 2005, 2009 and 2010. All inputs and outputs are considered in this analysis, except for power supply. The emissions are 75, 63.8 and 62.3 $kgCO_2$ per ton of finished product, respectively, showing a trend of decreasing CO_2 emissions over the years. We assume this is due to improvements in steel manufacturing processes, use of recycled scrap steel and decrease of energy use. Hence, we can expect even lower emissions for the reinforcing steel that will be produced in 2011, 2012 and 2013. However, as we do not know the date of production of the steel that will be delivered at Tverlandsbrua throughout the entire construction period, we can simply assume that the steel will be at least produced in 2011. As the construction of the bridge started in June 2011, we can expect that the production of reinforcing steel delivered this year emitted less than in 2010. If we follow the trend of 2% reduction of the CO_2 emissions from 2009 to 2010 compared to 2010, the average emissions in 2011 would be 60.8 $kgCO_2$ per ton of finished product, which is the value selected for our study. However, one should bear in mind that even if those data are very accurate since they directly come from an environmental report of the manufacturing plant, only CO_2 emissions are assessed, hence other greenhouse gases are not considered.

In order to model the electricity consumption omitted in the environmental analysis, we consider the power supply of a generic reinforcing steel production process selected from the database. This generic process uses two different steel manufacturing processes: basic oxygen furnace (BOF) and electric arc furnace (EAF). 63% of steel is produced by BOF and 37% by EAF. BOF and EAF require 2.19E-02 kWh and 4.24E-01 kWh of electricity per kg of steel, respectively, which makes 1.71E-01 kWh per kg of steel in average. A electricity production mix from Germany is then selected from the database to model electricity consumption. The main sources of electricity production in Germany are fossil (62.2%) and nuclear (30.4%). [27]

An environmental performance declaration (EPD) is provided by *Celsa* [29]. A cradle-to-gate analysis is performed, considering all energy supplies (fuel, heat and electricity), steel scrap acquisition, supply of commodities, steel works in Mo I Rana (melting, refining, casting, rolling) and core processes (transportation to the reinforcement steel factories, transportation of waste). The steel products are 100% made up of recycled steel scrap. The electricity required to make 1 ton of finished product is 2681 MJ. The source of electricity for the steel works, representing 90% of the overall electricity consumption, is almost only hydro power (99.8 %). The overall GWP is 340 $kgCO_2$-eq per ton of finished product (at the factory gate).

Prestressing equipment

Prestressing operations are used for two types of work in this project.

First, prestressing tendons are used in axis 2 for the foundation and bored piles, in axis 3 for the caisson platform and in axis 4 for the foundation. These tendons are used to anchor the concrete elements in the bed rock.

The second part of prestressing works is located in the post-tensioned bridge deck. Both companies realizing the bed rock anchoring and the post-tensioning provided all data related to the material type and amount of their products, but no information about the manufacturing processes. The products considered for the prestressing works are:

Prestressing steel: high-strength stressing steel Y1860S7 is used in this project. As this steel is drawn during manufacturing, a wire drawing process is selected from the database, including pre-treatment of the wire rod, dry or wet drawing, heat treatment and finishing [30]. The steel selected from the database is a low-alloyed steel.

Grouting: mortar is used for grouting the ducts. Cement mortar is selected from the database.

Plastic ducts: the prestressing cables for rock anchoring are inserted into plastic ducts. We assume a linear density of 1 kg/m. A combination of plastic raw material extraction and average plastic pipe extrusion is selected from the database. The latter process includes auxiliaries and energy demand [31].

Corrugated steel ducts: the strands used for deck post-tensioning are inserted into corrugated steel ducts. Low-alloyed steel and an average steel working process are selected from the database, the latter including average values for the steel processing by machines as well as the factory infrastructure and operation. Additional metal input in considered for the loss during processing [32].

Anchors: active and passive anchor heads are used to stress the strands at their extremities. Only amount of anchors for bridge deck post-tensioning are provided. Low-alloyed steel and an average steel working process are selected from the database.

Formwork

The formwork used is this project is provided by one single subcontractor. The formwork material is plywood. Due to absence of data from the subcontractors, we assume 18 mm thick plywood panels. An outdoor plywood use process in selected from the database, including the inputs to the production process and transport of those inputs [33].

Asphalt and waterproofing layers

This section covers the production of waterproofing and asphalt layers for the road lanes. Only the initial production of asphalt is considered since its maintenance is assessed in the maintenance & repair phase. All data are based on *Statens Vegvesen* general requirements and own assumptions since the asphalt subcontractor has not been chosen yet. The products are:

Waterproofing is based on two compounds: PmBE60 and Topeka 4S. This waterproofing method became a wide-spread method in Norway in 1990 and is currently applied and regulated by *Statens Vegvesen*. PmBE60 is an adhesive emulsion applied in very thin layers (0.3 - 0.5 kg/m^3) on the concrete deck surface. Topeka 4S is then applied on the PmBE60 layer, consisting in a mix of bitumen, filler and aggregates. To simplify our analysis, we will consider the waterproofing as a 20 mm layer composed of 30% crushed gravel, 60% sand and 10% bitumen, as was designed the initial *Topeka mix* [34].

Asphalt is laid in two layers: one for leveling and one for the surface course. Mastic asphalt is selected from the database. In this process are also included the laying and compacting of the layers with building machines, which should actually be considered in the construction life cycle phase [25]. A transportation distance of 100 km is considered between the asphalt supplier and the construction site.

Curing and chemical compounds

In this section are considered the different concrete curing methods used by the contractor (plastic sheeting, insulation membranes, etc.) as well as gluing of concrete and surface impregnation. All data are based on partial information from the contractor and own assumptions. The different items are:

Insulation membrane is used as a first layer on the curing concrete surface. The product used in this case is *Pieri Curing Clear*, a solvent based liquid that is used to prevent a premature evaporation of the water inside the concrete. We assume a density of 200 g/m^2. An organic solvent is selected from the database.

Plastic sheeting is used as a second layer on the curing concrete surface. The type of plastic used is not clearly identified, so EVA (ethylvinylacetate) foils are selected from the database and we assume a density of 950 g/m^2.

Polyethylene is used as a third and last layer on the curing concrete surface. As only granulate-shaped polyethylene is available from the database, a plastic film extrusion process is added, including auxiliaries and energy demand [31]. We assume a density of 105 g/m^2.

Epoxy resin is used to glue fresh concrete to cured concrete. Epoxy resin from the database is selected. We assume a density of 250 g/m^2.

Surface impregnation has not been clearly defined yet but corresponds to painting of the columns. An acrylic binder is selected from the database. We assume a density of 2 kg/m^2.

Bridge bearings and joints

This section covers the bridge bearings used at axis 1, 6, 7 and 8 as well as the steel finger joints used at axis 1 and 8. Data are partly provided by the subcontractor but assumptions are made for the manufacturing processes.

Bearings transmit the loads from the deck (viaduct part) to the columns at axis 6 and 7, as well as the loads from the deck to the abutments at axis 1 and 8. They are mainly made up of steel, cast iron and natural rubber. These components are selected from the database. Average metal working process is also considered for steel and cast iron.

Finger joints are used at axis 1 and 8. Low-alloyed steel and average metal working are selected from the database.

Railings and parapets

Three types of products are used: outer steel parapets, intermediate steel parapets and pedestrian guardrails. As the subcontractor in charge of these products has not been chosen yet, all data are based on *Statens vegvesen* specifications from the bill of quantities [23] and hand-made calculations of steel volumes. As the calculation of steel volume is highly uncertain, an uncertainty analysis is performed later in this report.

Outer steel parapets are used on the external edges of the road lanes. The model Sicuro H2 is used in this analysis. Low-alloyed steel and average metal working are selected from the database.

Intermediate steel parapets are used between the two traffic lanes. The model Monoline is used in this analysis. Low-alloyed steel and average metal working are selected from the database.

Pedestrian guardrails are used on the external edge of the pedestrian lane. The model Sicuro is used in this analysis. Low-alloyed steel and average metal working are selected from the database.

Piles

Bored and steel pipe piles are considered in this section. Only the steel production and work processing are assessed since concrete and reinforcing steel are considered in the previous sections. Data are partly provided by the subcontractors and own assumptions are made for manufacturing processes of the bored piles casings.

Bored piles: steel casings are used as formwork for the concrete bored piles. Low-alloyed steel and average metal working are selected from the database.

Steel pipe piles: an environmental report from the manufacturer of the steel pipe piles is used to assess the CO_2, CH_4 and N_2O emissions from the steel piles production. This study is a cradle-to-gate life cycle assessment, which means that all processes are taken into account from the raw material acquisition to the finished product, and it includes end-of-life recycling rate of 90% for steel [35]. The emissions for 1 ton of finished product are 1.07 tCO_2, 0.8 $kgCH_4$ and 6 gN_2O. Other greenhouse gases are not considered but they represent a negligible share of the overall global warming.

Ground and underwater works

This section includes explosives used for rock blasting and gravel. Data are mainly based on own assumptions.

Explosives : a mix of TNT and slurry is used by the subcontractors for blasting. Normally, TNT should be modeled for blasting below water, at it is the only suitable underwater blasting technology. However, only Tovex (partly modeled as a slurry explosive) is available and then selected from the database. Raw material provision, mixing process, packaging, internal processes (transport, etc.) and infrastructure are included [25]. According to the subcontractors, 70 kg of explosive is required for blasting 360 m^3 of rock.

Gravel : crushed gravel is used for backfilling against the abutments and ballast in the caisson. Crushed gravel is selected from the database.

Other products

This section covers all products that could not be clearly attributed to the bridge superstructure or substructure, or whose data quality was too low to be relevant if allocated to one of the previously listed categories. The amount of material is either taken from the bill of quantities or roughly assumed. The quality of data is said medium when the product can be assessed using accurate generic data from the database and poor when assumptions have to be made for input quantifications and selection of data from the database. The elements considered are:

Extra cement: supplementary cement is ordered by the main contractor in order to have a permanent amount of cement available at site. Portland cement 42.5 is selected from the database. Quality of data: medium.

Electrical cables: the necessary amount of cables for power supply is considered here. 12590 m are stated in the bill of quantities. All other electrical devices (Cadweld bolts, switching boxes, etc.) are not considered. Three-conductor cables are selected from the database. Quality of data: medium.

Lamp posts: devices used for public lighting. 30 units are ordered. We assume 50 kg of steel per unit. Low-alloyed steel and average steel working are selected from the database. Quality of data: poor.

Hollow rock shoes: devices mounted at the bottom of the steel pipe piles to prevent the piles from slipping against the bed rock. 64 units are ordered. We assume 2000 kg of steel per unit. Low-alloyed steel and average steel working are selected from the database. Quality of data: poor.

Grouting for bored piles: grouting is used between the rock and the steel casings for bored piles. We assume 60 kg of grouting for the 12 piles. Cement mortar is selected from the database. Quality of data: poor.

Corrosion protection for anchoring: includes corrosion protection of anchoring cables in foundations and piles. 26 m^2 of powder coating are stated in the bill of quantities. Powder coating is selected from the database. Quality of data: poor.

Supplementary formwork: includes supplementary formwork for recesses, edge beams and all architectural details of the bridge. The bill of quantities states 8073 m^2 of extra formwork for the entire bridge. We assume a thickness of 18 mm. Outdoor plywood is selected from the database. Quality of data: poor.

Fixed splicing connections: this type of connections is used for splicing the prestressing cables in the deck. 30 units are ordered. We assume 10 kg of steel per unit. Low-alloyed steel and average steel working are selected from the database. Quality of data: poor.

Skirts: devices used to prevent boats from being sucked up below the column foundations. 270 tons of concrete are stated in the bill of quantities for all skirts. Normal concrete is selected from the database. 8 tons of reinforcing steel are assumed here. Quality of data: poor.

Water runoff systems: pipes are used for water runoff on the bridge deck. 1340 m of plastic pipes are stated in the bill of quantities. PVC and plastic pipe extrusion process are selected from the database. Quality of data: poor.

Additional equipment for inspection: 2 stairs, 2 doors and 2 ladders are mounted for inspecting the foundation at axis 2 and the caisson at axis 3. 6000 kg of steel and 50 m^2 of stainless steel coating are assumed. Low-alloyed steel, average steel working and stainless steel coating are selected from the database. Quality of data: poor.

Excluded elements

All products from the bill of quantity not listed previously are considered here. These elements are not assessed in this analysis because no data are available. The elements considered are:

Grease: this is used to facilitate the insertion of the different prestressing components. However, as no information is given about grease type and amount, this is not included in the analysis.

Supplementary wood: wooden planks are used for security installation and other on-site uses. No information is provided about the amount and type of wood.

Barracks: different features for the personnel are used on the site, such as sleeping accomodations, offices, kitchens, bathrooms and meeting rooms. No information is provided about the production of these features.

Traveling formwork system, scaffolding, temporary bracings and covers: the production of these elements is not considered as the related products are likely to be reused in other projects. Furthermore, no data are available to make allocation procedures for assessing the wearing down of the elements in this project.

Cooling of concrete: a cooling system is to be used for the concrete in foundations at axis 2, 4, 5, 6 and 7. However, no data are available yet on the type of cooling process (cooling pipes, cooling compound, etc.). The production of this cooling system is then not considered.

4.2.2 Construction phase

The emissions due to the construction phase of the bridge are listed in three categories: transportation to the site, emissions from construction on the site and waste management.

The system boundaries of the construction phase is shown in figure 4.15.

The transportation to the site is divided in three types of transported unit: material, equipment and personnel. This division is due to very different assumptions made for the transportation assessment of each category (single or round-trip considered, type of transportation unit, etc.).

Emissions from construction on the site are due to three main sources (electricity, diesel and gasoline) and two secondary sources.

Waste management includes transportation of materials to recycling plant except for mixed waste that is transported to a landfilling area.

Finally, the category *Others* regroups transportation of the elements classified in the production phase category *Others* and construction-related processes that could not be clearly attributed to the bridge superstructure or substructure or to their related subcategories.

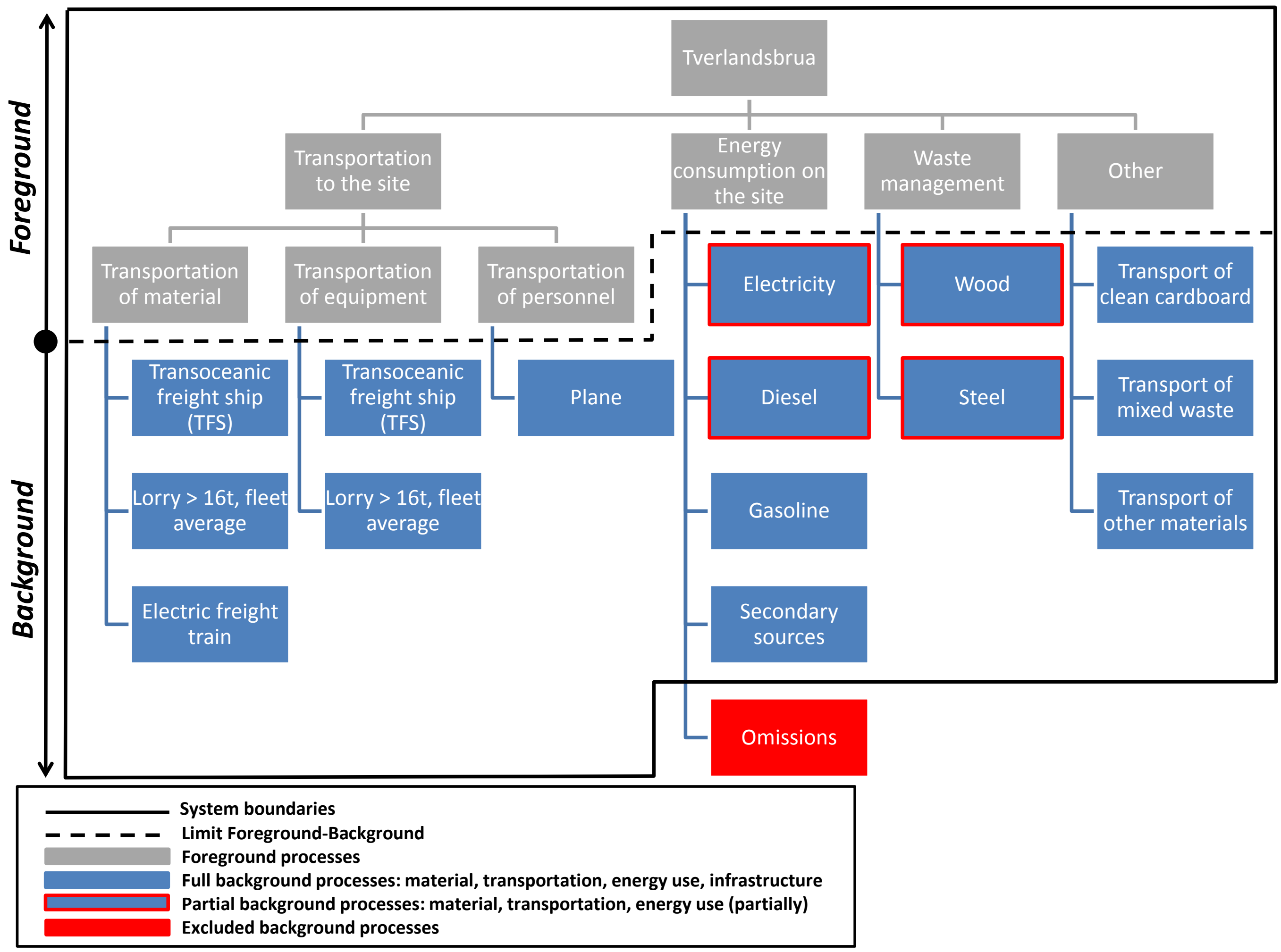

Figure 4.15: System boundary of the construction phase.

Transportation to the site

Transportation is included in the construction life cycle phase since means of transportation and traveling distances mainly depend on the location of the project, and not on the production of the transported materials. Almost all data are provided by the subcontractors. When some data are not available, assumptions are made. Transportation of material and equipment to the site is mainly performed using two means of transportation: transoceanic freight ship and lorry. A part of the prestressing equipment for the bridge deck is transported by train. Transportation of personnel is only performed by plane. Each type of transported unit, i.e. material, equipment and personnel, is assessed independently.

Transportation of material. Table 4.3 shows the mean of transportation, route, distance, amount of material transported and amount of kilometre-ton (i.e. the transportation of one metric ton over one kilometre) of each product category. The processes selected from the database are: Transoceanic freight ship (TFS), including operation and maintenance of the ship as well as construction and maintenance of port facilities; Lorry $>$ 16t, fleet average, including lorry operation and maintenance as well as construction and maintenance of road infrastructures and European freight train, including a mix of electricity and diesel supply as well as operation, maintenance and disposal of the rolling stock and the rail infrastructure [36].

Apart from concrete transportation, only one way of transportation is included. Indeed, transportation distances included in this project are often very important (between 600 and 2000 km) and the products are mainly delivered in one carriage for the entire bridge construction period, so no frequent round-trips are necessary. Moreover, the transport devices can deliver their products at other construction sites on their way back. For concrete, this is different since the concrete factory is based 20 km from the bridge site, so round-trips are considered. However, we assume that on its way back to the concrete factory, an empty truck weights 20% of the concrete weight transported on its way out.

Material	**Mean of transportation**	**Route**	**Distance (km)**	**Amount of transported material (t)**	**Amount of kilometre-ton (tkm)**
Concrete (round-trips)	Lorry	Bodø- Tverlandsbrua	24	4.349E+04	1.044E+06
Reinforcing steel	TFS	Germany - Oslo	850	1.14E+03	9.68E+05
		Germany - Harstad	2140	1.14E+03	2.44E+06
	Lorry	Oslo - Tverlandsbrua	1200	1.14E+03	1.37E+06
		Harstad - Tverlandsbrua	320	1.14E+03	3.64E+05
		Mo I Rana - Tverlandsbrua	237	9.76E+02	2.31E+05
Deck prestressing - Strands	TFS	Santander - Oslo	2322	7.67E+02	1.78E+06
	Frieght train	Oslo - Tverlandsbrua	1200	7.67E+02	9.21E+05
Deck prestressing - ducts, option 1	Truck	Cornaredo - Antwerp*	940*	7.77E+01	7.30E+04*
	TFS	Antwerp - Oslo*	1169*	7.77E+01	9.08E+04*

Continue on next page

Continued from previous page

Material	Mean of transportation	Route	Distance (km)	Amount of transported material (t)	Amount of kilometre-ton (tkm)
Deck prestressing - ducts, option 1	Train	Oslo - Tverlandsbrua*	1200*	7.77E+01	9.32E+04*
Deck prestressing - ducts, option 2	TFS	Barcelone - Oslo	4437	7.77E+01	3.45E+05
	Train	Oslo - Tverlandsbrua	1200	7.77E+01	9.32E+04
Deck prestressing - anchors	TFS	Barcelone - Oslo	4437	4.20E+01	1.87E+05
	Train	Oslo - Tverlandsbrua	1200	4.20E+01	5.04E+04
Deck prestressing - grouting	Truck*	Bodø- Tverlandsbrua*	20*	3.50E+02	7.00E+03*
Rock anchoring - tendons	Lorry	Linkping - Stavanger	1000	1.64E+01	1.64E+04
Rock anchoring - plastic ducts	Lorry	Nordsj - Stavanger	1400	9.56E-01*	1.34E+03*
Rock anchoring - grease	Lorry	Duisburg - Stavanger	1200	5.00E-01*	6.00E+02*
Rock anchoring - anchor heads	Lorry	Subingen - Stavanger	1700	1.00E+00*	1.70E+03*
Rock anchoring - assembled cables	Lorry	Stavanger - Bodø	1500	1.88E+01*	2.83E+04*

Continue on next page

Continued from previous page

Material	Mean of transportation	Route	Distance (km)	Amount of transported material (t)	Amount of kilometre-ton (tkm)
Rock anchoring - grouting	Lorry*	Bodø- Tverlandsbrua*	20*	5.90E+00	1.18E+02*
Formwork	Lorry	Trondheim - Tverlandsbrua	700	4.81E+02	4.81E+05
Asphalt	Lorry*	NR	100*	2.96E+03	2.96E+05*
Curing and chemical compounds	Lorry	N/A	700	1.77E+01	1.24E+04
Bridge bearings and joints	Lorry	Oslo - Tverlandsbrua**	1200	2.09E+01	5.00E+04
Railings and parapets	Lorry*	N/A	1000*	7.26E+02	7.26E+05*
Bored piles - steel casings	Lorry	Germany - Tverlandsbrua	2000*	8.80E+01*	1.76E+05*
Steel pipe piles	Lorry	Oulainen (Finland) - Tverlandsbrua	863	1.68E+02	1.45E+05
Ground works - explosives	Lorry*	NR	100*	1.40E-01	1.40E+01*
Ground works - gravel	TFS	Tomma - Tverlandsbrua	145	4.38E+03	6.34E+05
Other	Lorry*	NR	400*	5.06E+02	2.02E+05

* Estimations.

** 2 travels required.

Table 4.3: Transportation of meterials

Transportation of equipment. In this section are considered all machinery equipments and temporary products of the bridge construction phase (scaffolding, etc.). All transportation distances are hence counted twice since the rented material or equipment will be sent back at the end of the construction phase.

Table 4.4 shows the mean of transportation, route, distance, amount of equipment transported and amount of kilometre-ton per equipment category. TFS and lorry > 16t, average fleet are still selected from the database. Even if some machinery equipment are directly driven to the site (drilling rig, piling rig), lorries are the only means of transportation available in the database to model transportation of heavy machines. Transportation of machinery equipment for ground work (excavator, loader and driller) is not included since the subcontractor headquarters are based less than 1 km from Tverlandsbrua.

Equipment	Mean of transportation	Route	Distance one way (km)	Amount of transported equipment (t)	Amount of kilometre-ton (tkm)
Scaffolding	Lorry	NR	1400	7.50E+02*	2.10E+06*
Bored piles - drilling rig	Lorry	Germany - Tverlandsbrua	2000*	1.75E+02*	7.00E+05*
Steel pipe piles - piling rig	Lorry	Gteborg - Tverlandsbrua	1475	9.50E+01	2.80E+05
Tower crane	Truck	Kjeller - Tverlandsbrua	1200	2.00E+02	4.80E+05
* Estimations.					

Table 4.4: Transportation of equipment

Regarding the tower crane transportation, it is hard to allocate the burdens to specific categories since the crane helps handling all elements at site. An allocation based on a weight criteria is performed in table 4.5. The total burdens due to crane transportation (4.80E+05 tkm) is allocated according to the proportional weight of each component category.

Element category	Weight (tons)	Weight (%)	Superstructure - structural	Superstructure - non-structural	Substructure - structural
Total	5.02E+04	100.00	75.85	1.51	21.67
Concrete	4.35E+04	86.58	66.38	0	20.19
Reinforcing steel	3.25E+03	6.48	5.18	0	1.30
Prestressing	9.88E+02	1.97	1.92	0	0.05
Scaffolding	7.50E+02	1.49	1.49	0	0
Railings	7.26E+02	1.45	0	1.45	0
Formwork	4.81E+02	0.96	0.83	0	0.13
Bearings	2.09E+01	0.04	0	0.04	0
Curing	1.77E+01	0.04	0	0.03	0.01
Other	5.06E+02	1.01	-	-	-

Table 4.5: Weight analysis for electricity supply allocation

Transportation of personnel. In this section are included the transportation of personnel during the construction phase of the bridge. This personnel includes all members of the construction site team (workmen, drivers, site managers, etc.), representing 20 persons in total. The personnel works on site 6 weeks in a row and rests for 3 weeks at their home place. Travels between home places and construction site are made by plane, with an average distance of 1650 km (one way). An allocation of the total transportation based on the weight analysis showed in table 4.5 is realized.

Table 4.6 sums up information about transportation of personnel.

Item	Amount	Unit
Hired personnel	20	p
Total number of travels (both ways)	45	p
Traveling distance (one way)	1650	km
Total transportation	1.485E+06	pkm

Table 4.6: Transportation of personnel

Construction on the site

This section covers all processes related to energy consumption on the site. This consumption mainly comes from the cranes and other machinery equipments and use of petrol for boat transportation on the site (displacements between the abutments and to the column at axis 4). As this bridge is currently being constructed, having an accurate estimation of the total energy consumption for the overall construction period is a complicated task. Moreover, allocation methods have to be used since the amount of energy consumed can only be obtained in a bulk sum (power supply invoices, total number of gas cans bought, etc.).

There are three permanent sources of energy consumption at site: electricity, diesel and gasoline. Electricity is used for crane power supply, diesel for building machines and gasoline for displacements by boat. The energy is provided by the contractor during the entire construction period. The average energy consumption per month (from August 2011 to April 2012) is displayed in table 4.7. The data are provided by the contractor and are used to calculate the energy consumption for the overall construction period. An allocation procedure for electricity, diesel and gasoline consumption based on the weight analysis from table 4.5 is realized.

Energy category	**Source of consumption**	**Amount**	**Unit**
Electricity	Tower Crane	15000	kWh
Diesel	Mobile cranes	3000	l
Gasoline	transportation by boat	800	l

Table 4.7: Average energy consumption on the site per month

Electricity : the handling by the tower crane of the following element categories are considered for allocation of the power supply: scaffolding, concrete, reinforcing steel, formwork, prestressing work, curing compounds, bearings and joints, railings and parapets and other. Most of these elements are handled and installed by the fixed and mobile cranes, but other devices can be used (e.g. strand pushing machine for threading of the strands, hydraulic pump for stressing, etc.); however the infrastructure use is not considered in this analysis since no data are available. A Norwegian production mix is selected from the database to model the power supply process.

Diesel : diesel burnt in building machine is considered for mobile cranes. A process modeling the diesel burnt in building machine is selected from the database, including the machine infrastructure, lubricating oil and fuel consumption. [25]

Gasoline : gasoline is used for displacements by boat on the site. Heavy fuel oil is selected from the database.

Other temporary sources of energy consumption on the site are the use of tugboats during the construction of the caisson, use of boring and piling rigs for the piles and excavation of material. Those processes are considered separately since the subcontractors used their own energy supply. Data related to the type and amount of energy consumed are provided by the subcontractors or based on own assumptions and are shown in table 4.8. Heavy fuel oil for the tugboats (infrastructures not considered) and diesel burnt in machinery (infrastructures considered) are selected from the database.

Energy category	Source	Amount	Unit
Marine oil diesel	Tugboats for the caisson construction	28700	l
Diesel	Piles boring	28000	l
Diesel	Piling rig	30000*	l
Diesel	Excavation above water	3000	l
Diesel	Excavation below water	4125*	l
* Estimations.			

Table 4.8: Secondary sources of energy consumption during the construction phase

Finally, there are other probable sources of energy consumption during the construction period. However, as these elements are often small processes very complicated to assess, they are deliberately omitted since their contribution to the overall impact would be insignificant. These elements (directly taken from the bill of quantities) are:

Barracks: comprises transportation and power supply of the barracks. No information is provided about the consumption and assumptions would be very uncertain.

Logs: comprises recording of logs.

Supplementary site investigation: extra time used for site investigation.

Driving procedures for steel pipe piles: comprises driving and splicing (if applicable) of steel pipe piles.

Preparatory works for rock footing: comprises rigging and drilling for rock footing.

Chiselling/stop criteria in rock: comprises chiselling of the rock shoe into the bedrock to establish a rock footing.

Fine scaling of blasted rock surface: comprises fine scaling of blasted rock surface, including rough scaling.

Core drilling: Comprises drilling, removal, packing, storage and if relevant dispatch of rock and concrete cores, as well as any refilling of drillholes.

Dynamic control measurements (PDA measurements etc.): comprises all materials, works and documentation related to dynamic control measurements.

Waiting time and operating time: comprises unforeseen waiting time caused by the Project Owner.

Cutting of steel pipe piles: comprises cutting of steel pipe piles as well as delivery and mounting of pile heads.

Location of cables and service pipes: comprises collection of information regarding cables and service pipes in the ground.

Rigging: comprises all rigging works not considered previously.

Anchoring pipes/inspection ducts: comprises delivery and all works connected with anchoring pipes and inspection ducts fixed to the reinforcement cage of the bored piles.

Grouted bolts in rock above water: comprises installation of bolts/dowels in rock above the groundwater level or in a drained construction pit.

Earthing points for corrosion inspections: comprises installation of earthing point for corrosion protection.

Screeding and trimming of concrete surface: comprises final surface treatment in terms of sealing and smoothing of the concrete surface.

Heating of adjoining structural components: comprises heating of structural components against which concrete is placed, to avoid large temperature differences between cast sections.

Injection hose: comprises delivery and installation/embedding of injection hose with accessories and actual pressure injection of epoxy or polyurethane.

Connections: comprises special works with waterproofing and surface course at bridge deck side and end edges, connections with kerbing, edge beams or concrete parapets, guardrail posts, water outlets and with asphalt surface courses on abutting roads as well as laying in parapet area.

Anodes for cathodic protection: comprises delivery and installation of sacrificial anodes and anodes with impressed current for cathodic protection and connection to steel and power supply.

Reference points: comprises delivery and installation/grouting in position of bolts for measuring joint movements, levelling and position determination (reading of coordinates). Comprises precise measurement of reference point immediately after establishment and reporting.

Mooring equipment (pullers, bollards): comprises delivery and installation of mooring equipment.

Waste management on the site

Waste management on sites is strictly regulated in Norway. The *Statens Vegvesen* tendering documents specify that at least 70% of waste should be sorted [37] on Tverlandsbrua site. The materials are sorted in four main categories: wood, steel, clean cardboard and others. The main sources of waste are wooden formworks and planks, reinforcing steel and cardboard from packing. Table 4.9 shows the average amount of sorted material per category during the period August 2011 - April 2012, except for wood. The data are provided by the contractor.

Waste category	Source	Amount	Unit
Steel	Reinforcing steel	6.23	t
Clean cardboard	Packing	0.16	t
Other	Mixed waste	2.48	t

Table 4.9: Average amount of sorted material on the site per month.

We assume that steel and clean cardboard are 100% recycled and that mixed waste is landfilled. Since the benefits from recycling shall be attributed to other projects, recycling processes are not considered here, and as the composition of the mixed waste is unknown, the landfilling process is not considered either. The processes considered are then:

Transportation of reinforcing steel: a transportation distance of 300 km is considered.

Transportation of formwork: we consider that 100% of the plywood used as formwork is transported to a recycling plant. A transportation distance of 300 km is assessed.

Others

In this section, processes that could not be clearly attributed to an element category (even using allocation procedures) are regrouped. The processes considered are:

Transportation of clean cardboard and mixed waste: a transportation distance of 300 km is considered.

Transportation of the products from the production phase category *Others*: a transportation distance of 400 km is considered.

4.2.3 Operation phase

The operation phase considers all impacts due to the use of the bridge during its life cycle. Two main processes are considered: traffic-related emissions, including traffic growth rate and power supply for public lighting. Power supply for internal lighting and other electrical devices are not considered since it is very complicated to be assessed and no data are available.

Traffic related emissions. Estimation of the annual average daily traffic by *Statens vegvesen* at the bridge opening in 2013 and closing, estimated to be in 2113, are 8600 and 15000 veh/day all lanes considered, respectively. From these data are calculated an annual growth traffic rate, assuming a geometric progression, and the total number of vehicles for the 100-year expected life cycle. The results are shown in table 4.10.

	Value	**Unit**
AADT year 0	8600	veh/day
AADT year 100	15000	veh/day
Common ratio of the geometric expansion	$q = (\frac{15000}{8600})^{1/100} = 1.00588$	
Annual growth traffic rate	0.558%	
Cumulated AADT	$c = 8600 * \frac{1-1.00588^{100}}{1-1.00588} =$ 1.15E+06	veh/day
Total number of vehicle	$t = 1.14739E + 06 * 365 =$ **4.19E+08**	**veh**

Table 4.10: Calculation of the total number of vehicles for the 100-year expected life cycle.

Operation processes for transportation, quantified in vehicle-kilometres (vkm), are selected from the database. We assume 80% of diesel cars, 10% of petrol cars and 10% of lorries > 16t, fleet average. Only vehicle operation is considered, not the vehicle infrastructure. The wearing down of the road infrastructure is assessed in the maintenance and repair phase.

Power supply for public lighting. Public lighting for the entire bridge life cycle is the second operation process considered. Only energy consumption from the lamp posts is assessed (no electrical installation or maintenance of the light bulbs considered). Two types of mix are available in the database: production and supply mix. The production mix only considers domestic consumption (i.e. no trades with other countries), while the supply mix also considers imports and exports of energy [27]. In order to simplify our analysis and results interpretation, a Norwegian production mix is selected from the database. Data are provided by *Statens vegvesen* and *Datek*, a company providing communication systems for public and private services. Data are shown in table 4.11.

Item	Amount	Unit
Number of lamp posts*	30	p
Life time	100	years
Type of lamp*	250	W
Yearly average lighting time**	4000	hrs/year
Total energy consumption	**3E+06**	**kWh**
* Source: *Statens Vegvesen*.		
** Source: *Datek*.		

Table 4.11: Total electricity consumption for public lighting.

4.2.4 Maintenance & repair phase

The maintenance & repair phase considered in this analysis is divided in three main processes: a simple visual inspection every year, a main inspection every 5 years (including cable and underwater inspections) and a new asphalt course every 3 years. No important structural maintenance or repair interventions are considered since the bridge is supposed to be designed for a 100-year life cycle without repair. Accidental repairs are not considered either because no data are available.

Simple visual inspection (every year): according to the *Statens Vegvesen* Handbook n. 136 - Inspection for bridges [22], no special equipment is required for this inspection. Hence, we just consider the transportation of the staff to the bridge site (1 vehicle, both ways), assuming a distance of 500 km.

Main inspection (every 5 years): according to the *Statens Vegvesen* Handbook n. 136 - Inspection for bridges [22], this inspection requires machines for inspection (lifter). We assume that the machine is rented 200 km from the bridge site and we select a building machine from the database, working for 8 hours. We also consider the transportation of the staff to the bridge site (1 vehicle, both ways), assuming a distance of 500 km. Table 4.12 shows assumptions made for the main inspection.

Item	Amount	Unit
Life time	100	year
Frequency of inspection	5	years
Cars for staff displacement	1	unit
Distance traveled by car, both ways	1000	km
Total car operation	**2.00E+04**	**vkm**
Machines for inspection	1	unit
Distance traveled by the machine, both ways	400	km
Total machine operation	**8.00E+03**	**vkm**
Number of working hours (per inspection cycle)	8	hrs
Diesel consumption rate*	17.4	kg/hrs
Diesel consumption per unit*	0.023	kg/MJ
Total diesel burnt in building machines	**6.05E+03**	**MJ**
* Source: EcoInvent database v2.2.		

Table 4.12: Data for main inspection assessment.

Asphalt course renewal (every 3 years): the renewal of the asphalt surface course is considered. A 20 mm thick layer is removed from the wearing course due to the wearing down by the use of spiked tires in winter, representing 510 tons of asphalt each time. Removal of the old course as well as its transportation to a landfilling area and a sanitary landfilling process are also included. The re-asphalting process is the same as used for the first time, i.e. a mastic asphalt process including the laying and compacting of the layers with building machines. The transport of new asphalt to the bridge is considered, consideration a distance of 100 km. Traffic disruption due to the maintenance works are not considered since each traffic lane is renewed one after each other, and the operational traffic lane still have sufficient capacity. Some traffic jams could occur in the future due to traffic growth rate, but this cannot be accurately quantified and then is not considered. Since the frequency of asphalt course renewal is quite high, a sensitivity analysis considering lower frequencies of asphalt maintenance is performed later in this report. Table 4.13 shows the main assumptions for asphalt course renewal.

Item	Amount	Unit
Life time	100	year
Frequency of inspection	3	years
Amount of asphalt replaced for cycle	510	tons
Number of working hours	100	hrs
Diesel consumption rate*	17.4	kg/hrs
Diesel consumption per unit*	0.023	kg/MJ
Total diesel burnt in building machines for removal of asphalt course	**2.50E+06**	**MJ**
Transportation of new asphalt to the bridge	**1.68E+06**	**tkm**
Total amount of landfilled asphalt (transportation included)	**1.68E+07**	**kg**
Total amount of asphalt renewed	**1.68E+07**	**kg**
* Source: EcoInvent database v2.2.		

Table 4.13: Data for asphalt course renewal.

4.2.5 End-of-Life phase

In order to perform the EOL phase, cut-off criteria have to be used. Indeed, as end-of-life information is not available for all components, only the main ones are considered. Hence, all elements whose weight is inferior to 1% of the overall bridge weight are omitted. The elements considered in this phase are then reinforced concrete, asphalt, gravel (used for backfilling against the abutments and as ballast in the caisson) and steel from prestressing, railings and parapets, totalizing 98.6% of the overall weight, as shown in figure 4.16.

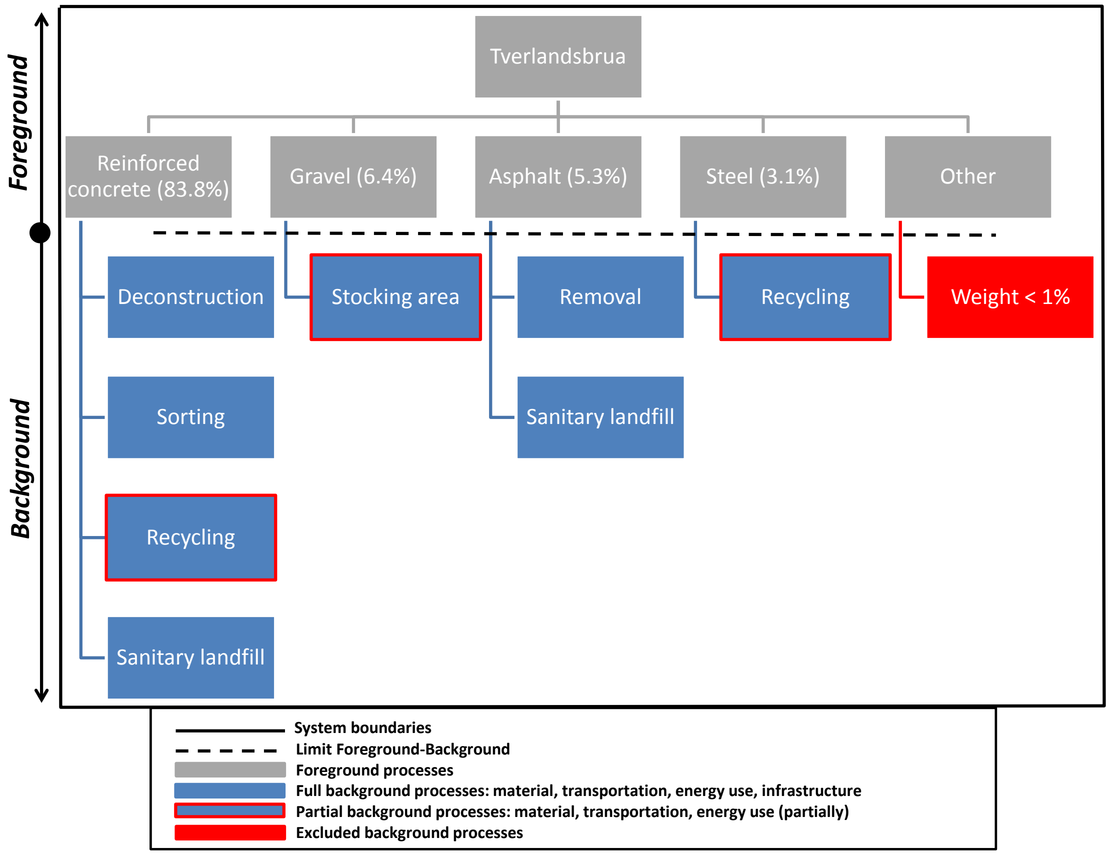

Figure 4.16: System boundary of the end-of-life phase.

The accuracy of the results for this phase are disputable since improvements in EOL treatment technology in 2113 could lead to other scenarios (improved sorting and recycling rates so less landfilling, improvement in deconstruction technologies, etc.). The consideration of different EOL scenarios would be interesting here, but this is beyond the scope of this study and is subjected to time and data limitations.

Reinforced concrete i.e. concrete and reinforcing steel, represents 83.8% of the overall bridge weight. An EOL treatment from the databse is selected, divided in three main process: deconstruction, sorting and disposal. The *Ecoinvent* center realized different reports for life cycle inventories per field of study. A reinforced concrete sorting process is selected from the database. The reinforced concrete is first dismantled, considering energy consumption and infrastructure. The infrastructure is built up considering average efficiencies of different dismantling machines (hydraulic rock chisel, concrete claws, concrete saws, etc.). The dismantled reinforced concrete is then transported to a sorting plant, where it is separated in two disposal categories: 61.2% is to be recycled and 38.8% is to be brought to a sanitary landfill [38]. For this latter disposal phase, transportation to a sanitary landfill and landfilling are included in the database process. For the recycled part, we consider an average distance of 100 km between the sorting and recycling plants. The recycling process is not considered for the same reasons as waste management on the site.

Gravel used for backfilling against the abutments and as ballast in the caisson represents 6.4% of the overall bridge weight. Only transportation of the gravel to a stocking area is considered, assuming a distance of 100 km, since gravel is an inert material that can be directly reused in other projects.

Asphalt & waterproofing constitute 5.3% of the overall bridge weight. The process considered here is the same as for maintenance operation, i.e. the waterproofing and asphalt layers are removed and transported to a sanitary landfill.

Steel from prestressing work, railings and parapets represent 3.1% of the overall bridge weight. The steel is assumed to be recycled and we consider a distance of 100 km to the recycling plant. The recycling process is not considered.

4.3 Results, interpretation and further analysis

In this section, the results from the LCIA phase are presented and interpreted; and uncertainty and sensitivity analyses are performed. The results are given for the impact category climate change and are presented in four different ways: overall results, results per function category, results per life-cycle phase and result per component category. The identification of the four types of presntation is displayed in figure 4.17.

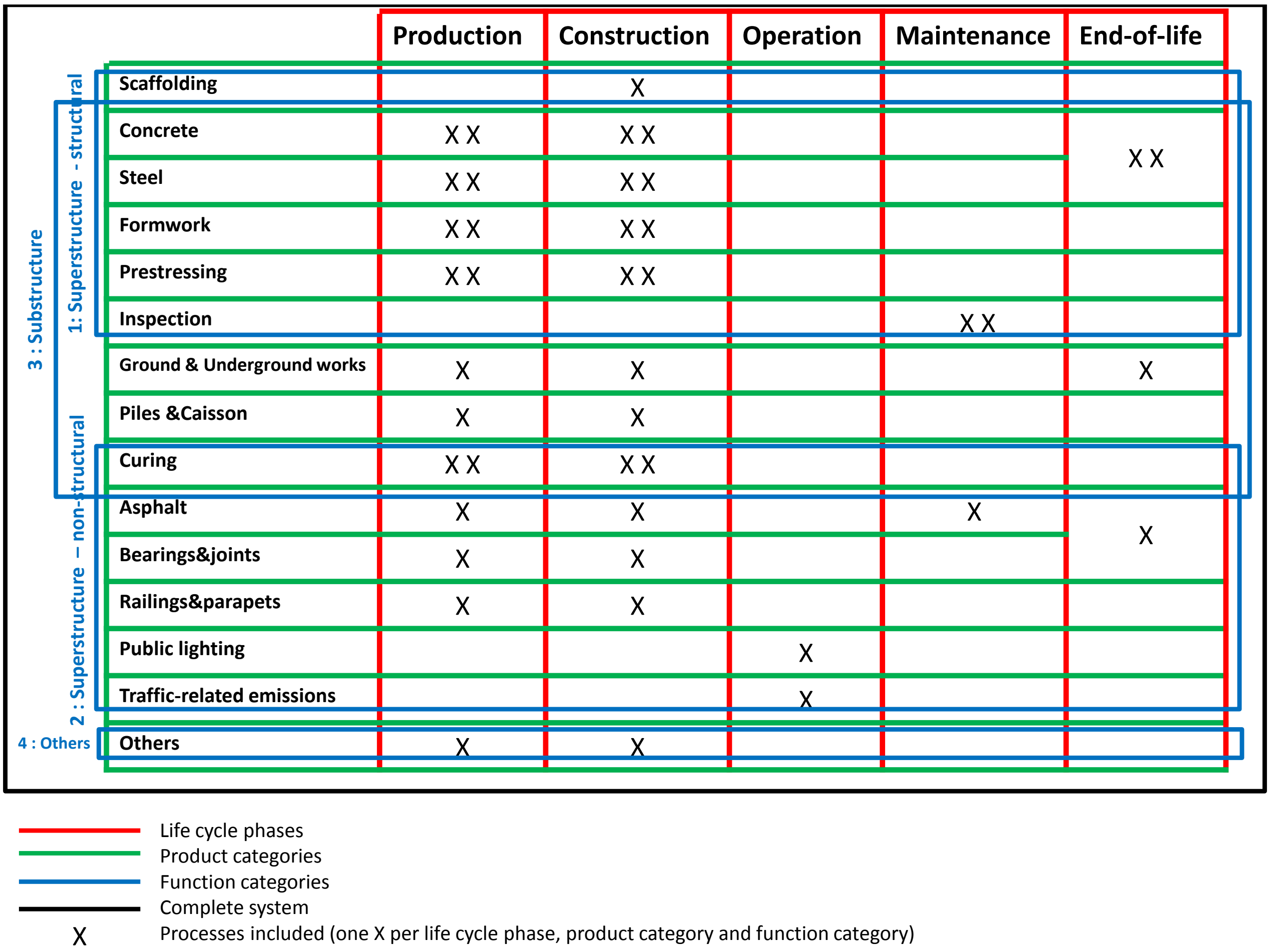

Figure 4.17: Presentation of the four result categories.

4.3.1 Overall results

The overall global warming impact, all life cycle phases considered, is 6665 kgCO_2-eq per FU (the FU is defined as 1 square meter effective bridge deck area through a lifetime of 100 years). The bridge deck area is 15711.5 m^2, which makes an overall impact of 104717 tCO_2-eq for the 100-year expected lifetime of the bridge. The burdens from the operation phase represent

79.6% of the overall impact, clearly overcoming the other life cycle phases. This is due to huge impacts from traffic-related emissions during the 100-year life cycle phase. The consideration of these emissions will be further detailed in the interpretation of the operation phase. If we omit the operation phase, the overall global warming impact is reduced to 1358 kgCO_2-eq per FU.

If we compare the overall global warming impact with similar studies and without considering the operation phase, we find out that the results are in the same range. The average value from the literature review of concrete bridges was 1590 kgCO_2 per FU (see table 2.1), while this study scores about 1258 kgCO_2 per FU. Comparisons with individual studies will be performed in the discussion part.

4.3.2 Results per function category

Four function categories are identified in this project: the structural part of the superstructure (BridgeSup1), the non-structural part of the superstructure (BridgeSup2), the substructure (BridgeSub3) and Other. If we include impacts from traffic-related emissions, BridgeSup2 greatly overcome other categories. This life cycle phase is then omitted in order to show more clearly the share of impacts between the different function categories but is obviously identified as a hot spot of this study. Figure 4.18 shows shares and amounts of global warming impact per function category.

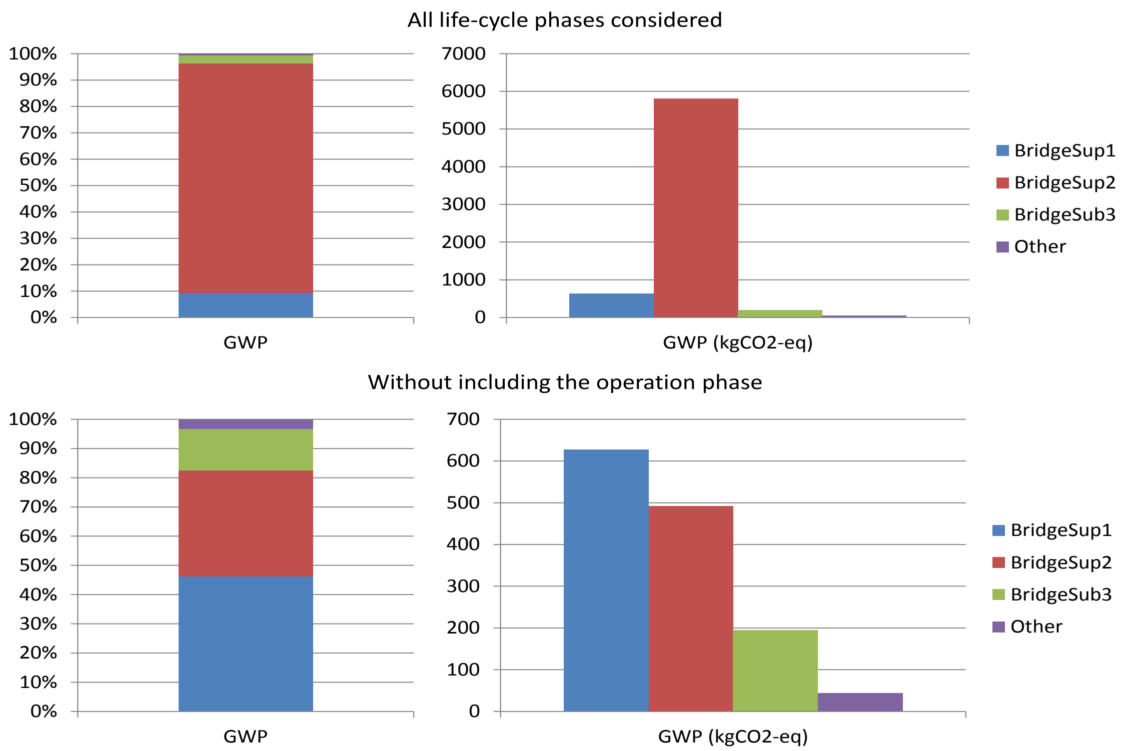

Figure 4.18: Global warming impact per function category.

Figure 4.19 shows global warming impact shares between the different components included in BridgeSup1 and BridgeSup2 categories. For BridgeSup1, concrete, prestressing and reinforcing steel account for 53.6, 25.1 and 13% of the impacts, respectively. For BridgeSup2, asphalt and railings & parapets account for 64.1 and 34.4% of the impacts, respectively.

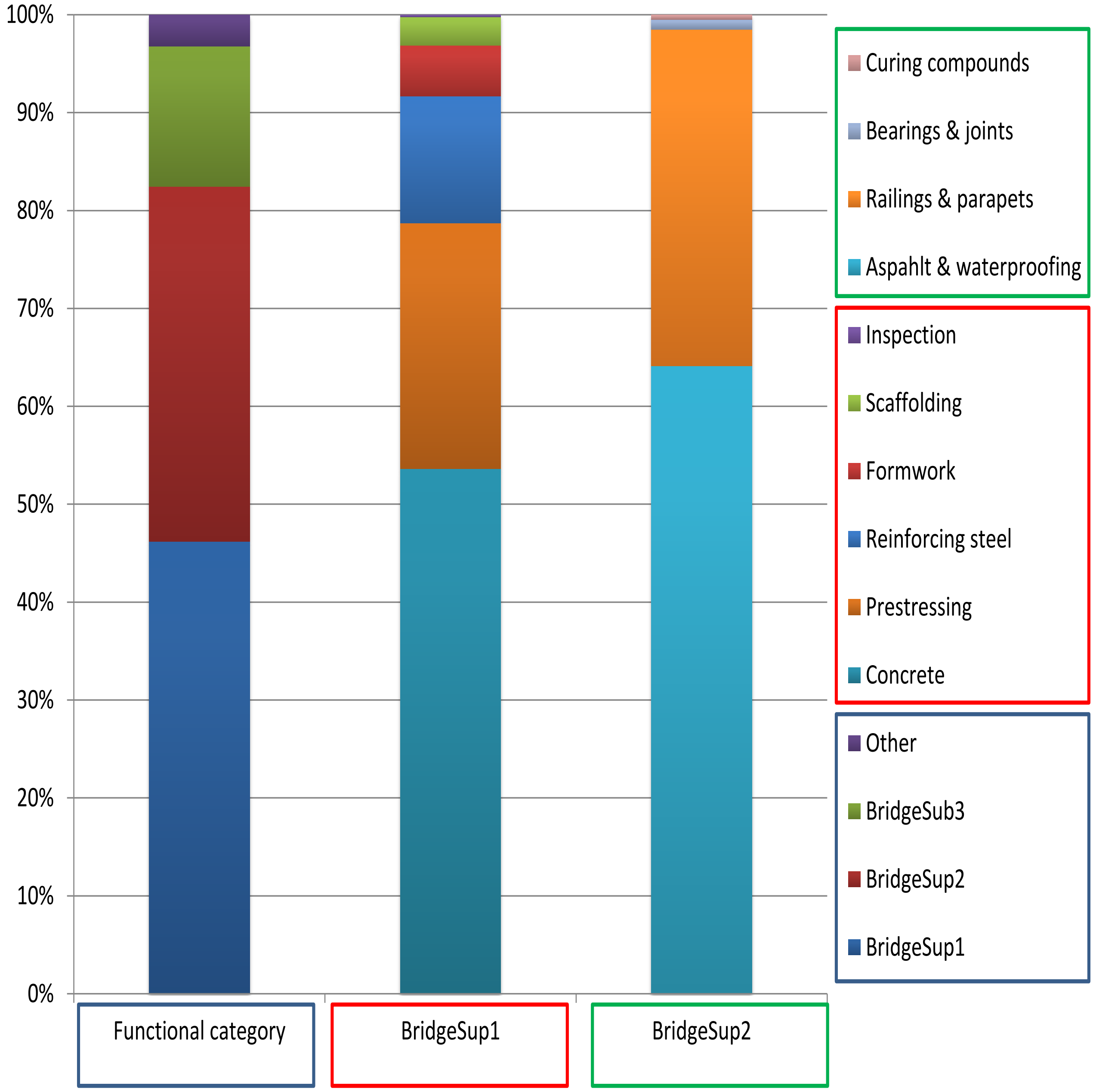

Figure 4.19: Global warming impact shares within BridgeSup1 and BridgeSup2 categories.

4.3.3 Results per life-cycle phase

5 life cycle phases were considered in this study: material production, construction, operation, maintenance & repair and end-of-life. Figure 4.20 displays shares and values of global warming impact per life-cycle phase.

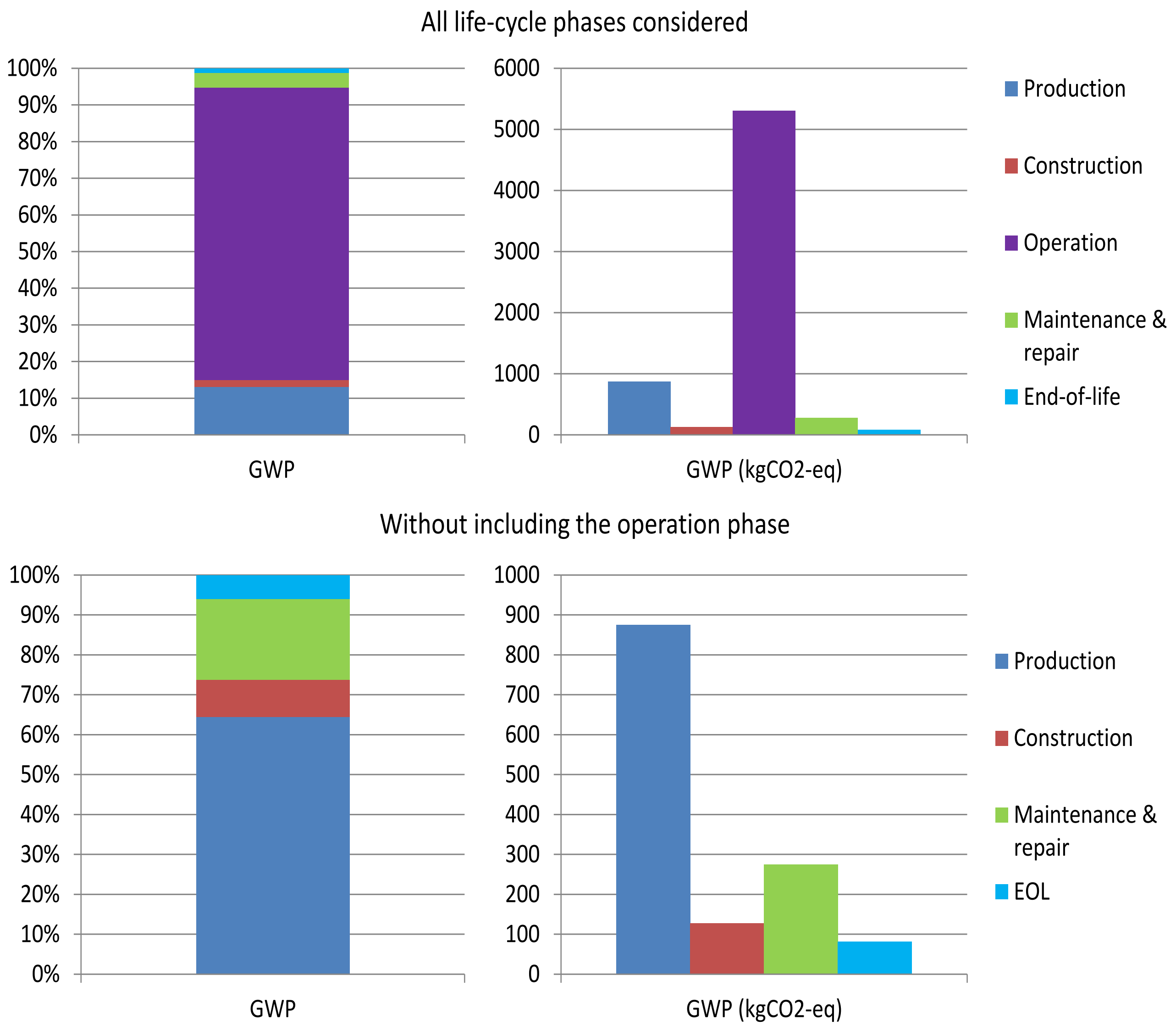

Figure 4.20: Global warming impact per life cycle phase.

The inclusion of the operation phase clearly shows that this life cycle phase overcomes the others. The material production phase comes in second but the impacts are about 5 times lower than those from the operation phase. The rest of the impacts are scored decreasingly by the maintenance & repair phase (about 3 times lower than the material production phase), the construction phase and the end-of-life phase (each of them being about 2 times lower than the maintenance & repair phase). Important differences of the impact shares between the life cycle phases are then analyzed.

Material production phase

The overall impact from the material production phase is 874.7 kgCO_2-eq per FU, representing 64.4% of the overall impact of the bridge (operation phase excluded).

The elements accounting for the most important shares are: concrete (41.5%), railings & parapets (18.6%) and prestressing (17.6%). These elements prevail on the others since production of cement and steel represent huge amounts of material and their production processes lead to large emissions of greenhouse gases. Figure 4.21 shows global warming impacts from the production phase.

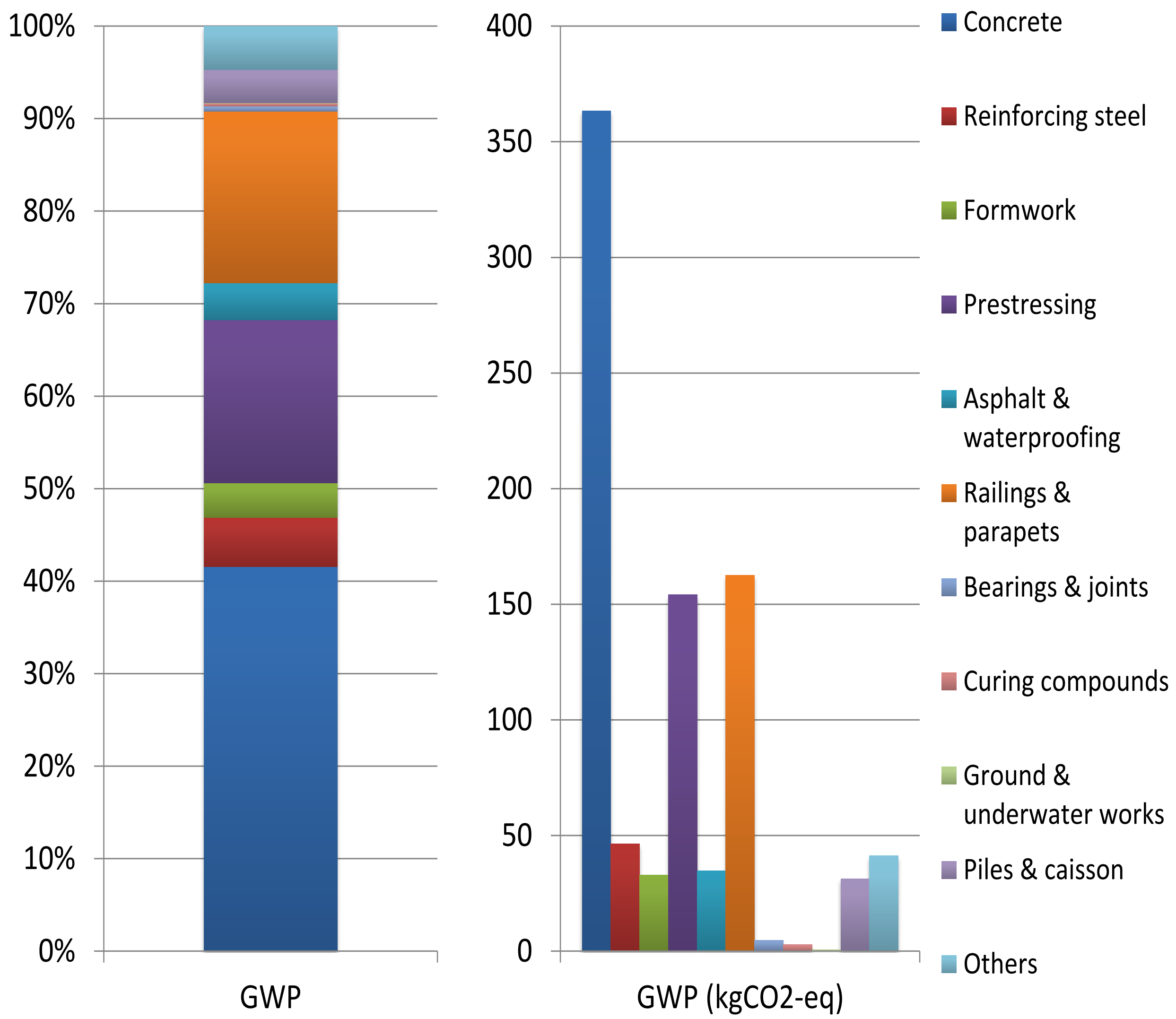

Figure 4.21: Global warming impacts from the production phase.

Construction phase

The overall impact from the construction phase is 127.2 kgCO_2-eq per FU, representing 9.4% of the overall impact of the bridge (operation phase excluded).

For construction, the main sources of emissions are: concrete (31.1%), piles & caisson (18%), reinforcing steel (17%) and scaffolding (14.4%). The crucial factors considered here are amounts of transported material, transportation distances or both at the same time. Figure 4.22 shows global warming impacts from the construction phase.

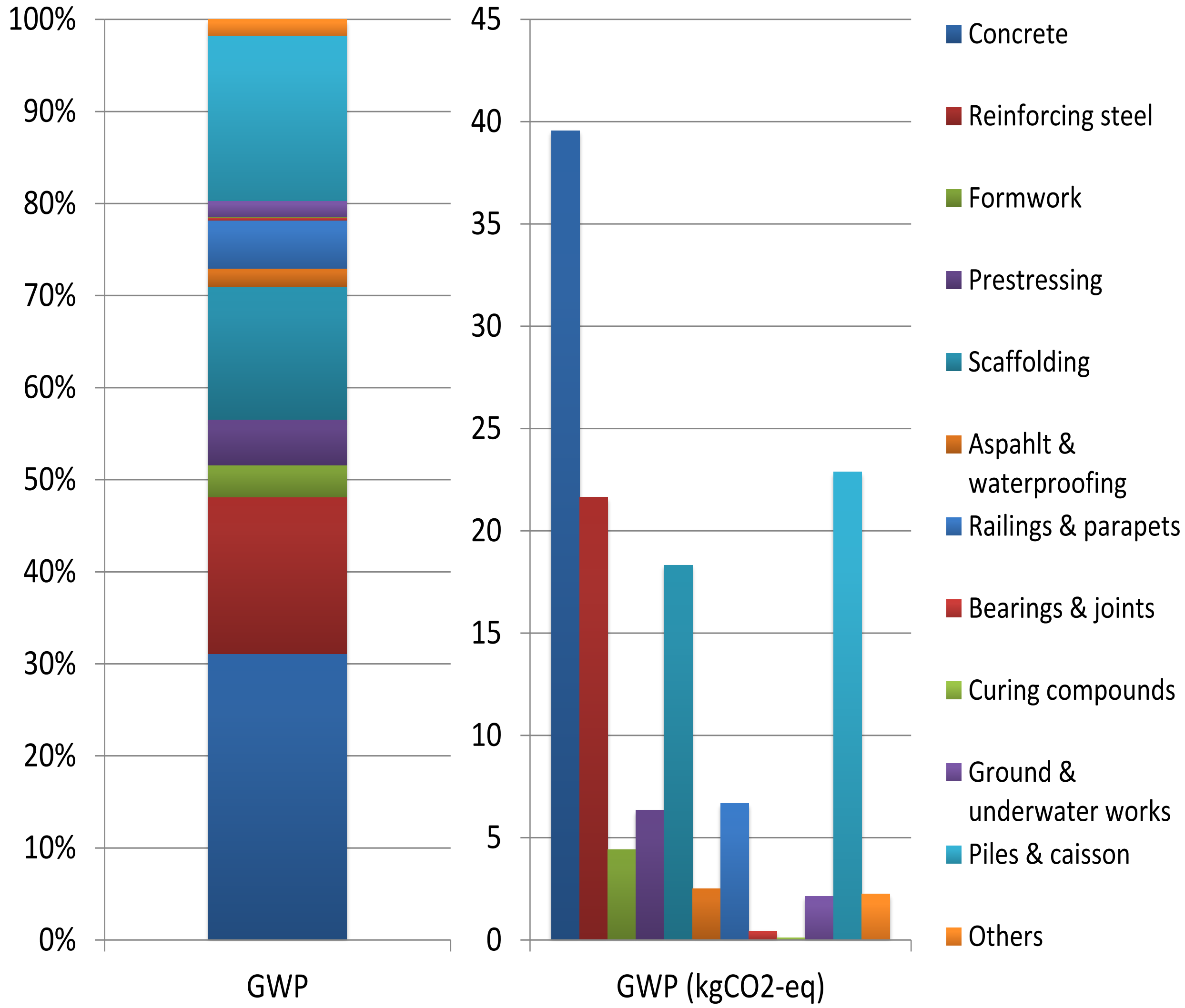

Figure 4.22: Global warming impacts from the construction phase.

The transportation represents 76.6% of the construction phase impacts, all means of transportation considered. Among the means of transportation, lorry, >16t is the most pollution one, accounting for 74% of the overall impact. Among the elements transported by truck; scaffolding, reinforcing steel and concrete represent 25, 23.9 and 17% of the impacts from transportation by truck, > 16t, respectively. Impacts from transport of plywood and reinforcing steel recovery (waste management on site) are included. Diesel consumption, heavy oil fuel and electricity respectively account for 22.5, 0.8 and 0.1% of the construction phase impacts. Figure 4.23 shows shares global warming of impacts from the construction phase, means of transportation and elements transported by truck, >16t.

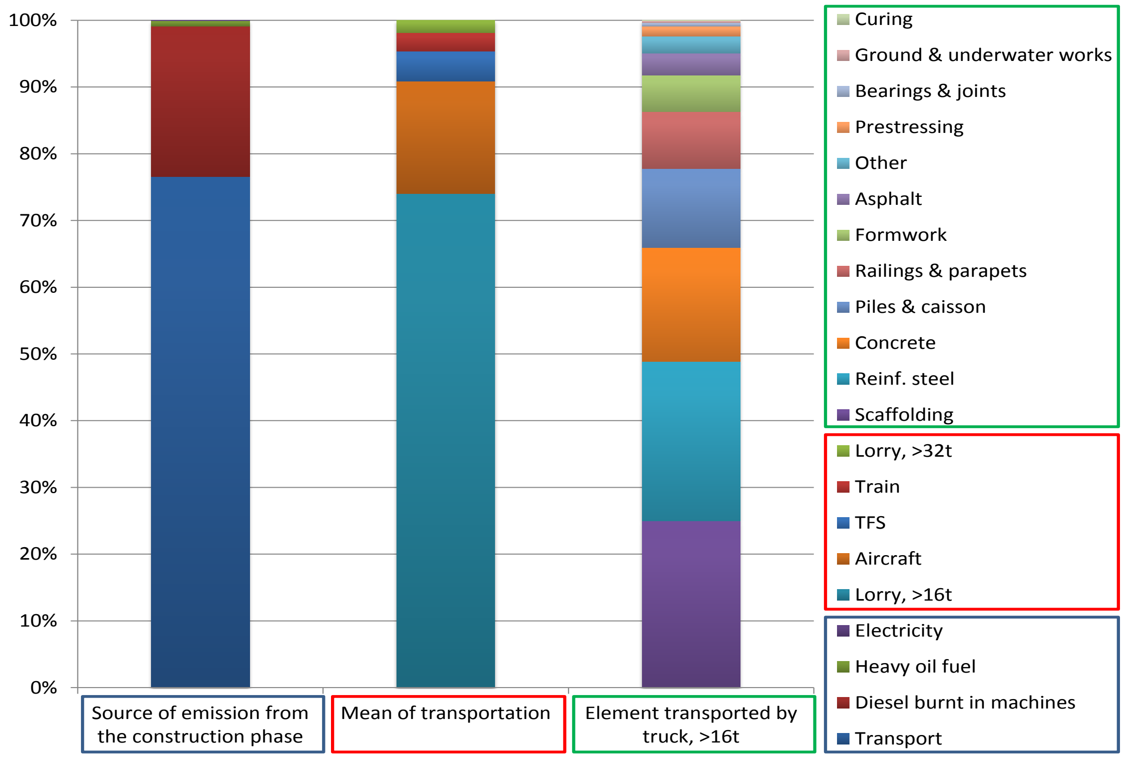

Figure 4.23: Global warming impact shares within the construction phase, means of transportation and elements transported by truck, >16t.

Operation phase

The overall impact from the operation phase is 5307.6 kgCO_2-eq per FU, representing 79.6% of the overall impact of the bridge. Traffic-related emissions represent 99.7% of the overall GWP value from this phase. Burdens from public lighting are then negligible (1.7115 kgCO_2-eq per FU). Traffic-related emissions clearly represent a hot spot for this study. However, if we consider a larger system including the current road built along the fjord, the bridge somehow saves traffic-related emissions since the distance is shortened. This aspect will be further analyzed in the discussion part. Figure 4.24 shows global warming impacts from the operation phase.

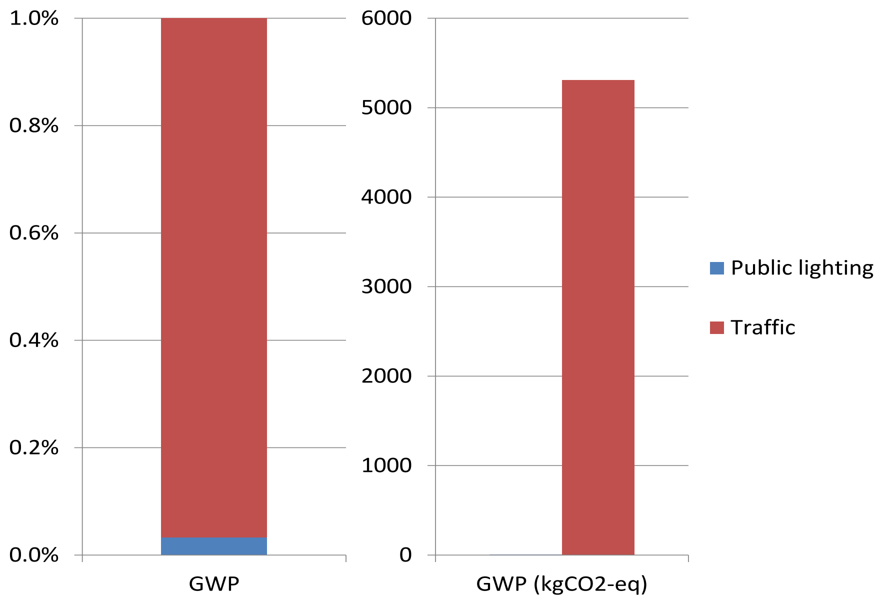

Figure 4.24: Global warming impacts from the operation phase.

Maintenance & repair phase

The overall impact from the maintenance and repair phase is 274.8 kgCO_2-eq per FU, representing 20.2% of the overall impact of the bridge (operation phase excluded).

Asphalt course renewal emissions represent 99.0% of the overall GWP value from this phase. Burdens from inspections are then negligible (2.859 kgCO_2-eq per FU). The asphalt course renewal is clearly identified as a hot spot of this study. Figure 4.25 shows global warming impacts from the maintenance & repair phase.

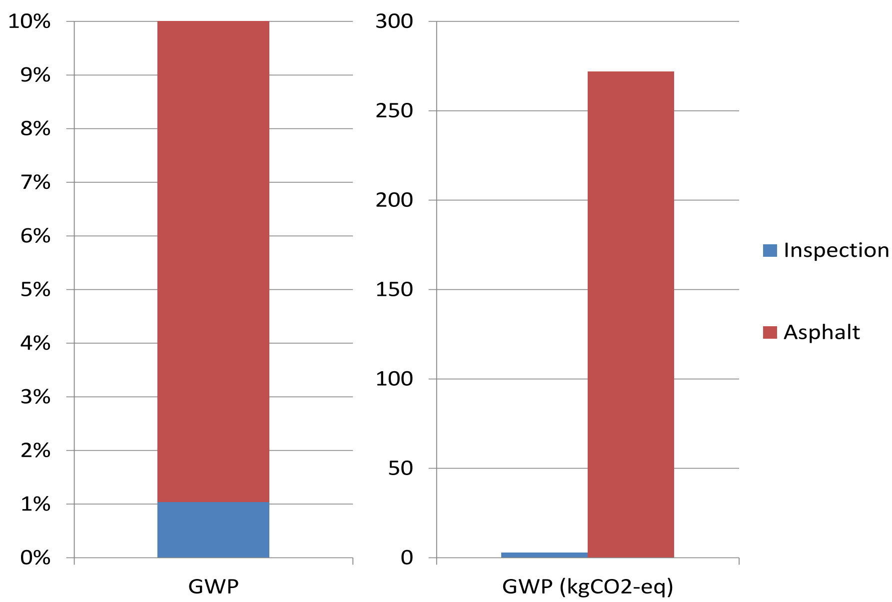

Figure 4.25: Global warming impacts from the maintenance phase.

End-of-life phase

The overall impact from the end-of-life phase is 80.9 kgCO_2-eq per FU, representing 6% of the overall impact of the bridge (operation phase excluded).

Reinforced concrete accounts for the most important share of the overall global warming impact from this phase, i.e. 85.9%. The impact shares between the different processes are: dismantling and sorting of reinforced concrete (56.7%), transportation (38.8%), asphalt disposal (4%) and diesel burnt in machine for asphalt removal (0.5%). Figure 4.26 shows global warming impacts from the end-of-life phase.

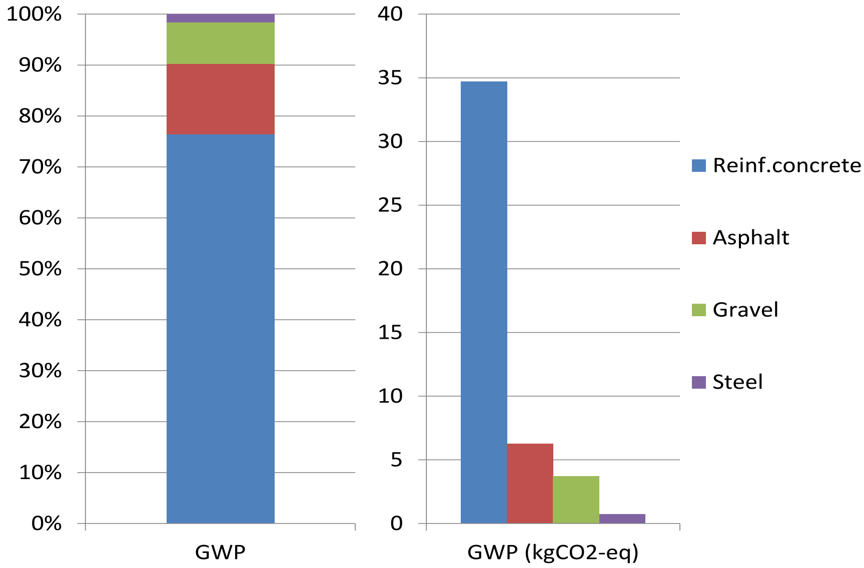

Figure 4.26: Global warming impacts from the end-of-life phase.

4.3.4 Results per component category and identification of hot spots

The component categories considered are: concrete, reinforcing steel, formwork, prestressing, scaffolding, ground & underwater works, piles & caisson, curing, asphalt, bearings & joints, railings & parapets, inspection and others. Burdens from the operation phase are not considered since public lighting impacts are irrelevant and traffic-related impacts greatly overcome the overall results and already constitute a hot spot of the study. Figure 4.27 presents global warming impact shares between the life cycle phases of the different component categories. We remind the reader that production of scaffolding equipment is not considered in this analysis and that production of new asphalt related to the maintenance works is considered in the maintenance & repair life cycle phase.

The different interpretations we can make from figure 4.27 are:

- When both production and construction phases are considered for a component, the production phase often greatly overcomes the construction phase (concrete, formwork, prestressing, railings & parapets, bearings & joints, curing compounds and others), except for ground & underwater works that require more transportation and/or energy use on the site. Reinforcing steel and piles & caisson share similar impacts between their production and construction phases.
- Maintenance of asphalt clearly shows that this phase greatly overcomes the other asphalt life cycle phases, and that the overall share is logical (2 layers of asphalt (leveling and surfacing courses) for the production and end-of-life phases, 13 equivalent layers of asphalt (surfacing course renewals) for the maintenance phase, since only 40% of the asphalt course is renewed each time).

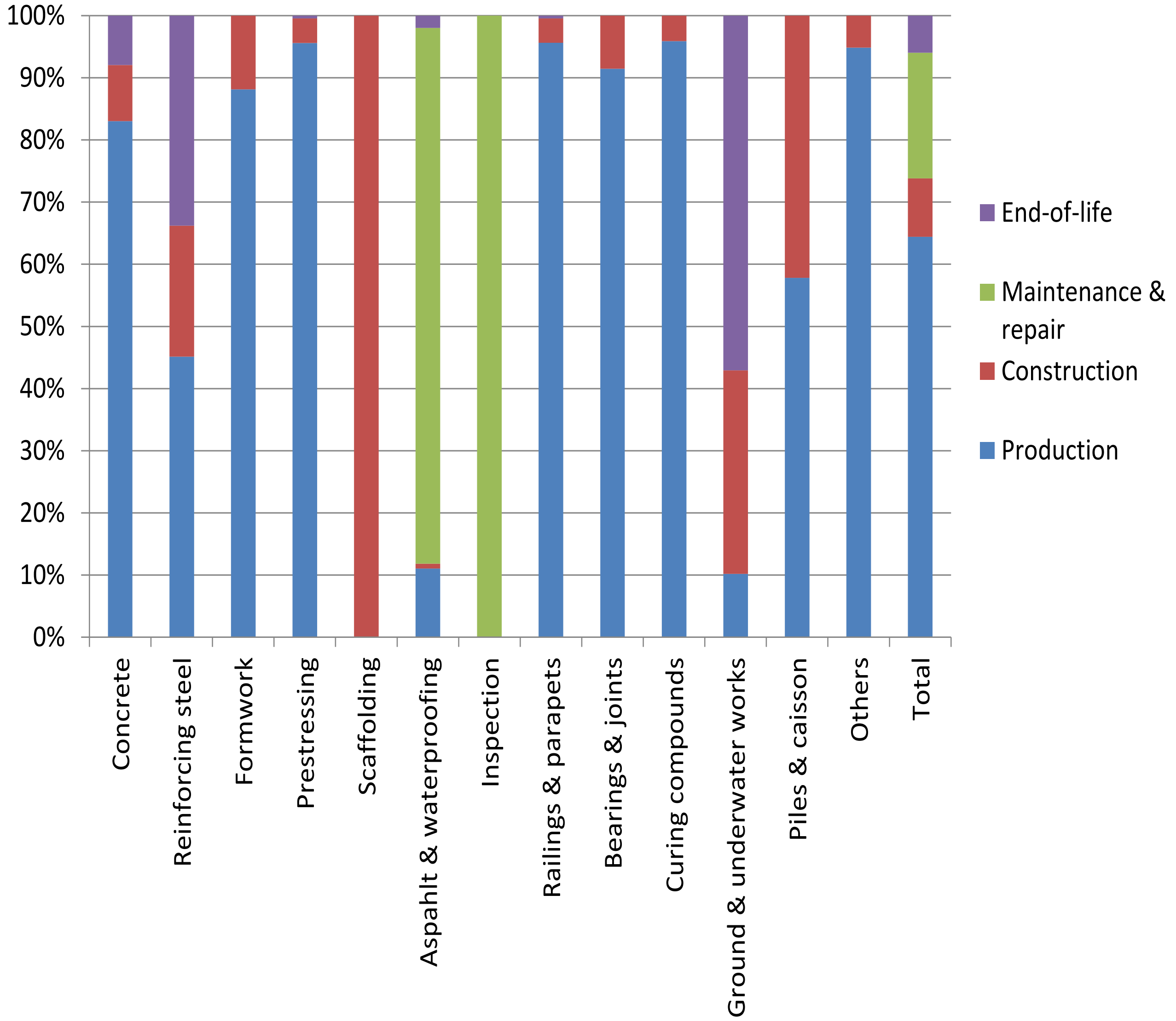

Figure 4.27: Global warming impact shares between the components life cycle phases.

Figure 4.28 presents global warming impact values per component category. The identified hot spots are listed below.

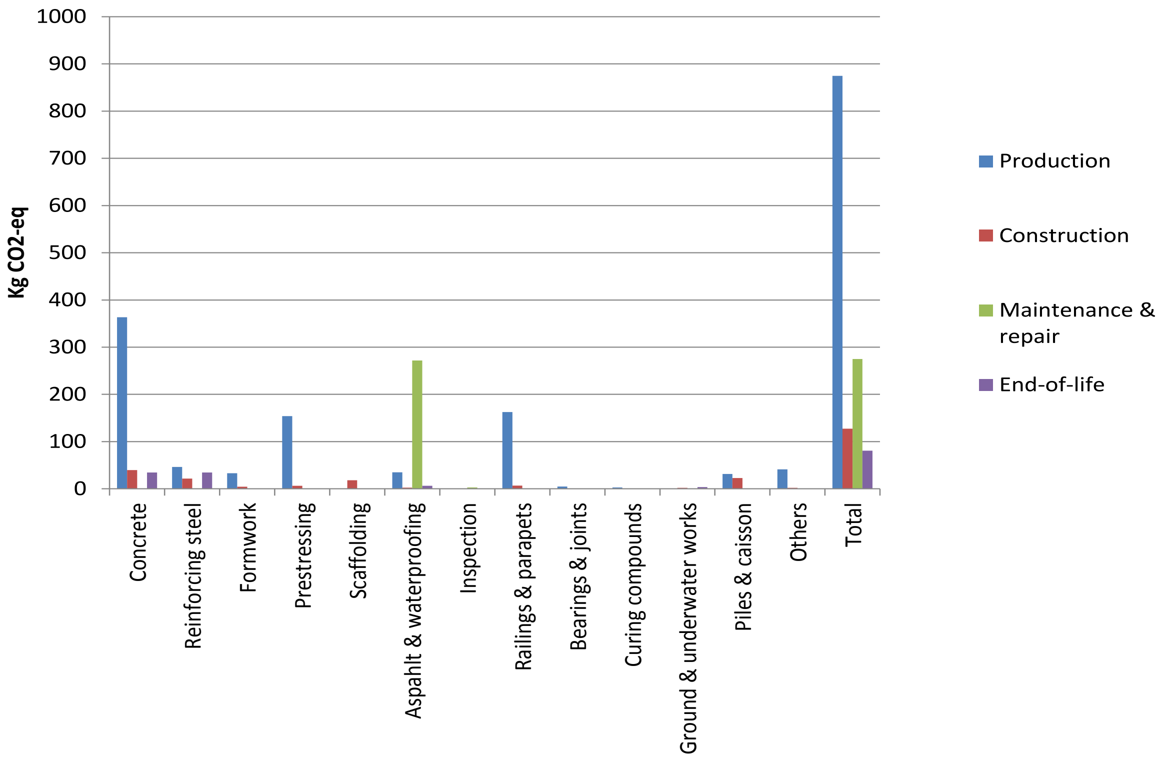

Figure 4.28: Global warming values per component category.

Concrete production accounts for 26.8% of the overall bridge impact and overcomes any other component production phase. When looking at the subprocesses, clinker production represents 91% of the overall impact. Clinker production is then the hot spot process.

Asphalt maintenance accounts for 20.0% of the overal bridge impact. The impact shares between the subprocesses related to asphalt maintenance are: asphalt production and laying (83%), asphalt disposal (6.7%), old asphalt course removal (5.3%) and transportation of new asphalt to the bridge (5%). Asphalt production and laying is then clearly identified as the hot spot process.

Railings & parapets production accounts for 12% of the overall bridge impact. The subprocesses related to railings & parapets production are average steel manufacturing process and raw material acquisition of low-alloyed steel, accouting for 48.9% and 51.1% of the impacts, respectively. Both processes can then be considered as hot spots.

Prestressing elements production accounts for 11.3% of the overall bridge impact. Prestressing production for the bridge superstructure accounts for 98.4%. The impact shares between the subprocesses are raw material acquisition of low-alloyed steel (70.1%), average steel manufacturing process (14.5%), wire drawing process (12.6%) and grouting (2.8%). Raw material acquisition of steel is then the hot spot process.

4.3.5 Uncertainty analysis

In this section, an uncertainty analysis is performed on data that are not 100% reliable and that lead to important shares of the overall global warming impact. The elements considered in this section are shares of reinforcing steel production and amount of steel in railings & parapets production. Regarding steel prestressing elements (strans, anchor heads and steel ducts), only the manufacturing process is uncertain (representing 26.6% of the impacts from prestressing production for the deck), but since no other more accurate processes are available, not much can be done to improve the data quality. Amount and type of steel are accurate data since they are provided by the manufacturer.

Shares of reinforcing steel : the shares of reinforcing steel between *Badische Stahlwerke GMBH* (German supplier) and *Celsa* (Norwegian supplier) considered in this analysis are 70% and 30%, respectively. However, according to the reinforcing steel subcontractor, the source of the reinforcing steel delivered on the site can somehow vary according to the stock availability. If sufficient steel is available from the Norwegian supplier, larger amounts could then be provided by this manufacturer in order to reduce transportation costs, for example. However, if the Norwegian supplier cannot provide enough steel, more will be ordered to the German supplier. According to the subcontractor, the shares can vary between 80%-20% and 60%-40%.

Figure 4.29 shows the differences in global warming impact according to the shares. Production and construction phases are considered. From this figure we can state that impact variations are not very important. The impacts range from 66.73 to 69.28 kgCO_2-eq per FU, which makes a variations of 3.7%. However, we notice than even if more transportation is required for the German steel, the overall impact is lower when the German steel accounts for higher shares. Hence, the German supplier is the prefered option.

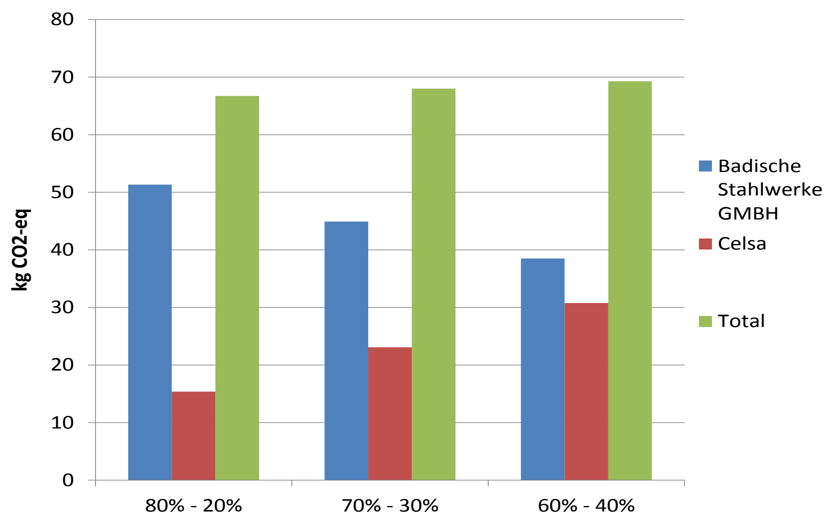

Figure 4.29: Uncertainty analysis on the impact shares of reinforcing steel supply.

Amount of steel in railings & parapets : the calculation of the amount of steel in railings & parapets is based on a raw assumption. Since no data are available for the products considered in terms of amount of material, a very uncertain geometrical assumption is made, multiplying an average steel density by a hand-made calculation of the steel volume. However, this assumption certainly overestimated the burdens from railings & parapets. In this analysis, we consider 40% less amount of steel, hence reducing burdens from both raw material acquisition and manufacturing processes.

Figure 4.30 shows the results from the uncertainty analysis realized on railings & parapets. By reducing the inputs of steel by 40%, the related emissions from the production, construction and end-of-life phases are also reduced by 40%. The impacts from railings & parapets decrease from 169.9 to 101.9 kgCO_2-eq per FU, which makes the overall bridge global warming impact decrease by 7.5%. Hence, importance should be attributed to the raw material acquisition and manufacturing processes of these products.

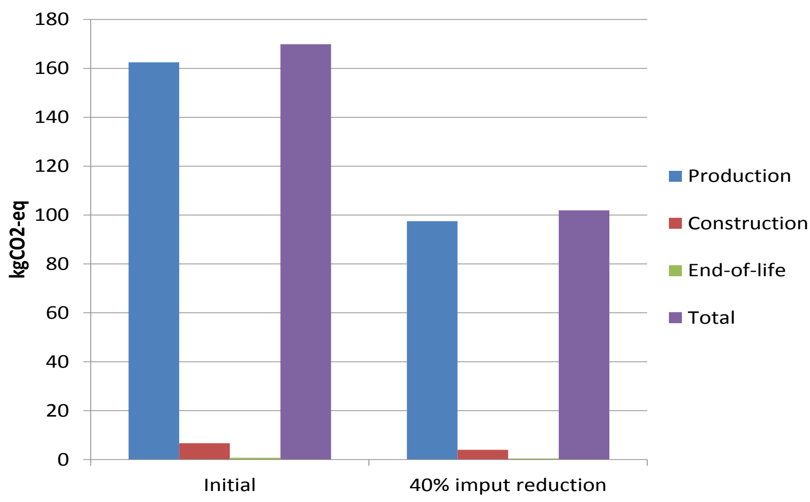

Figure 4.30: Uncertainty analysis on railings & parapets.

4.3.6 Sensitivity analysis

In this section are considered variations in source and amount of data related to the hot spots of this study (except for railings & parapets, that were considered in the uncertainty analysis). The elements analyzed are concrete production and asphalt course renewal.

Concrete production : concrete production represents the most important source of emissions in the bridge production phase. In order to rank the environmental quality of the concrete used in this project, the sensitivity analysis will focus on comparisons between the different types of concrete used in this project, a reference concrete and a fictitious low-carbon concrete. The reference unit for comparisons is the production of 1 cubic meter of concrete. A fresh concrete at plant selected from the database is chosen as a normal concrete reference, including the whole manufacturing process, internal transportation and infrastructure [25]. The fictitious cement is built on the concrete B55 SV-30 (Dmax=22 mm) composition, replacing the *Norcem Industrisement*, *Norcem Standard FA* and *Fesil Microsilica* by a cement composed of 70% Portland cement and 30% fly ash, silica fume or other additives without burdens. The ficititous concrete is based on the composition of a CEM II/B-V cement, according to NS-EN 206-1 standard.

Figure 4.31 shows the results of the sensitivity analysis on the concrete production.

A first remark is that the higher the strength of the concrete is, the higher the emissions are because more cement is required.

A second remark can be made about the B45 AUV concrete that contains an anti-washout admixture (modeled as carboxymethyl cellulose). The insertion of this additive increases the emissions by 6.6% compared to the normal B45 concrete, whereas it only represents 0.2% of the concrete mass. Careful interest should then be allocated to the choice of this anti-washout admixture.

Finally, we see that the reference concrete (strength B35, using 300 kg of Portland cement 42.5R) is less polluting than the concretes modeled in this project, which means than critical interest should be attributed to concrete production. The use of this reference concrete would decrease the overall bridge emissions by 4.5%. However, the actual reduction would be lower since this bridge requires mainly B55 concrete strength, while the reference concrete is a B35. The fictitious low-carbon concrete would be closer to our case study, since the cement and replacement admixtures amounts are the same but less Portland cement is used, in the limitations of 30% replacement admixtures. The use of this ficititous concrete for the overall bridge would decrease the overall global warming impact by 2.4%.

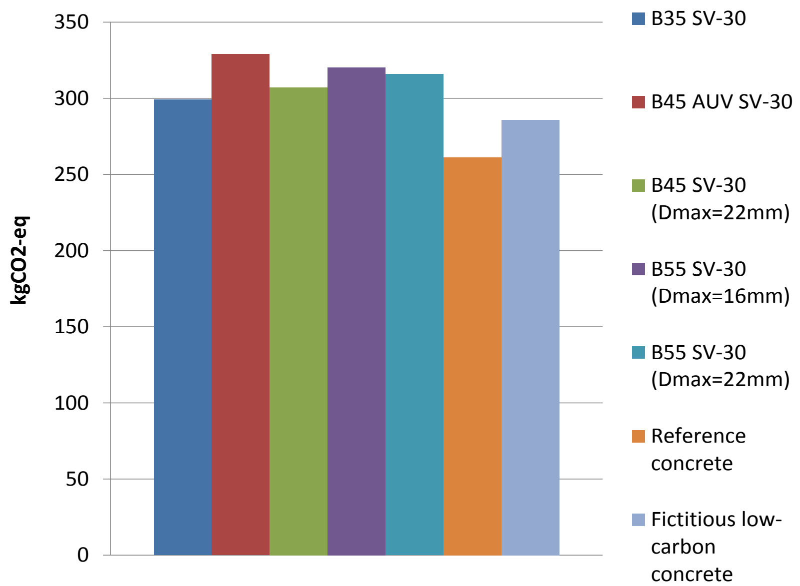

Figure 4.31: Sensitivity analysis on the production of 1 m^3 concrete.

Asphalt course renewal : this element has been identified as an important hot spot of this study, representing 20% of the overall bridge impact. As asphalt production has been identified as the main contributor of the emissions during the maintenance phase, no interest will be attributed to transportation distances between the asphalt manufacturing plant and the construction site. Amount of asphalt renewed will not be assessed either, since only 40% of the wearing course is changed. However, frequency of renewal can strongly lower the overall impact. We consider different sensitivity parameters that are frequency of renewal every 5, 7 and 9 years.

Figure 4.32 shows the results from the sensitivity analysis on asphalt course renewal. The results show that larger frequencies of asphalt renewal would decrease the overall bridge impact by between 7.9 and 13.4%. The latter is however more unlikely with a regular asphalt product since the wearing down of the course due to use of spiked tires in winter requires regular maintenance. However, more durable and environmentally friendly asphalt products could save important amounts of emissions.

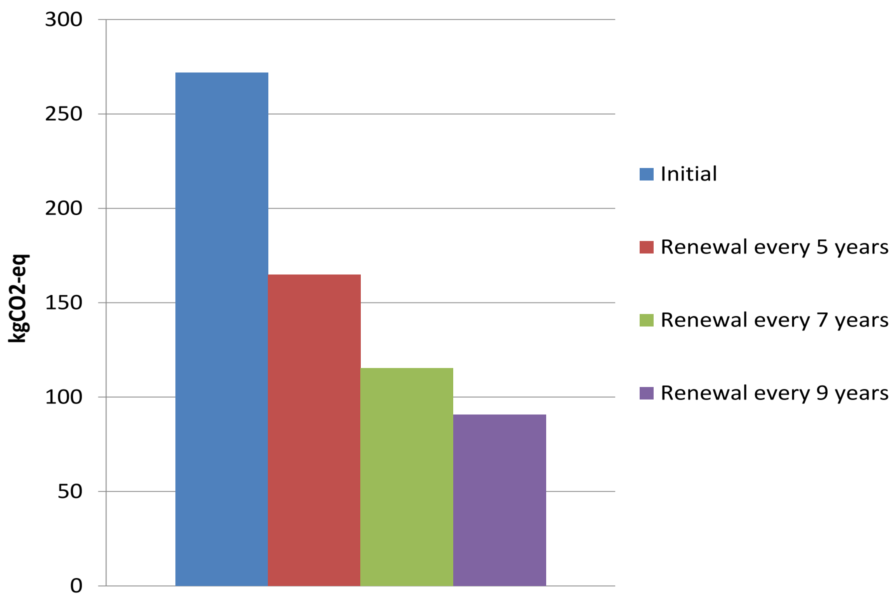

Figure 4.32: Sensitivity analysis on asphalt course renewal.

Chapter 5

Discussion

In this section, the results of the literature review, the LCA methodology description and the case study are gathered and discussed. The purpose of this discussion is to sum up the important aspects revealed by the thesis and check the consistency of the overall work. The discussion is divided in different topics.

5.1 Literature review

Among the 45 references reviewed, 2 are very similar to this study since they dealt with a complete LCA of a concrete bridge, i.e. including all life cycle phases and all bridge elements.

J. Hammervold et al. (2011) [10] found out that the emissions of a concrete box girder bridge were 600 kgCO_2-eq per FU for a relatively small bridge (417 m^2). The material production, transportation, construction, operation (excluding traffic disruption and regular traffic), maintenance, repair and end-of-life phases are included; as well as the entire structure (super- and substructure).

In this study however, the wearing course is renewed every 10 years with 65% of the initial amount of asphalt. Considering these assumptions for our asphalt course renewal, the emissions from Tverlandsbrua would be brought down to 1219.5 kgCO_2-eq per FU, hence decreasing by 10.2% the overall impact. The remaining difference of emissions between both studies is partly explained by the amount of concrete required per FU. The concrete box girder requires 0.69 m^3 concrete per FU while Tverlandsbrua requires 1.16 m^3 concrete per FU. Hence, Tverlandsbrua requires 68% more concrete per FU than the box girder bridge. ined by the huge amounts of steel required for the prestressing elements and railings of Tverlandsbrua.

The French report from the MEEDDM (2006) [15] found out that the emissions of a prestressed concrete bridge were 1370 kgCO_2-eq per FU. The bridge deck area is 495 m^2. As previously, all life cycle phases and bridge elements are included.

The wearing course renewal of the prestressed concrete bridge represents 1.14 tons of asphalt per FU, while Tverlandsbrua requires 0.96 tons of asphalt per FU, i.e. 15.8 % less. In addition, the prestressed concrete bridge requires 1.7 m^3 concrete per FU while Tverlandsbrua requires 1.16 m^3, i.e. 32% less concrete than the prestressed concrete bridge. However, Tverlandbrua requires 0.061 tons of prestressing works per FU for the bridge deck while the prestressed concrete bridge only requires 0.029 tons per FU, i.e. 52.5% less. The consideration of these three parameters would bring down the emissions from Tverlandsbrua to 1279 $kgCO_2$-eq per FU. However the emissions from railings & parapets would be higher for Tverlandsbrua than for the prestressed concrete deck since the latter uses concrete parapets, much less polluting.

The results of both reviews are quire consistent with our case study. The amount of concrete per FU for Tverlandsbrua is found higher compared to the concrete box girder since no prestressing is used and the bridge deck area is much more important, requiring a thicker box girder. However, the prestressed concrete bridge requires much more concrete per FU for the substructure part than Tverlandbrua. The overall results are found quire similar when considering close assumptions for asphalt renewal and steel and concrete production.

Finally, the impacts of Tverlandsbrua are found lower than the average impact of steel bridges (2180 $kgCO_2$ per FU) or steel-concrete composite bridges (2490 $kgCO_2$ per FU) identified in the literature study. This is in accordance with other concrete bridge studies and shows that concrete as a design material can be chosen for its environmental properties.

5.2 LCA methodology

The complete description of LCA methodology performed in this thesis aimed at building a robust framework of study for the application of this methodology on the case study Tverlandsbrua. A discussion is conducted for each main phase of LCA methodology.

5.2.1 Goal and scope definition

The initial reason for carrying out the study is the carbon footprint assessment of a Norwegian bridge using LCA methodology in order to compare the results with future bridge environmental assessments. Although the case study performed is somehow restrictive since it includes specific processes, the results constitute a rigid basis for comparisons with other studies. The definition of the system boundaries and the functional unit was chosen to allow future comparisons. The definition of the functional unit somehow skews the results for the entire bridge, as the substructure is not clearly represented in the FU. However, the consideration of a two-dimensional physical parameter, i.e. the bridge deck area, allowed the consideration of both length and width of the bridge superstructure. As this structural element was identified as the most polluting one, the choice of a one-dimensional physical parameter would have been inaccurate. The system boundary excluded all uncertain elements, such as traffic disruption from construction and maintenance activities or foreseeing of accidental repairs, that mainly depend on the bridge project. Allocation procedures were sometimes used to share the burdens of a process between its related subprocesses in order to avoid as much as possible the creation of independent subprocesses. The category *Others* is however an exception and could have been allocated to the super- or substructure elements with more time and information.

5.2.2 Life cycle inventory

The inventory of input flows was realized as precisely and accurately as possible. The source of input data mainly comes directly from the client or contractors, especially for the production phase. Hand-made calculations and assumptions were avoided as much as possible. Omitted input flows are composed of small additional products (grease, supplementary wood and concrete cooling), production of temporary equipments (barracks, scaffolding, traveling formwork system, bracings, temporary covers and cranes) and additional energy consumption on the site from the barracks and other identified processes. As these processes are not directly related to the hot spots of this study, we can assume that their omissions do not have an important impact on the results. Output flows are either collected from the subcontractors or calculated throughout a reliable generic database. More accuracy could have been brought to the results by using more EPD declarations or similar for the hot spot elements of this study instead of generic processes, but such documents have not been found.

5.2.3 Life cycle impact assessment

Only global warming impact category is considered in this study. All output data are collected or calculated using CO_2-eq units, except for the steel pipe piles (only CO_2, CH_4 and N_2O) and a part of the German reinforcing steel (only CO_2). The other greenhouses gases emitted by these processes are however negligible because of small amounts and low GWP100. Weighting, grouping and normalization were not considered to keep the transparency of the results for the project owner. Uncertainty and sensitivity analyses were performed to assess the consequences of variations in the data. This showed that large amounts of emissions could be saved by switching a component with a more sustainable one, especially for concrete, steel and asphalt.

5.2.4 Interpretation phase

The results of the impact assessment were presented different ways in order to show the most important sources of emissions per function, life cycle and component category and identify the hot spots. This allowed us to identify the bridge superstructure, production phase, maintenance phase, concrete, steel and asphalt as major contributors. The completeness, sensitivity and consistency checks (that were not explicitly included in the analysis) are briefly identified throughout the interpretation of the uncertainty and sensitivity analyses results.

5.3 Material production phase

This phase was one of the most complicated to assess since it included many processes and required a huge attention as it was expected to be a life cycle phase accounting for a large share of the emissions. Consequently, the input data of this phase are the most accurate and precise of all phases since they were almost entirely provided by the client and subcontractors of the bridge.

5.3.1 Concrete production

Concrete production (and subsequently clinker production) is responsible for the main share of the impacts. The sensitivity analysis showed that the environmental performance of the concretes used in this project could be improved. A low-carbon concrete modeled with 70% Portland cement and 30% cement replacement admixtures indicated that up to 2.4% of the overall emissions can be saved. The composition of this cement is however beyond the project owner concrete regulations about additives, since SV-30 concretes with a durability MF40 should not hold more than 11% and 5% silica fume for CEM I and CEMII/A-V cements, respectively [23]. Hopefully, changes in regulations in the future years will allow the use of such low-carbon concretes that are a first step towards the environmental performance improvements of concrete structures.

5.3.2 Reinforcing steel

The emissions from reinforcing steel production in this study are very low since the manufacturing process is mainly based on electric arc furnace (EAF), which is much more environmentally friendly than the other common process, basic oxygen furnace (BOF). Even if the transportation distance required for the German steel (about 2000 km in average) in much more important than for the Norwegian steel (237 km), the production of the German steel (about 170 kgCO_2-eq per ton of steel) is twice less polluting than the production of the Norwegian steel. Furthermore, the uncertainty analysis showed that consideration of both steels for the production and construction phases always favors the German steel in spite of bigger shares of steel products. Hence, both production and construction phases are important to consider before choosing one product instead of another.

5.3.3 Prestressing elements & railings

The production of the prestressing elements and the railings & parapets is certainly overestimated due to an average manufacturing process chosen by default and due to the absence of accurate data for the amount of steel from the railings & parapets production. The results of the uncertainty analysis show that the overall bridge impact could be actually decreased by 7.5%.

5.4 Construction phase

5.4.1 Transportation

The main source of emissions within the construction phase is transportation. The mean of transportation lorry, >16t accounts for 74% of the emissions from transportation. The input data are very accurate since they were almost always provided by the subcontractors of the project and the process selected from the database to model lorry transportation is quite representative of the actual mean of transportation.

Allocation procedures for the crane and personnel transportation were made by default but are not really representative of the actual impacts of these processes. Transportation of personnel by aircraft is clearly identified as the second most polluting mean of transportation, representing 1.2% of the overall impact. Moreover, only a small team (20 persons) is working on this project. Reductions in the number of travels, choice of local personnel or use of alternative means of transportation (train, car, boat) could lower these emissions.

A careful attention should be attributed to transportation by lorry, >16t of the scaffolding, reinforcing steel and concrete, representing 1.33, 1.27 and 0.9% of the overall bridge impact, respectively. The scaffolding is rented in Sweden and a local supplier could shorten the transportation distance. The reinforcing steel was considered more performing when produced in Germany, even if transportation distances are higher, but alternative means of transportation can be used instead of lorry (train or TFS). The concrete is produced locally (20km), so the burdens from its transportation can not be easily lowered.

Finally, in spite of large amounts (4380 tons), the transportation of gravel used for backfilling against the abutments and as ballast in the caisson did not account for many emissions (0.3% of the emissions from the construction phase), which means that transoceanic freight ship is an environmentally performing mean of transportation.

5.4.2 Energy consumption on the site

The assessment of energy consumption on the site was somehow uncertain due to a high number of assumptions on the input data. Indeed, the consumption of diesel, heavy fuel oil and electricity was really approximative and subjected to allocation methods based on the relative weight of each bridge component. However, as impacts from transportation greatly overcome those from energy consumption on the site, the uncertainties regarding these processes are then marginal, especially when we consider that the total impacts from the construction phase represent less than 10% of the overall bridge impact. Nevertheless, as diesel burnt in building machine is the second most important source of emissions from the construction phase, representing 2.1% of the overall bridge impact, the actual consumption at the end of the construction phase should be checked and alternative sources of energy could be considered (electricity or low carbon diesel).

5.5 Operation phase

This section will focus on the consideration of traffic-related emissions.

Traffic-related emissions in this analysis lead to tremendous changes regarding the overall global warming impact of the bridge. When included in the analysis, this process accounts for 79.6% of the overall impact, greatly overcoming any other life cycle phase. However, the inclusion of the operation phase in our case study depends on the considered approach.

Stricly sticking to the functional unit defined in this project, the emissions from traffic-related emissions should not be included in the life cycle of 1 square meter of deck since the traffic is not part of the bridge itself. However, a consequential approach would consider that the realization of the bridge will result in the circulation of vehicles on it. If we consider that the related traffic remains almost constant over the 2-year construction period, the impacts from the traffic on the current road passing along the fjord should decrease since part of this traffic is deported on the bridge. This would require a larger system considering both life cycle assessments of the current road and the new bridge, but this is beyond the scope of this study. Moreover, the intended purpose of this work was to realize a life cycle assessment of a Norwegian road bridge in order to use the results as a basis for future bridge projects, but traffic is an external factor of the bridge, mostly depending on the bridge location and not on the bridge design. This last point reveals that we should blame our cars and not our road infrastructures for such emissions, and focus our mind in alternative means of transportation. The latest aspect is clearly identified in the National Transport Plan 2010-2019. [2]

5.6 Maintenance & repair phase

This section will focus on the burdens from asphalt course renewal.

Asphalt course renewal was identified as a hot spot of the study, representing 20% of the overall impact. The production of new asphalt has been identified as the main contributor of the emissions (83%). The results of the sensitivity analysis showed that up to 67% of the emissions from asphalt renewal can be saved when the wearing course is renewed every 9 years. The main cause of the wearing down of the asphalt course is the use of skiped tires in winter.

Alternative solutions such as use of more environmentally friendly asphalts or de-icing agents could be considered. However, the use of such agents are often responsible for an early degradation of concrete structures due to chloride ingress. Hence, patching repairs, use of anti-corrosive substances or additional cathodic protection could be necessary and might counterbalance the emissions saved from asphalt course renewal.

5.7 End-of-life phase

The end-of-life phase mainly considered the sorting process of reinforced concrete, the landfilling process of asphalt and transportation of the elements to their disposal sites (whether recycling plants, landfilling areas or stocking areas). This life cycle phase was identified as the less polluting of all (6% of the overall impacts).

5.7.1 Recycling

Recycling processes were not considered since the related benefits are attributed to other products. However, the benefits from previous recycling processes were included in the assessment of the reinforcing steel and the steel pipe piles. Use of recycled steel could have been included in the production of the prestressing elements and the railings & parapets, but this has not been considered since no data related to amounts of recycled steel were available.

5.7.2 Dismantling and sorting of reinforced concrete

This process accounts for 56.7% of the end-of-life emissions, i.e. 3.4% of the overall impact. Hopefully, improvements in dismantling and sorting processes within the next 100 years will reduce the burdens.

5.7.3 Transportation

This process accounts for 37.7% of the end-of-life emissions. As the transportation distances to the disposal sites were only based on assumptions, alternative means of transportation (freight ship, train) should be considered.

Chapter 6

Conclusions

This chapter draws the final conclusions on this master thesis, considering the findings from the literature review, the LCA methodology description and the case study Tverlandsbrua; and gives recommendations for further studies dealing with life cycle assessment of Norwegian bridges. These recommendations are especially addressed to the project owner, *Statens vegvesen*.

6.1 General conclusions

This master thesis has been realized in several steps. A literature review has first been performed considering 14 references dealing with life cycle assessment in order to identify the main aspects that are important to consider when realizing a bridge LCA analysis. A comprehensive description of LCA methodology based on ISO standards 14040:2006 [4] and 14044:2006 [5] has then been realized in order to build a robust framework applied on a case study. Finally, the carbon footprint assessment of Tverlandsbrua using LCA methodology has been realized, and the results of this LCA analysis are to be used by *Statens vegvesen* as a basis for the assessment of future bridge projects.

The literature review allowed to identify the main findings from previous bridge LCAs as well as average values for carbon emissions and energy use. Material production is often considered as the biggest contributor. The second most contributing phase is generally either maintenance & repair or traffic disruption due to construction or maintenance & repair activities. Regular traffic is never considered. The bridge superstructure is almost always found as the biggest contributor, especially the structural part. Innovative bridge deck design (ECC link slabs, HPC concrete, minimized number of girders) is preferred than conventional bridge deck design. More architectural designs also often lead to more emissions.

Regarding the studies assessing different material choices, concrete is often the best environmental solution regarding the overall impact. However, for greenhouse gases emissions; steel, composite or wooden alternatives are sometimes preferred, especially if recycled material are used. The average carbon emissions for concrete design is 1590 $kgCO_2$, while those from steel and composite steel-concrete designs are 2180 and 2490 $kgCO_2$, respectively. Timber design can be interesting for small structures (about 250 m2 deck area) but no conclusions can be given for larger structures.

The LCA methodology description has been through all elements specified in the ISO standards. The methodology has been adapted to the needs of the case study but the goal and scope definition have been kept wide enough to allow comparisons with future bridge assessments.

Allocation procedures are avoided as much as possible, but a physical criteria (weight) is applied when no other choice is possible. Data quality requirements specify that the main sources of input data come from the client and the bridge contractors, and that output data are either collected from EPDs (or similar) or calculated using an LCA software, but never assumed. General and specific assumptions and limitations of the study are clearly stated.

The LCI phase is conducted using a decision making-process for input data source selection. When such data are missing or not provided on time, assumptions are made. The processes selected from the database for output data calculations are chosen as accurately as possible according to the information provided by the actors of the project or using a process by default.

The impact assessment focused on the global warming impact category, as carbon footprint is the principal concern of the client.

Finally, the interpretation phase is conducted by presenting the impacts throughout different categories (overall impact, functional categories, life cycle categories and component categories) in order to identify the main sources of emissions. Uncertainty and sensitivity analyses are performed for uncertain or critical data. A discussion is then conducted to consider all findings together and suggest some recommendations.

The overall impact of Tverlandsbrua is 6665 $kgCO_2$-eq per FU (1 FU = 1 square meter effective bridge deck area through a lifetime of 100 years), all life cycle phases considered. The impacts are brought down to 1358 $kgCO_2$-eq per FU when the operation phase (mainly traffic-related emissions) is not considered. The inclusion of the operation phase somehow depends on the approach of the study and the choice is left to the decision makers whether they want to consider it or not. The rest of the results are presented excluding this life cycle phase.

The structural part of the bridge superstructure accounts for 46.2% of the overall impacts, mainly due to concrete, prestressing and reinforcing steel life cycles. The non-structural parts of the bridge superstructure accounts for 36.3% of the overall impacts, mainly due to asphalt and railings & parapets life cycles. The bridge supestructure is then clearly identified as the hot spot element of the study.

The production phase is responsible for 64.4% of the overall impact. Concrete is identified as the main contributor, and a sensitivity analysis shows that a low-carbon concrete (using a cement containing 30% additives without burdens, such as fly ash, etc.) would decrease the overall impact by 2.4%. However, current concrete regulations in Norway do not allow such amounts of replacement admixtures. The other main contributors identified are prestressing devices (strands, anchor heads, steel ducts) and railings & parapets production, but use of 40% less amount of steel in the railings & parapets would decrease the overall impact by 7.5%. Use of recycling steel would also decrease burdens from both elements. Finally, the burdens from the German reinforcing steel are found unexpectedly low (170 kg CO_2-eq) but correspond to the information provided by the supplier.

The construction phase is responsible for 9.4% of the overall impact. Transportation by lorry, >16t is identified as the biggest process contributor and concrete as the main component contributor. Transportation distances could be shortened for some elements (the scaffolding equipment could be rented in Norway, for example) and alternative means of transportation (TFS or train) could be considered. Reduction of transportation distances for concrete is however very unlikely for this project (20km) but should be considered in future projects.

The repair & maintenance phase is responsible for 20.2% of the overall impact. Asphalt maintenance is the single biggest contributor. Division of asphalt maintenance schedules by 3 would decrease the overall impact by 13.4%. Use of de-icing agents or more environmentally friendly asphalts could also be interesting solutions.

The end-of-life phase is responsible for 6% of the overall bridge impact. Dismantling and sorting of concrete and transportation of the disposal materials are the main contributors. Improvements in dismantling and sorting processes within the next 100 years and use of alternative means of transportation are possible solutions to reduce the impacts from this life cycle phase.

6.2 Recommendations for future projects

From the previous conclusions, recommendations can be given for future bridge LCAs. These recommendations are addressed to the intended public of this study, that are NTNU university, LCA practitioners and *Statens vegvesen*, but should be especially considered by the decision makers.

Requirements for future comparisons: comparisons of the results of this study with future environmental assessments of bridges should first require the investigation of input data similarities with the hot spots of this study, that are concrete production, prestressing and railings & parapets production and asphalt maintenance.

Initial and final LCA analyses: in order to benefit completely from the results of LCA studies, two bridge environmental assessments should be realized. An initial study (before the material production phase) could be performed in order to make an early selection of environmentally performing processes. A final study (after the end-of-life phase) would aim at checking the accuracy of the data inventoried during the whole bridge life cycle.

Selection of impact categories: global warming impacts are often the main focus of institutions but other impact categories can be investigated to make a complete bridge environmental impact assessment.

EPDs: use of environmental performance declarations, environmental reports, etc. are advised since the output data are directly collected and the risk of using a wrong or inaccurate generic process in avoided. This should especially be considered for processes leading to important shares of the overall impact.

Low-carbon concretes: low-carbon concretes are strongly recommended but changes in the concrete regulations are required to allow the use of such products in future Norwegian bridge projects. For instance, the Norwegian cement producer *Norcem* provides a CEMII/B-V low-carbon cement composed of 60% clinker, 30% fly ash, 5% gypsum and 5% of other additives that only produces 488 kgCO_2-eq per ton of product (i.e. approximately 200 kgCO_2-eq per m^3 concrete). [39]

Recycled steel: if the use of recycled steel is now common in reinforcing steel products, this is much less common for other steel products, such as prestressing strands, parapets or bearings. The consideration of recycled steel in these products could however strongly reduce the impacts from their production.

Carbonation: carbonation process is a very long process, but its consideration over a 100-year lifetime could result in interesting saves in CO_2 emissions.

Uptakes from wood: in wooden construction projects, the consideration of CO_2 uptakes from wood during its life could strongly bring down the emissions, as presented in the literature review [12].

Economic and social impacts: even if this thesis focused on carbon footprint assessment, economical and social factors should be considered to keep in mind the idea of sustainability. Life cycle cost analysis (LCCA) and social life cycle assessment (SLCA) are existing methodologies considering a product from a holistic approach and could be investigated.

Preliminary works: all works required before the actual construction of the bridge (consultancy, investigations, administrative works, etc.) represent years of works during which emissions are released. An assessment of such emissions, even if probably very low compared to the overall bridge life cycle impact, could be carried out.

References

[1] Intergovernmental Panel on Climate Change. Climate Change 2007 - synthesis report. 2007.

[2] Norwegian Ministry of Transport and Communications. National Transport Plan 2010-2019.

[3] L. G. San Martin. LCA of a spanish railway bridge. *Master Thesis, KTH (Stockholm, Sweden)*, 2011.

[4] ISO 14040:2006 standard, environmental management. *Life cycle assessment - Principle and Framework*, 2006.

[5] ISO 14044:2006 standard, environmental management. *Life cycle assessment - Requirements and Guidelines*, 2006.

[6] Tverlandsbrua localization. http://www.vegvesen.no.

[7] Aas-Jakobsen. Tverlandsbrua tegningliste. 2011.

[8] A. H. Strømann. Methodological essentials of life cycle assessment. *Department of Energy and Process Engineering of NTNU*, August 2010.

[9] C. Zhang. Environmental evaluation of FRP in UK highway bridge deck replacement applications based on a comparative LCA study. *Advanced Materials Research*, 374-377:43–48, 2011.

[10] J. Hammervold et al. Environmental life-cycle assessment of bridges. *Journal of Bridge Engineering*, 2011.

[11] Z. Lounis et al. Towards sustainable design of highway bridges. *National Research Council of Canada*, 2010.

[12] L. Bouhaya, L. Le Roy, and A. Feraille-Fresnet. Simplified environmental study on innovative bridge structure. *Environ. Sci. Technol.*, pages 2066–2071, 2009.

[13] H. Gervásio and L.S. Da Silva. Comparative life-cycle analysis of steel-concrete composite bridges. *Structure and Infrastructure Engineering*, 4(4):251–269, August 2008.

[14] D. Collings. An environmental comparison of bridge forms. *Bridge Engineering*, (159), 2006. Issue BE4.

[15] MEEDDM. Analyse du cycle de vie d'un pont en béton. 2006.

[16] K. Steele. Environmental sustainability for bridge management. *Bridge Management 5*, 2005.

[17] G. A. Keoleian, A. Kendall, J. E. Dettling, V. M. Smith, R. F. Chandler, M.D. Lepech, and V. C. Li. Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints. *Journal of infrastructure systems*, (51), March 2005. ASCE.

[18] Martin. Concrete bridges in sustainable development. *Proceedings of the ICE*, 2004.

[19] Y. Itoh et al. Using CO_2 emission quantities in bridge life cycle analysis. *Engineering Structures*, (25):565–577, 2003.

[20] A. Horvath et al. Steel versus steel-reinforced concrete bridges: Environmental assessment. *Journal of Infrastructure Systems*, September 1998. ASCE.

[21] J. Widman. Environmental impact assessment of steel bridges. *Journal of Constructional Steel Research*, 46:291–293, 1998. Elsevier.

[22] Statens Vegvesen. Håndbok 136 - Inspeksjonhåndbok for bruer. 2000.

[23] Statens Vegvesen. Konkurransegrunnlag, Rv. 80 Løding - Vikan, Tverlandsbrua. *E - Beskrivelse og mengdefortegnelse*, 2011.

[24] Thomas Dequidt. TBA 4530 - Construction Engineering & Project Management, Specialization Report, NTNU. 2011.

[25] Daniel Kellenberger, Hans-Jorg Althaus, Tina Kunniger, Martin Lehmann, Niels Jungbluth, and Philipp Thalmann. Life cycle inventories of building products - Data v2.0 (2007). *Ecoinvent center*, 2007.

[26] Cement Admixtures Association. Admixture sheet ATS 5 - Concrete air-entraining admixtures. 2006.

[27] Roberto Dones, Christian Bauer, Rita Bolliger, Bastian Burger, Thomas Heck, Alexander Roder, Mireille Feist Hemmenegger, Rolf Frischknecht, Niels Jungbluth, and Matthias Tuchschmid. Life cycle inventories of energy systems - Data v2.0 (2007). *Ecoinvent center*, 2007.

[28] Badische Stahlwerke GMBH. Umwelterklarung (Environmental report). 2011.

[29] Celsa Steel Service AS. EPD: Steel reinforcement products for concrete. 2012.

[30] Mischa Classen, Hans-Jorg Althaus, Silvio Blaser, Wolfram Scharnhorst, Matthias Tuchschmid, and Niels Jungbluth. Life cycle inventories of metals - Data v2.1 (2009). *Ecoinvent center*, 2009.

[31] Roland Hischier. Life cycle inventories of packaging and graphical papers - part II: Plastics. Data v2.0 (2007). *Ecoinvent center*, 2007.

[32] Roland Steiner and Rolf Frischknecht. Metal processing and compressed air supply - Data v2.0 (2007). *Ecoinvent center*, 2007.

[33] Frank Werner, Hans-Jorg Althaus, Tina Kunniger, and Klaus Richter. Life cycle inventories of wood as fuel and construction material - Data v2.0 (2007). *Ecoinvent center*, 2007.

[34] Torbjørn Jørgensen. Seminar om fugtisolering af broer - Mastiksisolering med topeka 4S. *Statens Vegvesen*, 2009.

[35] Ruukki. Environmental product declaration and safety information sheet - Tubular products, steel sections and piles. 20011.

[36] Michael Spielmann, Christian Bauer, and Roberto Dones. Transport services - Data v2.0 (2007). *Ecoinvent center*, 2007.

[37] Statens Vegvesen. Konkurransegrunnlag, Rv. 80 Løding - Vikan, Tverlandsbrua. *A3 - Orientering*, 2011.

[38] Gabor Doka. Life cycle inventories of waste treatment services - Part V: Building material disposal - Data v2.1 (2009). *Ecoinvent center*, 2009.

[39] Norcem. Norcem Lavkarbonsement (EN 197-1, CEM II/B-V). *The Norwegian EPD foundation*, 2011.

Appendix A

Master Thesis contract

NTNU
Fakultet for ingeniørvitenskap og teknologi
Institutt for bygg, anlegg og transport

MASTER DEGREE THESIS

Spring 2012
for

Student: Thomas Dequidt

Life Cycle Assessment of a Norwegian Bridge

BACKGROUND

The Norwegian Ministry of Transport and Communications, throughout the realization of the National Transport Plan 2010 – 2019, is taking new measures in the transport sector in order to reduce the emissions between 2.5 and 4 million tons CO_2 equivalent by 2020. In such a context, the Norwegian Public Roads Administration (*Statens vegvesen*) is seeking to evaluate the carbon footprint of the Norwegian roads, bridges and tunnels.

TASK DESCRIPTION

In cooperation with the Norwegian Public Roads Administration and bridge contractors and subcontractors, the purpose of this master thesis is to evaluate the carbon footprint of an actual bridge project using an environmental management tool: life cycle assessment (LCA). The results of this work shall also be used as a reference for comparisons with future environmental assessments of Norwegian bridges.

The subtasks and research questions are:

1. The realization of a literature review of previous bridge life cycle assessment analyses.
2. A comprehensive description of LCA methodology and its application to a case study.
3. A large investigation of the data inventories related to the case study.
4. A careful attention to data quality and uncertainty.

General about content, work and presentation

The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords.(template on: http://www.ntnu.no/bat/skjemabank)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- Table of content including list of figures, tables, enclosures and appendices.
- If useful and applicable a list explaining important terms and abbreviations should be included.
- The main text.
- Clear and complete references to material used, both in text and figures/tables. This also applies for personal and/or oral communication and information.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1..
- The report musts have a complete page numbering.

Advice and guidelines for writing of the report is given in: "Writing Reports" by Øivind Arntsen. Additional information on report writing is found in "Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave ved Institutt for bygg, anlegg og transport" (In Norwegian). Both are posted posted on http://www.ntnu.no/bat/skjemabank

Submission procedure

Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

On submission of the thesis the candidate shall submit a CD with the paper in digital form in pdf and Word version, the underlying material (such as data collection) in digital form (eg. Excel). Students must submit the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU, Reinertsen AS and Statens vegvesen. The Department has the right to make use of the results from the work as if conducted by a department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description to be developed, if and when applicable. See http://www.ntnu.no/bat/skjemabank for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with " Fieldwork HSE Guidelines". The document is found on the NTNU HMS-pages at http://www.ntnu.no/hms/retningslinjer/HMSR07E.pdf

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Start and submission deadlines
The work on the Master Thesis starts on January 16, 2012

The thesis report as described above shall be submitted digitally in DAIM at the latest at 3pm June 11, 2012

Professor in charge: Amund Bruland

Trondheim, January 16, 2012. (revised: 07.06.2012)

A. Bruland

Professor in charge (sign)

Appendix B

GWP100 values

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m⁻² ppb⁻¹)	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435
Methyl bromide	CH_3Br	0.7	0.01		17	5	1
Methyl chloroform	CH_3CCl_3	5	0.06		506	146	45
HCFC-22	$CHClF_2$	12	0.2	1,500	5,160	1,810	549
HCFC-123	$CHCl_2CF_3$	1.3	0.14	90	273	77	24
HCFC-124	$CHClFCF_3$	5.8	0.22	470	2,070	609	185
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181
Hydrofluorocarbons							
HFC-23	CHF_3	270	0.19	11,700	12,000	14,800	12,200
HFC-32	CH_2F_2	4.9	0.11	650	2,330	675	205
HFC-125	CHF_2CF_3	29	0.23	2,800	6,350	3,500	1,100
HFC-134a	CH_2FCF_3	14	0.16	1,300	3,830	1,430	435
HFC-143a	CH_3CF_3	52	0.13	3,800	5,890	4,470	1,590
HFC-152a	CH_3CHF_2	1.4	0.09	140	437	124	38
HFC-227ea	CF_3CHFCF_3	34.2	0.26	2,900	5,310	3,220	1,040
HFC-236fa	$CF_3CH_2CF_3$	240	0.28	6,300	8,100	9,810	7,660
HFC-245fa	$CHF_2CH_2CF_3$	7.6	0.28		3,380	1030	314
HFC-365mfc	$CH_3CF_2CH_2CF_3$	8.6	0.21		2,520	794	241
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	15.9	0.4	1,300	4,140	1,640	500
Perfluorinated compounds							
Sulphur hexafluoride	SF_6	3,200	0.52	23,900	16,300	22,800	32,600
Nitrogen trifluoride	NF_3	740	0.21		12,300	17,200	20,700
PFC-14	CF_4	50,000	0.10	6,500	5,210	7,390	11,200
PFC-116	C_2F_6	10,000	0.26	9,200	8,630	12,200	18,200

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon: SAR‡ (100-yr)	20-yr	100-yr	500-yr
Perfluorinated compounds *(continued)*							
PFC-218	C_3F_8	2,600	0.26	7,000	6,310	8,830	12,500
PFC-318	c-C_4F_8	3,200	0.32	8,700	7,310	10,300	14,700
PFC-3-1-10	C_4F_{10}	2,600	0.33	7,000	6,330	8,860	12,500
PFC-4-1-12	C_5F_{12}	4,100	0.41		6,510	9,160	13,300
PFC-5-1-14	C_6F_{14}	3,200	0.49	7,400	6,600	9,300	13,300
PFC-9-1-18	$C_{10}F_{18}$	>1,000[d]	0.56		>5,500	>7,500	>9,500
trifluoromethyl sulphur pentafluoride	SF_5CF_3	800	0.57		13,200	17,700	21,200
Fluorinated ethers							
HFE-125	CHF_2OCF_3	136	0.44		13,800	14,900	8,490
HFE-134	CHF_2OCHF_2	26	0.45		12,200	6,320	1,960
HFE-143a	CH_3OCF_3	4.3	0.27		2,630	756	230
HCFE-235da2	$CHF_2OCHClCF_3$	2.6	0.38		1,230	350	106
HFE-245cb2	$CH_3OCF_2CHF_2$	5.1	0.32		2,440	708	215
HFE-245fa2	$CHF_2OCH_2CF_3$	4.9	0.31		2,280	659	200
HFE-254cb2	$CH_3OCF_2CHF_2$	2.6	0.28		1,260	359	109
HFE-347mcc3	$CH_3OCF_2CF_2CF_3$	5.2	0.34		1,980	575	175
HFE-347pcf2	$CHF_2CF_2OCH_2CF_3$	7.1	0.25		1,900	580	175
HFE-356pcc3	$CH_3OCF_2CF_2CHF_2$	0.33	0.93		386	110	33
HFE-449sl (HFE-7100)	$C_4F_9OCH_3$	3.8	0.31		1,040	297	90
HFE-569sf2 (HFE-7200)	$C_4F_9OC_2H_5$	0.77	0.3		207	59	18
HFE-43-10pccc124 (H-Galden 1040x)	$CHF_2OCF_2OC_2F_4OCHF_2$	6.3	1.37		6,320	1,870	569
HFE-236ca12 (HG-10)	$CHF_2OCF_2OCHF_2$	12.1	0.66		8,000	2,800	860
HFE-338pcc13 (HG-01)	$CHF_2OCF_2CF_2OCHF_2$	6.2	0.87		5,100	1,500	460
Perfluoropolyethers							
PFPMIE	$CF_3OCF(CF_3)CF_2OCF_2OCF_3$	800	0.65		7,620	10,300	12,400
Hydrocarbons and other compounds – Direct Effects							
Dimethylether	CH_3OCH_3	0.015	0.02		1	1	<<1
Methylene chloride	CH_2Cl_2	0.38	0.03		31	8.7	2.7
Methyl chloride	CH_3Cl	1.0	0.01		45	13	4

Appendix C

Contractors list

COMPANY NAME	FUNCTION
Reinertsen	Contracting company realizing the project
Norldland Betongindustri	Delivery of fresh concrete
Norskstaal	Delivery of prestressing steeel
Doka	Formwork and traveling formwork system
MK4	Delivery and installation of prestressing in the box-girder
Spennarmering Norge	Rock anchoring
Frico	Delivery and installation of scaffolding
M^3 Anlegg	Ground works
Holmgren Sjøservice	Underwater works
Zublin	Delivery and installation of bored piles
NSP	Delivery and installation of steel pipe piles
Kristiansund Taubatservice	Tugboats for the caisson
KB Spennteknikk AS	Delivery and installation of bearings and joints
Multi-Bygg AS	Construction and installation of the caisson
Ramirent	Barracks on the site
Malthus	Barracks on the site
Iris	Delivery of waste through and waste management
ED Knutsen	Delivery and installation of the tower crane
Vestkran	Delivery of the two mobile cranes
RE Polen	Hiring of site personnel and crane operators

Table C.1: List of the bridge contractors and subcontractors.

Appendix D

Foreground processes

Foreground processes (1/2)

NB: The Norwegian reinforcing steel foreground processes (ReinfSteelNor) do not hold an ID since the global warming impacts were directly collected and not calculated by the LCA software. The process Functional Unit designates the entire bridge.

FULL NAME	PROCESS ID	NAME	LOCATION	CATEGORY	SUBCATEGORY	UNIT
Functional Unit/NOR///p	10001	Functional Unit	NOR			p
BridgeSup1/NOR/Prod/Concrete/p	10002	BridgeSup1	NOR	Prod	Concrete	p
BridgeSup1/NOR/Prod/ReinfSteelGer/p	10003	BridgeSup1	NOR	Prod	ReinfSteelGer	p
BridgeSup1/NOR/Prod/ReinfSteelNor/p		BridgeSup1	NOR	Prod	ReinfSteelNor	p
BridgeSup1/NOR/Prod/Formwork/p	10004	BridgeSup1	NOR	Prod	Formwork	p
BridgeSup1/NOR/Prod/Prestressing/p	10005	BridgeSup1	NOR	Prod	Prestressing	p
BridgeSup2/NOR/Prod/Asphalt/p	10006	BridgeSup2	NOR	Prod	Asphalt	p
BridgeSup2/NOR/Prod/Railings/p	10007	BridgeSup2	NOR	Prod	Railings	p
BridgeSup2/NOR/Prod/Bearings&joints/p	10008	BridgeSup2	NOR	Prod	Bearings&joints	p
BridgeSup2/NOR/Prod/Curing/p	10009	BridgeSup2	NOR	Prod	Curing	p
BridgeSub3/NOR/Prod/Ground&Underwater/p	10010	BridgeSub3	NOR	Prod	Ground&Underwate	p
BridgeSub3/NOR/Prod/Piles&Caisson/p	10011	BridgeSub3	NOR	Prod	Piles&Caisson	p
BridgeSub3/NOR/Prod/Concrete/p	10012	BridgeSub3	NOR	Prod	Concrete	p
BridgeSub3/NOR/Prod/ReinfSteelGer/p	10013	BridgeSub3	NOR	Prod	ReinfSteelGer	p
BridgeSub3/NOR/Prod/ReinfSteelNor/p		BridgeSub3	NOR	Prod	ReinfSteelNor	p
BridgeSub3/NOR/Prod/Formwork/p	10014	BridgeSub3	NOR	Prod	Formwork	p
BridgeSub3/NOR/Prod/Prestressing/p	10015	BridgeSub3	NOR	Prod	Prestressing	p
BridgeSub3/NOR/Prod/Curing/p	10016	BridgeSub3	NOR	Prod	Curing	p
Other/NOR/Prod//p	10017	Other	NOR	Prod		p
BridgeSup1/NOR/Cons/Concrete/p	10018	BridgeSup1	NOR	Cons	Concrete	p
BridgeSup1/NOR/Cons/ReinfSteel/p	10019	BridgeSup1	NOR	Cons	ReinfSteel	p
BridgeSup1/NOR/Cons/Formwork/p	10020	BridgeSup1	NOR	Cons	Formwork	p
BridgeSup1/NOR/Cons/Scaff/p	10021	BridgeSup1	NOR	Cons	Scaff	p

Foreground processes (2/2)

FULL NAME	PROCESS ID	NAME	LOCATION	CATEGORY	SUBCATEGORY	UNIT
BridgeSup1/NOR/Cons/Prestressing/p	10022	BridgeSup1	NOR	Cons	Prestressing	p
BridgeSup2/NOR/Cons/Asphalt/p	10023	BridgeSup2	NOR	Cons	Asphalt	p
BridgeSup2/NOR/Cons/Railings/p	10024	BridgeSup2	NOR	Cons	Railings	p
BridgeSup2/NOR/Cons/Bearings&joints/p	10025	BridgeSup2	NOR	Cons	Bearings&joints	p
BridgeSup2/NOR/Cons/Curing/p	10026	BridgeSup2	NOR	Cons	Curing	p
BridgeSub3/NOR/Cons/Ground&Underwater/p	10027	BridgeSub3	NOR	Cons	Ground&Underwate	p
BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	BridgeSub3	NOR	Cons	Piles&Caisson	p
BridgeSub3/NOR/Cons/Concrete/p	10029	BridgeSub3	NOR	Cons	Concrete	p
BridgeSub3/NOR/Cons/ReinfSteel/p	10030	BridgeSub3	NOR	Cons	ReinfSteel	p
BridgeSub3/NOR/Cons/Formwork/p	10031	BridgeSub3	NOR	Cons	Formwork	p
BridgeSub3/NOR/Cons/Prestressing/p	10032	BridgeSub3	NOR	Cons	Prestressing	p
BridgeSub3/NOR/Cons/Curing/p	10033	BridgeSub3	NOR	Cons	Curing	p
Other/NOR/Cons//p	10034	Other	NOR	Cons		p
BridgeSup2/NOR/Oper/PublicLighting/p	10035	BridgeSup2	NOR	Oper	PublicLighting	p
BridgeSup2/NOR/Oper/Traffic/p	10036	BridgeSup2	NOR	Oper	Traffic	p
BridgeSup1/NOR/R&M/Inspection/p	10037	BridgeSup1	NOR	R&M	Inspection	p
BridgeSup2/NOR/R&M/Asphalt/p	10038	BridgeSup2	NOR	R&M	Asphalt	p
BridgeSub3/NOR/R&M/Inspection/p	10039	BridgeSub3	NOR	R&M	Inspection	p
BridgeSup1/NOR/EOL/Reinf.concrete/p	10040	BridgeSup1	NOR	EOL	Reinf.concrete	p
BridgeSup2/NOR/EOL/Asphalt/p	10041	BridgeSup2	NOR	EOL	Asphalt	p
BridgeSub3/NOR/EOL/Reinf.concrete/p	10042	BridgeSub3	NOR	EOL	Reinf.concrete	p
BridgeSub3/NOR/EOL/Gravel/p	10043	BridgeSub3	NOR	EOL	Gravel	p
BridgeSub3/NOR/EOL/Steel/p	10044	BridgeSub3	NOR	EOL	Steel	p

Appendix E

Input data inventory

NB: The values are given for the whole bridge.

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Sand (0-8mm)	sand, at mine/ CH/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	1.14861E+07	kg
Gravel (8-22m)	gravel, unspecified, at mine/ CH/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	1.30289E+07	kg
Portland cement 42.5R	portland cement, strength class Z 42.5, at plant/ CH/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	4.98604E+06	kg
Cold water	tap water, at user/ RER/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	2.34673E+06	kg
Superplasticizer	acrylic filler, at plant/ RER/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	6.28428E+04	kg
Set-retarding admixtures	sodium carbonate from ammonium chloride production, at plant/ GLO/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	1.18881E+03	kg
Air-entraining admixtures	diethanolamine, at plant/ RER/ kg	BridgeSup1/NOR/Prod/Concrete/p	10002	1.69955E+04	kg
Energy use for mixing	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Prod/Concrete/p	10002	7.06023E+04	kWh
Transportation by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSup1/NOR/Prod/Concrete/p	10002	7.38848E+06	tkm
Transportation by lorry	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Prod/Concrete/p	10002	4.29701E+05	tkm
Energy use for reinforcing steel production	electricity, production mix DE/ DE/ kWh	BridgeSup1/NOR/Prod/ReinfSteelGer/p	10003	3.11220E+05	kWh
Plywood formwork	plywood, outdoor use, at plant/ RER/ m3	BridgeSup1/NOR/Prod/Formwork/p	10004	6.96E+02	m3
Steel, raw material (strands, anchors and ducts)	steel, low-alloyed, at plant/ RER/ kg	BridgeSup1/NOR/Prod/Prestressing/p	10005	9.64E+05	kg
Strands, manufacturing process	wire drawing, steel/ RER/ kg	BridgeSup1/NOR/Prod/Prestressing/p	10005	7.67E+05	kg
Anchors and ducts, manufacturing process	steel product manufacturing, average metal working/ RER/ kg	BridgeSup1/NOR/Prod/Prestressing/p	10005	1.97E+05	kg
Grouting paste	cement mortar, at plant/ CH/ kg	BridgeSup1/NOR/Prod/Prestressing/p	10005	3.50E+05	kg
Gravel, waterproofing layer	gravel, crushed, at mine/ CH/ kg	BridgeSup2/NOR/Prod/Asphalt/p	10006	1.35E+05	kg
Sand, waterproofing layer	sand, at mine/ CH/ kg	BridgeSup2/NOR/Prod/Asphalt/p	10006	2.45E+05	kg
Bitumen, waterproofing layer	bitumen, at refinery/ RER/ kg	BridgeSup2/NOR/Prod/Asphalt/p	10006	2.56E+04	kg
Asphalt, leveling and surface courses	mastic asphalt, at plant/ CH/ kg	BridgeSup2/NOR/Prod/Asphalt/p	10006	2.55E+06	kg
Steel, raw material (railings & parapets)	steel, low-alloyed, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Railings/p	10007	7.26E+05	kg
Steel, manufacturing process (railings & parapets)	steel product manufacturing, average metal working/ RER/ kg	BridgeSup2/NOR/Prod/Railings/p	10007	7.26E+05	kg
Steel, raw material (bearings and jonts)	steel, low-alloyed, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Bearings&joints/p	10008	1.84E+04	kg
Cast iron, raw material (bearings)	cast iron, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Bearings&joints/p	10008	2.20E+03	kg
Natural rubber (bearings)	natural rubber based sealing, at plant/ DE/ kg	BridgeSup2/NOR/Prod/Bearings&joints/p	10008	2.50E+02	kg
Steel and cast iron, manufacturing process (bearings and joints)	metal product manufacturing, average metal working/ RER/ kg	BridgeSup2/NOR/Prod/Bearings&joints/p	10008	2.06E+04	kg

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Insulation membrane	solvents, organic, unspecified, at plant/ GLO/ kg	BridgeSup2/NOR/Prod/Curing/p	10009	2.04E+03	kg
Plastic sheeting, raw material	ethylvinylacetate, foil, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Curing/p	10009	9.68E+03	kg
Polyethylene, raw material	polyethylene, LDPE, granulate, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Curing/p	10009	1.60E+03	kg
Polyethylene, manufacturing process	extrusion, plastic film/ RER/ kg	BridgeSup2/NOR/Prod/Curing/p	10009	1.60E+03	kg
Gluing	epoxy resin, liquid, at plant/ RER/ kg	BridgeSup1/NOR/Prod/Curing/p	10009	4.55E+01	kg
Surface impregnation	acrylic binder, 34% in H2O, at plant/ RER/ kg	BridgeSup2/NOR/Prod/Curing/p	10009	2.60E+02	kg
Explosives, complete process	blasting/ RER/ kg	BridgeSub3/NOR/Prod/Bast-Excav-Backf/p	10010	1.40E+02	kg
Gravel for backfilling and ballast	gravel, unspecified, at mine/ CH/ kg	BridgeSub3/NOR/Prod/Bast-Excav-Backf/p	10010	3.58E+06	kg
Bored piles steel casings, raw material	steel, low-alloyed, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Piles&Caisson/p	10011	8.80E+04	kg
Bored piles steel casings, manufacturing process	drawing of pipes, steel/ RER/ kg	BridgeSub3/NOR/Prod/Piles&Caisson/p	10011	8.80E+04	kg
Sand (0-8mm)	sand, at mine/ CH/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	3.62716E+06	kg
Gravel (8-22m)	gravel, unspecified, at mine/ CH/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	3.80446E+06	kg
Portland cement 42.5R	portland cement, strength class Z 42.5, at plant/ CH/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	1.48593E+06	kg
Cold water	tap water, at user/ RER/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	7.45467E+05	kg
Superplasticizer	acrylic filler, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	1.32791E+04	kg
Set-retarding admixtures	sodium carbonate from ammonium chloride production, at plant/ GLO/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	5.00935E+03	kg
Air-entraining admixtures	diethanolamine, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	9.67306E+03	kg
Anti-washout admixtures	carboxymethyl cellulose, powder, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Concrete/p	10012	1.75500E+03	kg
Energy use for mixing	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Prod/Concrete/p	10012	2.18818E+04	kWh
Transportation by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSub3/NOR/Prod/Concrete/p	10012	2.15397E+06	tkm
Transportation by lorry	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Prod/Concrete/p	10012	5.10301E+04	tkm
Energy use for reinforcing steel production	electricity, production mix DE/ DE/ kWh	BridgeSub3/NOR/Prod/ReinfSteelGer/p	10013	7.81470E+04	kWh
Plywood formwork	plywood, outdoor use, at plant/ RER/ m3	BridgeSub3/NOR/Prod/Formwork/p	10014	1.05E+02	m3

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Strands, raw material	steel, low-alloyed, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Prestressing/p	10015	1.64E+04	kg
Strands, manufacturing process	wire drawing, steel/ RER/ kg	BridgeSub3/NOR/Prod/Prestressing/p	10015	1.64E+04	kg
Ducts, raw material	polyvinylchloride, at regional storage/ RER/ kg	BridgeSub3/NOR/Prod/Prestressing/p	10015	9.56E+02	kg
Ducts, manufacturing process	extrusion, plastic pipes/ RER/ kg	BridgeSub3/NOR/Prod/Prestressing/p	10015	9.56E+02	kg
Grouting paste	cement mortar, at plant/ CH/ kg	BridgeSub3/NOR/Prod/Prestressing/p	10015	5.90E+03	kg
Insulation membrane	solvents, organic, unspecified, at plant/ GLO/ kg	BridgeSub3/NOR/Prod/Curing/p	10016	1.79E+02	kg
Plastic sheeting	ethylvinylacetate, foil, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Curing/p	10016	6.58E+02	kg
Polyethylene, raw material	polyethylene, LDPE, granulate, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Curing/p	10016	5.47E+01	kg
Polyethylene, manufacturing process	extrusion, plastic film/ RER/ kg	BridgeSub3/NOR/Prod/Curing/p	10016	5.47E+01	kg
Surface impregnation	acrylic binder, 34% in H2O, at plant/ RER/ kg	BridgeSub3/NOR/Prod/Curing/p	10016	3.20E+03	kg
Extra cement	portland cement, strength class Z 42.5, at plant/ CH/ kg	Other/NOR/Prod//p	10017	2.50E+03	kg
Electrical cables	cable, three-conductor cable, at plant/ GLO/ m	Other/NOR/Prod//p	10017	1.26E+04	m
Lamp posts, hollow rock shoes, splicing connections, additional equipment for inspection, raw material	steel, low-alloyed, at plant/ RER/ kg	Other/NOR/Prod//p	10017	1.36E+05	kg
Lamp posts, hollow rock shoes, splicing connections, additional equipment for inspection, processes	steel product manufacturing, average metal working/ RER/ kg	Other/NOR/Prod//p	10017	1.36E+05	kg
Grouting for bored piles	cement mortar, at plant/ CH/ kg	Other/NOR/Prod//p	10017	6.00E+01	kg
Corrosion protection for anchoring	powder coating, steel/ RER/ m2	Other/NOR/Prod//p	10017	2.60E+01	m^2
Skirts, concrete	concrete, normal, at plant/ CH/ m3	Other/NOR/Prod//p	10017	1.13E+02	m3
Skirts, reinforcing steel	reinforcing steel, at plant/ RER/ kg	Other/NOR/Prod//p	10017	8.00E+03	kg
Water runoff systems, raw material	polyvinylchloride, at regional storage/ RER/ kg	Other/NOR/Prod//p	10017	1.34E+03	kg
Water runoff systems, process	extrusion, plastic pipes/ RER/ kg	Other/NOR/Prod//p	10017	1.34E+03	kg
Extra plywood formwork	plywood, outdoor use, at plant/ RER/ m3	Other/NOR/Prod//p	10017	1.45E+02	m3
Additional equipment for inspection, stainless steel coating	selective coating, stainless steel sheet, black chrome/ CH/ m2	Other/NOR/Prod//p	10017	5.00E+01	m^2

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Concrete, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Cons/Concrete/p	10018	1.12E+06	tkm
Concrete, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup1/NOR/Cons/Concrete/p	10018	9.86E+05	pkm
Concrete, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Cons/Concrete/p	10018	2.49E+05	kWh
Concrete, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/Cons/Concrete/p	10018	1.69E+06	MJ
Concrete, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup1/NOR/Cons/Concrete/p	10018	1.33E+04	kg
Reinforcing steel, transport by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	2.72E+06	tkm
Reinforcing steel, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	1.63E+06	tkm
Reinforcing steel, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	7.69E+04	pkm
Reinforcing steel, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	1.94E+04	kWh
Reinforcing steel, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	1.32E+05	MJ
Reinforcing steel, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup1/NOR/Cons/ReinfSteel/p	10019	1.04E+03	kg
Formwork, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Cons/Formwork/p	10020	4.22E+05	tkm
Formwork, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup1/NOR/Cons/Formwork/p	10020	1.24E+04	pkm
Formwork, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Cons/Formwork/p	10020	3.12E+03	kWh
Formwork, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/Cons/Formwork/p	10020	2.12E+04	MJ
Formwork, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup1/NOR/Cons/Formwork/p	10020	1.66E+02	kg
Scaffolding, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Cons/Scaff/p	10021	2.11E+06	tkm
Scaffolding, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup1/NOR/Cons/Scaff/p	10021	2.22E+04	pkm
Scaffolding, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Cons/Scaff/p	10021	5.60E+03	kWh
Scaffolding, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/Cons/Scaff/p	10021	3.81E+04	MJ
Scaffolding, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup1/NOR/Cons/Scaff/p	10021	2.99E+02	kg

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Prestressing, transport by freight train	transport, freight, rail/ RER/ tkm	BridgeSup1/NOR/Cons/Prestressing/p	10022	1.16E+06	tkm
Prestressing, transport by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSup1/NOR/Cons/Prestressing/p	10022	2.40E+06	tkm
Prestressing, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/Cons/Prestressing/p	10022	8.92E+04	tkm
Prestressing, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup1/NOR/Cons/Prestressing/p	10022	2.85E+04	pkm
Prestressing, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup1/NOR/Cons/Prestressing/p	10022	7.20E+03	kWh
Prestressing, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/Cons/Prestressing/p	10022	4.90E+04	MJ
Prestressing, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup1/NOR/Cons/Prestressing/p	10022	3.84E+02	kg
Waterproofing and asphalt, transport by lorry	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/Cons/Asphalt/p	10023	2.96E+05	tkm
Railings & parapets, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/Cons/Railings/p	10024	7.33E+05	tkm
Railings & parapets, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup2/NOR/Cons/Railings/p	10024	2.15E+04	pkm
Railings & parapets, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup2/NOR/Cons/Railings/p	10024	5.42E+03	kWh
Railings & parapets, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup2/NOR/Cons/Railings/p	10024	3.69E+04	MJ
Railings & parapets, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup2/NOR/Cons/Railings/p	10024	2.89E+02	kg
Bearings & joints, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/Cons/Bearings&joints/p	10025	5.02E+04	tkm
Bearings & joints, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup2/NOR/Cons/Bearings&joints/p	10025	6.16E+02	pkm
Bearings & joints, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup2/NOR/Cons/Bearings&joints/p	10025	1.56E+02	kWh
Bearings & joints, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup2/NOR/Cons/Bearings&joints/p	10025	1.06E+03	MJ
Bearings & joints, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup2/NOR/Cons/Bearings&joints/p	10025	8.30E+00	kg
Curing compounds, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/Cons/Curing/p	10026	9.67E+03	tkm
Curing compounds, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSup2/NOR/Cons/Curing/p	10026	4.03E+02	pkm
Curing compounds, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSup2/NOR/Cons/Curing/p	10026	1.02E+02	kWh
Curing compounds, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSup2/NOR/Cons/Curing/p	10026	6.92E+02	MJ
Curing compounds, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSup2/NOR/Cons/Curing/p	10026	5.42E+00	kg
Gravel for backfilling and ballast, transport by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSub3/NOR/Cons/Ground&Underwater/p	10027	6.34E+05	tkm
Excavation of material	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Ground&Underwater/p	10027	2.42E+05	MJ
Excavated material and explosives, transport by lorry	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Ground&Underwater/p	10027	3.33E+04	tkm

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Piles boring, process	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	1.97E+06	MJ
Tugboats for caisson	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	2.87E+04	kg
Piling rig, transport	transport, lorry >32t, EURO5/ RER/ tkm	BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	2.80E+05	tkm
Bored piles steel casings, steel pipe piles and boring rig, transport by lorry	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	1.02E+06	tkm
Concrete, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Concrete/p	10029	3.44E+05	tkm
Concrete, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSub3/NOR/Cons/Concrete/p	10029	3.00E+05	pkm
Concrete, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Cons/Concrete/p	10029	7.57E+04	kWh
Concrete, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Concrete/p	10029	5.15E+05	MJ
Concrete, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/Concrete/p	10029	4.04E+03	kg
Reinforcing steel, transport by ship	transport, transoceanic freight ship/ OCE/ tkm	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	6.83E+05	tkm
Reinforcing steel, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	4.09E+05	tkm
Reinforcing steel, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	1.93E+04	pkm
Reinforcing steel, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	4.87E+03	kWh
Reinforcing steel, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	3.31E+04	MJ
Reinforcing steel, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/ReinfSteel/p	10030	2.60E+02	kg
Formwork, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Formwork/p	10031	6.35E+04	tkm
Formwork, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSub3/NOR/Cons/Formwork/p	10031	1.86E+03	pkm
Formwork, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Cons/Formwork/p	10031	4.69E+02	kWh
Formwork, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Formwork/p	10031	3.19E+03	MJ
Formwork, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/Formwork/p	10031	2.50E+01	kg
Prestressing, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Prestressing/p	10032	4.86E+04	tkm
Prestressing, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSub3/NOR/Cons/Prestressing/p	10032	6.87E+02	pkm
Prestressing, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Cons/Prestressing/p	10032	1.73E+02	kWh
Prestressing, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Prestressing/p	10032	1.18E+03	MJ
Prestressing, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/Prestressing/p	10032	9.25E+00	kg

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Curing compounds, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/Cons/Curing/p	10033	2.90E+03	tkm
Curing compounds, allocation procedure for transport of personnel	transport, aircraft, passenger, Europe/ RER/ pkm	BridgeSub3/NOR/Cons/Curing/p	10033	1.21E+02	pkm
Curing compounds, allocation procedure for electricity consumption	electricity, production mix NO/ NO/ kWh	BridgeSub3/NOR/Cons/Curing/p	10033	3.06E+01	kWh
Curing compounds, allocation procedure for diesel consumption	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/Cons/Curing/p	10033	2.08E+02	MJ
Curing compounds, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	BridgeSub3/NOR/Cons/Curing/p	10033	1.63E+00	kg
Other, transport by lorry and allocation procedure for transport of the crane	transport, lorry >16t, fleet average/ RER/ tkm	Other/NOR/Cons//p	10034	2.27E+05	tkm
Other, allocation procedure for transport of personnel	diesel, burned in building machine/ GLO/ MJ	Other/NOR/Cons//p	10034	2.57E+04	MJ
Other, allocation procedure for electricity consumption	transport, aircraft, passenger, Europe/ RER/ pkm	Other/NOR/Cons//p	10034	1.50E+04	pkm
Other, allocation procedure for diesel consumption	electricity, production mix NO/ NO/ kWh	Other/NOR/Cons//p	10034	3.78E+03	kWh
Other, allocation procedure for gasoline consumption	heavy fuel oil, at regional storage/ RER/ kg	Other/NOR/Cons//p	10034	2.02E+02	kg
Public Lighting, power supply	electricity, production mix NO/ NO/ kWh	BridgeSup2/NOR/Oper/PublicLighting/p	10035	3.00E+06	kWh
Diesel car, traffic	operation, passenger car, diesel, fleet average 2010/ RER/ vkm	BridgeSup2/NOR/Oper/Traffic/p	10036	2.24E+08	vkm
Petrol car, traffic	operation, passenger car, petrol, fleet average 2010/ RER/ vkm	BridgeSup2/NOR/Oper/Traffic/p	10036	2.81E+07	vkm
Lorry, traffic	operation, lorry >16t, fleet average/ RER/ vkm	BridgeSup2/NOR/Oper/Traffic/p	10036	2.81E+07	vkm
Diesel car, inspection	operation, passenger car, diesel, fleet average 2010/ RER/ vkm	BridgeSup1/NOR/R&M/Inspection/p	10037	6.00E+04	vkm
Machine transport, main inspection	operation, lorry >16t, fleet average/ RER/ vkm	BridgeSup1/NOR/R&M/Inspection/p	10037	4.00E+03	vkm
Machine use, main inspection	diesel, burned in building machine/ GLO/ MJ	BridgeSup1/NOR/R&M/Inspection/p	10037	6.05E+04	MJ
Asphalt removing, maintenance	diesel, burned in building machine/ GLO/ MJ	BridgeSup2/NOR/R&M/Asphalt/p	10038	2.50E+06	MJ
Asphalt disposal, maintenance	disposal, asphalt, 0.1% water, to sanitary landfill/ CH/ kg	BridgeSup2/NOR/R&M/Asphalt/p	10038	1.68E+07	kg
Asphalt surfacing course renewal, maintenance	mastic asphalt, at plant/ CH/ kg	BridgeSup2/NOR/R&M/Asphalt/p	10038	1.68E+07	kg
Asphalt transportation to the site, maintenance	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/R&M/Asphalt/p	10038	1.68E+06	tkm
Diesel car, inspection	operation, passenger car, diesel, fleet average 2010/ RER/ vkm	BridgeSub3/NOR/R&M/Inspection/p	10039	6.00E+04	vkm
Machine transport, main inspection	operation, lorry >16t, fleet average/ RER/ vkm	BridgeSub3/NOR/R&M/Inspection/p	10039	4.00E+03	vkm
Machine use, main inspection	diesel, burned in building machine/ GLO/ MJ	BridgeSub3/NOR/R&M/Inspection/p	10039	6.05E+04	MJ
Reinforced concrete, sorting	disposal, building, reinforced concrete, to sorting plant/ CH/ kg	BridgeSup1/NOR/EOL/Reinf.concrete/p	10040	3.59E+07	kg
Reinforced concrete, transport to recycling	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup1/NOR/EOL/Reinf.concrete/p	10040	2.20E+06	tkm

Background process name	*EcoInvent v2.2 background process name*	*Foreground process name*	*F.p. ID*	*Value*	*Unit*
Asphalt removing, end-of-life	diesel, burned in building machine/ GLO/ MJ	BridgeSup2/NOR/EOL/Asphalt/p	10041	7.57E+04	MJ
Asphalt transportation to sanitary landfill, end-of-life	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSup2/NOR/EOL/Asphalt/p	10041	2.96E+05	tkm
Asphalt disposal, end-of-life	disposal, asphalt, 0.1% water, to sanitary landfill/ CH/ kg	BridgeSup2/NOR/EOL/Asphalt/p	10041	2.96E+06	kg
Reinforced concrete, sorting	disposal, building, reinforced concrete, to sorting plant/ CH/ kg	BridgeSub3/NOR/EOL/Reinf.concrete/p	10042	1.08E+07	kg
Reinforced concrete, transport to recycling	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/EOL/Reinf.concrete/p	10042	5.96E+05	tkm
Gravel transportation, end-of-life	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/EOL/Gravel/p	10043	4.38E+05	tkm
Prestressing and railings & parapets transportation, end-of-life	transport, lorry >16t, fleet average/ RER/ tkm	BridgeSub3/NOR/EOL/Steel/p	10044	1.71E+05	tkm

Appendix F

Output data inventory

NB: The values are given for the whole bridge.

Stressor name	EcoInvent v2.2 stressor name	Foreground process name	Foreground process ID	Value	Unit
Carbon dioxide	Carbon dioxide, fossil/ air/ unspecified	BridgeSup1/NOR/Prod/ReinfSteelGer/p	10003	1.13E+05	kg
Carbon dioxide equivalent	-	BridgeSup1/NOR/Prod/ReinfSteelNor/p	-	2.65E+05	kg
Carbon dioxide	Carbon dioxide, fossil/ air/ unspecified	BridgeSub3/NOR/Prod/Piles/p	10011	1.80E+05	kg
Methane	Methane, biogenic/ air/ unspecified	BridgeSub3/NOR/Prod/Piles/p	10011	1.34E+02	kg
Dinitrogen	Dinitrogen monoxide/ air/ unspecified	BridgeSub3/NOR/Prod/Piles/p	10011	1.01E+00	kg
Carbon dioxide	Carbon dioxide, fossil/ air/ unspecified	BridgeSub3/NOR/Prod/ReinfSteelGer/p	10013	2.78E+04	kg
Carbon dioxide equivalent	-	BridgeSup1/NOR/Prod/ReinfSteelNor/p	-	6.66E+04	kg

Appendix G

Global warming impacts per foreground process

NB: The values are given per functional unit.

FULL NAME	PROCESS ID	Global warming (kgCO2-eq)
Functional Unit/NOR///p	10001	6665.114568
BridgeSup1/NOR/Prod/Concrete/p	10002	279.1501007
BridgeSup1/NOR/Prod/ReinfSteelGer/p	10003	20.18178721
BridgeSup1/NOR/Prod/ReinfSteelNor/p		16.8794
BridgeSup1/NOR/Prod/Formwork/p	10004	28.55782639
BridgeSup1/NOR/Prod/Prestressing/p	10005	151.6227391
BridgeSup2/NOR/Prod/Asphalt/p	10006	34.82334301
BridgeSup2/NOR/Prod/Railings/p	10007	162.4933588
BridgeSup2/NOR/Prod/Bearings&joints/p	10008	4.693922469
BridgeSup2/NOR/Prod/Curing/p	10009	2.290675425
BridgeSub3/NOR/Prod/Ground&Underwater	10010	0.66289013
BridgeSub3/NOR/Prod/Piles&Caisson/p	10011	31.35129955
BridgeSub3/NOR/Prod/Concrete/p	10012	84.23520814
BridgeSub3/NOR/Prod/ReinfSteelGer/p	10013	5.068011567
BridgeSub3/NOR/Prod/ReinfSteelNor/p		4.24148
BridgeSub3/NOR/Prod/Formwork/p	10014	4.29825294
BridgeSub3/NOR/Prod/Prestressing/p	10015	2.420753008
BridgeSub3/NOR/Prod/Curing/p	10016	0.447173243
Other/NOR/Prod//p	10017	41.25329781
BridgeSup1/NOR/Cons/Concrete/p	10018	30.30063613
BridgeSup1/NOR/Cons/ReinfSteel/p	10019	17.29532112
BridgeSup1/NOR/Cons/Formwork/p	10020	3.839458622
BridgeSup1/NOR/Cons/Scaff/p	10021	18.32346349
BridgeSup1/NOR/Cons/Prestressing/p	10022	5.910502951
BridgeSup2/NOR/Cons/Asphalt/p	10023	2.504495516
BridgeSup2/NOR/Cons/Railings/p	10024	6.667932437

FULL NAME	PROCESS ID	Global warming (kgCO2-eq)
BridgeSup2/NOR/Cons/Bearings&joints/p	10025	0.438717908
BridgeSup2/NOR/Cons/Curing/p	10026	0.090419702
BridgeSub3/NOR/Cons/Ground&Underwate	10027	2.126417992
BridgeSub3/NOR/Cons/Piles&Caisson/p	10028	22.87210753
BridgeSub3/NOR/Cons/Concrete/p	10029	9.260632612
BridgeSub3/NOR/Cons/ReinfSteel/p	10030	4.343396369
BridgeSub3/NOR/Cons/Formwork/p	10031	0.577447509
BridgeSub3/NOR/Cons/Prestressing/p	10032	0.426426427
BridgeSub3/NOR/Cons/Curing/p	10033	0.027175015
Other/NOR/Cons//p	10034	2.239062116
BridgeSup2/NOR/Oper/PublicLighting/p	10035	1.722429728
BridgeSup2/NOR/Oper/Traffic/p	10036	5305.831833
BridgeSup1/NOR/R&M/Inspection/p	10037	1.429299968
BridgeSup2/NOR/R&M/Asphalt/p	10038	271.9264777
BridgeSub3/NOR/R&M/Inspection/p	10039	1.429299968
BridgeSup1/NOR/EOL/Reinf.concrete/p	10040	53.82878682
BridgeSup2/NOR/EOL/Asphalt/p	10041	6.256200588
BridgeSub3/NOR/EOL/Reinf.concrete/p	10042	15.61596386
BridgeSub3/NOR/EOL/Gravel/p	10043	3.706889466
BridgeSub3/NOR/EOL/Steel/p	10044	1.452253382