Master's thesis

NTNU
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Comparative Life Cycle Analysis of the Langenuen Fjord Crossing

Master's thesis in Sustainable Manufacturing
Supervisor: Geir Ringen
July 2020

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Statens vegvesen

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Preface

For the completion of the master's degree in Sustainable Manufacturing at the Norwegian University of Science and Technology a thesis research marks the final step. The core of the thesis will be within manufacturing design process with a focus on sustainability in the environment, climate, society and economy. Using the knowledge gained throughout the curriculum a market relevant topic will be analyzed to further the scientific knowledge in this field. This thesis has been conducted on behalf of the development division of Complex Structures within the Norwegian Public Road Administration (NPRA).

The Norwegian parliament has set the goal of making the E39 coastal highway one continues road. As part of this goal the NPRA has been working on several fjord crossing concepts to replace the ferries that are currently in use. One of the ferries in operation is crossing the Bjørna fjord. As a replacement there has been a scenario developed to construct two bridges. One spanning over the Bjørna fjord and the other over the Langenuen fjord, the second will be the focus of this research. The goal of the research is to analyze possible reduction of environmental burden by utilizing aluminum in the girder instead of steel.

This thesis would not have been possible without the support of Geir Ringen, I would like to express my deepest appreciation for the time and guidance provided during this process. I would like to extend my sincere thanks to Lizhen Huang and Johan Berg Pettersen, who provided valuable feedback on the LCA part of my research. I am also grateful to Harald Vestøl and Daniel Tran, respectively from Hydro and NPRA. They formed the bridge between industry and the university and allowed the use of their industry contacts to gather information. Finally, I would like to thank everyone who has supported me, either personally or academically during my time at the NTNU.

Jeroen Graafland
Trondheim, 15-07-2020

Abstract

Background

For the crossing of the Langenuen fjord in the Ferjefri E39 project there are currently two rapports with bridge concepts on the table. The main difference between the two rapports is the bridge girder. Where both parties suggest constructing a suspension bridge, Olav Olsen designed two concepts using aluminum in the girder in contrast to the steel variant of Norconsult (Olav Olsen, 2019; Norconsult, 2015).

This study has explored the environmental impact of the three concepts, with the goal to generate a realistic basis of comparison to ultimately support the product development of the Langenuen fjord crossing. An LCA was conducted to distinguish the most impactful processes in the bridge concepts lifetimes in pursuit to compare the environmental impacts based on existing technology.

Method

The LCA study follows the methodology as described by ISO 14040 and 14044. It has been aimed to assess the full life cycle of the fjord crossing with the functional unit defined as; 'one bridge crossing with a main span of 1235m over the Langenuen fjord during the lifetime of 100 years'. For the impact assessment the Simapro software and, the Ecoinvent v3.5 dataset combined with data from EPD-Norge have been be used to analyze the inventory (Wernet et al., 2016; PRé Consultants, 2019). The ILCD 2011 Midpoint+ V1.10 method has been selected as it is designed for LCA in European context based on European best practices (JRC, 2010).

Results

If only the lifecycle emission from material extraction till the end of life disposal is considered the steel concept has the lowest environmental impact. In six of the eight considered impact categories the panel concept is at least 18.9% and the plate concept 21.8% higher than the steel bridge concept. Especially the freshwater ecotoxicity potential (FEP) shows a big contrast, the CTU emitted by the panel and plate concepts are respectively 374 and 313 percent higher than the steel concept.

When the reduced production emissions of the next product due to the use of recycled bridge material are allocated to the lifecycle impact of the Langenuen bridge the panel concept is the most sustainable solution according to this study. In all but two impact categories the panel concept has a lower environmental impact than the plate concept as the AP and MEP is 6.4 and 1.0% higher respectively. The panel concept has a lower emission in seven of the eight impact categories compared to steel with five categories emitting at least 17.4% less.

Conclusion

As is often the case with LCA studies the conclusion of the research is multifaceted. It has been aimed to analyze the realistic environmental impact of the Langenuen fjord crossing concepts like they are currently being considered. Within the scope of this study the aluminum panel concept is only more sustainable when recycling credits are included otherwise steel has a lower environmental impact.

DR. TECHN.
OLAV OLSEN

Statens vegvesen

Hydro

LEIRVIK®

NTNU

Sammendrag

Bakgrunn

For kryssing av Langenuen-fjorden i Ferjefri E39-prosjektet er det i dag to rapporter med brokonsepter på bordet. Hovedforskjellen mellom de to rapportene er brobjelken. Begge parter foreslår å anlegge en hengebro, hvor Olav Olsen designet to konsepter som bruker aluminium i bjelken i motsetning til stålvarianten av Norconsult (Olav Olsen, 2019; Norconsult, 2015).

Denne studien har undersøkt miljøpåvirkningen fra de tre konseptene, med mål om å generere et realistisk sammenligningsgrunnlag for å til slutt å støtte produktutviklingen av Langenuen fjordovergang. Det ble utført en LCA for å skille de mest effektive prosessene i brokonseptets levetid for å sammenligne miljøpåvirkningene basert på eksisterende teknologi.

Metode

LCA-studien følger metodikken som beskrevet i ISO 14040 og 14044. Den har hatt som mål å vurdere hele livssyklusen til fjordovergangen med den funksjonelle enheten definert som; 'En brokryssing med et hovedspenn på 1235m over Langenuenfjorden i løpet av 100 års levetid'. For konsekvensutredningen er programvaren Simapro og Ecoinvent v3.5 datasettet kombinert med data fra EPD-Norge blitt brukt til å analysere inventaret (Wernet *et al.*, 2016; PRé Consultants, 2019). ILCD-metoden 2011 Midpoint + V1.10 er valgt fordi den er designet for LCA i europeisk sammenheng basert på europeisk beste praksis (JRC, 2010).

Resultater

Hvis bare livssyklusutslipp fra materialutvinning til slutten av levetiden og avhending anses, har stålkonseptet den laveste miljøpåvirkningen. I seks av de åtte vurderte påvirkningskategoriene er panelkonseptet minst 18,9% og platekonseptet 21,8% høyere enn stålbrokonseptet. Spesielt økotoksisitetspotensialet til ferskvann (FEP) viser en stor kontrast, CTU-utslipp fra panel- og platekonsepter er henholdsvis 374 og 313 prosent høyere enn stålkonseptet.

Når de reduserte produksjonsutslippene til det neste produktet på grunn av bruk av resirkulert bromateriale blir allokert til livssykluseffekten av Langenuen-broen, er panelkonseptet den mest bærekraftige løsningen i henhold til denne studien. I alle, unntatt to påvirkningskategorier, har panelkonseptet lavere miljøpåvirkning enn platekonseptet, da AP og MEP er henholdsvis 6,4 og 1,0% høyere. Panelkonseptet har lavere utslipp i syv av de åtte slagkategoriene sammenlignet med stål med fem kategorier som slipper ut minst 17,4% mindre.

Konklusjon

Som ofte er tilfelle med LCA-studier er konklusjonen av forskningen mangefasettert. Det har vært som mål å analysere den realistiske miljøpåvirkningen av Langenuen fjordkryssende konsepter som de for tiden vurderer. Innenfor denne studien er aluminiumspanelkonseptet bare mer bærekraftig når gjenvinningskreditter er inkludert, ellers har stål lavere miljøpåvirkning.

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List of Abbreviations

ABM	Abrasive Blast Material
AP	Acidification Potential
CFC	Chlorofluorocarbons
CTU	Comparative Toxic Units
DFT	Dry Film Thickness
EoL	End of Life
EPD	Environmental Product Declaration
FEP	Freshwater Ecotoxicity Potential
FSW	Friction Stir Welding
GHG	Greenhouse Gas
GMAW	Gas Metal Arc Welding
GWP	Global Warming Potential
HAZ	Heat affected zone
HTP	Human Toxicity Potential cancer effects
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEP	Marine Eutrophication Potential
NMVOC	Non-Methane Volatile Organic Compound
NPRA	Norwegian Public Road Administration
NTNU	Norwegian University of Science and Technology
ODP	Ozone Depletion Potential
PM	Particulate Matter
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Ozone Formation Potential
RH	Relative humidity
SVV	Statens Vegvesen
TKM	Ton Kilometer
TSZ	Thermally Sprayed Zinc

1. Introduction

Aluminum is one of the more recent metals that have been discovered as recent at the 19th century. Since then it has been introduced in nearly every product segment, due to the versatile properties of aluminum. The main use of aluminum in transportation and packaging sector lie in the lightweight of the product to increase the fuel mileage of cars and lower the transport cost of goods. Aluminum has been proven to be beneficial in movable products with regards to the carbon footprint (Bertram and Bayliss, 2019). In this research, the environmental impact of using aluminum for a fixed bridge structure will be analyzed to see whether it will be favorable over steel.

The Background of the E39 Coastal Highway Route.

In 2011 the project named “Ferjefri E39” was started to assess the possibility of replacing the ferries along the coastal highway E39 (Vegvesen, 2012). The Norwegian parliament has set its goals on making the E39, that connects Kristiansand and Trondheim, one continuous route. Currently there are seven ferry connections required to cross the fjords as listed in figure 1, resulting in a travel time of around 21 hours between the two cities. By replacing the ferries with bridges and tunnels the 1100km long road will only take around 11 hours (Vegvesen, 2012).

Besides reducing the travel time between two of the biggest cities in Norway the project will also bring other cities and municipalities closer together. The area the road runs through holds around 30% or Norway’s population and produces approximately 50% of Norway’s income (not including oil and gas) (Dunham, 2016). Some major cities along the E39 are; Stavanger, Bergen, Førde, Ålesund and Molde.

Figure 1: Illustration of the E39 with ferry crossings and major cities (Vegvesen, 2019).

The coastal highway route project is subdivided into many smaller projects due to its scale. Some parts are already finished but most large projects are still working towards the actual construction. The progress of all the parts within the Ferjefri E39 project can be followed online on the interactive map made with ArcGIS (Johannessen, 2018).

Project Langenuen.

The project to replace the ferry that currently is in use to cross the Bjørnafjord south of Bergen consists of two bridges. One bridge crossing the Bjørna fjord, the second the Langenuen fjord. Since the measurements of the Bjørna fjord does not allow a traditional bridge, a concept of a floating bridge has been proposed (Norconsult, 2020). The Langenuen fjord will be crossed with a suspension bridge and will form the main focus of this thesis research. As shown in figure 2, the place of the Langenuen fjord crossing has been marked with a red circle. The Langenuen suspension bridge is projected to have a total span of around 1775 meter with a main span of 1235 meter (Olav Olsen, 2019).

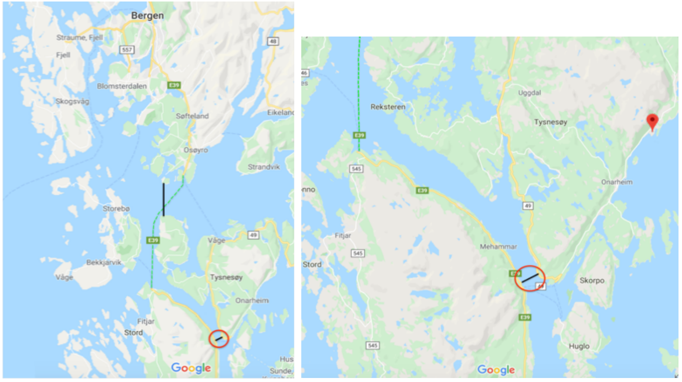


Figure 2: Google maps image showing construction and factory location for Langenuen (Olav Olsen, 2019).

Currently three concepts are considered: one is a traditional steel girder suspension bridge developed by Norconsult and the other two using aluminum for the girder developed by Olav Olsen with support from Hydro, Leirvik and NTNU. The involvement of the parties within the development of the aluminum concept for the Lanuenuen fjord crossing have been given in table 1.

Stakeholder	Role	Interest
The Norwegian Public Roads Administration	Client/Purchaser	Low cost and high-quality bridge, with esthetic design to be part of the Ferjefri E39 project.
Norsk Hydro ASA	Production of aluminum alloys, sheets and profiles	New market opportunity for large quantities of aluminum.
Leirvik AS	Assembly and construction bridge girder	Acquiring a large construction project, to expand and display their expertise. Main competence lays in aluminum solutions, especially large offshore living quarters.
Olav Olsen AS	Engineering Consultancy bureau	Acquiring a large construction project. Being able to construct a prestigious project to use as showcase of engineering quality.
The Norwegian university of Science and Technology (NTNU).	Researching possibilities and difficulties within the project to further academic knowledge	Generating research opportunities by assisting companies in projects, ultimately create ties and possibly acquiring funding.

Table 1: Stakeholder overview regarding the aluminum concept development for the Langenuen fjord crossing.

The construction of the aluminum bridge sections will likely take place north of Onarheim which is marked with a red dot on figure 2. Here is enough space to build a factory hall and yet it is close enough to keep transportation costs of the assembled bridge sections to a minimum. Leirvik, which commissioned the factory hall proposed to locate the hall at Melkevika, north of Onarheim less than 15 km away from the Langenuen bridge site. Even though the factory hall has yet to be built, it is not expected to a temporary production location but will remain in use for a long time after the Langenuen project is concluded.

History of aluminum use in bridges.

The use of aluminum as structural element in bridges is not very a common practice, nonetheless, the first application of aluminum in a bridge date back to 1933 when the bridge deck at Smithfield Street Bridge in Pittsburgh was redone (Growdon, Riegel and Tremplin, 1934). By replacing the wooden deck and steel beams with an aluminum deck with asphalt road the weight was decreased with 675 ton and the carrying capacity was improved from 4.5 to 16 ton (Siwowski, 2006).

Figure 3: Side view of Arvida bridge (Potvin, 2006).

In 1950 the first bridge fully constructed of aluminum, 2014-T6 alloy, over the Saguenay River in Arvida, Canada (Trynidad, 1994). At the moment, it is the longest full aluminum bridge in the world with a total length of 153m and 9.75m wide weighing 150 ton (Siwowski, 2006). As can be seen in figure 3, the bridge is still in operation today.

Most early aluminum bridges were mainly built to show engineering capability and promote aluminum as structural material. It has been proven that the characteristics such as the corrosion resistance and the strength to weight ratio of aluminum makes an excellent material for bridge construction.

Problem definition

The production of aluminum out of bauxite requires much more energy than the production of other construction metals and hence creates much more GHG emissions (Norgate, Jahanshahi and Rankin, 2007). The global aluminum production is responsible for approximately 1% of the yearly GHG emissions (IEA., 2009). In the car industry the high emissions of aluminum production are often justified by the lower emission in the use stage due to the lower weight of the cars (Bertram and Bayliss, 2019). In stationary objects it is harder to justify the high production emissions, yet it can be argued that the lower weight of an aluminum structure will require smaller supporting structures and hence will still deliver emission reduction in that way.

For the Langenuen fjord crossing, besides the light weighting, the aluminum will eliminate the need of a corrosion protective coating on the girder. Whether these two differences will prove enough to offset the high material production emission will be looked into when conducting the LCA. For this reason, the life analysis of all three bridge concepts will be conducted and compared to try to answer the following research question:

Will an aluminum bridge girder lower the environmental life cycle impact of the Langenuen suspension bridge compared to a steel girder?

Due to the high pollution during production, it is obvious that the conservation of energy and reduction of emissions is of importance to the aluminum industry. The increasing pressure on global sustainable development has pushed the world to rethink consumption and hence the significance of researching the possibilities of aluminum as a sustainable bridge construction material.

Research goal

Currently suspension bridges have been built with steel girders and that is still common practice. A fully aluminum girder for a suspension bridge has, as of today, never been used before. Opportunities for applications of structural aluminum products, i.e. in bridges are still limited since technology and adaptable solutions are not widely available yet. To expand use of aluminum beyond the car industry, efforts have been made to develop new applications of existing technology and knowledge to investigate the possibilities of creating new aluminum products such as the aluminum girder concepts (Olav Olsen, 2019).

This study is aimed to test assumption that the use of an aluminum bridge girder for the Langenuen fjord crossing will lead to a reduced environmental life cycle impact. The three proposals for the Langenuen bridge will be compared based on existing technology to see whether an aluminum or steel bridge girder is the more sustainable solution. To give a basis for environmental comparison to ultimately support the product development of the Langenuen fjord crossing.

2. Method

In this chapter an overview is given on the LCA methodology. For a more in dept explanation refer to i.e. ‘Life cycle analysis’ by Hauschild et al. (Hauschild, 2018). The actual analysis on the case study and data of Langenuen can be found in chapter 5, as well as the methodological decisions that have been made.

Introduction

Conducting environmental impact analysis for products started out in the 1960s when the problem of resource scarcity and environmental pollution became more of a concern (Bjørn et al., 2018). LCA came forward out of the view that the environmental impact of a product should be analyzed throughout the complete lifecycle. Most LCA’s are conducted with a Cradle to Grave perspective where the product’s life cycle includes; raw material extraction, processing, distribution, storage, use, and disposal or recycling stages (Manfredi *et al.*, 2012).

Besides conducting a full LCA there are the Cradle to Gate or Gate to Gate perspectives where only part of the lifecycle is analyzed. These boundaries are often selected due to lack of information in certain or assumed irrelevance of phases of the product lifecycle. Regardless of the perspective all relevant in- and outputs within the boundaries should be considered to get an accurate insight in the environmental impact of the product system. Apart from creating a new category of comparison for products, the adapted view on environmental impact assessment throughout product life also contributed to reducing the ‘burden shifting’ problem. A term used when environmental solutions create unwanted environmental impacts down the value chain.

The LCA methodology and standardization has come a long way since its introduction and was first standardized in 1997 by the International Organization of Standardization (ISO) in the ISO 14040 (ISO, 1997). In the family of ISO standards, the 14000 series focusses on the implementation of environmental management systems (Da Fonseca, 2015). All ISO standards get revised and updated when deemed necessary and get reviewed every five years to ensure relevance. Although there are some differences between the current version, ISO 14040:2006, and the original the fundamental structure of lifecycle analysis has remained stable (Hauschild, 2018).

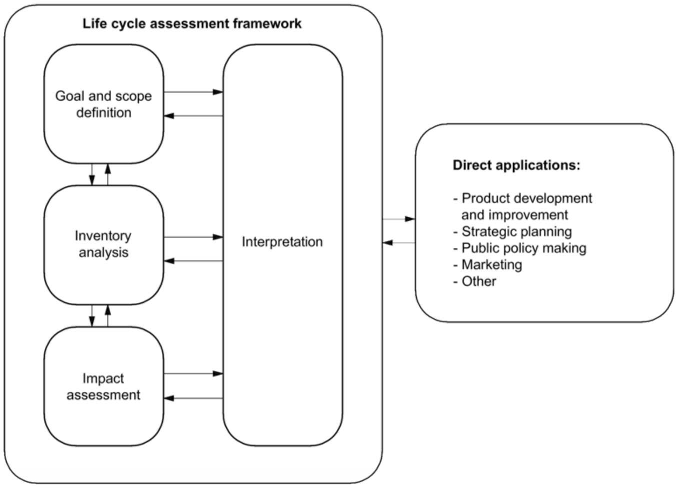


Figure 4: Phases in the LCA framework (ISO, 2006b).

The four phases of an LCA as described in ISO14040:2006 are as followed;

- Goal and scope definition phase
- Inventory analysis phase
- Impact assessment phase
- Interpretation phase.

Goal and Scope/Phase 1:
Before collecting data and conducting the actual analysis it is important to start with creating a clear overview of the goal and scope of the study. The use of the goal statement is to guide the analysis and must include the reason for the study, its intended use, if it is comparative and whether it will be available to the public (ISO, 2006b). A good goal statement as; “The goal of this research is to evaluate the environmental impacts of Norwegian salmon farming and to identify of hot-spots. The results of the study are intended to guide the industry to minimize its environmental footprint and can be used in comparative assertion to be disclosed to the public.” forms the fundamental basis for defining the scope of the LCA.

The scope, including the system boundary and level of detail, can be decided after the goal is set since the depth and the width of an LCA can vary significantly depending on the goal of the LCA (ISO, 2006b). System boundaries define which processes should be included in the analysis of the system. This includes that any co-products have to be accounted for by allocation (Finnveden et al., 2009). The boundaries are set to best serve the goal of the study, in the above-mentioned example the boundaries will be the complete value chain of the fish farming industry and not just the energy consumption in the filleting process since the latter will not generate the results the goal requires. The scope is meant to provide background information to the study, explain methodological choices, and lays out the report format. The additional information explains the boundaries set on the product system and are often tied to the functional unit.

The functional unit is a term used to describe exactly what is being studied. It quantifies the product or service delivered by the system, provides reference to the related in- and outputs, and provides a basis of comparison for alternative goods or services (Rebitzer et al., 2004). Examples of the functional unit of farmed salmon could be; 1kg of farmed salmon fillet. This gives a quantifiable amount that can be delivered and hence alternatives can be compared based on equal measures.

In this phase also the allocation and cut-offs are analyzed. Where the allocation shows how much of the system its inputs end up in the eventual product, the cut-off goes into the detail of the study. As in the example of farmed salmon not the whole salmon will be turned into sellable fillets. It is understandable that some parts of the fish will be used and sold to be made into pig feed for instance. This needs to be considered in the allocation since the inputs of the system not just lead to the functional unit but also the co-product. The cut-offs allow for conduction an LCA without analyzing the system into the finest detail. Often the inputs smaller than one percent are not included into the final LCA since it complicates the analysis without making a significant influence on the results.

Inventory/Phase 2:
In the second phase of the LCA the data needed to meet the goals of the study are collected and analyzed (ISO, 2006b). Conducting the life cycle inventory (LCI) is where all in- and outputs within the system, i.e. its material and energy flows, will get quantified. The LCI is considered the most thorough and complex phase of the LCA. This is because determining what data is needed requires splitting up the processes and products down to the unit process level what can make tracking of material and energy flows complicated.

The databases used to conduct an LCA do not have the LCI data of complete products/processes (e.g. production of 1kg specialized salmon feed) but do contain data on unit-processes like production of 1kg soybeans. This allows the researcher to combine the data accordingly to account for the product/processes in the LCA. Hence the quality of the background data influences the quality of the LCA results. Generally the ecoinvent database is used since it is the largest transparent unit-process LCI database (Wernet et al., 2016). Besides the use of databases or literature to obtain LCI data it is possible to use measured data from industry. The quality of measured data is high, but it is not easy to acquire since conducting the measurements is time consuming and companies often keep the data undisclosed.

Impact assessment/Phase 3:

The third phase of the LCA is the life cycle impact assessment (LCIA). The purpose of LCIA is to provide additional information to help evaluate a product system's LCI results so as to better understand their environmental significance. The assessment of the magnitude and significance of the potential environmental impacts is done through classification and characterization of the LCI results (ISO, 2006b; 2006a).

The first step in the LCIA phase is the Classification. Here the life cycle inventory data gets separated into categories based on what environmental impact it contributes to. The primary categories are; Climate change, Stratospheric ozone depletion, Photochemical ozone formation, Acidification, Eutrophication, human toxicity, Particulate Matter and, Ecotoxicity.

After the classification the inventory data within the same impact category is given a so-called common or shared unit in the characterization step. This gives each impact category a single unit that shows the impact instead of numerous small units. For instance, the way CO_2 equivalents are used in the Global Warming Potential (GWP) impact category. The emission of each greenhouse gas contributes on different factor to global warming. Methane for example contributes roughly 25 stronger than CO_2, the emission of 1 kg CH_4 is thus accounted for by 25kg CO_2 in the GWP impact category (IPCC, 2014). Hereby all of the greenhouse gases can be expressed as a single unit what allows for easy comparison between alternatives.

Following the classification and characterization, the environmental impact of the product system is still given by the shared units in each impact category. Although possible, comparing alternatives at this stage often leads to indecisive answers since the alternative might perform better in some impact categories and worse in others. To get to a single impact score normalization and weighting can be conducted. Normalization is defined by ISO as; "the calculation of the magnitude of an impact indicator score relative to reference information with the aim to better understand the relative magnitude for each indicator result of the product system under study" (ISO, 2006a). This process makes the impacts unitless and allows the comparison of categories. Also, each category can then be combined to one single impact score where it has share of the total. The weighting of factors is supposed to factor in the relative importance of each impact category. Where this does allow the researcher to put emphasis on certain categories, it is susceptible to bias.

In the case of the Norwegian salmon farming example, the impact categories with regard to water pollution such as marine eutrophication or freshwater ecotoxicity would most likely get a higher weighting factor by the researcher thus putting emphasis on those categories. If the weighting factor is selected too steep, increased emissions in other categories that received a low weighting factor could go unnoticed leaving the product with a better single score even though this is heavily skewed. For this reason the use of weighing in comparative assertions which are intended to be disclosed to the public are not allowed according to the LCA standards described in ISO 14040 and 14044 (ISO, 2006a; 2006b).

Interpretation/Phase 4:

The fourth and final phase of the LCA is the Life cycle interpretation. In this phase the results of the inventory analysis and the impact assessment are summarized and discussed in accordance with the defined goal and scope. Uncertainty associated with the decisions made in the earlier phases are also analyzed along with the quality of the results. The interpretation can result in reinvestigating certain parts of the analysis to assure accuracy. Since this will form the basis for further conclusions and recommendations to aid decision-making (ISO, 2006a).

3. Methodology applied to Langenuen

Introduction

For the crossing of the Langenuen fjord in the Ferjefri E39 project there are currently two rapports with bridge concepts on the table. One that has been conducted by Norconsult and finished in 2015, the other is conducted by Olav Olsen and currently under review by DNV GL. The main difference between the two rapports is the bridge girder. Where both parties suggest constructing a suspension bridge, Olav Olsen recommends using aluminum in the girder in contrast to the steel variant of Norconsult. The aluminum girder concepts developed by Olav Olsen are based on different production techniques, the first is based on extrusion panels and the other on hot rolled plate material hence the names Panel and Plate (Olav Olsen, 2019).

Since most emissions of a product are emitted in the production phase, the information in table 2 formed the starting point of the research. The reasoning in favor of the aluminum girder falls into two main arguments. Firstly, the better recyclability of aluminum and the corrosion resistance is expected to offset the higher production emissions and make it more sustainable than steel. Secondly, due to the lower weight of aluminum, the size of the support structures can be reduced what should make the aluminum solution also cost effective.

		Steel	Panel	Plate
Bridge Girder	Mass (kg/m)	12010	7598	9045
	Total weight (t)	14831	9391	11080
Main Cable	Diameter (m)	0.711	0.681	0.644
	Total weight (t)	12387	11437	10178
Hangers	Diameter (m)	0.072	0.046	0.044
	Center distance (m)	24	12	12
	Total weight (t)	151	127	122
Concrete Towers	Saddle elevation (m)	206	214	206

Table 2: Overview of the main material differences between the three concepts (Olav Olsen, 2019).

Goal

The goal of the study is evaluating the environmental profile of the three proposed solutions for the Langenuen fjord crossing to perform a comparative analysis and find the more sustainable solution. The functional unit used in this study is the function of one bridge crossing with a main span of 1235m over the Langenuen fjord during the lifetime of 100 years. The results will be presented to the NPRA to aid the decision-making process towards selecting a fjord crossing solution at Langenuen. It is expected that the rapport will be disclosed to the public either through the databases of the NTNU or by the NPRA wished to do so.

Scope

The boundaries of the analysis are set at cradle to grave. The LCA will start by the retrieving of resources from the earth and will end after the end of life treatment of the materials including possible environmental benefits and burden by reusing/remanufacturing/recycling. Due to data unavailability regarding the onsite construction and demolition of large civil projects the sections A5 and C1 are often not incorporated. This will also be the case during this LCA. Besides that, in the use stage of the bridge only section B3 and B6, respectively repainting and dehumidification, are included since the other steps cannot be quantified or can be assumed to be equal across the concepts. This gives the boundaries as shown in figure 5.

The focus will be kept on the four main components of the suspension bridge due to the early phase the project is in; girder, main cable, towers and hangers. This can be justified since the concepts are equal in many aspects. Hence leaving parts of the bridge out of the analysis will not make a difference in the comparison. Examples of these are; the viaducts, tarmac road, road lining/painting, traffic signs, tunnels, lighting, etc. By leaving these out the focus will be put on the difference the aluminum girder makes and avoiding an unnecessary complicated analysis.

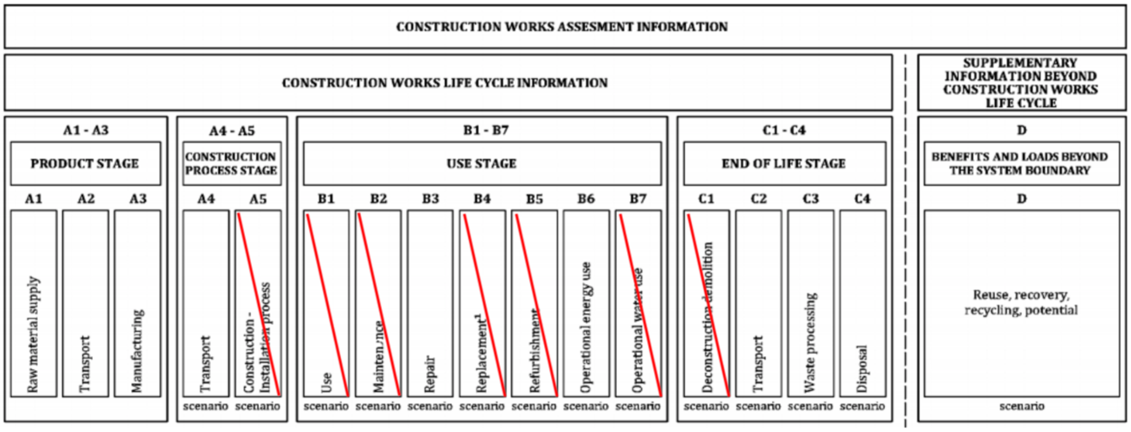


Figure 5: System boundaries Langenuenfjord crossing LCA.

Finally, the End of Life (EoL) scenario is evaluated based on the current state-of-the-art regarding construction waste processes within Norway. Whether materials will be recycled, incinerated or landfilled will be based on statistics made available by Statistisk Sentralbyrå (Statistics Norway, 2020).

For the impact assessment, the Simapro software and, the Ecoinvent v3.5 dataset combined with data from EPD-Norge will be used to analyze the inventory (Wernet et al., 2016; PRé Consultants, 2019). The ILCD 2011 Midpoint+ V1.10 method has been selected as it is designed for LCA in European context based on European best practices (JRC, 2010). With the following impact categories being considered:

- Climate change (GWP)
- Ozone depletion (ODP)
- Human toxicity, cancer effects (HTP)
- Particulate matter formation (PMFP)
- Photochemical ozone formation (POFP)
- Acidification (AP)
- Marine eutrophication (MEP)
- Freshwater ecotoxicity (FEP)

Validity and limitations

Conducting an LCA is always prone to have uncertainty and this is mainly in regards with the data on product/unit process level and uncertainty in lifecycle scenario. As nearly every product is produced by multiple companies it has become increasingly hard to have a good detailed overview of what specific unit processes are used to create a product. This combined with the fact that companies are often not willing to share details due to company secrets makes it hard to cross reference data. The impacts of unit processes that are available can deviate from each other due to differences in the production conditions what can lead to different emissions than expected in the LCA results.

Besides data uncertainty, the assumptions made by the researcher can also influence the results of the LCA. Within the scientific world the parameters of LCA studies are set to include as much of the product lifecycle as there is data on and no stages are left out to provoke favorable LCA results by shifting the burden. But, trying to predict the lifecycle events of a product rarely leads to the real case scenario as there often is no data available what exactly will happen during the product lifetime. Even though the researcher is striving to plot the LCA as close to the real case scenario as possible it is to be expected that there will be some deviations.

For example, as shown by Lui et al. in a literature review, the reviewed LCA studies either focused on a limited geographical- and/or life cycle scope and differentiated in the system boundaries which led to significantly different LCA results. The GHG emissions per produced kilogram primary aluminum in the reviewed LCAs were found to range from 5.92 to 41.10 kg CO_2-equivalent (Liu and Müller, 2012). This spread does not directly show that the LCA was conducted incorrectly but it gives insight to the importance of the contexts that the study is conducted in. Assumptions such as the allocation of recycling credit can influence the overall lifetime impact heavily and when comparing results should be considered.

To overcome the data uncertainty there have been very valuable efforts, such as done by Nunez et al., to provide robust data stems for the use in LCA studies (Nunez and Jones, 2016). The application of LCA as a tool for aiding decision makers on material and design choices relies on up-to-date information to provide to be able to generate as accurate as possible results (Nunez and Jones, 2016). As in the Langenuen LCA, as accurate as possible data and interviewing bridge experts has been used to uncover lifecycle events the effort is made to ultimately improve the validity of the research and create valuable results.

3.1. Life Cycle Inventory

As mentioned earlier in the rapport the life cycle inventory is created by listing all the unit processes that are involved within the boundaries of the system. It has been decided to separate the inventory into four parts, one for each life cycle stage. This chapter is reserved to give an overview of the inputs required per concept for one functional unit. Further explanation about the data will be given in chapter 5 and an overview of the inventory data including data sources and assumptions is listed in the appendix.

Manufacturing stage

In table 3 the unit processes of the stages A1 till A4 are listed and organized per concept. To calculate the distances that needed to be traveled by ship the online tools of sea-distances.org and marinetraffic.com were utilized for the transoceanic and inland shipping respectively.

Bridge part	Material/energy	Unit	Steel	Panel	Plate
Girder	Steel production	t	14831	0	0
	Hot rolling	t	14831	0	6648
	Welding	m	325791	0	325791
	Sandblasting	m^2	89228.75	0	0
	Galvanizing	m^2	89228.75	0	0
	Seal/primer paint	m^2	33962.5	0	0
	Full multi coat paint	m^2	55266.25	0	0
	Aluminum alloy prod.	t	0	9391	11080
	Extrusion	kg	0	9391	4432
	Friction stir welding	m	0	189337	0
Transportation	Transoceanic shipping	tkm	301484568	22314105.36	26326855.6
	Truck	tkm	0	2629480	1240960
	Inland barge	tkm	0	187820	3915228.8
Main Cable	Steel production	t	12387	11437	10178
	Wire rod production	t	12387	11437	10178
	Galvanization	m^2	1615161.451	1481736.446	1325099.451
	Wrapping	t	27.821	26.647	25.199
Transportation	Freight train	tkm	990960	914960	814240
	Transoceanic shipping	tkm	10578498	9767198	8692012
Hangers	Steel production	t	151	127	122
	Wire drawing	t	151	127	122
	galvanization	m^2	1974.43	2522.78	2413.09
	Paint	m^2	1974.43	2522.78	2413.09
Transportation	Freight train	tkm	110230	92710	89060
	Transoceanic shipping	tkm	177576	149352	143472
Towers	Concrete	m^3	32064.03	24536.32	25042.88
	Steel, reinforcement	t	5606.29	4290.10	4378.67
Transportation	Truck	tkm	5420021.13	4147556.8	4233184.19

Table 3: Inventory data on the manufacturing stage.

Use stage

As mentioned in the scope section earlier in this chapter only B3 and B6 of the use stage are included in the LCA. Due to lack of data the other steps in the use stage cannot be quantified or can be assumed to be equal across the concepts. The section B3, repair, was narrowed down to the repainting of the hangers and the steel girder. For the operational energy use in B6 only the dehumidification system of the main cables was included. Other parts that usually also fall within the B3 and B6 categories such as lighting, pothole repairs etc, were expected to be equal across the concepts and hence kept out of the analysis.

	Material/energy	Unit	Steel	Panel	Plate
Girder	Topcoat	m^2	221065	-	-
	Sandblasting	m^2	199761.25	-	-
	Galvanizing	m^2	89228.75	-	-
	Seal/primer	m^2	33962.5	-	-
	Full paint coat	m^2	165798.75	-	-
Main Cable	Dehumidifying	kwh	5925000	5675000	5366666.67
Hangers	Sandblasting	m^2	17769.87	22705.02	21717.81
	Full paint coat	m^2	17769.87	22705.02	21717.81
Tower	-	-	-	-	-

Table 4: Inventory data on the repair and operational energy use at the Use stage.

End of Life stage

In the EoL stage all steps will be included except C1, the demolition of the bridge. The information required to include the onsite demolition of large civil projects is not available to be able to get sufficient inventory data and include it in the LCA. The transport of the material in C2 is expected to be fulfilled by truck to either, nearby recycling, incineration or landfill locations. All transport by truck throughout the LCA is expected to be category freight, lorry >32 metric ton, EURO6, which is the least polluting transport method for trucks larger than 32 ton. The processing and recycling of concrete and metal is expected to take place respectively at Metallco Bergen As and Betong Vest AS which are both located about 65km away from Langenuen. At the same distance is the location of BIR Gjenvinningsstasjon which will separate and process the elastomeric cable wrapping after it will be either recycle or incinerate at this location. The landfill where the generated waste of Langenuen during the EoL stage will go is expected to share similar distance of 65 km.

	Material/energy	Unit	Steel	Panel	Plate
	Galvanized steel	t	27369	11564	10300
	Aluminum alloy	t	0	9391	11080
	Elastomer	t	27.821	26.647	25.199
	Concrete	m^3	23887.7	18279.56	18656.95
		t	56852.73	43505.35	44403.54
	Steel reinforcing	t	4860.09	3719.09	3795.87
Total weight		t	89109.641	68206.087	69482.609
Total processes	Transport by truck	tkm	5792126.67	4433395.66	4516369.59
	Processing at waste facility	t	89109.641	68206.087	69482.609
	Sandblasting of painted steel	m^2	91203.18	2522.78	2413.09

Table 5: Inventory data on material to be transported and treated at End of Life stage.

To get information on the processing of the material in the EoL stage the statistics of Statistisk sentralbyrå were used. Given in table 6 is the treatment scenario of construction-, rehabilitation- and, demolition waste of 2018 (Statistics Norway, 2020). The recycling process of aluminum, plastics and galvanized steel are not available in the current version of Ecoinvent (Wernet et al., 2016). To overcome this, the recycling galvanized steel was assumed to be the same as for steel rebar. For the plastics of the elastomer cable wrapping was assumed to be incinerated fosr energy recovery and only the energy required in the recycling process of aluminum was accounted for. Recycled aluminum is easy to produce compared to the primary metal, using only 5% of the energy, around 2.8 kWh/kg of produced aluminum (Das and Kaufman, 2006; Hydro, 2020a). Using this information, the amount of material that will either be recycled or incinerated has been calculated in table 7.

	Treatment. Total (t)	Recycled (t)	% Recycled	Energy Recovery (t)	% Recovery	Landfill (t)	% landfilled	Unspecified (t)	% Unspecified
Plastics	10538	4860	46.12	2952	28.01	2727	25.88	0	0.00
Metals	96078	96078	100.00	0	0.00	0	0.00	0	0.00
Bricks and concrete	677459	396042	58.46	0	0.00	277390	40.95	4024	0.59
Mixed waste	264696	1580	0.60	263116	99.40	0	0.00	0	0.00
Hazardous waste	47031	9694	20.61	9769	20.77	17068	36.29	10500	22.33

Table 6: Statistics on the End of Life treatment scenario per material (Statistics Norway, 2020).

	Material	Weight(t)	Category	Recycle	Energy recovery
Steel	Galvanized steel	27369	Metal	27369	0
	Elastomer	27.821	Plastic	0	20.6237073
	Concrete	56852.73	Brick and concrete	33236.10596	0
	Steel rebar	4860.09	Metal	4860.09	0
Panel	Aluminum Alloy	9391	Metal	9391	0
	Galvanized steel	11564	Metal	11564	0
	Elastomer	26.647	Plastic	0	19.7534211
	Concrete	43505.35	Brick and concrete	25433.22761	0
	Steel rebar	3719.09	Metal	3719.09	0
Plate	Aluminum Alloy	11080	Metal	11080	0
	Galvanized steel	10178	Metal	10178	0
	Elastomer	25.199	Plastic	0	18.6800187
	Concrete	44403.54	Brick and concrete	25958.30948	0
	Steel rebar	3795.87	Metal	3795.87	0

Table 7: Amount of material recycled or incinerated based on Statistisk sentralbyrå and limitations of the database (Statistics Norway, 2020; Wernet *et al.*, 2016).

Final disposal

Even though all the metal will be sent for recycling and in theory is 100% recyclable, there will be waste generated during recycling process what will end up being landfilled. The recycling process of steel using an electric arc furnace requires about 1085 ton scrap for every ton of steel produced (Bowyer et al., 2015). The 8.5% material entering the furnace is lost during the production process, mainly ending up within slag.

Within the European aluminum recycling industry, around 2% of the material entering the recycling process is lost and eventually landfilled (Boin and Bertram, 2005). This shows the knowledge and capability to safeguard the energy and material used initially produce aluminum to ultimately keep material out of the landfills to a very degree. The section that is listed as unspecified in table 6 is also expected to be landfilled. Combining the waste material from the recycling process with the information in table 6, the total material to go to final disposal in C4 is calculated in table 8.

	Material	Category	Landfill
Steel	Galvanized steel	Metal	2326.365
	Elastomer	Plastic	7.2000748
	Concrete	Brick and concrete	23616.624
	Steel rebar	Metal	413.10765
Panel	Aluminum Alloy	Metal	187.82
	Galvanized steel	Metal	982.94
	Elastomer	Plastic	6.8962436
	Concrete	Brick and concrete	18072.1224
	Steel rebar	Metal	316.12265
Plate	Aluminum Alloy	Metal	221.6
	Galvanized steel	Metal	865.13
	Elastomer	Plastic	6.5215012
	Concrete	Brick and concrete	18445.2305
	Steel rebar	Metal	322.64895

Table 8: Total amount of material to be landfilled in C4.

Stage D, Benefits and loads beyond the system boundary

The reduced production emissions of the next product due to the use of recycled bridge material will be subtracted from the bridge production emissions to see what the influence of recycling and energy recovery is beyond the system boundaries. The plastic wrapping is assumed to be burned in a municipal solid waste incinerator and the energy content is assumed to be equal to general plastic containing 32.564 GJ/t (Tchobanoglous, Theisen and Vigil, 1993). The energy generated from the incineration of is assumed to replace energy generated by hydro energy as this is the main source of energy production in Norway (Government.no, 2016). The concrete that has been sent to recycling will be repurposed as inert filler and the metal recovered from the recycling process will replace primary material. The total amount avoided use of primary material generated per concept is given in table 9.

	Steel credit (t)	Aluminum credit (t)	Inert filler credit (t)	Energy credit (GJ)
Steel	29489.61735	0	33236.10596	671.5904045
Panel	13984.02735	9203.18	25433.22761	643.2504047
Plate	12786.09105	10858.4	25958.30948	608.2961289

Table 9: Total amount of prevented primary material and energy production due to recycling and incineration of bridge material.

4. Aluminum versus Steel

When comparing two metals to be used as construction material often the physical properties are compared to analyze the limitations and opportunities. The main differences in physical properties between steel and aluminum are given in the table 10.

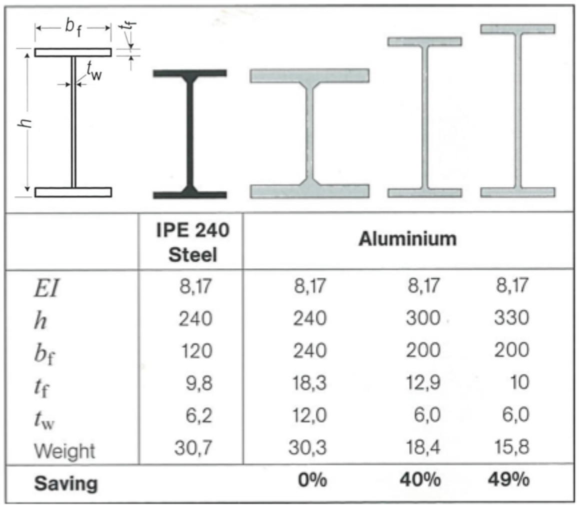
Physical properties	Steel	Aluminum alloys
Melting point	1425-1540 °C	660 °C
Density at 20°C	7850 kg/m^3	2700 kg/m^3
Thermal elongation	$12 \cdot 10^{-6}$ °C^{-1}	$23 \cdot 10^{-6}$ °C^{-1}
Specific heat	~ 440 J/kg °C	~ 920 J/kg °C
Thermal conductivity	~ 54 W/m °C	~ 240 W/m °C
Elasticity modulus	210 000 N/mm^2	70 000 N/mm^2
Shear modulus	81 000 N/mm^2	27 000 N/mm^2

Table 10: Physical properties of steel and aluminum alloys (Skejić, Boko and Torić, 2015).

The properties of the metals give information on how the performance characteristic of aluminum in bridges compare to the use of steel;

- The light unit weight of aluminum, roughly one third that of steel, allows for higher carrying capacity without reinforcing or replacing the main structure and foundation.
- Aluminum has a high toughness and good resistance to low-ductility fractures even in artic environments (Das and Kaufman, 2007).
- Strengths can be achieved comparable to steel structures, as explained in figure 6.

To compensate for the lower elasticity modulus of aluminum (one third compared to steel) and yet keep the height and the stiffness (EI) of the I-beam the same the flanges have to be increased by a factor three (Sapa Profiler, 2015). This leads to a beam with roughly the same weight compared to the steel I-beam. When increasing the height of the beam is acceptable, significant weight reductions can achieved with aluminum while having the same stiffness as the steel variant (Sapa Profiler, 2015).



	IPE 240 Steel	Aluminium		
EI	8,17	8,17	8,17	8,17
h	240	240	300	330
b_f	120	240	200	200
t_f	9,8	18,3	12,9	10
t_w	6,2	12,0	6,0	6,0
Weight	30,7	30,3	18,4	15,8
Saving		**0%**	**40%**	**49%**

Figure 6: Reducing weight in aluminum I-beams by optimizing structure (Sapa Profiler, 2015).

The main drawbacks to using aluminum in bridge construction are the high initial cost and the lack of knowledge on lifetime performance. The mid-range baseline material price for aluminum is roughly four times higher than steel, leading to a higher initial investment (Tisza and Czinege, 2018). The knowledge gap between steel and aluminum in bridge construction is explained by the more experience extensive with steel as it forms the current general practice (Das and Kaufman, 2007).

Besides the differences in mechanical properties between steel and aluminum, the methods for manufacturing and welding along with the corrosion resistance of the metals form big contrasts which will explained below.

Hot rolling process

For the manufacturing of steel plate material, the hot rolling process is most commonly used. Essentially, the process of hot rolling steel is pressing heated steel between two rollers to create a sheet out of the steel slab, as can be seen in figure 7. The slab is heated with the use of a reheating furnace to temperatures over 925 degrees Celsius. The high temperature will allow the steel to be formed by the rollers. Depending on the desired thickness of the final sheet of steel more or less rollers can be used.

The production of aluminum plate material can also be done through hot rolling. For aluminum hollow shapes optimized for structural design and assembly the extrusion process is used. Extrusion of steel is not achievable.

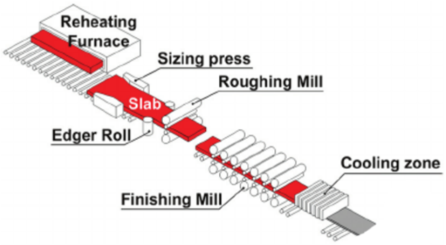


Figure 7: Schematic illustration of hot rolling process (Lee *et al.*, 2015).

Extrusion process

The extrusion of aluminum is in theory nothing more than heated material being forced through a die to create a profile as can be seen in figure 8. The aluminum is heated with the use of an induction furnace to a temperature around 450-500 degrees Celsius. The hot extrusion billet is then forced through the die creating the profile in the shape of the die opening. It is a fairly quick production method with creating 5-50 meter of profile per minute which are usually 25 to 50 meters of length. After extrusion the profiles are cut to the desired length and the strength is often improved by natural or artificial aging.

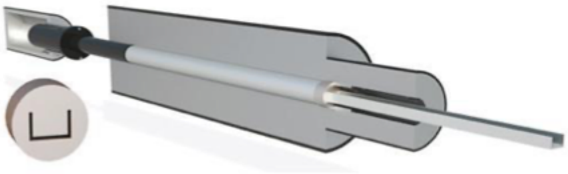


Figure 8: Schematic diagram of the extrusion process of aluminum (GDA, 2019).

Gas metal arc welding

The Gas Metal Arc Welding (GMAW) is a welding process where an electric arc is formed between the electrode wire and the workpiece. The heat from this arc melts the metal at both sides of the seam and the two metal pieces are joint together. Along with the electrode wire also a shielding gas is consumed in the process which protects the welding process from atmospheric contamination as can be seen in figure 9 (Kalpakjian and Schmid, 2006). GMAW is a common welding process used for joining steel.

Friction stir welding

Friction stir welding (FSW) is a metal joining technique where the metal is plastically deformed and intermixed under mechanical pressure at elevated temperatures (Ansari, 2001). FSW a solid-state welding process since the joints are created at temperatures below the melting point of the workpiece material. FSW is not practical to be used to join steel due to its high melting point and hence is only used for aluminum joinery. In figure 9 is a schematic given of the FSW process. The FSW tool, consisting of a specifically designed probe and shoulder, is plunged with a downward force into the workpiece. Once the probe is fully inserted in the metal and the shoulder makes contact with the surface, the tool is moves along the weld seam generating heat through friction and the two sections are mixed together to form the joint (Shrivastava, Krones and Pfefferkorn, 2015).

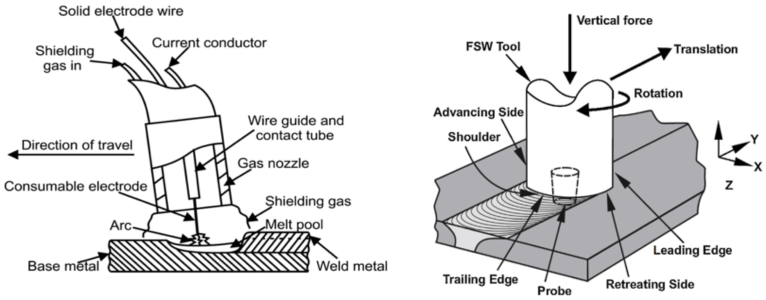


Figure 9: Schematic visualizations of the GMAW and FSW process (Shrivastava, Krones and Pfefferkorn, 2015; Kalpakjian and Schmid, 2006).

Initial surface quality

Where steel requires extensive surface treatment to prevent deterioration due to rust, aluminum on the other hand is not susceptible to this problem due to the layer of aluminum oxide that quickly forms after production what prevents loss of metal and/or structural weakening.

The steel products that come straight out of the production line after e.g. the hot rolling process often have rust and scale on its surface. In figure 10 examples are given of the different grades of rust as are described by the 8501-1 ISO standard (ISO, 2007). The surface of newly produced steel elements normally fall in the first two categories since there is limited to no pitting of the material.

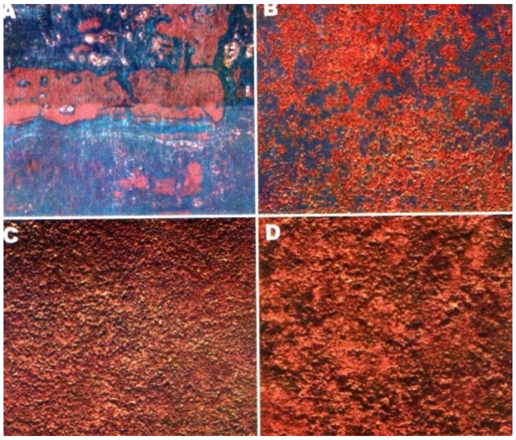


Figure 10: Examples of different rust grades (BCSA, 2012).

The different grades described by ISO are as following;

- A: Steel surface has little to no rust but has lots of mill scale
- B: Rust has begun to form on the steel surface and mill scale starts to flake
- C: The mill scale has rusted off or is only loosely attached to the steel surface, light pitting can be seen by normal inspection
- D: All the mill scale has rusted off from the steel surface and pitting is observable by normal inspection (ISO, 2007).

Abrasive blast cleaning

To thoroughly remove the rust and mill scale from steel surfaces the main method used in industry is abrasive blast cleaning. Hereby the surface gets cleaned by the impact of abrasive material using the force of compressed air or a jet stream. Sandblasting is a commonly used example of abrasive blast cleaning but also steel grit or shot can be used. The process of abrasive blast cleaning can completely remove all mill scale and rust of surfaces provided using the appropriate abrasive and force. Besides the selected abrasive material, the particle size is also of importance to sufficiently clean the surface. For a smoother finish or to treat heavily pitted surfaces is a smaller particle size is appropriate since it leaves smaller marks on the surface and can reach the impurities in the pits.

The grades for abrasive blast cleaning as described in ISO 8501-1 are as following;
Sa 1 – Light blast cleaning
Sa 2 – Thorough blast cleaning
Sa 2½ – Very thorough blast cleaning
Sa 3 – Blast cleaning to visually clean steel

Structural steel components used in bridges are usually required to be cleaned to grade Sa 2½ or Sa 3. To assure that the right quality is obtained the cleaned surface will be compared to references plates as seen in figure 11.

Figure 11: Surface comparator made by manufacturer Elcometer.

Recycling of abrasives

The recycling of the abrasive can be obtained through many techniques one of them is utilizing separator screens where finer particles are let through and the abrasive material can be collected. In a study conducted on ferrous-nickel slag abrasive by Katsikaris et al. a reclamation yield of over 80% was obtained in the first three life cycles. The laboratory tests showed that the recycled abrasive material has similar properties as first lifecycle abrasive material in terms of particle size distribution, consumption and other physical-chemical properties (Katsikaris et al., 2002).

By using a thermal reclamation system, Sandstrom and Patel were able to recycle 70% of the sandblasting waste back into useful product (Sandstrom and Patel, 1990). According to Peng et al., cleaning a steel surface of one square meter requires 3.6g steel abrasive and 0.995 kWh electricity when abrasive recycling is used (Peng et al., 2016). This has been taken as input for the abrasive cleaning process in the Langenuen LCA.

Final preparations before coating

Besides removing the mill scale and rust of the steel surface it is of importance to clean any dust and debris that came undone during the blast cleaning before the coating is applied to ensure proper adhesion. This is often done by mechanical brushes and air blowers, but vacuum cleaning is another les used option. To prevent re-rusting of the blasted material it should either be stored in a dehumidified environment, or the coating i.e. the primer should be applied fairly quickly. If any re-rusting does occur, it should be re-blasted as it hinders the coating adhesion.

5. Case study Langenuen

This case study refers mainly to the rapports on the steel and aluminum bridge concepts created respectively by Norconsult and Olav Olsen (Norconsult, 2015; Olav Olsen, 2019). Since these rapports do not include all the required information to conduct the lifecycle analysis, the Hardanger and Hålogaland bridge have been used as reference.

5.1 Girder concepts

5.1.1. Steel girder

The construction of the steel box girder is assumed to take the same manufacturing route as the Hardanger bridge which started at Zhenhua Port Machinery Co., Ltd, in Shanghai, China (Brekke, 2011). The cross section of the steel box girder for Langenuen is given in figure 12. Steel box girders are characterized by the use of steel hot rolled sheets that have been provided with rigidity by welding stiffeners to the sheets.

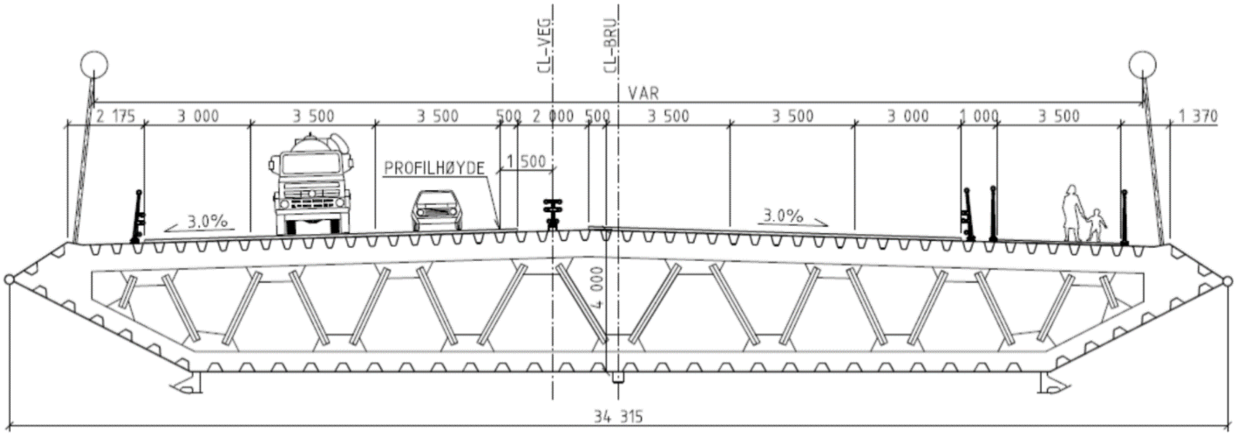


Figure 12: Cross section of the steel bridge girder concept (Norconsult, 2015).

To manufacture the 1235m girder, the hot rolled sheets are expected to first be assembled into 12-meter girder sections using the GMAW process. After that the 12m sections will then be welded together into a total of 20 sections each 60-meter in length, the remaining 35m section will be made separately.

The steel concept for Langenuen was developed back in 2015 there was no information available on the amount of welding that would be required. It was not possible to find welding information on the Hardanger- or Hålogaland bridge. To overcome this obstacle, it was tried to find inventory data on other steel box girder suspension bridges, without success.
As solution, the welding required for assembly of the steel box girder is assumed to be equal to the plate concept. The aluminum plate concept is designed to match the manufacturing strategy of the steel concept, this will be explained later. What has led to believe that the amount of welding should be similar. This is not ideal since the quality of the data is substandard but since the welding has only a small influence on the total life cycle emissions material it is considered acceptable.

Rust prevention steel.
The steps taken to protect the steel bridge girders from corrosion are all explained and documented by SVV in the document called; "Håndbok R762. Prosesskode 2, Standard beskrivelse for bruer og kaier" (Vegvesen, 2018). The most common protection system that is also used at Hardanger is called System 1, and consists of the following:

1. minimum 100 μm Thermal Sprayed Zinc (TSZ) or a zinc alloy with up to 15% aluminum
2. maximum 25 μm two-component epoxy polyamide sealer
3. 125-150 μm epoxy resin
4. 60-100 μm polyurethane or polyurethane acrylic

Total coating thickness: Minimum 285 μm (Vegvesen, 2018).

To prepare the girder sections for the protective coating the complete outside will be cleaned by abrasive blast cleaning with a grit abrasive to the Sa 3 grade (Vegvesen, 2018). The grit abrasive will ensure proper surface texture for the TSZ adhere. The method of thermally spraying metal onto steel creates a layer of donor metal that prevents rusting of the steel surface underneath the coating. Most often zinc or aluminum are used since these metals have a high corrosion resistance. As is usual with steel bridge coatings, Langenuen is expected to have a duplex coating system, like mentioned above, where thermal sprayed metal is strengthened by a multicoat of paint.

According to one of the site managers at the Hardanger project, the multicoat paint was system applied the whole outside except where the asphalt road will be placed (Meyer, 2020). The rust protection under the asphalt road consists only of the TSZ and a primer. The protection that the other paint layers provide will be substituted by the asphalt road (Meyer, 2020). Based on figure 12, the exterior surface area of the Langenuen girder that will require to be protected against rust is given in table 11.

	Circumference/width	Girder length	Surface area
Girder exterior	72.25m	1235m	89228.75 m^2
Asphalt road	27.5m	1235m	33962.5 m^2
Girder exterior excl asphalt road	44.75m	1225m	55266.25 m^2

Table 11: Exterior surface calculation of the Langenuen steel girder (Norconsult, 2015).

The complete paint system applied on the rest of the outside of the girder consist of a tie coat/primer, a layer of intermediate epoxy paint and a finishing layer of polyurethane (Isaksen, 2012; Schultz and Christensen, 2014). The coating at Hardanger was applied with a minimum dry film thickness (DFT) of 300 μm instead of the usual 285 μm mentioned in manual R762 (Schultz and Christensen, 2014; Vegvesen, 2018). The same thickness will be used in the Langenuen analysis where the extra thicknesss is assumed to be added to the topcoat to give extra protection during transit from manufacturing to installation location.

To account for the environmental impact of the TSZ and paint coating the eco-invent database and EPD's from Jotun A/S have been used respectively. Jotun A/S is an industrial producer of paints and coatings with the main office situated in Sandefjord, Norway. Using EPD data from Jotun has been selected since they produce products that correspond with the paint coating of the Hardanger bridge and there was no comparable data available in the eco-invent.

The EPD's used are as following;

- Tie coat/sealer: Penguard Express ZP E, Jotun U.A.E. (Jotun A/S, 2018c).
- Intermediate epoxy paint: Penguard WF, Jotun Zhangjiagang (Jotun A/S, 2018a).
- Topcoat of polyurethane: Hardtop Eco, Jotun Zhangjiagang (Jotun A/S, 2018b).

Some of the ingredients in Jotun EPD’s are not listed due to the confidentiality of the recipe. To account for the missing description of the ‘Binder, Filler and Solvent’ mentioned in the declarations they will be assumed to be the same as generally used paints. For Binders most commonly resins or oils are used and within high performance steel coatings of metal often polyurethane or epoxy is preferred. The solvents function to dissolve the binder and allow better paint application. The solvents are usually organic liquids or water, in this case water will be selected. The fillers in paint are used to give structure and increase the volume. Fillers are inert materials and often cheap, examples are lime, clay, barytes. Since there is no way of finding out what fillers have been used in the EPD’s, equal parts of the three mentioned fillers were used.

The inside of the girder is not coated, the corrosion will be prevented by the dehumidification system of the main cable which is integrated with the box girder (Isaksen, 2012; Brekke, 2011). The function and operation of the dehumidification system will be further explained in the main cable section.

Once the girder sections are assembled and the rust preventive coating has been applied in the shanghai based manufacturing site, they will be shipped directly to Langenuen. The shipping is expected to take the shortest route, which is approximately 20328km, through the Suez Canal.

Maintain and repair

The maintenance protocol of SVV requires yearly inspection, and repairs of the paint will be executed where necessary. It is assumed that the unscheduled yearly repairs during a 50-year period will add up to a be equal to sandblasting and replacing the full paint coating of 55266.25m^2, the un-asphalted exterior surface of the steel girder.

Besides the yearly repairs, there is also scheduled repainting such as applying a new topcoat every 15-20 years to prevent more serious repairs being necessary later on at around 25-30 year (Nygård, 2020). Since the paint gets brittle overtime and the adhesion of paint on old paint layers is not optimal the full rust prevention coating is expected to be completely redone at the 50-year marker (Nygård, 2020). The data included in the LCA and to get a good overview of the repair work required to adequately protect the Langenuen steel girder is given in table 12.

year	Scheduled	Unscheduled but to be expected
15	55266.25m^2 Topcoat	Year 1-50 local repairs equal to: 55266.25m^2 Sandblasting 552662.5m^2 Full multi coat
30	55266.25m^2 Topcoat	
50	89228.75m^2 Sandblasting 89228.75m^2 Galvanizing 33962.5m^2 Seal/primer paint 55266.25m^2 Full multi coat	
65	55266.25m^2 Topcoat	Year 51-100 local repairs equal to: 55266.25m^2 Sandblasting 55266.25m^2 Full multi coat
70	55266.25m^2 Topcoat	

Table 12: Included LCA data on the steel girder rust prevention.

Total repair work for the steel girder included in the B3 stage comes to;

Topcoat	221065m^2
Sandblasting	199761.25m^2
Galvanizing	89228.75m^2
Seal/primer	33962.5m^2
Full multi coat	165798.75m^2

In the EoL stage the girder will be fully sandblasted once more to remove the paint so the steel can be recycled. This, along with the EoL treatment will be included in C3, since metal is expected to be sent fully for recycling. As explained in chapter 3.1, only the waste generated during the recycling process will be landfilled.

5.1.2. Panel girder

The panel concept has been designed with the goal to utilize the manufacturing properties of aluminum to its maximum potential. 98.7% of the girder will be formed by extruded profiles that are joined through friction stir welding (FSW) and the amount of rolled plate material is kept to a minimum at 1.3% (Olav Olsen, 2019).

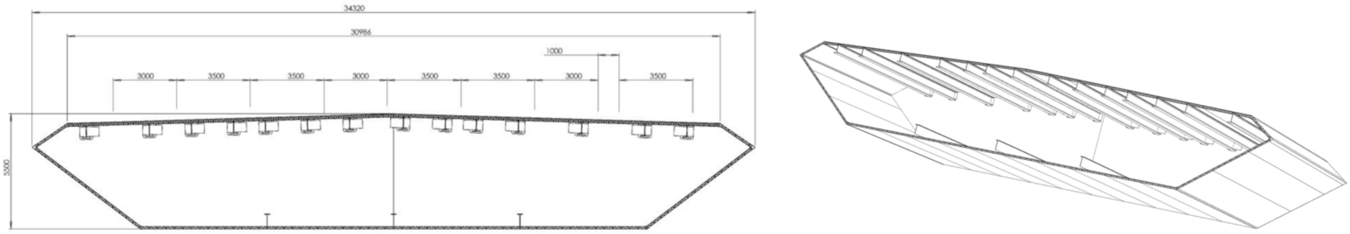


Figure 13: The cross section and 3D image of the panel concept bridge girder (Olav Olsen, 2019).

Due to the low percentage of hot rolled products used in the girder the full panel concept is seen as extruded aluminum in the LCA. The aluminum alloy is assumed to be produced with the same emission as the average European market. The for the transport distances the aluminum alloy is assumed to be produced in Norway by one of the factories of Hydro. Most likely Sunndalsøra will be the factory responsible for the aluminum production since it is one of the largest and most modern factories of Europe.

The alloying elements required to produce the aluminum alloys used in the bridge girder will also be added before shipping to the extrusion factory. The alloying elements that have been accounted for in this LCA have calculated in the appendix. From Sunndalsøra the aluminum will be shipped 1383km to Rotterdam harbor where the alloys will be transported 140km per truck to Hydro's Harderwijk extrusion plant. This facility has the capabilities of producing the size extrusions required for the bridge girder.

It is possible to create costume profiles to meet customer demands, but the limitations lay in the extrusion press mouth size. For large cross-sectional extrusions as is the case for the panel concept, the length of the profile might be limited by the maximum billet length the press can handle (Olav Olsen, 2019). The profiles for the panel concepts should not form a bottleneck in the supply chain when the extrusion supplier is included during the design phase of the girder.

The finished extrusions are assumed to be sent per truck to Rotterdam harbor where the aluminum will get shipped 993km to the production facility of Leirvik at Melkevika. The girder assembly location lays north of Onarheim less than 15 km away from the Langenuen bridge site as was mentioned earlier in the paper, see figure 2.

The assembly steps of the eventual bridge girder will take place as shown in figure 14. The design of the assembly plant allows for all the assembly and joining of the bridge sections to be done inside what eliminates the influence of the weather. The two tracks and the open design on both ends of the plant allow for two assembly stations to work simultaneously. After completion of a 12m section it will be slid outwards of the plant and the next section will be assembled and attached. When both stations have assembled and joined five 12m sections each, the final joint of the 120m section will be friction stir welded. After completion of each 120m girder section it will be ready for shipping to the construction site.

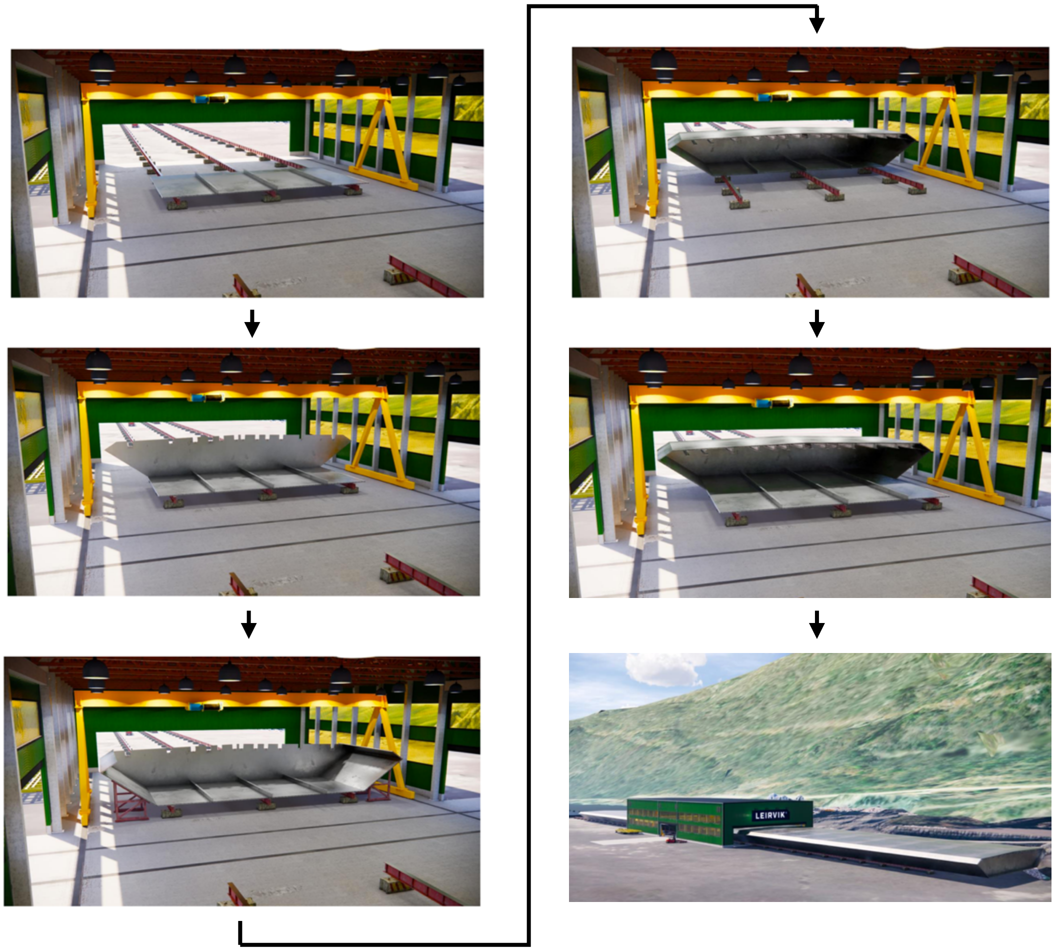


Figure 14: Overview of the assembly steps of the panel concept bridge girder (Olav Olsen, 2019).

The total amount of welding that will be required to create the panel girder sections are given in table 13. Where the type of weld is indicated with either F, PP1, PP2, FP1 or FP2. The kind of weld is indicated with the letters that are used, a fillet weld being F, Partial Penetration weld PP and Full Penetration FP (Olav Olsen, 2019). The number gives of what sides the weld is being made, this is dictated by the accessibility of the workpiece, so PP2 is a partial penetration weld made from both sides of the seam.

Weld name	Type	Thickness (mm)	Length (m)		
			Assembly 12m sections	Joining 12m sections	Total
W1	F	5	7200		7200
W2	F	7	69400		69400
W6	F	14	1200		1200
W8	PP1	7	28400		28400
W9	PP1	10	52800		52800
W12	FP1	10	14200	12960	27160
W13	FP2	20		270	270
W14	FP2	22		900	900
W18	FP2	49		450	450
W19	FP1	60		90	90
Total			173200	14670	187870

Table 13: Data on the amount of factory friction stir welding for the Panel concept (Olav Olsen, 2019).

5.1.3. Plate girder

The plate concept has been designed with the idea to mimic the steel box girder design to keep material cost relatively low and use the light weight of aluminum as it's advantage. Approximately 60% of the material for the girder will be rolled plate products, 40% are extruded profiles and only the aerodynamic side skirts (1.5%) are FSW-panels (Olav Olsen, 2019).

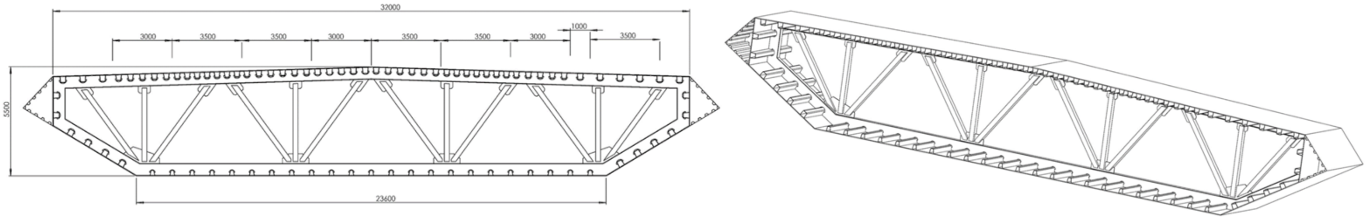


Figure 15: The cross section and 3D image of the plate concept bridge girder (Olav Olsen, 2019).

Due to the low percentage of FSW-panels used in the girder, in the LCA the plate concept is seen as 60% hot rolled aluminum products and 40% extruded aluminum. The production of extruded products will follow the same sourcing path as described in the panel concept. The hot rolled products follow a similar path where is expected that the aluminum alloy is assumed to be produced by Hydro in Sunndalsøra, Norway and from there shipped 1383km to Rotterdam harbor. To get to the hot rolling facilities in Neuss, Germany the aluminum alloy will be shipped 278km by inland barge over the Rhine. The finished hot rolled plates will follow the Rhine back to Rotterdam to be shipped 993km together with the extruded products to Melkevika.

The total amount of welding that will be required to create the panel girder sections are given in table 14. In contrast to the panel concept where the rigidity of the material used to assemble the girder comes from the shape of the extrusion panels, the plate concept requires stiffeners to be welded to the sheets. This is the same production technique as used in the steel box girder and leads to a significantly higher amount of welding.

Comparable to the steel concept the assembly and joining of the plate girder sections will be done through the MGAW process. It is of importance to note that the temperatures of the welded workpiece will increase beyond the melding point of the aluminum alloy hence a Heat Affected Zone (HAZ) will form around the seam. This HAZ will lower the strength of the aluminum and should be taken into account when calculating the allowable forces on the girder. Also, to assure the MGAW leaves a strong weld, the oxide layer on the aluminum should be removed since it has a high melting point (2050 °C) and might cause weld defects (Olav Olsen, 2019).

Weld	Type	Thickness (mm)	Length (m)		
			Assembly 12m sections	Joining 12m sections	Total
W1	F	5		14760	14760
W6	F	7	1200		1200
W7	PP+F	14	269900		269900
W11	PP2	7	24000		24000
W12	FP1	10		6030	6030
W15	FP1	10		270	270
W16	FP2	20		6300	6300
W17	FP1	22		450	450
Total			295200	27810	323010

Table 14: Data on the amount of factory welding for the Plate concept (Olav Olsen, 2019).

5.2 Main cable

The main cable system design of the Langenuen fjord crossing will be based on the Hålogaland bridge according to the Norconsult rapport (Norconsult, 2015). The product sourcing and manufacturing will follow the supply chain as in the Hardanger bridge since there was limited information on the sourcing of the Hålogaland main cable.

The manufacturing of the cable wire is expected to be fulfilled by Bridon in Doncaster, England. Here the steel wire will be hot rolled to a diameter of around 5-6 mm and galvanized through hot dipping as are the strands in Hålogaland and Hardanger. The exact diameter of the wires will need to be decided upon later in the project since this is depended on the exact execution of the bridge. The diameters and weight of the main cable combined with the surface that requires galvanization is shown in table 15. The latter has been calculated based on the information given on the cables in the Olav Olsen rapport and the technical description of Hålogaland (Olav Olsen, 2019; Vegvesen, 2015). The full description can be found in the appendix.

	Steel concept	Panel concept	Plate concept
Diameter total cable	$\emptyset 71.1cm$	$\emptyset 68.1cm$	$\emptyset 64.4cm$
Total weight [ton]	12387	11437	10178
Calculated surface area [m^2]	1615161.451	1481736.446	1325099.451

Table 15: Data main cable Langenuen concepts (Olav Olsen, 2019).

The galvanization of the wires is applied with a minimum thickness of 275 g/m^2 (Isaksen, 2012). Using the data given in ISO 1461 this transfers to a minimum coating of approximately 38.5 µm (ISO, 2009). This coating combined with the dehumidifying system should prevent structural deterioration of the cables by rust forming.

The transport from the manufacturing facilities in Doncaster is expected to be executed by freight train and ship. The freight train will take the hangers 80 km from the production facility to Immingham harbor where they will be loaded onboard and shipped 854km to Langenuen. These distances have been used to calculate the transport emissions given in the inventory. To create the full thickness of the main cable out of the wire strands that get the Langenuen construction site a process called air spinning will be utilized. The cable will be spun back and forward over the fjord to reach the full thickness after which the cables are compressed. However, the air spinning and compressing of the cable is not included in the LCA since it falls within the A5 category and no inventory data has been found on the process.

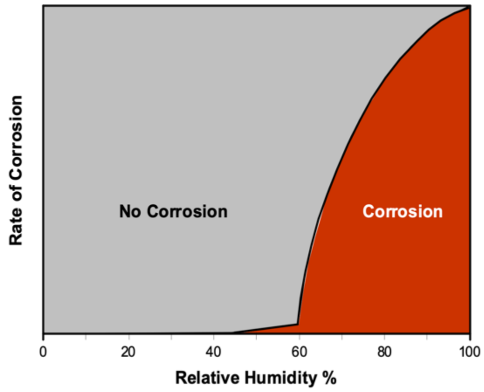


Figure 16: Influence of the relative humidity on the corrosion rate as found by Prof. H. H. Uhlig, MIT Corrosion Laboratory (Bloomstine, 2011)

Dehumidifier system.

To further strengthen the rust prevention of the cables an air/watertight wrapping and a dehumidifying system will be applied to keep the moisture levels down. Research has shown that by keeping the humidity under the 60% the formation of rust will be slowed dramatically. Even though rust forming is only stopped under 40%, reducing the humidity to low levels is very energy intensive. For this reason, dehumidifier systems are often set just below the 60% threshold. Hereby cable deterioration is reduced to a minimum without creating high expenses (Mahmoud, 2013).

Rust protection of the main cables with a dehumidification system is achieved with, the dry air system, cable sealing and a monitoring system. These three main components will be further explained in the sub headers below.

Dry air system

The dehumidification starts with a system that produces dry air and is capable of running that through the cables. Even though creating a fully sealed wrapping is nearly impossible since minor leaks are inevitable, the pressure created inside of the cable will prevent any water and moisture from entering the cables (Bloomstine, 2011). In figure 17, a visual representation is given of a common design of a dry air system consisting of dry air production, fan or pump and injection and exhaust sleeves.

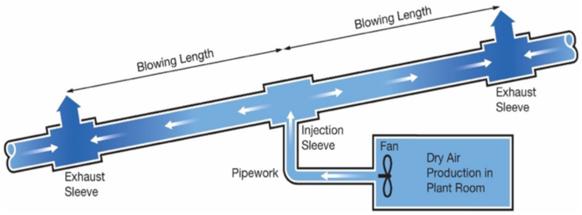


Figure 17: Conventual design of a dry air system for the purpose of main cable dehumidification (Morey, 2018).

Sealing, cable wrapping

To create the air and watertight barrier a specialized wrapping material is used to seal off the cables. According to Bloomstine et al., who have significant knowledge and experience on the topic, the Cableguard^{TM} Wrap System from the D.S. Brown Company is superior and is commonly used (Bloomstine and Melén, 2019). The wrap is applied under pressure with an overlap which is just over 52% what makes the minimal total thickness of the sealing 2.2mm.

The wrapping is available in different widths up to 300mm, at Hardanger which had a cable diameter of 610mm the 200mm wide wrapping was used (Mathey, 2020). It is assumed that the same wrapping will be used for Langenuen. Following the 52% overlap per rotation the wrapping advances 96mm, or 48%. The weight of the Cableguard^{TM} wrapping is 0.33 lb/ft², converted to metric that is 1.61120112kg/m^2 (Mathey, 2020). Combining the weight and overlap the full thickness of the wrapping system will come to be 3.286850285kg/m^2 (factor 2.04). With this information the total weight of the wrapping can be calculated which is shown in table 16.

	Steel concept	Panel concept	Plate concept
Diameter total cable	$\emptyset 71.1cm$	$\emptyset 68.1cm$	$\emptyset 64.4cm$
Calculated surface main cable [m^2]	8464.35	7666.72	8107.20
Calculated weight wrapping [t]	27.821	26.647	25.199

Table 16 : Weight cable wrapping per concept based on the Cableguard system (Mathey, 2020).

Although not included in the LCA, yet interesting, the wrapping is applied manually with a called the Skewmaster that keeps tension on the wrapping and ensures the correct overlap (D.S. Brown, 2016). To complete the seal and fully cure the wrapping a specialized heat blanket is used to slightly shrink and melt the layers of elastomeric wrapping together as seen in figure 18 (Bloomstine, 2013).

Figure 18: Pictures of the manual application process of the CableGuard system and heat sealing (Mathey, 2020).

System monitoring

To ensure the proper functioning of the dehumidification system throughout its lifetime proper monitoring and data collection is key. The data acquired from the sensors in e.g. the injection and exhaust sleeves can be used to adjust the output of the dehumidification plants. An example of data that can help recognize possible leakages in the wrapping is the airflow injection and exhaust. Other useful data is the relative humidity and temperature between the injection flow and the air at the exhaust, this gives an insight on how much water is taken out of the cables. In early stages of the systems lifetime, this data shows how the cables are drying up and later on the data shows if the cables are properly protected and no water is reaching the cables.

Dehumidification system optimization

Every system gets designed specifically to fit the bridge and cables to create an as efficient as possible system under the given circumstances. Main points that are considered are the injection points, flow resistance and buffer chamber which all be explained further below.

In the ideal world each cable would have one injection point and one exhaust point since this would require less injection equipment in designing the dehumidification system. Due to the length and structure of the cables of most suspension bridges, this is not feasible since it would require more pressure to force the air through the cable than the wrapping can handle. Depending on the flow resistance cable and the allowable pressure of the wrapping, the length of the flow sections will be selected. Generally, it is not recommended to exceed overpressure of approximately 2.000 Pascal to safeguard the durability of the wrapping along with limiting leakages and the energy consumption (Bloomstine, 2011).

Flow resistance

The dehumidification of cables requires voids in the cables to allow dry air to flow through the length of the cable. To let the dry air flow through a section of cable, without using high amounts of pressure, the resistance in the cable should be as low as possible.

The flow resistance of the cable is heavily influenced by the diameter of the cable, the condition of the wire and the way it is spun. Logically, air flow through cables with a larger diameter meets less resistance and allows for longer blow lengths. Wires in poor condition i.e. rust formation will result in higher flow resistance and hence reduce blow lengths. The two most common cable designs are the parallel wire cable and helical strand cable. Even though the typical void ratio in helical strand cable is lower at 10% compared to the 20% void ratio in the parallel wire cables the flow resistance is higher in parallel wire cables since the pressure loss is related to the void area divided by the void perimeter (Beabes, Faust and Cocksedge, 2015). In the helical strand cable there are less total, but larger, voids since the strands cannot be compacted as closely as the parallel wires what leads to a less obstructed path for the air to flow allowing for longer flow sections (Beabes, Faust and Cocksedge, 2015). With the flow resistance of parallel wire main cables generally around 10 Pa/m, the flow lengths are often not surpassing 200m. Hardanger, for example, has maximal flow lengths of 177m which is considered long (Bloomstine and Melén, 2017). The flow length of just under 360m of the helical strand cable at the Älvsborg bridge greatly exceeds Hardanger what shows the difference in flow resistance between the cable designs (Bloomstine, 2013). It is possible to have much longer flow sections with strand cables due to the lower flow resistance which is generally around 1 Pa/m (Bloomstine and Melén, 2017). Even though there is a good understanding of how the characteristics of the cable will influence the flow resistance of the cable it is of importance that tests are conducted. Adjustments on the system design can be made according to the flow resistance results to optimize the system.

Integration and buffer chamber

Besides reducing the need for additional injection and exhaust points by testing for the optimal flow lengths, the buffer chamber solution and integration of other bridge components into the dehumidification system has proven to be effective to increase efficiency. The first buffer chamber solution was developed in 1995 on the Humber bridge and the tower leg was used to mix the dehumidified air with ambient air to reach 40% RH what would subsequently be used to combat the water ingression in the saddles (Bloomstine, 2013). The method of using a buffer chamber altered the system since it did not blow the extreme dry air, roughly 0% RH, straight from the dehumidifier into the saddles instead used the 40% RH mix. This reduced the energy consumption of the system drastically since the running time of the dehumidification system was lowered by 70-80 percent (Bloomstine and Melén, 2017).

Current dehumidification systems are generally designed with a buffer camber, especially suspension bridges with a steel box girder benefit greatly from this technique. The use of the box girder as buffer chamber does not just provide energy savings, placing the dehumidification system inside of the girder protects the equipment from the elements and the lack of moisture also protects the inside of the girder from corrosion, which minimizes maintenance requirements of both the system and the girder.

Since existing structures are used as buffer chamber the back draw is that the optimal size is not always available. Ideally the buffer chamber should have enough volume to give maximum energy savings but creating a separate structure to function as buffer chamber is often avoided. The chamber size can heavily influence the energy savings, the two buffer chamber solutions on the Högakusten Bridge for example provide roughly 50% and 75% energy savings. The buffer chambers in the cross beams of the towers are less efficient than the chamber created in part of the box girder since the volume is significantly smaller (Bloomstine, 2013). Also, the structures should be airtight what often proves easier said than done, locating leaks in a box girder for example can be like searching for a needle in a haystack.

Examples

Two good examples of integrated dehumidification systems are the Hardanger and Älvsborg bridge. Both bridges are very different but give a good overview of the current technological possibilities.

Hardanger

The dehumidification of the main cable on the Hardanger Bridge in Norway is delivered by two units located inside the steel box girder. The full volume of the box girder is utilized as buffer chamber and through the ducts running along two of the shorter hanger cables and through the towers the dry air is fed into the main cables. Hereby each of the two parallel wire cables has four injection points providing the dry air to protect the cable from corrosion (Bloomstine, 2011). Through this design the box girder has been integrated into the dehumidification and is the inside of the girder protected from corrosion. It has been tried to also incorporate the anchorage chambers. Since this was not feasible, these have been outfitted with a smaller dehumidification system. According to Statens Vegvesen the total dehumidification operations at Hardanger use approximately of 50000 kwh per year (Nygård, 2020). This includes the rust protection of the main cables, inside of the 1310m long box girder, the tower saddles and the anchorage chambers.

Älvsborg

The dehumidification of the Älvsborg bridge located in Gothenburg Sweden is in many ways very different but yet similar to Hardanger. The construction of the Älvsborg bridge was finalized in December 1967 but the dehumidification system was only installed in 2011 (Bloomstine, 2013). In figure 19 a visual representation is given on the design the dry air system installed on the Älvsborg bridge. Along with the small size of the bridge, main span of just 414m, the fact that the main cables are helical strands allowed the dehumidification system to be installed with just one injection point per cable (Bloomstine, 2013). The integration of the anchorage chambers has been incorporated in the system design. Besides the long flow length in the cable, this contributes to improving the efficiency of the system.

The dehumidification plant is located in the one of the anchorage chambers on the south side of the bridge, shown with a B in figure 19. Using the volume of part of the anchor house as buffer chamber the dry air flows through ducts to the injection point in the middle of the main cables. From injection the dry air flows about 400m in both directions and leaves the system through the anchorage chambers. Since part of the dry air flow is directed back into the southern end where the buffer chamber is located this air is re-circulated, reducing the energy costs of the system (Bloomstine, 2013).

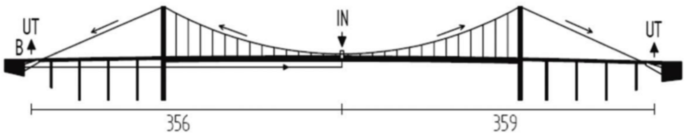


Figure 19: Schematic representation of the dehumidification system on the Älvsborg Bridge in Sweden (Bloomstine, 2011)

5.3 Towers

Figure 20: Computer designed image of one of the towers at Langenuen (Norconsult, 2015).

There is very little information available on the definitive solution that will be used to construct the towers for the Langenuen fjord crossing. It was expected by Norconsult that the towers would be made of reinforced concrete as is usually done for large suspension bridges (Norconsult, 2015). But there has also been a project to analyze the feasibility of constructing a fully steel tower to reduce the onsite construction time (Vegvesen, 2020). For this study it is assumed that the traditional route will be selected and reinforced concrete will be used for the constructions of the pillars as has been done for the bridges in Hålogaland and Hardanger (Vegvesen, 2015; Brekke, 2011).

When it comes to the amount of material that will be used for the towers at Langenuen there is no definitive data available. As shown in the beginning of this rapport (table 2), only the saddle height of the towers is presented by Olav Olsen which leaves an information gap (Olav Olsen, 2019). The saddle elevation of the towers of the Panel concept are expected to be taller than the other two at 214m compared to 206,1m (Olav Olsen, 2019). This is to reach the criterion for the critical wind speed, but it is assumed not to increase the total weight of the towers.

To get the exact required amount of reinforced concrete for each concept a structural analysis should be conducted for each scenario, but this falls outside the scope of this research. To overcome this problem and get an acceptable assumption on the amount of material, the Hålogaland- and Hardanger bridge have been used as reference. The ratio between the average supported weight and the average required amount of concrete and reinforcement has been calculated for the bridges and this has been applied to the Langenuen concepts. This is not ideal since the quality of the data is substandard but since the differences in the concepts are only in the amounts of material it is considered acceptable.

	Tower Hight	Weight to support (t)			Ratio		Concrete	Reinforcing steel
	m	Girder	Cable	total	Concrete/weight	Steel/Weight	m^3	ton
Hålogaland	210/195.5	7000	4000	11000	1.565818182	0.27263636	17224	2999
Hardanger	201.5	9200	6400	15600	0.9047435897	0.15897436	14112	2480
Average of the above	-	8100	5200	13300	1.178045113	0.20597744	15668	2739.5
Steel Concept	206.1	14831	12387	27218	1.178045113	0.20597744	32064.03	5606.29
Panel	214	9391	11437	20828	1.178045113	0.20597744	24536.32	4290.10
Plate	206.1	11080	10178	21258	1.178045113	0.20597744	25042.88	4378.67

Table 17: Quantity calculation on reinforced concrete for Langenuen fjord crossing based on the Hålogaland- and Hardanger bridge (Vegvesen, 2015; Brekke, 2011).

The production of the concrete and steel reinforcement is expected to be fulfilled locally by the respectively Betong Vest AS and Smith Stål Vest Armering. The transport of the material will take place by truck since the manufacturing location of concrete is just 65km and steel 82km away from Langenuen. With the weight of concrete being approximately 2380kg/m^3 the total transport can be calculated in ton kilometer (tkm) as given in the inventory (Wernet *et al.*, 2016).

End of life

At the end of life stage of the bridge the tower foundation is expected to be left in the ground. Due to its inert properties this will not lead to any further environmental impact and hence will not be included in the end of life treatment. Based on the Hardanger bridge, the foundation of the towers be made out of approx. 25.5% of the concrete and 13.3% of the steel reinforcement used in the towers (Brekke, 2011). The amount of material that will left in the ground and what will be included in the end of life treatment is given in table 18.

	Unit	Steel	Panel	Plate
Concrete in foundation	m^3	8176.33	6256.76	6385.93
Concrete to EoL treatment	m^3	23887.7	18279.56	18656.95
Concrete Total	m^3	32064.03	24536.32	25042.88
Steel in foundation	t	746.2	571.01	582.8
Steel to Eol treatment	t	4860.09	3719.09	3795.87
Steel reinforcing Total	t	5606.29	4290.1	4378.67

Table 18: Calculation on material from the towers that will enter the EoL stage.

5.4 Hangers

The hangers are expected to follow the Hardanger production process and supply chain. The manufacturing of 120 of the 130 hangers of the Hardanger bridge was fulfilled by ArcelorMittal in Bourg-en-Bresse, near Lyon in France (Brekke, 2011). The ten shortest of the hangers were produced at a different location, but for the Langenuen case it is assumed that all hangers will be manufactured by ArcelorMittal. The hangers will be transported by freight train from the production facility to Antwerp harbor where they will be loaded onboard and shipped to Langenuen. These distances have been used to calculate the transport emissions given in the inventory.

A hanger is the connecting element between the main cable and girder of the suspension bridge and consist of one cable with a cast steel socket at each end. As shown in figure 21 the cast steel sockets function as connection points and the cable gives it the proper length. The 70mm thick hanger cables are made from locked coil cable, of which the outer three of seven layers of galvanized wires are Z-shaped to maintain shape and prevent moisture to penetrate the cables (Brekke, 2011).

The length of the hangers varies due to the sag in the main cable with the measurements at Hardanger between 2.04 m to 127.6 m. The five shortest pairs hangers of are made as one piece of cast steel but due to the larger size at Langenuen it is expected that a cable system as for the longer hangers will be used. To connect the hangers to the cable and to the steel box girder large bolts will be required. The exact measurements will have to be decided on in a later stage, it is to be expected the bolts will surpass the size of 160mm at the Hardanger bridge.

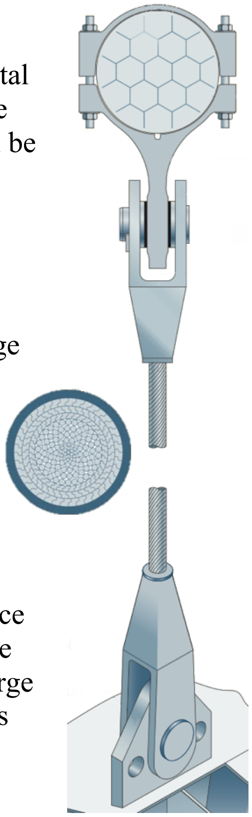


Figure 21: Components of the hangers on the Hardanger bridge (Brekke, 2011).

One part that most definitely will have to be looked into is rust protective coating. The hangers at Hardanger are made with galvanized steel so the paint coating, according to the NPRA manual, is supposed to be done in the same fashion as the girder (Vegvesen, 2018; Brekke, 2011). This paint system is described in chapter 5.1. Since the hangers are not ridged like the box girder, they move and sway slightly due to wind and other forces working on the bridge what has led to chipping of the paint (Nygård, 2020). This is troublesome since the paint system was not expected to have such serious damage this early on. Currently the NPRA is looking into how to retrofit the paint system at Hardanger to adequately protect the hangers from corrosion. Langenuen is expected to have a different system, yet it has not been decided what solution will be durable and suitable for the rust protection of the hangers.

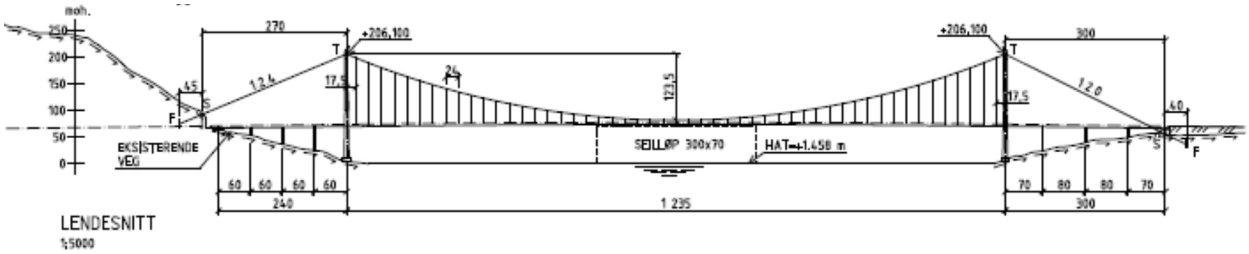
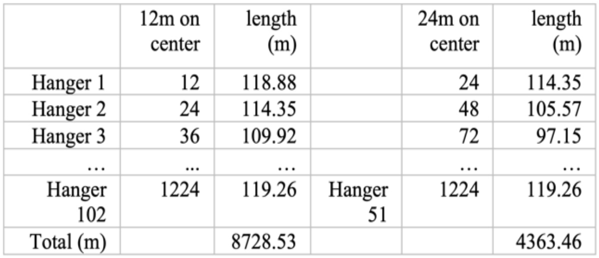


Figure 22: Technical drawing of the Langenuenfjord crossing based on a steel girder (Vegvesen, 2020).

Based on the information given in figure 22 the length of the main cable was calculated as shown in the appendix. This also involved deriving a formula to describe the distance between the girder and the main cable. This formula was utilized to calculate the surface area of the hangers that required paint. The spacing of the hangers of the aluminum concepts is 12m on center where the steel concept has 24m on center spacing (Olav Olsen, 2019). Filling in X at every position of the hangers (24, 48, 72, etc. for the steel concept) the length each hanger was calculated as can be seen in table 19. Having the diameter and the length of the hangers the surface was calculated assuming the hangers are cylindrical, giving the data as shown in table 20.



	12m on center	length (m)		24m on center	length (m)
Hanger 1	12	118.88		24	114.35
Hanger 2	24	114.35		48	105.57
Hanger 3	36	109.92		72	97.15
…	...	…		…	…
Hanger 102	1224	119.26	Hanger 51	1224	119.26
Total (m)		8728.53			4363.46

Table 19: Calculation hanger length based on a steel girder (Vegvesen, 2020).

		Steel	Panel	Plate
Hangers	Diameter (m)	0.072	0.046	0.044
	Center distance (m)	24	12	12
	Calculated total length (m)	4363.46	8728.53	8728.53
	Calculated surface area (m^2)	1974.43	2522.78	2413.09

Table 20: Data hangers Langenuen concepts (Olav Olsen, 2019).

The hangers at Hardanger were painted with the same paint system as the girder which has been described in chapter 5.1. Nevertheless, there have already been reports of serious paint damage since the hangers are constantly moving due to the forced of traffic, wind etc. The maintenance department of SVV, in cooperation with Vestland Fylkeskommune, is preparing to do tests to find a better surface protection system for the hangers by utilizing either a different paint coating or tape systems (Nygård, 2020). A more flexible paint system could be an option if does not break under the stresses of the hanger cables, but paint tends to stiffen up over time. An air/watertight wrapping can also provide a solution but is harder to inspect since it hinders direct view of the hangers.

Since the tests have yet to start and solution has been selected, it is not clear what surface protection system will be applied at Langenuen. For this reason, the current state of the art needs to be assumed which is the same coat as applied at Hardanger. The Hardanger bridge is now seven years in use and the paint on the hangers is getting close to needing replacement (Nygård, 2020). This led to assume the repaint schedule with this paint system at Langenuen will be once every 10 years and the hangers will have to be stripped and recoated nine times during the use stage.

6. Results

Before the final results of the impact assessment can be generated the uncertainty of the data should be considered. To see how the data quality of the data influences the eventual LCA results a simplified sensitivity analysis was conducted.

Sensitivity analysis

To see how the data quality of the data influences the eventual LCA results a simplified sensitivity analysis was conducted. The three categories that have been used in the sensitivity analysis to separate the data are high, medium, and low quality. To check the impact of the data quality the following distribution of data sources and margin of error have been selected:

- High-quality data have been estimated to have a 10 % margin error and include data obtained directly from the case studies of Langenuen or by checking related handbooks. The data considered high quality are for example, the production amount of steel and aluminum and the transport distances.
- Medium-quality data have been estimated to have a 30 % margin error and include data obtained from databases or when EPD information was used to combination with related handbook data. The data considered medium quality are mainly the paint coating for the rust protection of steel structures.
- Low-quality data have been estimated to have a 50 % margin error and include data obtained from literature or when substantial assumptions had to be made. The data considered low quality are for example, the production amount of concrete and reinforcing steel, the abrasive blast cleaning process and the welding amount required for the steel girder assembly.

Including the margins as set in the sensitivity analysis in the impact assessment gave the results as shown in table 21, 22 and 23. The results of the impact assessment have been given both with and without the recycling credit from stage D due to the high impact it has on the emission. Respectively, the tables give the total emissions of the steel, panel, and plate concept.

Impact category	Unit	Total Results Steel	Sensitivity analysis results excluding recycling credit (%)
Climate change (GWP)	t CO^2 eq	116024.735	19.9
Ozone depletion (ODP)	g CFC-11 eq	6594.03245	24.9
Human toxicity, cancer effects (HTP)	CTUh	22.9329523	27.3
Particulate matter (PMFP)	kg $PM_{2.5}$ eq	100369.645	20.6
Photochemical ozone formation (POFP)	kg NMVOC eq	502074.106	21.7
Acidification (AP)	molc H^+ eq	1261922.25	15.0
Marine eutrophication (MEP)	kg N eq	159084.311	20.8
Freshwater ecotoxicity (FEP)	CTUe	1044427599	25.5

Table 21: Impact assessment results of the steel concept Langenuen fjord crossing with a 100-year lifetime and the sensitivity analysis results as percentage change to the baseline case.

Impact category	Unit	Total Results Panel	Sensitivity analysis results excluding recycling credit (%)
Climate change (GWP)	t CO^2 eq	157439.4189	17.7
Ozone depletion (ODP)	g CFC-11 eq	10276.89264	19.5
Human toxicity, cancer effects (HTP)	CTUh	47.76125836	15.5
Particulate matter (PMFP)	kg PM$_{2.5}$ eq	119969.7412	15.9
Photochemical ozone formation (POFP)	kg NMVOC eq	458992.3295	19.0
Acidification (AP)	molc H$^+$ eq	1500067.361	13.0
Marine eutrophication (MEP)	kg N eq	168979.7791	17.1
Freshwater ecotoxicity (FEP)	CTUe	4312364211	12.3

Table 22: Impact assessment results of the panel concept Langenuen fjord crossing with a 100-year lifetime and the sensitivity analysis results as percentage change to the baseline case.

Impact category	Unit	Total Results Plate	Sensitivity analysis results excluding recycling credit (%)
Climate change (GWP)	t CO^2 eq	169487.298	17.2
Ozone depletion (ODP)	g CFC-11 eq	11271.6391	18.0
Human toxicity, cancer effects (HTP)	CTUh	57.3637709	16.6
Particulate matter (PMFP)	kg PM$_{2.5}$ eq	130089.712	15.5
Photochemical ozone formation (POFP)	kg NMVOC eq	494932.345	18.2
Acidification (AP)	molc H$^+$ eq	1537514.95	12.8
Marine eutrophication (MEP)	kg N eq	179170.43	16.5
Freshwater ecotoxicity (FEP)	CTUe	4949650463	12.3

Table 23: Impact assessment results of the plate concept Langenuen fjord crossing with a 100-year lifetime and the sensitivity analysis results as percentage change to the baseline case.

The results of the sensitivity analysis show a range of how the results per impact category are influenced by the uncertainty in the data. Total results of the steel concept have the broadest spread ranging between 15.0 percent for AP and 27.3 percent for HTP. The panel and plate concepts have a narrower spread at the lowest 12.3 and highest 19.5 and 18.2 percent respectively. This can be explained by the high-quality data in the metal production for the girders which have a larger influence in the aluminum concepts what made the results more robust and less influenced by the uncertainty of the data in the maintenance and end of life stage.

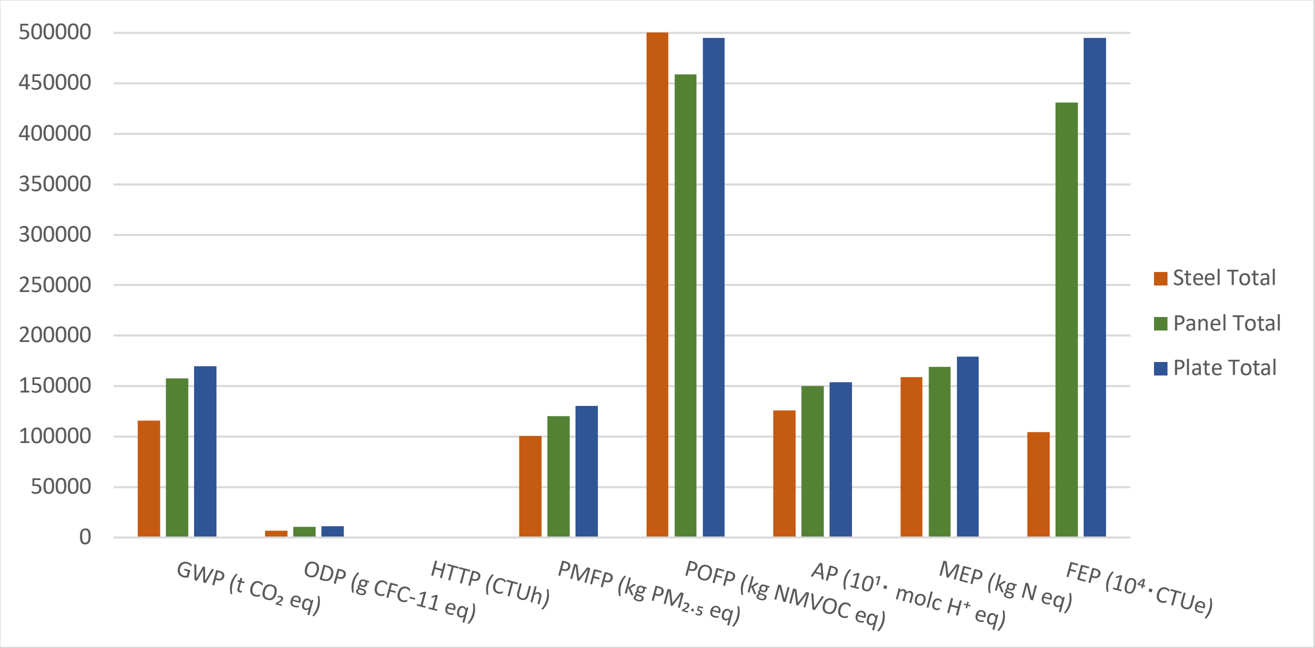


Figure 23: Impact assessment results of the Langenuen fjord crossing concepts with a 100-year lifetime.

To be able to give a visual overview of the impact assessment results figure 23 has been made. The units of the impact categories Acidification Potential (AP) and Freshwater Ecotoxicity Potential (FEP) in the chart have been adjusted by a factor 10^1 and 10^4 respectively for aesthetic reasons. Steel concept performs the best with the panel and plate concepts in second and third place respectively. This seems to be a trend across all the impact categories except for Photochemical Ozone Formation Potential (POFP) where all panel concept has the lowest impact at approximately 459000 kg NMVOC equivalent followed by the plate and steel concepts with ~ 495000 and ~502000 kg NMVOC equivalents respectively.

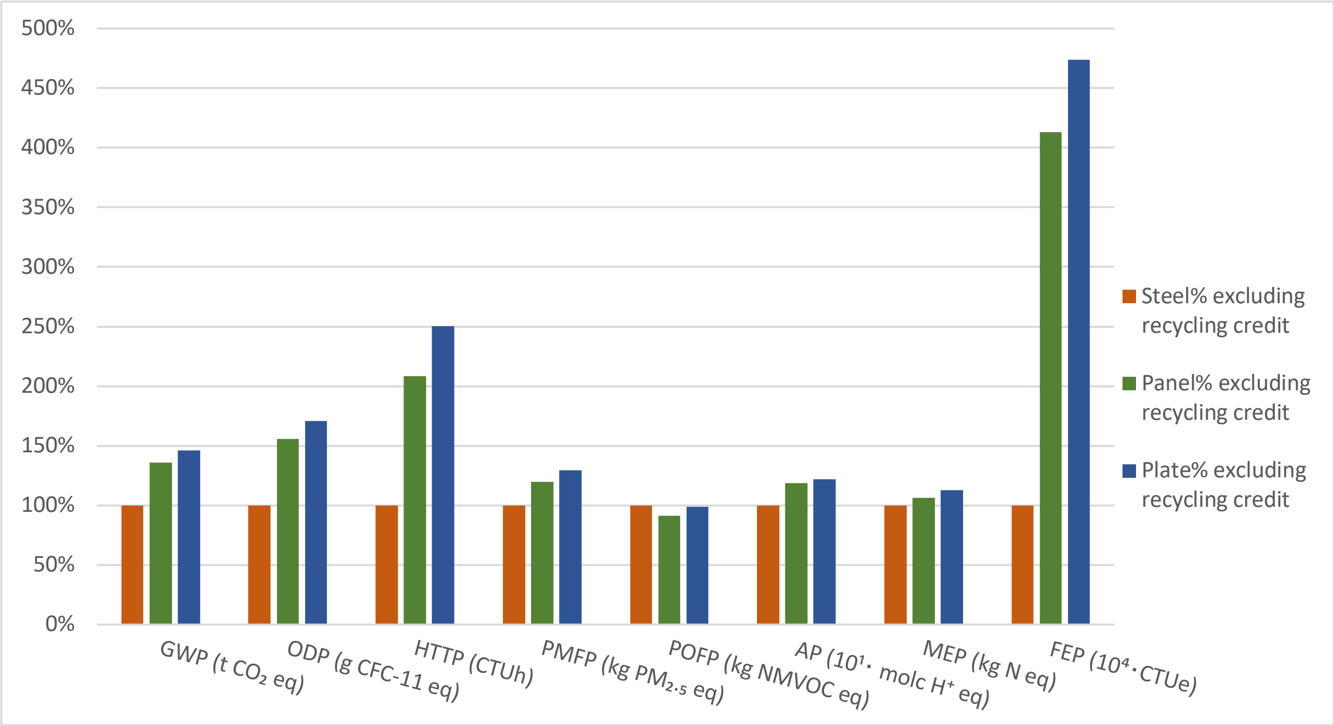


Figure 24: Overview of the relative environmental impact of the Langnuen concepts.

The relative environmental impact of the aluminum concepts is higher for seven of the eight impact categories compared to the steel concept. In six of these categories the panel concept is at least 18.9% and the plate concept 21.8% higher than the steel bridge concept. Especially the freshwater ecotoxicity potential (FEP) shows a big contrast, the CTU emitted by the panel and plate concepts are respectively 374 and 313 percent higher than the steel concept as can be seen in figure 24. This can be explained due to the metal production for the bridge girder in stage A1-A3 where the aluminum production for the panel and plate girders emit a factor 19 and 22 respectively of the 176.48 million CTU the steel production causes.

Like the FEP, a large majority of the emission in each category is generated during the production phase (A1-A3) of the bridge concept. The GWP of the steel concept, for example, 89.7% of the ~116000ton CO^2-eq emissions is generated in the A1-A3. The panel and plate concepts have a higher total emission at ~157500 and ~169500ton CO^2-eq respectively but the percentage of emission for the aluminum production is also higher at 96.6 and 96.7% respectively. To see in what areas of the lifecycle of the concepts have high environmental impact the figures 25a, 25b and 25c were created.

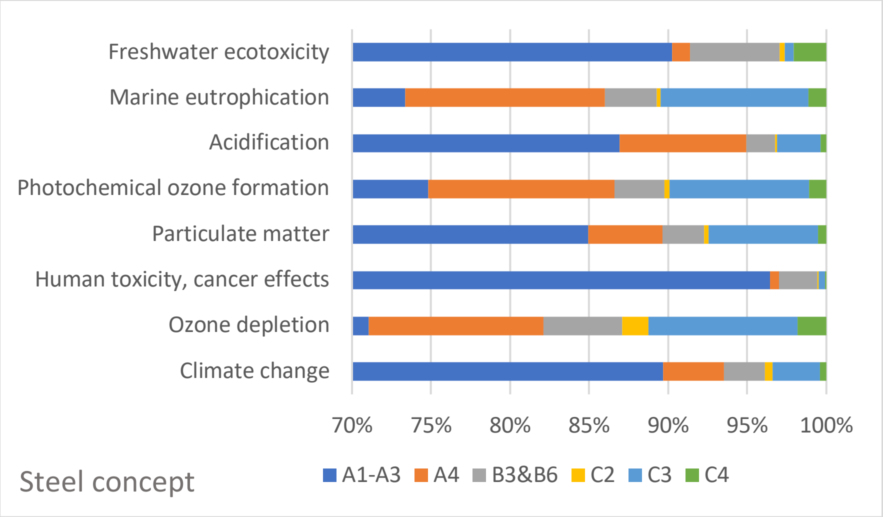


Figure 27a: The relative contribution of each stage to the total environmental impact of the steel concept.

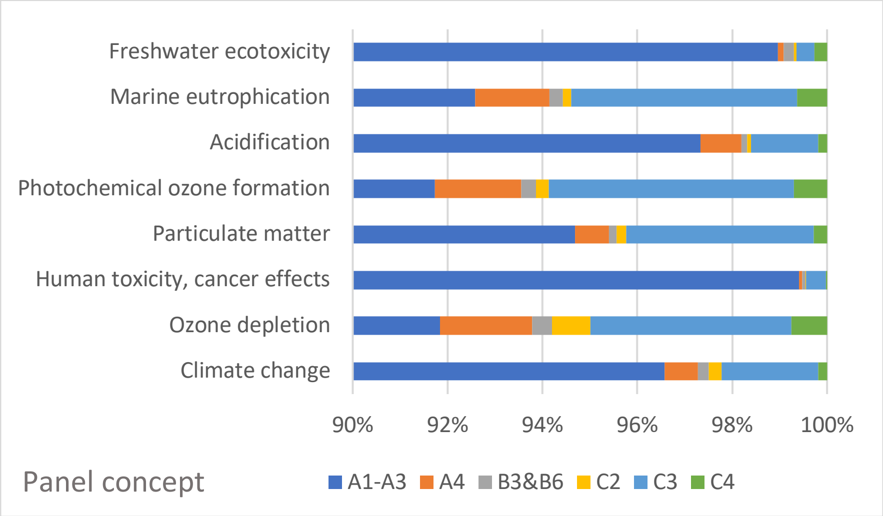


Figure 27b: The relative contribution of each stage to the total environmental impact of the panel concept.

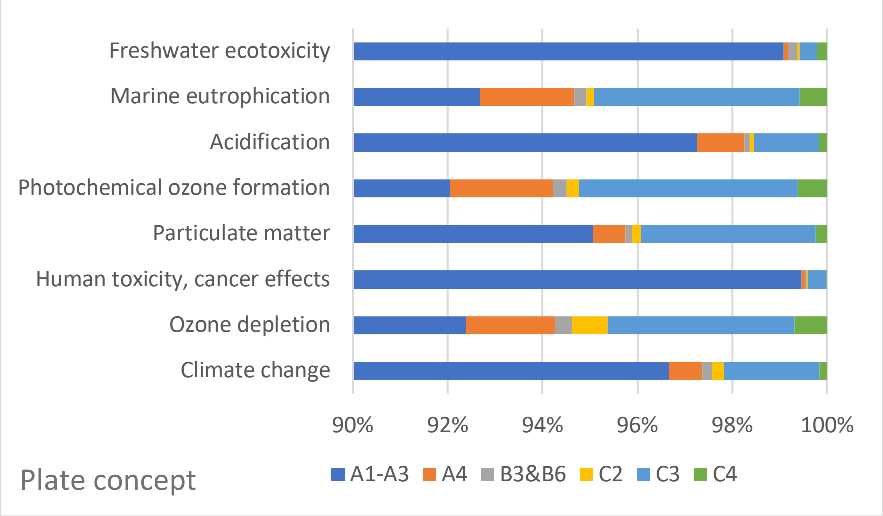


Figure 27c: The relative contribution of each stage to the total environmental impact of the plate concept.

To estimate of the reduced production emissions of the next product due to the use of recycled bridge material the emission of the prevented products was calculated in stage D. These calculations have a very high uncertainty as it is difficult to create a scenario that resembles the actual prevented emission. This is due to many uncertainties in the technological advancements in the 100-year lifetime. To get an impression on the recycling credit beyond the system boundaries the calculations are based on the prevention of primary products, as presented in table 9, using the current EoL scenario and available technology. The results of the environmental credit calculations generated by the energy recovery and recycling due to avoided use of primary material are given per concept in figure 26.

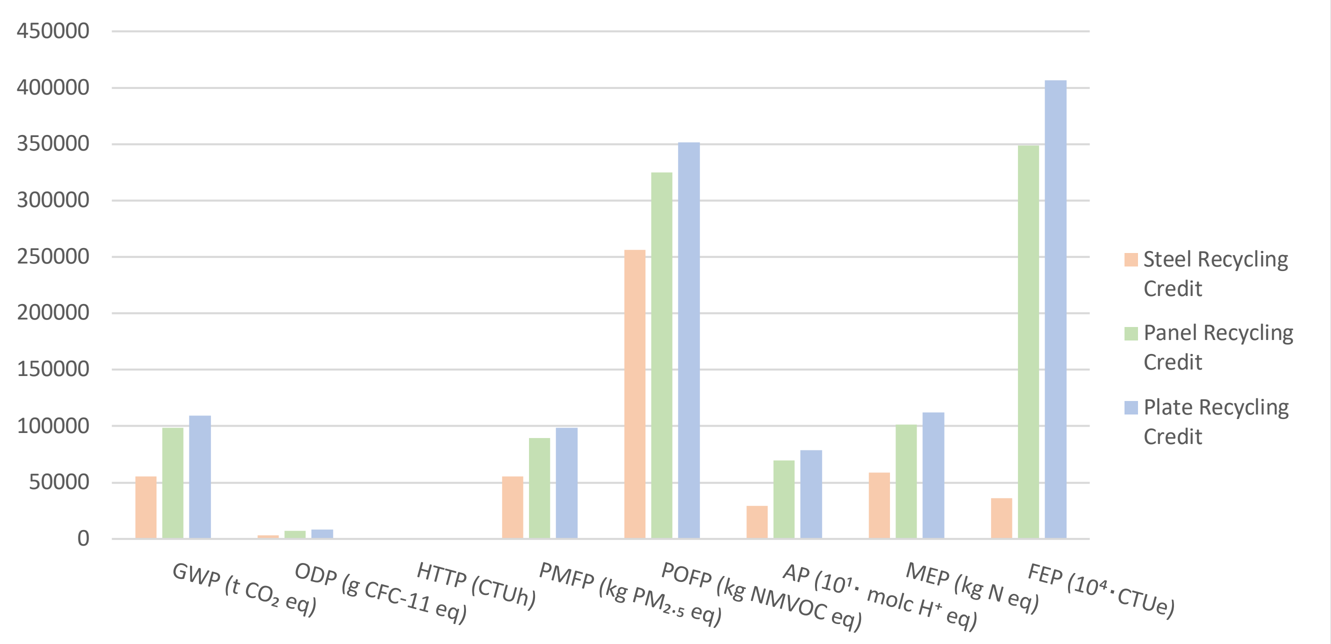


Figure 28: Benefits beyond the system boundarties per concept based on current methods and technology.

When the environmental credit calculations are included the impact of the recycling potential of aluminum is clearly shown as it brings the results of the concepts much closer together. The panel concept outperforms the steel concept in every impact category except the FEP, the plate concepts has a higher FEP and HTTP than steel. The figure 27 shows the emission of the concepts with and without the inclusion of the environmental credit.

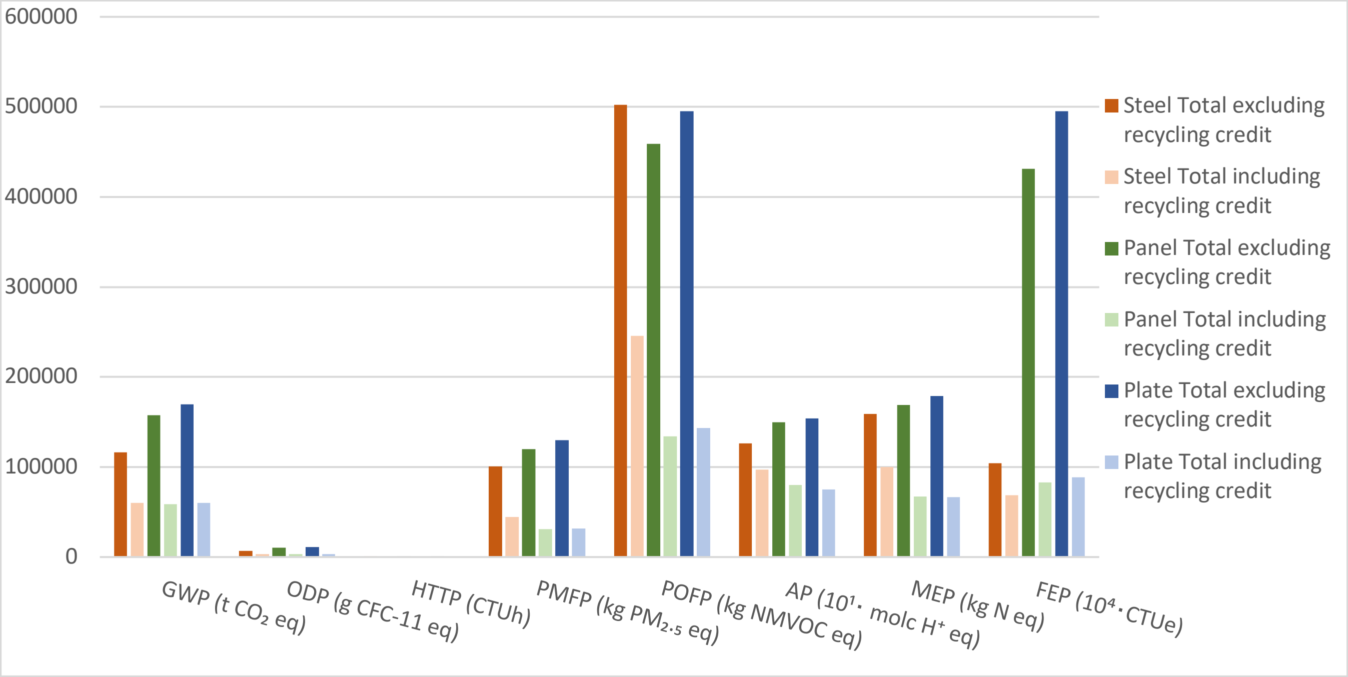


Figure 29: Environmental impact of the Langnuen concepts compared to the impact including benefits beyond system boundaries.

With CO_2-eq emissions in the climate change category often being seen as the main sustainability index the spread of the three concepts is considerable different when recycling is included or when only the initial emission is taken into consideration. The difference between the concepts when the recycling credit is included is marginal with the panel and plate respectively, only 2.43 and 0.23% lower relative to the steel concept.

In all but two impact categories the panel concept has a lower environmental impact than the plate concept as can be seen in figure 28. The AP and MEP of the panel concept is higher than the plate concept, but the difference only is 6.4 and 1.0% respectively. The panel concept has a lower emission in seven of the eight impact categories compared to steel with five categories emitting at least 17.4% less.

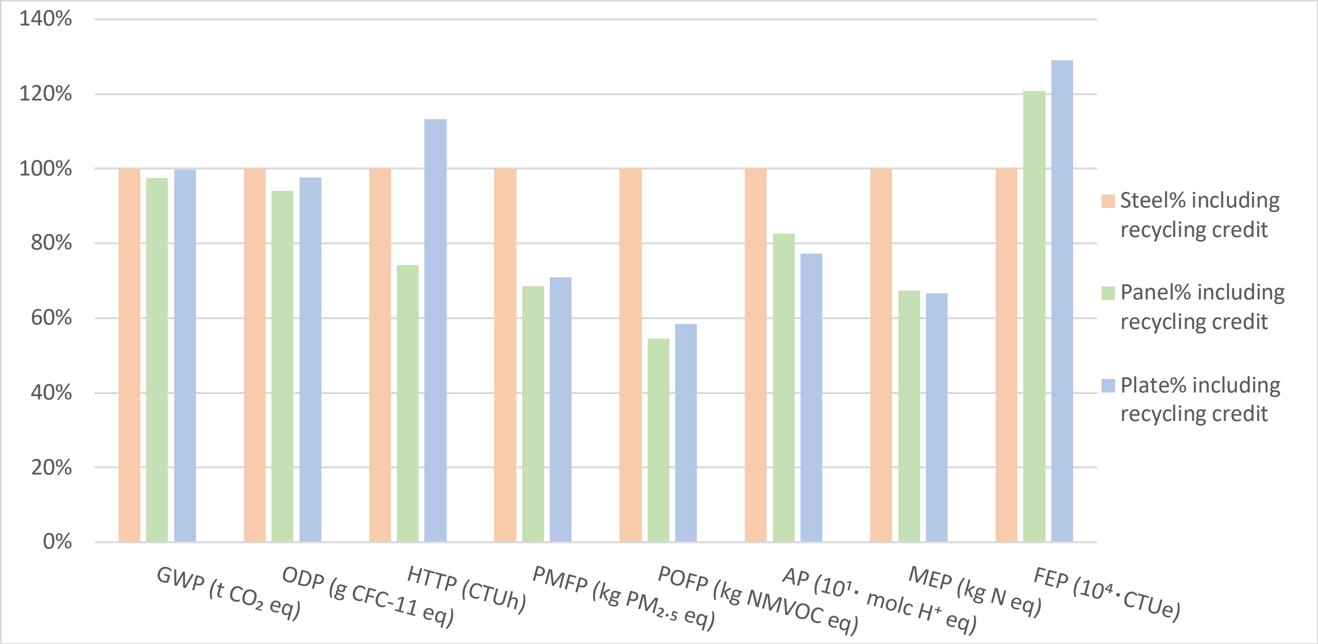


Figure 30: Overview of the relative environmental impact of the Langnuen concepts with recycling credits included.

7. Discussion

Sensitivity analysis results of the Langenuen concepts indicate that the influence of medium and low-quality data mainly impacted the steel concept. Whereas the panel and plate concepts where more influenced by the high-quality data. This can be explained by the high-quality data in the metal production for the girders which have a larger influence in the aluminum concepts what made the results more robust and less influenced by the uncertainty of the data in the maintenance and end of life stage. As expected, the bulk of the lifetime pollution was emitted in the production stage. The A1-A3 stage is responsible for 83.4% of the emissions generated during the 100-year lifetime of the steel concept. The contribution of production stage of panel and plate to the total lifetime emission was even higher at 95.4%, and 95.6 respectively.

The LCA results show a far lower environmental impact for the steel concept than the aluminum counterparts when recycling credit is not considered. The largest emission difference is in the freshwater eutrophication potential where the CTU emission of the panel and plate concepts are respectively 374 and 313% higher than the steel concept.

The efficient recyclability of aluminum lowers the results drastically when the credits beyond the system boundary are included. With the credits beyond the system boundary included, the panel and plate concepts have a lower impact than steel in every impact category except for the freshwater eutrophication potential which are, respectively, still 20.9 and 29% higher than steel.
In all but two impact categories the panel concept has a lower environmental impact than the plate concept as the AP and MEP of the panel concept are respectively 6.4 and 1.0% higher. The panel concept has a lower emission in seven of the eight impact categories compared to steel with five categories emitting at least 17.4% less than steel.

LCA limitations

As explained earlier, conducting an LCA is often prone to uncertainty. With analyzing the three concepts as done in the case study of Langenuen, the following areas have been identified that might have limited the research;

- Data limitations
- System boundaries and assumptions
- Unpredictable lifecycle events
- Aluminum sourcing
-

Data limitations

Where most LCA studies are conducted as part of an EPD or to show comparative assertion between products or services they have in common that the product is already in production. This is not the case for the Langenuen project. With the Langenuen fjord crossing still being in the design stage, retrieving accurate lifecycle data on the concepts has proven a limiting factor especially with regard to the bridge towers (Olav Olsen, 2019). With the steel concept being designed back in 2015 there also have been some data gaps concerning the welding requirements (Norconsult, 2015).

With the use of the sensitivity analysis an effort has been made to see how the results were influenced by the data uncertainty, yet the result quality would definitely have been higher if more detailed information would have been available.

System boundaries and assumptions

Tied into the data limitations of the Langenuen project is the data availability issue throughout the lifecycle of large civil projects. Due to the unknown environmental impact of the onsite bridge construction and demolition it was not possible to get an insight on how the Langenuen concepts would differ in the phases A5 and C2. Hence these phases had to be excluded from the LCA.

The long lifetime of the civil projects also brings the tough problem of making a valuable calculation regarding end of life scenario and the benefits and loads beyond the system boundary. In the research the calculations have been based on the current methods and technologies but it is to be expected that the eventual end of life treatment will differ due to technological advancements. This eventually will influence the total lifetime emission of the Langenuen concepts hereby also relative sustainability performance.

Another factor that might influence the results of the environmental impact of the concepts is the metal degradation due to corrosion. When (galvanized) steel and aluminum are left untreated the material degrades due to corrosion resulting into structural weakening and material loss. The Swedish Corrosion Institute has conducted tests to analyze the weight loss of untreated metals in marine environment. The results of the tests have been adjusted to the weight loss over 10-year time and presented in table 24 (Sapa Profiler, 2015).

	Marine environment
Aluminum (g/m^2)	8.75
Carbon steel (g/m^2)	1166.25
Galvanized steel (g/m^2)	166.25

Table 24: Weight loss due to atmospheric corrosion of untreated metals over a period of ten years (Sapa Profiler, 2015).

In the Langenuen LCA it is the corrosion protection applied to the steel is assumed to be flawless and corrosion of aluminum zero. So, all the metal that is produced for the bridge concepts in the LCA is expected to fully be sent for recycling with the only metal waste created in the recycling process without incorporating metal corrosion during the lifetime due to e.g. paint failure. It is unlikely to be accurate that all metal used in the concepts will reach the EoL stage without some form of corrosion hence influencing the treatment required to recycle the material, the recycling credit and eventually the impact assessment results.

Besides the material loss due to metal corrosion also the environmental impact of anchoring the main cable has not been included into the Langenuen LCA. The anchoring has been left out due to two reasons, firstly, the environmental impact of the anchorage lays mainly in the onsite construction and the data on the processes involved are limited. Secondly, the production of material in A1-A3 for the anchorage chambers is not expected to be of much difference between the concepts as the main cables are anchoring into solid rock of the mountains in near Langenuen. Due to Norwegian way of anchoring the cables the light weighting of the girder is not expected to have a heavy influence since the mountain is used as anchoring weight and only a relatively small concrete slap is poured to distribute the forces to the rock formation (Meyer, 2020). Anchoring in countries where solid rock is not available e.g. the Netherlands the anchoring system is often obtained by pouring larger concrete structure to obtain the required weight what would make light weighting of the girder more influential on the environmental impact of the bridge.

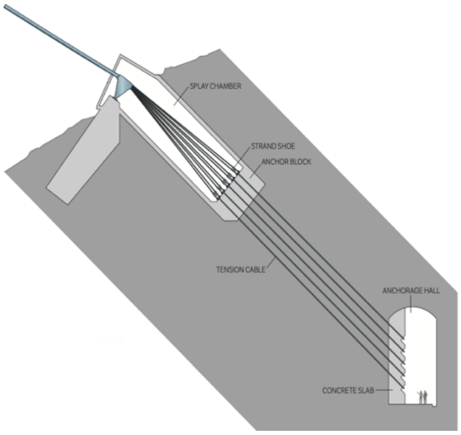


Figure 31: Visualization of the cable anchorage of the main cable at the Hålogaland bridge (Vegvesen, 2015).

Unpredictable lifecycle events
As explained in the validity and limitation section earlier in the rapport, trying to predict the lifecycle events of a product rarely leads to the real case scenario as there often is no data available what exactly will happen during the product lifetime. Even though the researcher is striving to plot the LCA as close to the real case scenario as possible it is to be expected that there will be some deviations. This will also be the case for the Langenuen concepts.

Speaking with multiple experts did uncover some lifecycle events on previous bridge projects that were not expected in advance. For example, the topcoat of the steel girder of the Hardanger bridge had to be replaced due to damages during transport from manufacturing location and construction location (Meyer, 2020). As explained in the hanger section of the langenuen case study earlier in the rapport the hangers at the Hardanger bridge are coated with the same duplex coating as the bridge girder. Since the hangers are not rigid like the girder, serious paint damage has already occurred, and the coating will need to be reevaluated earlier than expected. These are problems that in this stage of the Langenuen project cannot be foreseen and included in the LCA.

Mentioned during the interview with Nygård was the funding of the maintenance department having influence on the environmental impact. In the first 15-20 years the galvanized steel bridge girder will require yearly paint repairs where necessary and the whole topcoat should be redone but, "often the funds required to renew the topcoat are not supplied to the maintenance department what leads to more intensive and costly repairs around the 25-year mark. At that time large parts of the steel girder will need to be sandblasted and completely recoated." These more intensive repairs will have a higher environmental impact and influence the total lifetime emissions.

Another part is the wrapping that forms the air seal for the dehumidification of the main cables. According to Nygård it is to be expected that some parts of the wrapping will have to be repaired or changed (Nygård, 2020). Yet, quantifying the amount of required repair for each concept is not possible hence left out of the LCA.

Aluminum sourcing
In the panel and plate concepts the European market average has been used to for impact assessment of the aluminum production. The European average aluminum production has a higher emission than the Norwegian aluminum production based on hydro power. As aluminum production is a very energy intensive process the emission is dependent on the energy source. This would have a significant influence on the total lifecycle emission of the panel and plate concepts. But, as the exact sourcing of the aluminum is unclear, the European average has been selected as it gives a more realistic impact assessment. Besides that, the recycling credit has also been assumed to prevent new production according to todays European market average what compensates the initial higher emission.

The ideal scenario, aluminum with a high percentage postconsumer recycled material would be used such as the productrange CIRCAL 75R, produced by Hydro (Hydro, 2020b). The CIRCAL 75R range has a guaranteed minimum of 75% postconsumer scrap reducing the energy requirements of aluminum production and also reducing the environmental impact. This could lead to a lower lifecycle impact for the aluminum Langenuen bridge concepts but production on large scale of 75R is limited due to the higher demand than available aluminum scrap.

Proposed follow-up research

Once over, there are always differences in expected resource consumption and the correlated environmental impact when conducting an LCA in the early planning and design stage and the final construction stage. For this reason, it is advised to reanalyze the environmental impact of the Langenuen fjord crossing when more details of the actual bridge are known. Further LCA research could be done on the optimization of the concepts where the best-case scenario of both the aluminum and steel concepts are compared.

Another interesting LCA study could be to conduct on the three fjord crossing concepts when assumed that the bridge towers would be constructed out of steel instead of reinforced concrete, since the feasibility of such steel pylons have been analyzed by Kværner AS (Vegvesen, 2020). An LCA comparing bridge concepts based on steel bridge towers would uncover how the sustainability aspects compares to traditional bridge towers and whether a lightweight aluminum girder would have positive impact.

Besides LCA studies, a research on the economic and environmental impact of bridge repair and maintenance could provide valuable information. Especially since the rust preventive coating of steel bridge girder is a substantial contributor in the cost and emission during the use stage. Researching accurate and effective repair scheduling can provide data on optimal rust prevention and prevent extensive repairs.

8. Conclusion

Using the description of the bridge concepts given by Olav Olsen and Norconsult this study has explored the environmental impact of the Langenuen fjord crossing. With the goal to generate a realistic basis of comparison between the environmental impact of the three concepts currently on the table. An LCA was conducted to distinguish the most impactful processes in the lifetime in pursuit to answer the following research question;

Will an aluminum bridge girder lower the environmental life cycle impact of the Langenuen suspension bridge compared to a steel girder?

When comparing the aluminum concepts to each other results of the impact assessment showed that the panel concept has a lower environmental impact than the plate concept in all eight categories. Yet, the lifecycle impact of the aluminum concepts is far higher than the steel concept due to the resource intensive nature of primary aluminum production. The relative environmental impact of the aluminum concepts is higher for seven of the eight impact categories compared to the steel concept. In six of these categories the panel concept is at least 18.9% and the plate concept 21.8% higher than the steel bridge concept.

When the benefits beyond the system boundaries due to recycling of the bridge material are included in the lifecycle emission the results show the panel has a lower emission in seven of the eight impact categories compared to steel with five categories emitting at least 17.4% less. The panel concept also has a lower environmental impact than the plate concept in all but two impact categories. The AP and MEP of the panel concept is higher than the plate concept, but the difference only is 6.4 and 1.0% respectively.

As is often the case with LCA studies the conclusion of the research is multifaceted and the answer on the research question depends on what boundaries are set. If strictly taken the lifecycle emission from material extraction till the end of life disposal the steel concept has the lowest environmental impact. But, when the reduced production emissions of the next product due to the use of recycled bridge material are allocated to the lifecycle impact of the Langenuen bridge the panel concept is the most sustainable solution according to this study.

It has been aimed to analyze the realistic environmental impact of the Langenuen fjord crossing concepts like they are currently being considered. Within the scope of this study the aluminum panel concept is only more sustainable when recycling credits are included otherwise steel has a lower environmental impact.

9. Acknowledgements

This research is conducted for examination of the course Tøl4902 as final part before graduation of the master track Sustainable Manufacturing at the Norwegian university of science and technology in Gjøvik. In addition, the rapport has been written for, and supported by, the NPRA to provide them insight on the environmental impact of the Langenuen bridge concepts.

10. Appendix

Calculations of the number of squared meters of wire that needs to be galvanized based upon the Hålogaland bridge. The following numbers where used in the calculations:

	Main span	Length main cable	Diameter total cable	Radius total cable	Number of wires in each wire strand	Number of wire strands in main cable	Diameter single wire
Hålogaland bridge main cable	$1145m$	$1621m$	$\emptyset 47.5cm$	$23.75cm$	127	40	$\emptyset 5.96mm$

Table 25: Data Hålogaland bridge as given by Statens vegvesen (Vegvesen, 2015; IFME, 2020).

To calculate the square meter surface of the individual wires of the main cable there are several steps taken:

1. Calculate the ratio wires per m^2 in the Hålogaland bridge
2. Use this ratio to calculate the number of wires

Based on the information given in figure 22 a rough calculation of the length of the Langenuen main cable can be calculated using some basic math. The cable in between the towers can be described with the parabolic formula:

- $y = \frac{240}{381306.25}x^2 - \frac{96}{247}x + 123.5$

By integrating that formula over the length of 0 to 1235 (distance between the towers) the length of that section of the cable is 1265.424m

The length of cable from each tower to anchor was calculated using cosine, giving a rough total length of 1894.716 meter per cable.

3. Use the calculated cable length and number of wires from step 2 to the total length of wire can be calculated.
4. Now calculate the wire surface using: $2\pi r^2 + 2\pi rh$

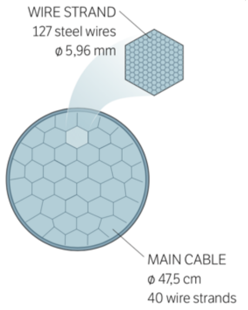


Figure 32: Cross section of the Hålogaland main cable (Vegvesen, 2015).

Steel concept:

1. $\emptyset 47.5cm \rightarrow \pi r^2 \rightarrow \pi(0.2375)^2 = 0.1772054606m^2$
   $40 \cdot 127 = 5080\ wires\ with\ \emptyset 5.96mm$
   $\frac{5080}{0.1772054606} = 28667.28814$ wires per m^2
2. $\emptyset 0.711m \rightarrow \pi r^2 \rightarrow \pi(0.3555)^2 = 0.397035265m^2$
   $0.397035265 \cdot 28667.28814 = 11381.92434\ wires$
3. $11381.92434 \cdot 3.789432 = 43131.02832$ total km wire
4. $(2\pi(0.00596)^2) + 2\pi \cdot 0.00596 \cdot 43131028.32 = \mathbf{1615161.451m^2}$

Panel concept:

1. $\emptyset 47.5cm \rightarrow \pi r^2 \rightarrow \pi(0.2375)^2 = 0.1772054606m^2$
   $40 \cdot 127 = 5080\ wires\ with\ \emptyset 5.96mm$
   $\frac{5080}{0.1772054606} = 28667.28814$ wires per m^2
2. $\emptyset 0.681m \rightarrow \pi r^2 \rightarrow \pi(0.3405)^2 = 0.3642370377m^2$
   $0.3642370377 \cdot 28667.28814 = 10441.68811\ wires$
3. $10441.68811 \cdot 3.789432 = 39568.06706$ total km wire
4. $(2\pi(0.00596)^2) + 2\pi \cdot 0.00596 \cdot 39568067.06 = \mathbf{1481736.446m^2}$

Plate concept:

1. $\emptyset 47.5cm \ \rightarrow \pi r^2 \rightarrow \pi(0.2375)^2 = 0.1772054606m^2$
   $40 \cdot 127 = 5080\ wires\ with\ \emptyset 5.96mm$
   $\frac{5080}{0.1772054606} = 28667.28814$ wires per m^2
2. $\emptyset 0.644m \ \rightarrow \pi r^2 \rightarrow \pi(0.322)^2 = 0.3257328927m^2$
   $0.3257328927 \cdot 28667.28814 = 9337.878692\ wires$
3. $9337.878692 \cdot 3.789432 = 35385.25633$ total km wire
4. $(2\pi(0.00596)^2) + 2\pi \cdot 0.00596 \cdot 35385256.33 \ = \mathbf{1325099.451m^2}$

Selection of aluminum to use in the LCA.

Since aluminum alloys can contain many different alloying elements it can severely complicate an LCA without adding value to the results of the research in accurately representing the environmental impact of the product. For this reason, the cutoff has been made to exclude all alloying elements in alloys where aluminum represents 95% or more by weight. Alloys that fall in this range will be accounted for as if it were pure aluminum. Alloying elements in alloys with less than 95% will be included in the LCA only if they represent half a percent or more by weight. Alloying elements falling below the half percent mark will be accounted for in the LCA by being replaced with pure aluminum.

With regards to the aluminum alloys utilized in the bridge girder in the Plate and Panel concept there are four different ones as seen in the table 26 below. Using the cut of described the alloys will be accounted for as described in table 27.

	Al%	Mg%	Mn%	Si%	Zn%	Fe%	Cr%	Cu%	Zr%	Ti%
6005A-T6	98.7	0.5	-	0.8	-	-	-	-	-	-
6082-T6	96.92	0.78	0.5	1.2	0.05	0.33	0.14	0.08	-	-
5083-H116	94.7	4.4	0.7	-	-	-	0.2	-	-	-
5383-0	Balance	4.0–5.20	0.7–1.0	≤0.25	≤0.40	≤ 0.25	≤0.25	≤ 0.20	≤0.20	≤0.15

Table 26: Table of alloying elements in the aluminum alloys used in the bridge girder concepts (Davis, 2001; Mrówka-Nowotnik, Sieniawski and Nowotnik, 2006; Wahid, Siddiquee and Khan, 2019).

	Al%	Mg%	Mn%
6005A-T6	100	-	-
6082-T6	100	-	-
5083-H116	94.9	4.4	0.7
5383-0	94.55	4.6	0.85

Table 27: Table of alloying elements included in the LCA using the cutoff.

Weight alloying elements per 12m section

Plate Concept	Total	Al	Mg	Mn
6005A-T6	36145kg	36145kg	-	-
6082-T6	4836kg	4836kg	-	-
5083-H116	64963kg	61649.887kg	2858.372kg	454.741kg
5383-0	972kg	919.026kg	44.712kg	8.262kg
unallocated	1620kg	1620kg	-	-
Total	108536kg	105169.913kg	2903.084kg	463.003kg
Panel Concept	Total	Al	Mg	Mn
6005A-T6	89960kg	89960kg	-	-
6082-T6	0kg	-	-	-
5083-H116	241kg	228.709kg	10.604kg	1.687kg
5383-0	972kg	919.026kg	44.712kg	8.262kg
Total	91173kg	91107.735kg	55.316kg	9.949kg

Table 28: Calculated weight alloying elements panel and plate concept per 12m section.

Inventory data including sources and assumptions

Material/energy	Steel	Panel	Plate	Data sources	Comments
Girder					
Steel production (t)	14831	0	0	(Olav Olsen, 2019)	
Hot rolling (t)	14831	0	6648	(Olav Olsen, 2019)	
GMA Welding (m)	325791	0	325791	(Olav Olsen, 2019)	Welding required for steel girder assembly assumed the same amount as the plate concept.
Abrasive blast cleaning (m^{2})	89228.75	0	0	(Norconsult, 2015; Peng *et al.*, 2016)	No process available in Simapro so process created based on literature.
Galvanizing (m^{2})	89228.75	0	0	(Norconsult, 2015)	No process for TSZ available in Simapro so impact is assumed to be equal to hot dip galvanization.
Seal/primer paint (m^{2})	33962.5	0	0	(Norconsult, 2015; Jotun A/S, 2018c; Vegvesen, 2018)	
Full multi coat paint (m^{2})	55266.25	0	0	(Norconsult, 2015; Jotun A/S, 2018b; 2018c; 2018a; Vegvesen, 2018)	Paint coat is modeled after the paint system described in the handbook R762.
Aluminum alloy prod. (t)	0	9391	11080	(Olav Olsen, 2019)	European market average has been selected.
Extrusion (t)	0	9391	4432	(Olav Olsen, 2019; Thinkstep AG, 2016)	No comparable process available in Simapro hence inventory data from literature has been used.
Friction stir welding (m)	0	189337	0	(Olav Olsen, 2019; Shrivastava, Krones and Pfefferkorn, 2015)	No FSW process available in Simapro so process created based on literature.
Transoceanic ship (tkm)	301484568	22314105.36	26326855.6	(Brekke, 2011)	Steel concept shipping from shanghai to Langenuen. Aluminum concepts from Sunndalsøra to Rotterdam and back.
Truck (tkm)	0	2629480	1240960	(Baars, 2020)	Transport aluminum from Rotterdam harbor to Harderwijk extrusion plant.
Inland barge (tkm)	0	187820	3915228.8	(Baars, 2020; Olav Olsen, 2019)	Transport Rotterdam to Neuss and back for plate concept. Also includes the transport of the finished bridge sections from Melkvika to Langenuen.
Main Cable					
Steel production (t)	12387	11437	10178	(Olav Olsen, 2019)	
Wire rod production (t)	12387	11437	10178	(Olav Olsen, 2019)	
Galvanization (m^{2})	1615161.451	1481736.446	1325099.451	(Brekke, 2011; Isaksen, 2012; Schultz and Christensen, 2014; Vegvesen, 2015; ISO, 2009)	The coating has been based on the Hålogaland and Hardanger bridges.
Wrapping (t)	27.821	26.647	25.199	(Mathey, 2020; Vegvesen, 2020)	No process available in Simapro so a comparable elastomeric process has been used.
Freight train (tkm)	990960	914960	814240	(Brekke, 2011)	Transport from Doncaster to Immingham harbor.
Transoceanic ship (tkm)	10578498	9767198	8692012	(Brekke, 2011)	Transport Immingham to Langenuen.

Hangers					
Steel production (t)	151	127	122	(Olav Olsen, 2019)	
Wire drawing (t)	151	127	122	(Olav Olsen, 2019)	
Galvanization (m^2)	1974.43	2522.78	2413.09	(Olav Olsen, 2019; Vegvesen, 2020)	Calculations of the hanger length and surface are based on the height difference between the main cable and girder of the steel concept.
Full multi coat paint (m^2)	1974.43	2522.78	2413.09		Assumed same paint coat as the steel girder.
Freight train (tkm)	110230	92710	89060	(Brekke, 2011)	Transport from Bourg-en-Bresse to Antwerp harbor.
Transoceanic ship (tkm)	177576	149352	143472	(Brekke, 2011)	Transport Antwerp to Langenuen.
Towers					
Concrete (m^3)	32064.03	24536.32	25042.88	(Vegvesen, 2015; Brekke, 2011; Schultz and Christensen, 2014)	Material used for Langenuen concepts the towers have been calculated on the ratio of weight to be supported and material used in the Hardanger and Hålogaland bridges.
Steel, reinforcement (t)	5606.29	4290.10	4378.67		
Truck (tkm)	5420021.13	4147556.8	4233184.19		Transport from local suppliers by truck (EURO6) to Langenuen.

Use stage

Material/energy	Steel	Panel	Plate	Data sources	Comments
Girder					
Topcoat (m^2)	221065	-	-	(Norconsult, 2015; Jotun A/S, 2018c; Vegvesen, 2018; Jotun A/S, 2018b)	The processes used to repair and revise the rust protection of the steel girder are assumed to have the same environmental impact as the shop processes. The required repairs have been based on information from the maintenance department of SVV.
Abrasive blast cleaning (m^2)	199761.25	-	-	Norconsult, 2015; Peng et al., 2016)	
Galvanizing (m^2)	89228.75	-	-		
Seal/primer (m^2)	33962.5	-	-	(Norconsult, 2015; Jotun A/S, 2018c; Vegvesen, 2018)	
Full paint coat (m^2)	165798.75	-	-	(Norconsult, 2015; Jotun A/S, 2018b; 2018c; 2018a; Vegvesen, 2018)	
Main cable					
Dehumidifying (kwh)	5925000	5675000	5366666.67	(Brekke, 2011; Nygård, 2020)	The energy use has been adjusted based on the Hardanger bridge.
Hangers					
Abrasive blast cleaning (m^2)	17769.87	22705.02	21717.81	(Olav Olsen, 2019; Vegvesen, 2020)	Same paint coat as the girder with same expected emission as shop painting.
Full paint coat (m^2)	17769.87	22705.02	21717.81		
Tower	-	-	-		There is no expected maintenance required for the towers.

End of Life Stage

Material/energy	Steel	Panel	Plate	Data sources	Comments
Galvanized steel (t)	27369	11564	10300	(Olav Olsen, 2019)	All materials that were input for the bridge construction are expected to reach EoL without material degradation. The foundation of the bridge towers is expected to be left in the ground hence not included in the EoL treatment.
Aluminum alloy (t)	0	9391	11080	(Olav Olsen, 2019)	
Elastomer (t)	27.821	26.647	25.199	(Mathey, 2020; Vegvesen, 2020)	
Concrete (m^3)	23887.7	18279.56	18656.95	(Vegvesen, 2015; Brekke, 2011; Schultz and Christensen, 2014)	
(t)	56852.73	43505.35	44403.54		
Steel reinforcing (t)	4860.09	3719.09	3795.87		
Total weight (t)	89109.641	68206.087	69482.609		
Transport by truck (tkm)	5792126.67	4433395.66	4516369.59		All waste treatment facilities are approx. 65km from Langenuen.
Processing at waste facility (t)	89109.641	68206.087	69482.609	(Statistics Norway, 2020)	What treatment the material will receive in the EoL stage is based on the statistics of Statistisk sentralbyrå see table below.
Abrasive blast cleaning of painted steel (m^2)	91203.18	2522.78	2413.09	(Norconsult, 2015; Peng et al., 2016; Olav Olsen, 2019; Vegvesen, 2020)	Extra abrasive blasting is included in the EoL treatment for painted steel surfaces.

End of Life treatment

Material	Recycle	Energy recovery	Landfill	Sources	Comments
Steel concept					
Galvanized steel (t)	27369	0	2326.365	(Statistics Norway, 2020; Bowyer *et al.*, 2015)	No recycling process available in Simapro for galvanized steel so the process is assumed to be same for rebar recycling. 8.5% of the steel in the recycling process is assumed to be landfilled due impurities.
Elastomer (t)	0	20.6237073	7.2000748	(Statistics Norway, 2020)	No recycling process available in Simapro so the part supposed to do recycling is expected to be sent for energy recovery.
Concrete (t)	33236.10596	0	23616.624	(Statistics Norway, 2020)	
Steel rebar (t)	4860.09	0	413.10765	(Statistics Norway, 2020)	Again 8.5% of the steel in the recycling process is assumed to be landfilled due impurities.
Panel concept					
Aluminum Alloy (t)	9391	0	187.82	(Statistics Norway, 2020; Boin and Bertram, 2005)	No recycling process available in Simapro for so only the electricity consumption is accounted for. 2% of the aluminum in the recycling process is assumed to be landfilled due impurities.
Galvanized steel (t)	11564	0	982.94	(Statistics Norway, 2020)	Same as steel concept.
Elastomer (t)	0	19.7534211	6.8962436	(Statistics Norway, 2020)	Same as steel concept.
Concrete (t)	25433.22761	0	18072.1224	(Statistics Norway, 2020)	Same as steel concept.
Steel rebar (t)	3719.09	0	316.12265	(Statistics Norway, 2020)	Same as steel concept.

Plate concept					
Aluminum Alloy (t)	11080	0	221.6	(Statistics Norway, 2020)	Same as the panel concept.
Galvanized steel (t)	10178	0	865.13	(Statistics Norway, 2020)	Same as steel concept.
Elastomer (t)	0	18.6800187	6.5215012	(Statistics Norway, 2020)	Same as steel concept.
Concrete (t)	25958.30948	0	18445.2305	(Statistics Norway, 2020)	Same as steel concept.
Steel rebar (t)	3795.87	0	322.64895	(Statistics Norway, 2020)	Same as steel concept.

Stage D, Benefits and loads beyond the system boundary

	Avoided production	Sources	Comments
Steel concept			
Steel credit (t)	29489.61735	(Wernet *et al.*, 2016)	The steel recycling is expected to prevent steel production based on primary material.
Aluminum credit (t)	0		
Inert filler credit (t)	33236.10596	(Wernet *et al.*, 2016)	Concrete is expected to be recycled into an inert filler material.
Energy credit (GJ)	671.5904045	(Tchobanoglous, Theisen and Vigil, 1993; Government.no, 2016)	The plastic wrapping is assumed to be burned in a municipal solid waste incinerator and the energy content is assumed to be equal to general plastic containing 32.564 GJ/t. Expected to prevent energy based on hydropower production.
Panel concept			
Steel credit (t)	13984.02735	(Wernet *et al.*, 2016)	Same as steel concept.
Aluminum credit (t)	9203.18	(Wernet *et al.*, 2016)	The aluminum recycling is expected to prevent aluminum production based on primary material.
Inert filler credit (t)	25433.22761	(Wernet *et al.*, 2016)	Same as steel concept.
Energy credit (GJ)	643.2504047	(Wernet *et al.*, 2016)	Same as steel concept.
Plate concept			
Steel credit (t)	12786.09105	(Wernet *et al.*, 2016)	Same as steel concept.
Aluminum credit (t)	10858.4	(Wernet *et al.*, 2016)	Same as panel concept.
Inert filler credit (t)	25958.30948	(Wernet *et al.*, 2016)	Same as steel concept.
Energy credit (GJ)	608.2961289	(Wernet *et al.*, 2016)	Same as steel concept.

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