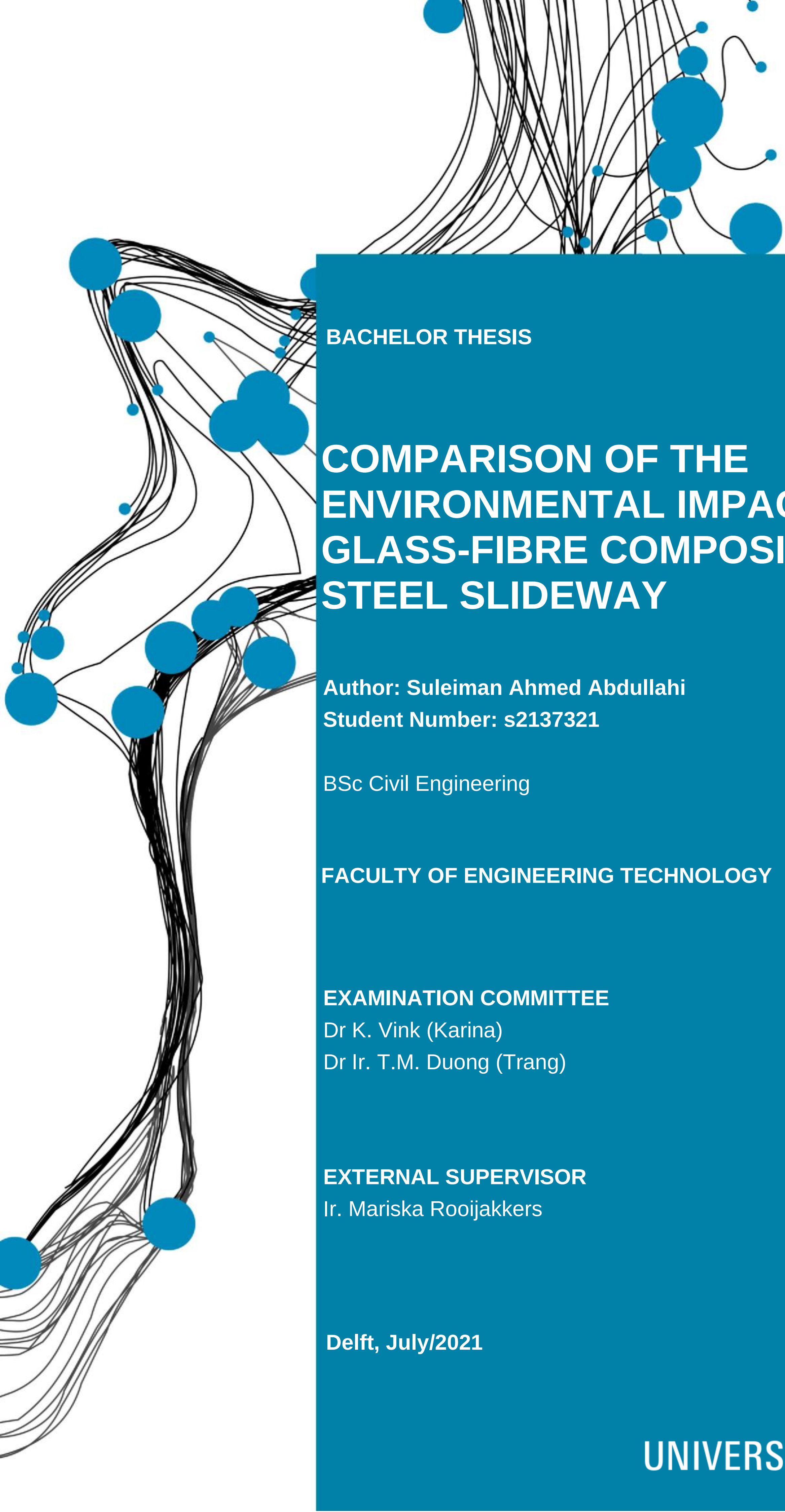

BACHELOR THESIS

COMPARISON OF THE ENVIRONMENTAL IMPACT OF A GLASS-FIBRE COMPOSITE AND STEEL SLIDEWAY

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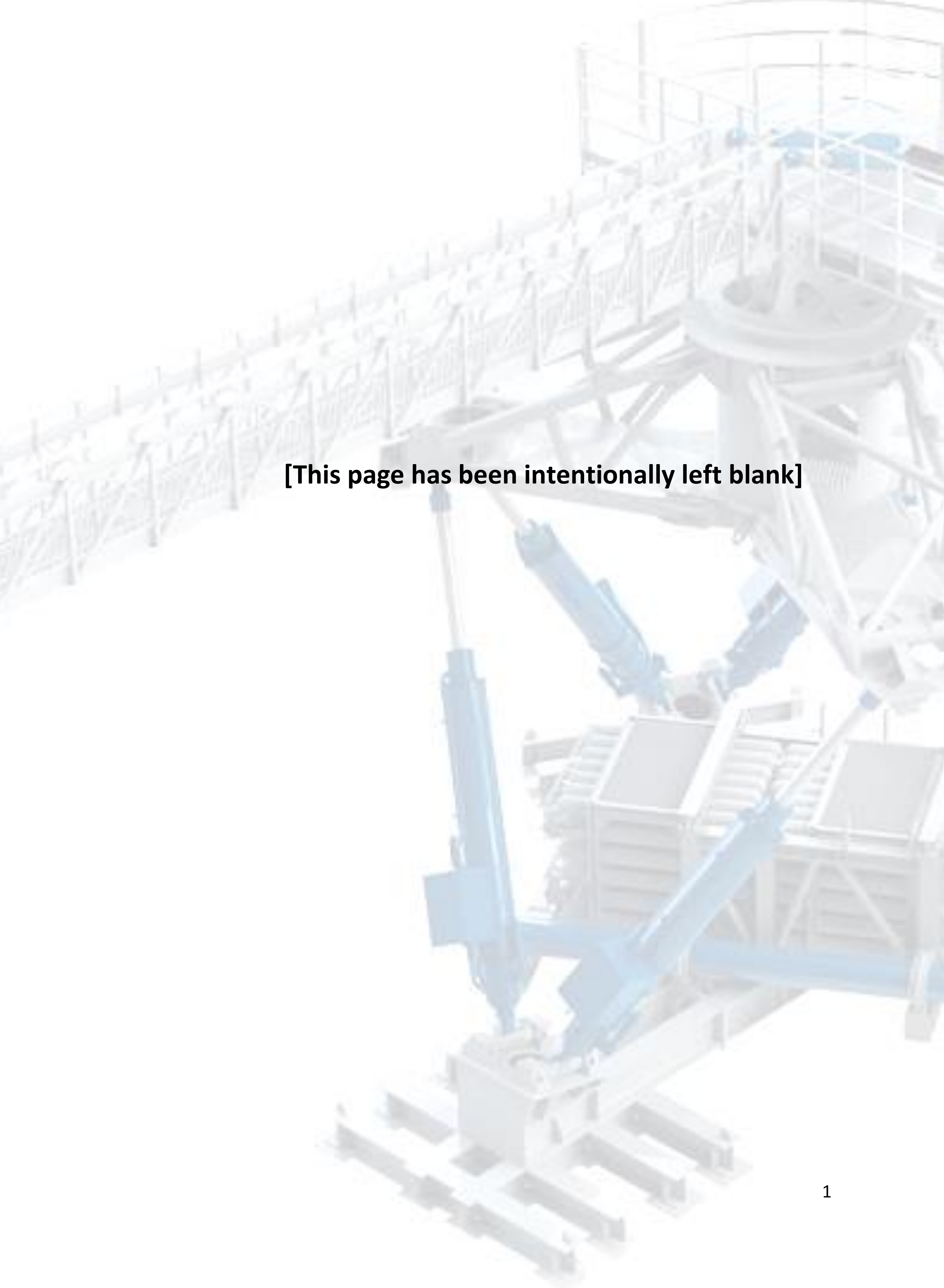

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Preface

Dear reader, I present to you this dissertation entitled “Comparison of the environmental impact of a GFRP composite and a steel slideway”. The basis of this report is the Life Cycle Analysis of a transport slideway that is mounted on a system of motion compensating hexapod. This report has been written to fulfil the graduation requirements of the BSc Civil Engineering program at the University of Twente. I was engaged in researching, modelling and writing this dissertation from May to July 2021.

This project was undertaken at the behest of Ampelmann Operations where I undertook my internship period. Ampelmann provides offshore access systems and services for both people and cargo. The research questions were formulated by the host company and as such, the required research was predefined. This enabled me to focus on developing a research methodology to answer the client’s demand. This research was intensive in terms of data collection and LCA modelling. Fortunately, Ir. M. Rooijakkers from Ampelmann was always available and she was always willing to answer my queries, help me collect data and give suggestions on the LCA model.

This project would have been very difficult without the help and support of many people that were directly or indirectly involved in my life. I would, therefore, like to take this opportunity to express my gratitude to them. My sincere thanks go to my parents for their patience, encouragement and moral support. They have been the source of my happiness, and they stood by my side with unconditional love and counsel. They gave me the best of education that they could not afford for themselves. I will always be indebted to them and always pray that they live to reap the fruits of my education.

I would also like to thank my daily supervisor dr Karina Vink. This project would not have been possible without her, dr Vink was kind enough to allow me to work under her guidance and provide me with feedback in preparing the research proposal as will the final dissertation. Last but not least, I express my utmost gratitude to Ir. Mariska Rooijakkers at Ampelmann Operations, she was an excellent supervisor and provided me with daily support. I appreciate the meetings and the discussion we had over the course of this internship. She contacted fabricators, engineers and the maintenance team within Ampelmann on my behalf and I am grateful for that.

Finally, I believe that the discussions in this thesis will allow stakeholders to make a better-informed decision regarding sustainable design development of composite materials and limiting the negative impacts that their services and products may have on the environment.

Suleiman Ahmed Abdullahi

Delft, 15th July 2021 (First edition)

Hengelo 20th August 2021 (Revised edition)

Abstract

The extraction, production and fabrication of materials used in building of new structures cause different environmental side effects such as emission of greenhouse gases, nutrification of soils and surface water. The environmental impacts of some of the most widely used building materials like steel have been extensively studied and quantified through various scientific approaches. The need to curb the environmental impacts of such material have led to development of new materials such as glass-reinforced plastic (GRP) composites. These materials are structurally viable and inexpensive compared to other building materials like steel, however, studies that evaluate and quantify their environmental impacts are limited and require a thorough analysis in order to make climate-friendly choices regarding their application.

This study is about an extensive study to quantify the environmental impacts of a glass-fibre-reinforced plastic (GFRP) composite slideway according to Life Cycle Analysis (LCA) methodology as stipulated within the International Organization for Standardization ISO standards and compare the results with a steel slideway of similar functionality. The identifications and quantification of these impacts provide insights into the performance of GRP under various climatic metrics such as global warming potential (GWP), Ozone layer depletion potential (ODP), etc. For each material, a detailed cradle-to-grave assessment including both production and use pollutions were performed. The data that was used in the analysis was collected based on the design specifications of Ampelmann^{TM} and fabrication techniques of Airborne^{TM}.

The postulated hypothesis was that the composite slideway would perform better under different environmental categories, this hypothesis has been tested and results indicate that steel slideway has higher total environmental impact over a 10-year period when compared with the GRP composite slideway. The total amount of pollution in various stages of composite is 1.8% more than the steel for the GWP potential and 15% more in the case of ozone layer depletion potential. The most burdening life cycle phase is the use and maintenance phase which contributes the highest environmental effects for both slideways as a result of their operation period. Furthermore, the impact of the GFRP composite on acidification potential and Eutrophication is lower per kg compared to the steel slideway. On the other hand, the inventory data indicated slightly larger production waste for the GFRP especially in terms of epoxy and PVC waste. Most of the impact categories are influenced by the amount of energy consumed and the toxicity of emission associated with the production of epoxy used in the GFRP and the life cycle of steel production.

Overall, the outcome of this study can be used to understand the current sustainability levels of GFRP composite and to be used to weigh the climatic pros of using them in place of steel. The decisions stemming from such policies will contribute to the sustainability of the organization's business model through cost cutting while simultaneously curbing the impacts of global warming by reducing the potential greenhouse emission associated with extraction and production of the building material.

Keywords Life cycle analysis, LCA, composite, glass-fibre reinforced plastic, GRP, impact categories, steel, slideway, ISO, impact assessment

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GLOSSARY

LCA	Life cycle Assessment/analysis: an analytical method used to evaluate environmental impact of a product through its life cycle stages.
LCI	Life cycle inventory analysis: collection, compilation and quantification of all resources used to produce a given product.
FU	Functional Unit: a standard quantity used to describe the performance requirement that the product fulfils.
GWP	Global Warming Potential – An impact category that measures the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of heat that would be absorbed by the same mass of carbon dioxide
GaBi	A software application that was developed to model and perform life cycle analysis calculations.
ISO	The International Organization for Standardization (ISO) is an international nongovernmental organization made up of national standards bodies; it develops and publishes a wide range of proprietary, industrial, and commercial standards and is comprised of representatives from various national standards organizations
Cradle-to cradle	This assessment includes extraction of raw materials to recycling of components of a product.
Cradle-to-grave	This assessment type includes only production up to the end of life without recycling material components of the product.
Plan	A plan contains the visual overview of the product life cycle with processes and flows in the form of a flowchart.
Process	Processes are simplified models of operation in which a conversion of objects or substance take place, they can be seen as black boxes with input and outputs in the form of flows.
Flow	They represent the transfer of materials, resources and emission. They are used to connect input and outputs between processes in the process plan. They are expressed in quantities with corresponding units.
GRP	Glass reinforced plastic
QHSE	Quality, Healthy, Safety and Environmental Management: the department responsible for policies in accordance with ISO9001, ISO14001, OHSAS18001
CFGF	Continuous filament glass fibre are made by pulling molten glass through specific diameter dies under very high temperatures.
EOL	End-of-Life: the final stage of a products life cycle, where it has ceased to perform its intended functionality.
POM	Polyoxymethylene
PTFE	Polytetrafluorethylene
SHS & RHS	Square hollow section and Rectangular hollow section
CFRP	Carbon fibre reinforced plastic

MMBtu	1 million British thermal units “1MMBtu = 1,055.06 MJ”
LCIA	Life cycle impact assessment
CFCs	Chlorofluorocarbons
AP	Acidification potential
ODP	Ozone layer depletion potential
EP	Eutrophication potential
MDS	Material Data Sheet

List of figures and tables

1. Introduction

1.1. Background

Climate change poses the biggest challenge of our time (Caro, 2019). It is a global phenomenon characterized by climate transformations in which unusual climate variations (in e.g. precipitation, temperature and wind) are observed. These variations are amplified directly by human activities such as increase in greenhouse effects stemming from burning of fossil fuel, transportation, construction and deforestation. Due to these reasons, governments, local authorities, private companies and NGOs are called to constantly monitor their impacts on climate change through adoption of suitable tools. To monitor the influence of an organization's activities on climate change, the environmental impacts associated with the organization's goods and products are assuming a greater importance in informing the material choices for use.

Understanding the fundamental loops and processes of the material life cycle enables organizations and individuals to make informed choices that are aimed towards sustainable development (Corbierre-Nicollier, Laban, L. Lundquist, Manson, & Jolliet, 2001). The different life cycle stages such as the extraction, use and disposal of materials indeed have a substantial environmental and economic implication. In many cases, far more materials are extracted and translocated than what is actually used in the end product itself. Most of the objects of every-day life have a much shorter life span than their intermediate constituents. In order to reduce the environmental emission and resource consumption, there is need for greater understanding of material efficiency and the loops involved in its production, use and disposal.

Conventional materials like metals, steel and wood have had dominant positions in many fields such as in the construction and manufacturing industries. This is mainly due to their mechanical properties and chemical properties as well as their low processing costs (Rosario, Pilar, & Daniel, 2008). However, these conventional materials proved to be a major contributing factor to the global crisis of climate change (Sarah, Michael, Renate, & Yves, 2015) as they consume 49% of energy produced in the U.S.A alone and contribute close to 47% of greenhouse gases. On the other hand, the capacity to manufacture modified plastics and engineer them by combining with other substance like fillers, reinforcing fibres, stabilizers and plasticizers has increased in the last decades to offset the need for metals and wood in fabrication, construction and automotive industries. These engineered polymers in combination with glass fibres form a basis for processing of composite structures. The structure delivers more strength per unit weight when compared with steel while at the same time being lighter with the ability to be moulded into any desired shape. In their study about structural analysis of composite materials (Wittmann, Roelfstra, & Sadouki, 1984) have shown that composite material perform well when used as a structural material.

However, from an environmental point of view, conventional plastics i.e. fuel derived polymers, not only consume non-renewable finite resources but also impact heavily upon waste disposal. Composite materials which usually are substituents of two or more constituent phases of polymers have increased in popularity in the fields of wood decking, automotive and offshore industries with countless new applications being envisioned for the future (Paul, Hughes, & Elias, 2006). In order to confirm such optimistic prospects, it becomes paramount to properly assess the environmental performance of these materials throughout their life cycle, from raw materials to disposal. This dissertation is therefore a basis for an environmental analysis of a composite structure made from epoxy resin and glass fibres using the Life Cycle Assessment methodology.

1.2. Motivation

As mentioned in the introductory section, life cycle thinking has become a major tool of focus that is used to formulate environmental policies. Different governments and organizations have developed strategies to promote life cycle thinking as a key concept in their activities. This led major companies to report the sustainability aspects of their operations and justify the choices they make.

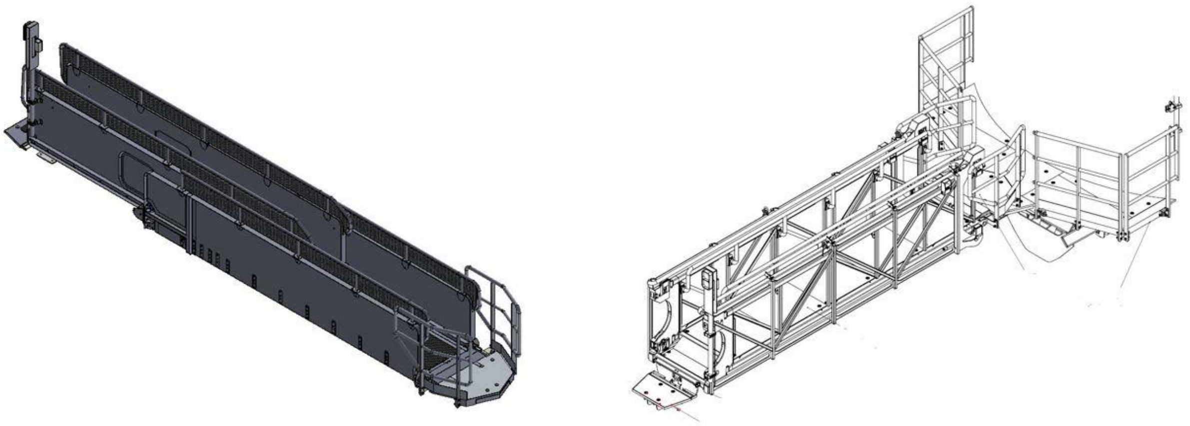
For this reason, Ampelmann is developing its first composite gangway to replace the current steel gangway that is in operation. However, it unclear the environmental implications associated with the composite compared to the steel structure. On the other hand, Ampelmann wants to develop its products according to its environmental policies i.e. trying to reduce the impacts of its manufacturing process and products on the environment, I am going carry out a LCA study to analyse the environmental impacts of developing a composite gangway compared with a steel slideway.

The outcome from this study will not only benefit Ampelmann^{TM} but also companies or organizations that produce, trade or manufacture composite materials for various purposes. By providing an insight into the environmental impacts of these materials and a comparing it with a known material like steel, organizations can generate environmental-friendly policies and reduce their immediate footprints. Consequently, the results will provide a comprehensive view of the alternatives of using composite materials over steel with regards to environmental protection guidelines.

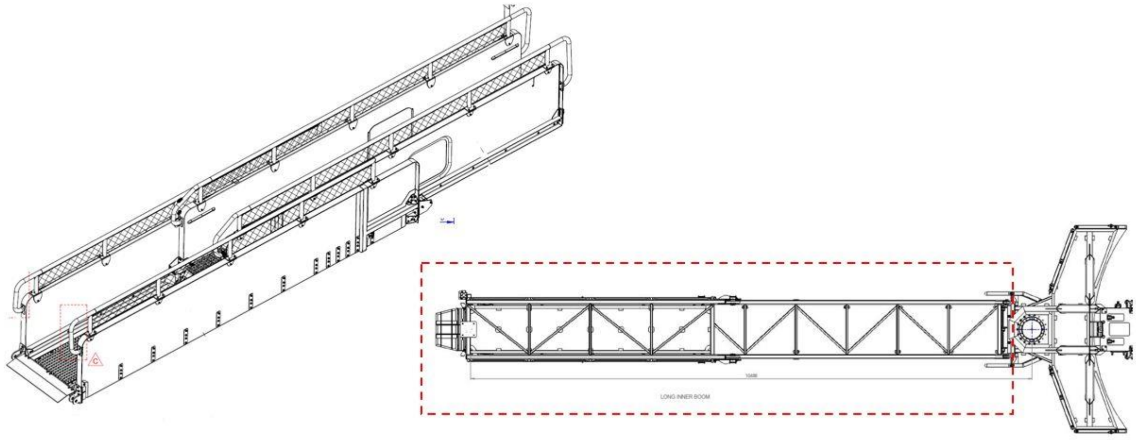
1.3. Aim of the study

The needs to monitor and map the environmental soundness of a product stems from the ever-growing demand to curb environmental emission and consequently offset negative impacts of climate change. The procedure of mapping such an environmental soundness of a product is complicated and demands a specific set of standards and rules to be applied. The aim of this study is to create a quantifiable comparison of two transport slideways made of two different materials i.e. steel and GRP composite shown in Figure 1. Traditionally, steel is the most used building material whose environmental characteristics have been studied and documented.

On the other hand, composite structures like GRP or Carbon-reinforced plastic composites (CRP) are novel materials that have seen their application accelerate at different fields due to their material and cost-efficient characteristics. However, their environmental impacts is not clear yet. This study aims to achieve an environmental comparison of a steel and GRP slideways by applying the LCA standard techniques postulated by the International Organization for Standardization (ISO). A major goal of this study is to present the consequences of the material choice and provide necessary tools for designers and other decision-makers at Ampelmann operations to evaluate the trade-offs they must make between environment-friendly materials. Consequently, the result of this study can be applied by all relevant industries such as composite manufacturers and builders in making similar choices or creating a basis for which their operational policies are implemented.



a) Composite slideway b) Steel slideway



a) Composite slideway b) Steel slideway

Figure 1: Ampelmann slideways (Netherlands Patent No. 9663195, 2015)

1.4. Background on composite structures

Specific materials have specific chemical or physical characteristics that are unique to them (Dorey, 2011). Some of these characteristics may not be suitable for a given function and duration. Composite materials are therefore formed from a combination of two or more materials in order to achieve a desired characteristic such as strength, durability, etc. The materials are combined using a binder or matrix which forms a bond with the reinforcement materials (Royal Society of Chemistry, 2015). Fillers are other particles that are sometimes added to the composite as a means to improve specific properties like fire retardancy, strength and cost reduction. The Addition of fibre to the polymer matrix also increases the mechanical strength of the composite material as compared to the neat polymer.

The application of composite materials has been growing in different sectors, most notably in automotive, aerospace, offshore and energy industries because they are lightweight, have higher strength, require less maintenance and have longer life span (Yang Y. , et al., 2012) when compared to steel.

There are different types of composites (Pickering, 2005) and are usually classified based on two main criteria i.e. structural and materials used. The structural classification as shown in Figure 2 describes how the components are put together and fabricated while the material classification (shown in Figure 3) describe the type of materials that the composite is made of. In this report, I deal with glass-fibre reinforced plastic composite which consists of PVC foams and textile fibre glass filaments. Glass-Fibre-Europe, the European Glass Fibre Producers Association, represents approximately 95% of the European production of Continuous Filament Glass Fibre (CFGF) which has been commercially manufactured and marketed for more than 60 years (PwC, 2016).

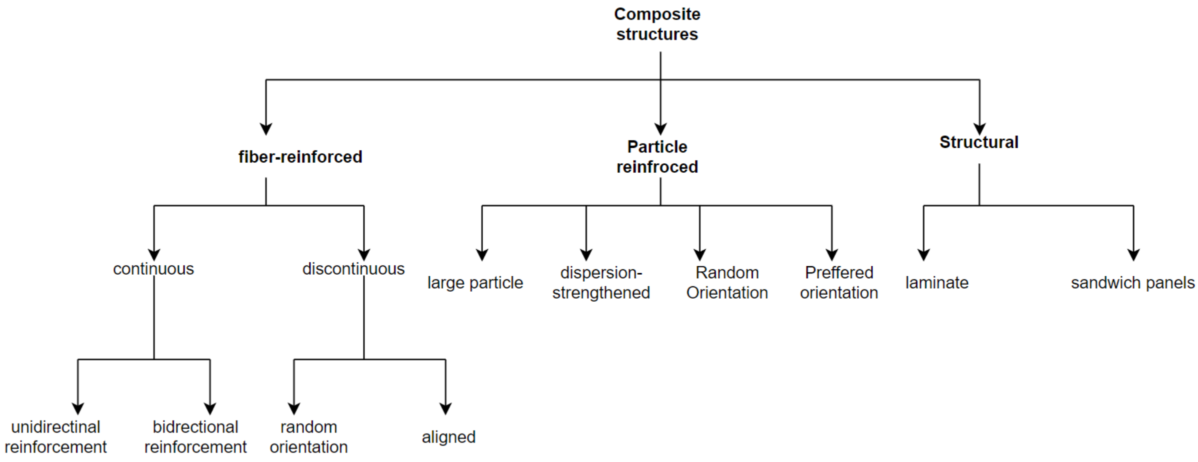


Figure 2: Structural basis of composite classification (Jayaram & Lang, 2013)

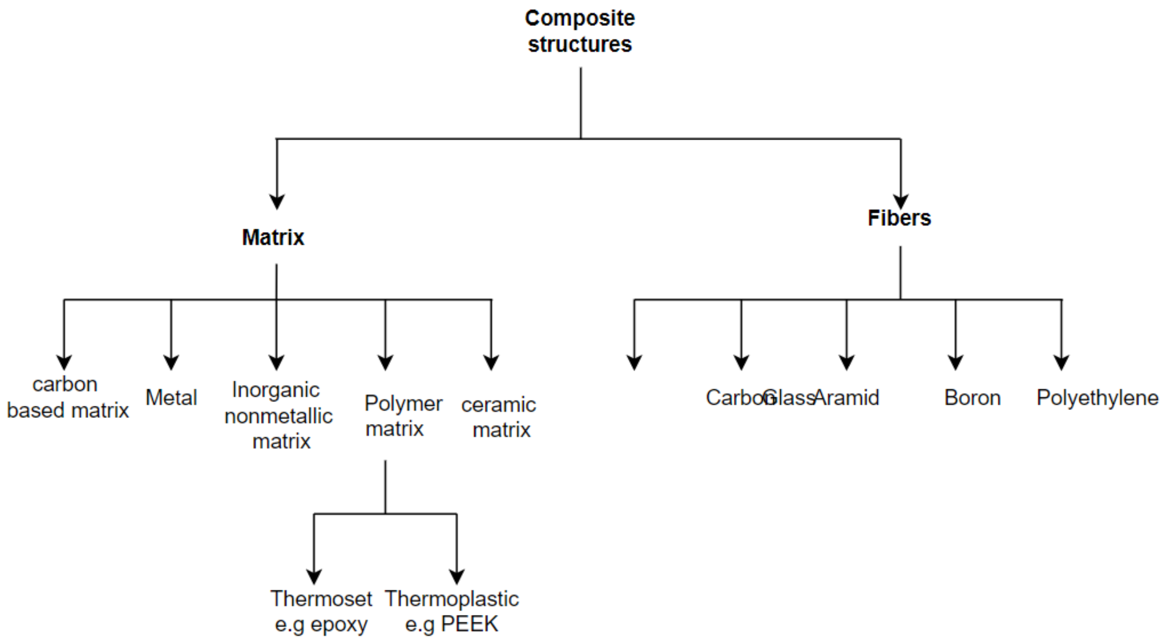


Figure 3: Material basis of composite classification (Jayaram & Lang, 2013)

Epoxy is one of the thermosetting polymer resins with excellent properties (Yongtao, et al., 2015) and possesses an outstanding cost to performance ratio. Some of the properties possesses by epoxy are good adhesion to substrate materials, low viscosity, high strength low creep and low shrinkage during curing (Yasser, Abdolhossein, & Amin, 2015). Due to these excellent properties epoxy resin is widely used for many composite applications such as in ship building, aerospace, automobile and structural applications. Epoxy adheres to Carbon Fibre, Fiberglass, and Aramid (Kevlar) very well and forms a virtually leak- proof barrier (Yasser, Abdolhossein, & Amin, 2015). Epoxy also adheres to older epoxy and to most materials quite well. Typical shrinkage of an epoxy is reduced to around 2%.

Having mentioned the structural integrity of fiberglass epoxy, it then becomes paramount to improve the environmental performance of this product across its life cycle. Increasing demand for information on the environmental impact of any products has led major companies and governments to carry out Life Cycle Assessment of their product and incorporate it into their eco-design (PwC, 2016). For this reason, this study provides the required information on the LCA performance of an epoxy glass fibre reinforced with plastic to form a glass reinforced plastic (GRP) composite.

The information from this assessment will contribute to the limited studies that are available on LCA performance of composites and can be used as a basis for the assessment of environmental impacts of glass-based composites.

1.5. Background on steel

Steel has been a dominant material in all sectors of production, fabrication and construction. It continues to be the leading metals' industry in scale and value and a significant indicator of an economic wellbeing (National academy of science, 1975) . steel is an alloy of iron and carbon in which the carbon content ranges up to 2% (Wente, Wondris, & Nutting , 2019). By far the most widely used material for building the world's infrastructure and industries, it is used to fabricate everything from sewing needles to oil tankers. In addition, the tools required to build and manufacture such articles are also made of steel. As an indication of the relative importance of this material, in 2013 the world's raw steel production was about 1.6 billion tons (World steel production, n.d.), while production of the next most important engineering metal, Aluminium, was about 47 million tons (World steel production, n.d.). The main reasons for the popularity of steel are the relatively low cost of making, forming, and processing it, the abundance of its two raw materials (iron ore and scrap), and its unparalleled range of mechanical properties.

Steel will continue to be manufactured on a larger scale throughout the twenty-first century to meet future material consumption needs, according to several research. Primary steel production is expected to peak around 2045 due to the increasing secondary steel production, which will dominate the production and market by around 2065 (Ryaber, Wang, Kara, & Hauschild, 2018).

However, the environmental consequences of steel production, fabrication and use has been an interesting issue among scholars and stakeholders (Suzzanne, Damien Giurco, Paul James Brown, & Renu Agarwal, 2014). This LCA study was - therefore - developed to map out the environmental impacts associated with steel construction by soliciting the support (provision of reliable primary data) from Ampelmann Operation's design models. Recommendations made by the EU include the use of full life cycle assessment (LCA) to measure the footprint of products and materials (European commission, 2019). In order to identify environment-related emissions and improve manufacturing processes in an economical and environmentally friendly manner, LCA can be used to track and quantify the most important sources of emissions throughout the life cycle, from the extraction of raw materials to the final product. Use or elimination [(Chisalita, et al., 2019), (Burchart-korol, 2013)].

2. Methodology

2.1. Approach

Life cycle assessment (LCA) is a method that is used to evaluate the environmental impacts associated with any given product, processes or services. This evaluation is done through specific methods that have been developed over the years by different researchers and organizations. The International Organization for Standardization has developed consistent standards that are applicable in a global sense such as ISO 14040 (LCA-Principals and guidelines), ISO 14041 (LCA-Life Inventory analysis), ISO 14042 (LCA-Impact Assessment) and ISO 14043 (LCA-Interpretation).This methodology identifies energy, materials and emissions that are involved in the life cycle of a product in four main stages: material production phase including raw material extraction and processing, manufacturing phase, use phase and end-of-life phase.

The environmental uncertainties that are involved in the development of new products can be overcome by performing an LCA prior to deployment and comparing the outcome with an already available product. Thus, this study performs the life cycle assessment of a glass-fibre reinforced plastic slideway and a steel slideway that both function as a transportation link between a vessel deck and a platform. The LCA methodology based on ISO 14044 standard is used in GaBi software database whereas the life cycle inventory data of the GRP including energy input and fabrication process is collected based on UK standards since the GRP slideway were fabricated in the United Kingdom while the assembly and use phase inventory data of the Netherlands is used. All the input and output data for the steel slideway was derived from the Dutch standards.

The environmental impacts of the GRP composite are then compared with a steel slideway of a similar function. From cradle-to-grave life cycle inventory studies were performed for each of the slideways. For the disposal phase, two scenarios were implemented i.e. incineration and landfilling for the GRP composite while steel waste was recycled. On the other hand, three main impact categories were used to indicate the quantitative impact assessment, these are: global warming potential (GWP) over a period of 100 years, Ozone layer depletion, and acidification

In order to quantify the environmental performance of both materials i.e. steel and GRP, a quantitative LCA methodology was used according to (ISO 14040, 2006) and (ISO 14044, 2006) standards. A complete LCA study includes four stages i.e. goal and scope definitions, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation (ISO 14040, 2006).

In this report, the life cycle assessment is carried out from the material acquisition, processing, manufacturing, product life and end-of-life stages generally referred to as cradle-to-grave (ISO 14040, 2006). Due to the limited time and lack of resourceful data, recycling was not included in this study and the end-of-life (EOL) materials were either sent to incineration or landfills. A complete LCA usually follows from analysing an inventory of all emissions and resource consumptions during a product’s entire life (Prek, 2004) in a table termed as inventory results.

This study will be available to different departments of Ampelmann that assess engineering improvements during production and design, set new sustainable goals and create a tool to implement innovative projects. They include: -

a) Concept and innovation.

b) Engineering design and production.

c) Quality, Healthy, Safety and Environmental Management (QHSE).

Data collection, verification and validation was done through internal company data [e.g. design models], supplier and fabricator information, EU life cycle databases and UK life cycle databases for composite fabrication. The output data were measured in terms of emission and converted to CO_2 equivalent indicator under the LCIA heading. Impact categories are scientific definition linking specific substance to a specific environmental issue. For example, the issue of global warming is represented by the global warming impact category. Any emission to air that contributes to the global warming potential such as CO_2 and methane are classified as contributors. It may also be the case that substance may contribute to more than one impact category. If this is the case, they were classified as contributors to all relevant impact categories. The results of the LCIA are then converted into the reference unit of the impact category. For example, for global warming potential all quantities are converted to kgCO_2 equivalent because CO_2 is the reference category in this case.

The data used for this study includes the design of slideway as shown in Figure 1 without the inclusion of the hexapod, or the base frame. The energy calculated during use phase is limited to energy demand of the slideway opening and closing and does not include the energy needed to operate the entire Ampelmann system.

2.2. Assumption and Exclusion

Due to time constraints, a streamlined LCA was performed in this study. A streamlined LCA is a slimmed down version of full LCA (desai, 2009) where techniques that purposely adopt a simplifying approach to LCA are implemented. (Curran & Young, 1996) have concluded that 80% of the environmental cost of a product are determined at the design phase and consequent modification have little effect. In order to prevent streamlining away any core information, the following rules are applied: -

- Screening for non-acceptable elements, e.g. if lead or asbestos is present, the streamlining is halted.
- Include only selected environmental impacts
- Include only selected inventory in the above impacts.
- Peripheral tools used to manufacture the slideways were not taken into account, such as the use of hardhats, gloves, first-aid kits, fire prevention materials, storage facilities etc.
- Transportation fuel used over the distance of travel was included.

The above rules have been used in various studies such as (Yixuan, James, & Morton, 2021) and (Curry, Gribbel, Powel, & Waite, 2011). The results from these studies indicated the revelation of up to 86% of the main environmental issues within a small-time frame of conducting a full LCA. These rules ensure that any core information that would be included in a full LCA is not streamlined away while allowing simple and cost-effective method of getting an accurate result.

The following rules were applied to materials and manufacturing: -

- Parts that have the same material were grouped together (in weight) and not considered as separate parts. An example would be that All materials made of MDS 155 (Stainless steel) or MDS 312 (aluminium plates) were grouped together instead of separating them into handrails, welding etc.

- Too small parts with diversified materials (such as small electronics) were be combined and simplified, provided these parts do not have an accumulated weight of more than 0,5% of the total weight of the slideway. Due to their small weight compared to the whole slideway, simplifying should have a negligible effect on the outcome.
- Materials that account to less than 0,2% of the total weight of the slideway were initially not taken into account (provided that material doesn't have an extremely large environmental impact and all the neglected materials combined do not add up to more than 1% of the total).
- Extra-added material (such as: trace metals in steel) were taken into account during processing but not their extraction.
- The oil (hydraulic fluid) needed for the moving parts (such as sliding wheels, and boom's in and out motion) were considered as lubricants during use phase.

The use scenario of the slideways was modelled as follows: -

- The average lifespan of the Ampelmann system was taken be 10 years with maintenance occurring periodically including daily inspection, 6-month maintenance and yearly maintenance.
- Energy consumption was calculated based on average 10 hours of daily operation in terms of kWh. This calculation can be found under the appendix.

2.3. Software

In order to apply the aforementioned methodology in a reliable and standardized way, LCA is performed by means of commercial software. There are a lot of suppliers of LCA software tools in the market that are intended for different types of users and designs. The major difference between these types of software is in the database and in the methodology adopted.

GaBi is one of the most trusted LCA software tools with a largely trusted dataset that encompasses fast and reliable reporting, hence the reason for its application in this project. There are several methods of LCA available in GaBi such as Recipe (midpoint and endpoint approach), IMPACT 2002+, CML 2001, Eco-indicator 99, IPCC 2001 (Climate change) and IPCC 2007 (Climate change), TRACI, etc. The capacity of each of these methods to be used and the applicable impact categories are limited. For example, CML 2001 does not include categories such as fine particle formation, Fossil resource scarcity etc even though its data scope is within the global framework. On the other hand, the data scope of TRACI method is limited to North America and it would not be therefore suitable to be used in a European context much less in a Dutch framework. Eco-indicator 99 has limited environmental impact categories for it which it was modelled. This method does not include global warming, acidification potential or any environmental categories for assessment. It mainly focuses on human health and ecosystem quality (Park, Kim, Roh, & Ban, 2020).

For this project, Recipe (midpoint and endpoint approach) for impact assessment was applied. This method is the most suitable in a European context both in terms of data scope and the available impact categories. ReCiPe transforms the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. Unlike other approaches such as Eco-indicator 99, IMPACT 2002+, EPS method; ReCiPe does not include potential impacts from future extraction in the impact assessment but assumes impacts have been included in the inventory analysis (RIVM, 2011). Figure 17 shown the overall structure of the ReCiPe method.

3. Life Cycle Analysis (LCA)

Life Cycle Assessment (LCA) is a tool that has been put in place in order to analyse and quantify the environmental burdens associated with the production, use and disposal of material or a product (Haggar, 2005). An LCA study involves a thorough inventory of the energy and the materials that are required across the industry value chain of the product, processes or services, and calculates the corresponding emissions to the environment. For this reason, I can conclude that LCA assesses the cumulative potential environmental impacts with the aim to improve the overall environmental profile of the product. Widely recognized procedures for conducting LCAs are included under the international organization for standardization (ISO) 14000 series of environmental management standards. In particular ISO 14040 and ISO 14044. They provide the framework and principles of the standard as well as the requirements and guidelines for LCA studies.

The essence of a LCA is the identification, examination, and evaluation of the relevant environmental implications of material, process, products or systems across its life span from creation to waste, or preferably re-creation of the product in the same or different form.

A life cycle assessment is a large and complex effort, and there are many variations. However there is a general agreement on the formal structure of LCA, which contains four stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation.

This section of the report details and discusses various stages that are necessary to perform a LCA study as shown in Figure 4.

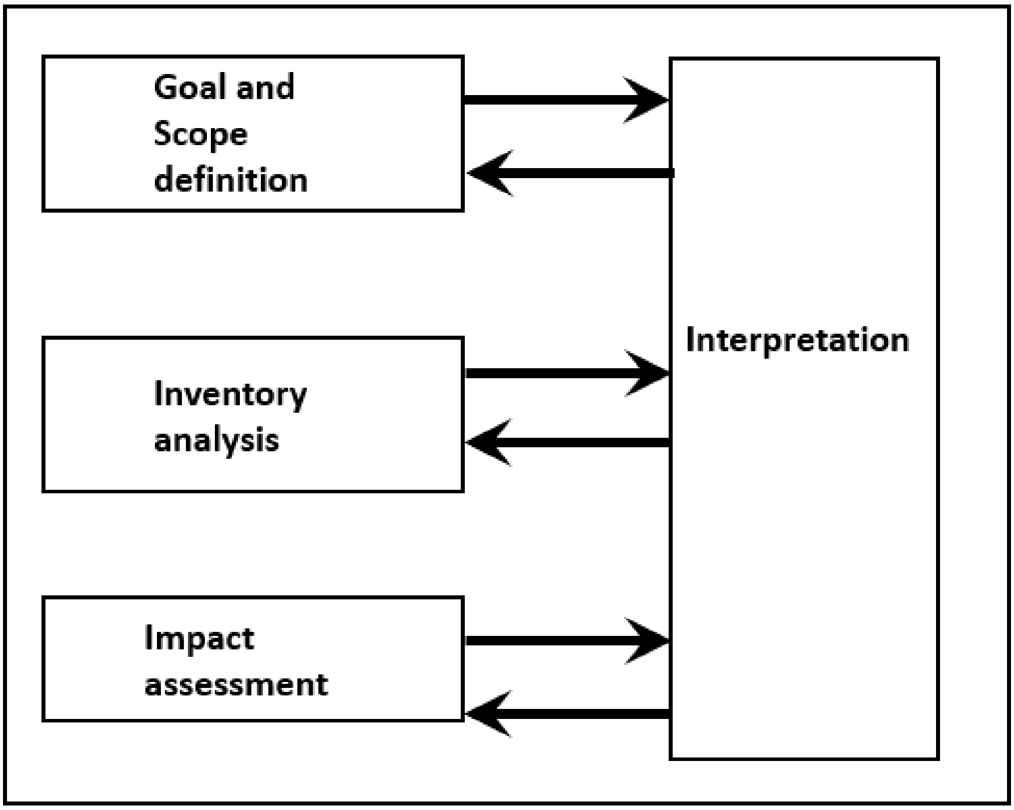


Figure 4: Phases of LCA (ISO 14044, 2006)

3.1. Goal

The definition of the purpose of the LCA is an important part of the goal definition (ISO 14044, 2006). The goal of an LCA should unambiguously state the intended application including the reason for carrying out the study and intended audience, i.e. to whom the results of the study are intended to be communicated. The goal definition has to define the intended use of the results and the user of the results (ISO 14044, 2006).

The goal of this study is "to evaluate the environmental impacts of two transportation slideways throughout their entire lifespan and to also assess their energy needs and optimization scenarios." The slideways are made of either steel, or glass-reinforced plastic composite. The lifetime of all the slideways are assumed to be 10 years which is consistent with their design criteria. The maintenance is evaluated according to the company policies which are daily inspections, 6-monthly and yearly maintenance.

The results is intended for internal use at Ampelmann Operations. This study will provide the company a better understanding of the environmental impacts of a composite slideway compared with steel slideway.

3.2. Scope Definition

The scope of the LCA sets the borders i.e. what is integrated into the system and what assessment methods are to be used. It is required that the scope should be defined such that the breadth, depth and details of the study are sufficient to achieve the required goal (ISO 14044, 2006). The following are items included in the scope definition: -

- Functional unit (FU)
- System boundaries
- Allocation procedures
- Impact types and impact evaluation methods
- Data requirements

3.2.1. Functional unit

Functional unit is the quantified definition of the function of a product system with a physical unit (Consequential-LCA, 2015). Functional unit is important when products with different range of functionalities are to be compared. All data collected in the inventory phase was related to the functional unit. When comparing different products fulfilling the same function, then defining a consistent functional unit for all these products is of essence (ISO 14044, 2006). Functional unit's principal intention is to provide a reference to all inputs and outputs.

The functional unit of this study is "1kg of slideway that can transport people from the ship platform to the deck over a life span of 10 years". This is adopted in order to compare the endurance and carbon footprint of the different materials over long periods of operation. In addition, this functional unit provides us with the evaluation criteria for materials of different masses since the slideway components have different values per material. This functional unit also makes it possible to compare results of the same material if it's applied under different circumstances of application. For example, if the composite structure is used as a floor slab, then it becomes possible to use same results of comparison since a floor slab is designed to carry specified load for a certain duration.

3.2.2. System boundaries

To determine which unit process are included in the LCA study, the system is broken down into process units that encompass all elements, materials, and components that constitute the slideway. The system boundaries define the processes/operations (e.g. manufacturing, transport, and waste), and the inputs and outputs to be taken into account in the LCA. The input can be the overall input to a production as well as input to a single process- and the same is true for the output.

The definition of the system boundary is quite subjective. For example, one may decide to include all parts of a product system that contribute more than 5% to the overall weight, other criteria might include the number of processing steps, or the estimated contribution of the materials or processes to the estimated overall environmental impact. To determine which unit processes are included in the LCA study, the system is broken down into process units which encompass all the elements, materials, and components that constitute the slideway. Fully establishing the system boundaries requires not only defining process units but also determining the life cycle phases to be included in the assessment ((ISO 14040, 2006).

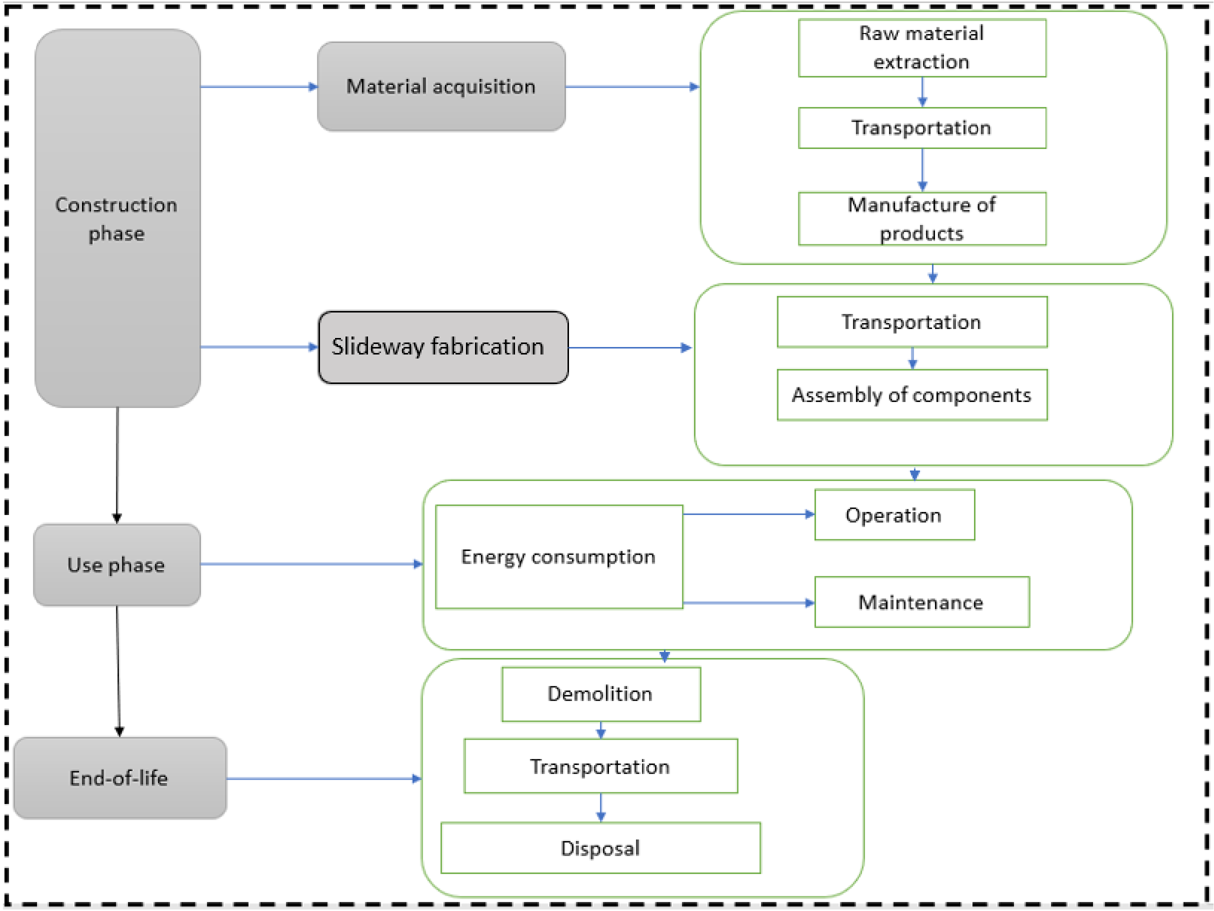


Figure 5: System boundary of this study

When more than one product is produced, the input and output data has to be portioned according to their relative contribution to one product or the other in what is called allocation. (ISO 14044, 2006) advises to avoid such partitioning as it could be difficult and requires carefully chosen procedures. Figure 5 shows the breakdown of the life cycle phases of the system where the boundary of the study is defined from extraction of raw materials to disposal of waste at the end of its life cycle.

3.2.3. Data quality requirement

The use and collection of quality data is reflected in the quality of final LCA (Jose & Gutierrez, 2010). The description and assessment of data is done in a systematic way in order to allow others to control the data quality. (ISO 14044, 2006) establishes parameters for initial data quality such as geographical coverage, time related, precision, representativeness, consistency, reproducibility, and technological coverage. The ISO 14040 and 14044 documents do not further define how these areas are to be addressed, but rather leaves this task to the discretion of the individual.

First, the production and fabrication data as well as energy input data in this study was collected from a European-based processing and fabrication company. This was done to fulfil the geographical coverage requirements of the ISO standards. Netherlands and UK national annex electricity grid was the primary source of energy input for both slideways. Furthermore, to ascertain the time related coverage requirement, data used was specified to have been collected and stored in program database for not more than 5 years. This includes the extraction and production of each input as stipulated by ISO 14044. This was meant to guarantee that the used data was relevant for the specified time ranges. Another important factor to ascertain was that the input data was complete as per the goal and scope definition, this was achieved by comparing and simultaneously recording both the design data from Ampelmann and the fabrication data sheet from Airborne. This step provided an extra check to ensure that all relevant input and output data for each category were implemented in the database.

The data representativeness was also addressed by creating a correlation between time period the data was collected and stored in the program database and the year of model fabrication. For most cases, the database contains records from the year 2017 to 2021 which falls within the design year of the slideways.

3.3. Life cycle inventory analysis

The inventory analysis involves quantifying the different flows from and to nature for the product system (ISO 14040, 2006). The quantitative values of the materials and the energy inputs and inputs and outputs of all process stages within the life cycle of the slideways are determined and recorded in Table 1and Table 2. The elements in the list are taken from the design models of Ampelmann systems and Airborne Manufacturing Record Book. The energy use is a combination of calculation of production and estimation from the daily operating hours of the entire Ampelmann system scaled to only the slideway.

For the energy production of composite and steel structures, figures from previous studies are taken and assumed to hold since the geographical area of production and techniques used to produce them are similar.

Table 1: Steel slideway inventory data

Components	**Material type**	**Code**	**Quantity**	**Unit**	**Normalized quantity (kg)**	**Functional unit**
Plates	Stainless steel	MDS 155	9.52	Kg	6.06E-3	Kg/kg
	Structural steel	1.0570 S355J2+N	253.22	Kg	1.61E-01	Kg/kg
	POM		3.67	Kg	2.34E-03	Kg/kg
	PTFE		8.66	Kg	5.51E-03	Kg/kg
	Nylon		0.1	Kg	6.36E-05	Kg/kg
Welding assembly	Steel hot rolled	S355J2+N	61.97	Kg	3.94E-02	Kg/kg
	aluminium	MDS 312	39.48	Kg	2.51E-02	Kg/kg
Grating	GRP		93.9	Kg	5.98E-02	Kg/kg
	Stainless steel	MDS 155	0.72	Kg	4.58E-04	Kg/kg
connections	Stainless steel cold rolled	MDS 155	14.44	Kg	9.19E-03	Kg/kg
	Structural steel	S355J2+N	19.52	Kg	1.24E-02	Kg/kg
SHS & RHS	Steel sections	S355J2+N	875.91	Kg	5.57E-01	Kg/kg
Angels	Structural steel	S355J2+N	81.92	Kg	5.21E-02	Kg/kg
LED*	diodes	--	--	kWh/day	--	kWh/kg
Rod	Steel alloy	1.658(34CrNiM06)	80.54	kg	5.13E-02	Kg/kg
	Structural steel		14.34	kg	9.13E-03	Kg/kg
TOTAL			**1557.91**			

Table 2: Inventory data of composite slideway

Components	**Material type**	**Code**	**Quantity**	**Unit**	**Normalized quantity**	**Functional unit**
Stainless steel		MDS 155	315.01	kg	2.68E-01	Kg/kg
Aluminium plate	aluminium	MDS 312	6.59	kg	5.61E-03	Kg/kg

Handrails	Aluminium extrusion profile	MDS 302	47.3	kg	4.02E-02	Kg/kg
PVC	plastic		121.19	kg	1.03E-01	Kg/kg
Glass	Glass fibre		315	kg	2.68E-01	Kg/kg
Epoxy adhesive	epoxy		19.55	kg	1.66E-02	Kg/kg
Epoxy resin	epoxy		229	kg	1.95E-01	Kg/kg
grating	GRP		80.45	kg	6.85E-02	Kg/kg
Vacuum bag	nylon		4.8	kg	4.08E-02	Kg/kg
LED*	diodes		--	kWh/day	--	kWh/kg
Paint	Epoxy primer + hardener	Interthane 300DS/990DS	36.6	kg	3.23E-02	Kg/kg
Total			**1138.89**			

*See the calculation in appendix and table 7

Table 12 and Table 13in the appendix shows how the above inventory is represented and modelled in GaBi software.

3.3.1. Energy calculation and estimation

Energy input for slideways occurs at different levels i.e. fabrication phase, use phase and end-of- life phase. Due to the unavailability of energy input during fabrication by Airborne, an estimate taken from previous studies such as (Dai, Kelly, Sullivan, & Elgowainy, 2015) who have analysed the energy input at different levels of fibreglass manufacturing process. They focus mainly on the energy intensity of E-glass production which is the same type of glass used in the Ampelmann slideway. On the other hand, energy consumed during epoxy production have been documented by (Sunter, Morrow, Cresko, & Lidell, 2015) in their study of energy intensity production of carbon fibre polymers. The production techniques and material input in these studies are similar both during extraction and production to the Ampelmann slideway, making them a relevant estimate applicable to this study. The calculation of energy use during operation and end-of-life is represented below. Table 3 shows a comparison of different studies in the energy use during fabrication of different composites e.g. GFRP and Carbon-fibre-reinforced plastic (CFRP) while Table 5 shows energy used by glass-reinforced composite fabrication process.

Table 3: Energy values for composite production (Sunter, Morrow, Cresko, & Lidell, 2015)

Process	Current Typical [MJ/kg]	State of the art [MJ/kg]	Practices [MJ/kg]
Carbon Fibre production	1134	1134	330
Resin (epoxy) Production	89.8	8.70	3.63
Composite Production (CFRP)	39.5	39.5	29.3

Table 4: Energy consumption for E-glass production (MMBtu/ton) (Dai, Kelly, Sullivan, & Elgowainy, 2015)

Processing stage	(Ruth & Dell'Anno, 1997)	(DOE, 2002)	(Worrel, Galitsky, Masanet, & Graus, 2008)	(Rue, Servaites, & Wolf, 2017)	(Scalet, Garcia, M., Roudier, & Delgado , 2013)
Batch preparation	1.15	0.68	1.1	1.1	--
Smelting and refining	9.89	5.6-10.5	6-7	5.6-10.5	6.02-15.48
Forming	7.24	7.2	1-2	2-5.5	--
Post forming	2.74	3.28	1-2	3.3	--

Table 5: Energy consumption for GRP composites fabrication process (Dai, Kelly, Sullivan, & Elgowainy, 2015)

Input	SMC	Prepregs	RTM
Energy consumption (MMBtu/ton)	3.0[a] 3.3[b]	3.7[a]	11.0[a]

[a] (Suzuki & Takahashi, 2005) [b] (Das, 2011)

Table 6: Assumption for fabrication energy of steel (Sunter, Morrow, Cresko, & Lidell, 2015)

	Value	Unit
Raw material embodied energy	23	MJ/kg
Energy required to manufacture steel ingot into coil	6.4	MJ/kg
Energy required to stamp steel	5.1	MJ/kg
Energy required for steel assembly	0.7	MJ/kg

Table 11 shows the daily operation hours of the hexapod which is used to calculate the energy use and scaled down to reflect the energy demand of the slideway. This energy is calculated in twofold: -

1. Energy used to signal and operate the traffic lights
2. Energy used to move the slideway

Table 7: Energy used to signal and operate traffic light

Type	Model	Power (W)	Quantity	Operation [hours/day]	Energy (kWh/day)
Traffic light	**30PRG100HDUAL**				
	68/76 LED green	10.6	1	10	1.06E-01
	68/76 LED red	7.3	1	10	7.3E-02
LED light	Dutch-electro TR40WT_409mm-solid REV001	8	4	10	3.2E-01

Table 8: Energy used to operate the slideway

Energy demand	Power (W)	Duration of operation (hrs)	Energy (kWh/day)
Composite slideway	18.32	10	0.183
Steel slideway	17.47	10	0.175

3.3.2. Transportation estimates

The transport is made with a maximum of 14ton truck and EU diesel mix at the refinery. Estimated distance from the fabricator (Airborne) to the Ampelmann assembly site = 540km.

Table 9: Transportation estimates

Transport type	Distance [km]	Diesel efficiency	Diesel energy	Energy for transportation
Truck 12–14-ton gross weight	540	3.33litres/km	34.62MJ/litre	4.42MJ*

* See the calculation in the appendix

3.4. Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment is the third phase of a LCA study and it involves evaluating the environmental impacts that stem from elementary flows (environmental resources and releases) "by converting the life cycle inventory results into specific impact indicators" (Mu, Xin, & Zhou). GaBi is modelled to calculate the quantification factor of each impact category and outputs a potential contribution to the environmental load. The (ISO 14044, 2006) standards formulate the mandatory steps needed to conduct LCIA and they include: -

Selecting impact categories which are divided into ecosystem impacts, human impacts and resource depletion as shown in Figure 6. As the environmental performance of a product may differ depending on the environmental impact assessment categories or assessment criteria, these categories and assessment criteria were defined according to the assessment target and purpose.

Figure 6: Impact categories (Mu, Xin, & Zhou)

The second step involves *assigning the inventory results* into different impact categories where each resource and emission was assigned to one or more impact categories (otherwise known as classification). Impact categories are scientific definitions that link specific substances to a specific environmental issue. The third step is the *calculation of the potential* impact indicators. The calculations are automatically generated by the model program and displayed in graphical format which is used in the result evaluation.

In this study, four impact categories were implemented in GaBi software, namely: -

1. *Global Warming Potential* (GWP) which represents the issue of climate change due to greenhouse gas emissions and is characterized by $kgCO_2$ equivalent.
2. *Ozone Layer depletion* (OD) that results from the combination of chlorine and bromine in the stratosphere to cause destruction of ozone molecules.
3. *Eutrophication Potential* which indicates the “amounts of nutrients released into fresh water sources such as rivers and lakes that lead to excessive algae growth” (Wildeman, 2020) and
4. Acidification potential which shows the amount of acids in the atmosphere that may lead to acid rain (Dincer & Abu-Rayash, 2020).

The choice of these impact categories is entirely subjective and depends on the aim of study being performed as well as the desired outcome. Given the right input, GaBi program can calculate wide variety of impact categories, some of which are not necessary in this study because they don’t generate significant loads on the environment. This study performs the assessment of slideways from climate change perspective which is represented by GWP category. This category is applied to assess how much heat is trapped in the atmosphere as a result of greenhouse gases emitted during production and fabrication of the slideways. Terrestrial acidification is chosen as a method to quantify the release of acid-rain-inducing sulphates and nitrates. Furthermore, ozone layer depletion occurs due to the release of chlorofluorocarbons such as CFC-11 which is used in the production of rigid foams. Such a foam is also an input for the composite slideway, which makes the application of this impact category relevant to this study. It is also important to assess the impacts of the slideways on water sources such as lakes, rivers or seas. This assessment is achieved by calculating the eutrophication potential of the slideway inputs and outputs. The EP is expressed as a Phosphate equivalent, which is used as flame retardants in plastics and as an agent to reduce corroding and insulation for steel production.

On the other hand, the applied LCIA method i.e. ReCiPe is a midpoint-level (problem-oriented) approach where environmental impacts are classified based on problems by inputs and outputs which makes these categories a suitable assessment method.

3.5. LCA modelling

The collected inventory data, characterization and the LCA methodology introduced in the previous chapters is modelled in a LCA software called GaBi. The program is equipped with various calculation techniques, impact assessment methodologies and contains large dataset that enables an easy modelling and detailing of the LCA study. This report uses the educational license of the software, implying that there is limited access to some of the database.

GaBi operates its LCA models in terms of plans, processes and flows which form a related and interconnected web of information that comes together to run an inbuilt calculation on the chosen categories. A plan contains the visual overview of the product life cycle with processes and flows in the form of a flowchart, while processes are simplified models of operation in which a conversion of objects or substance take place, they can be seen as black boxes with input and outputs in the form of flows.

The LCA model is divided into three main phases for both the composite and steel slideway as discussed below: -

3.5.1. Production phase

The production phase includes the extraction of materials, transportation and assembly of the slideway. The composite slideway is fabricated in the United Kingdom and transported to the Netherlands where is it is assembled. GaBi has an inbuilt database for extraction and production of different materials in forms of processes which are then combined together in a plan. An assembly flow diagram of the composite slideway is shown in Figure 16.

The production phase consists of different systems that are embedded into the plan. These systems are grouped on basis of composition, manufacturing techniques and material codes. The logic of these grouping is that the outcome of their environmental impact contribution is the same. For example, if different components, say, bolts, wheels and washers are made of same material (i.e. stainless steel) then they are grouped together (by weight) and modelled as stainless steel. The transportation of the products from the fabricator to the assembly point is modelled once since there return journey of the truck will not have an impact associated with the slideway.

During the inventory of the construction phase, I defined the flows of material and energy related to building the components of the slideways. The unit processes in GaBi are matched with their quantities from Table 1and Table 2. In addition to production of all construction materials, I also included their phases of transportation and assembly. The assembly of the components were created as process in which all materials (PVC, glass, epoxy resin, adhesive connection, railings, etc.) together with energy needed are inflows and the outflow being a unit slideway and emissions. To obtain the impact of transportation, truck 14 tons with a transportation distance of 540 km was used coupled with refinery diesel. Country specific energy sources are used since the GaBi data provides only regional aspects for this phase. Figure 7 shows the plan for composite production while figure 8 shows steel production plan.

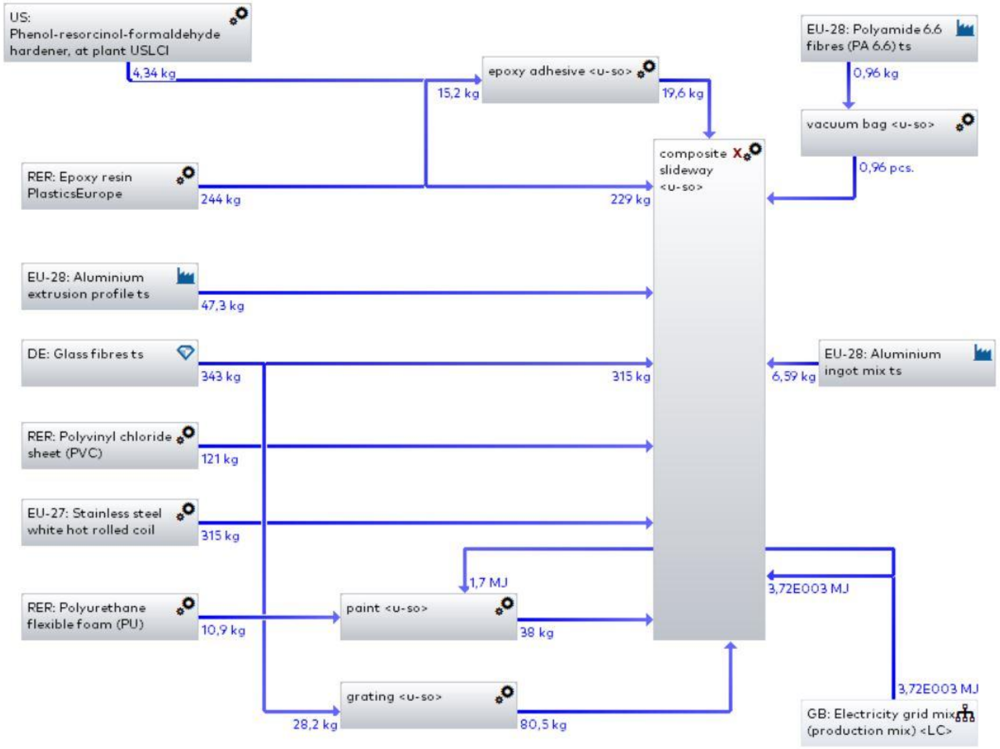


Figure 7: Composite slideway production plan

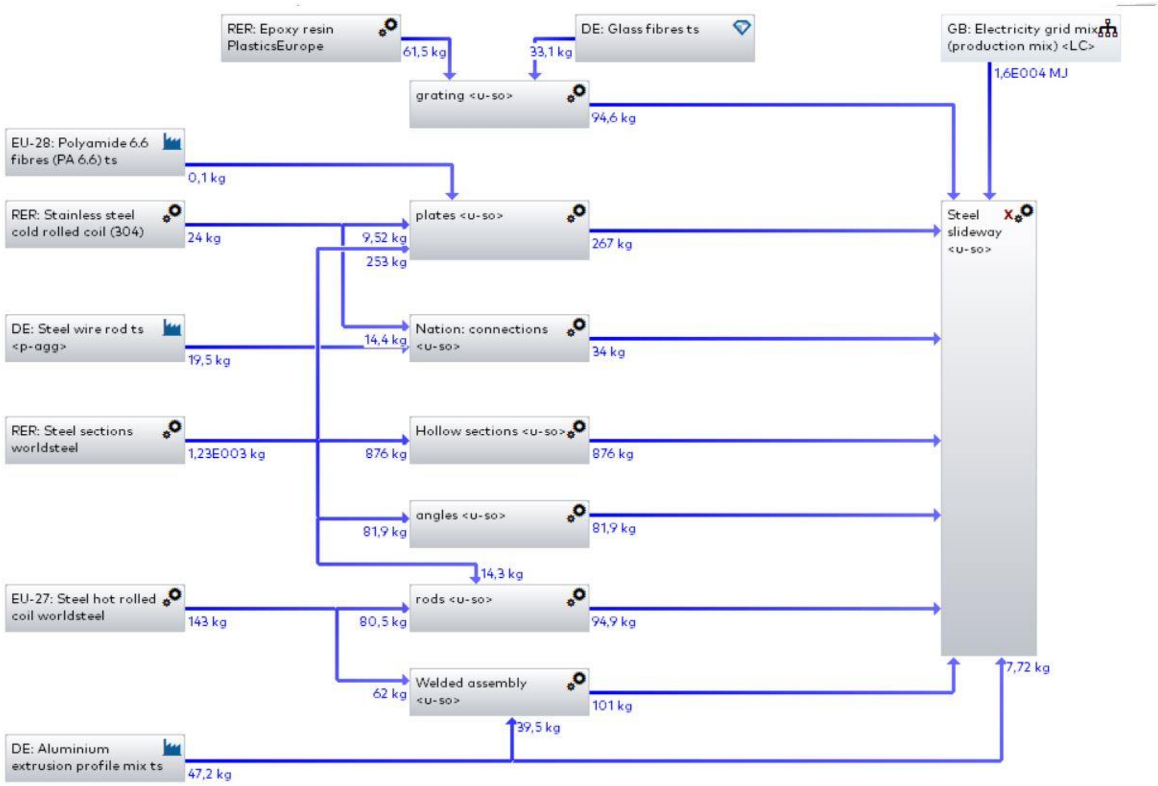


Figure 8: Steel assembly plan

3.5.2. Use and maintenance phase

The use and maintenance phase is modelled over a lifespan of 10 years which is line with the design guidelines for both slideways. In this phase, the systems is maintained periodically starting with daily inspections, 6-month maintenance and yearly maintenance. The internal company data shows that lubrication, painting and bolt replacement require most of the maintenance resources. the use of energy and electricity is modelled in kWh/day over a period of 10 years and included into the system intake.

The energy sources considered is electricity which is used primarily to operate the system in terms of signalling, lighting and slideway motion. The calculation and estimates of the energy consumption is described in the inventory analysis chapter. The input for this phase is therefore only electricity grid, spare parts for each component, lubricants, paints and transportation of these materials. The use of the same input data and the same calculation method enabled us to compare the energy performance of slideways easily and consistently.

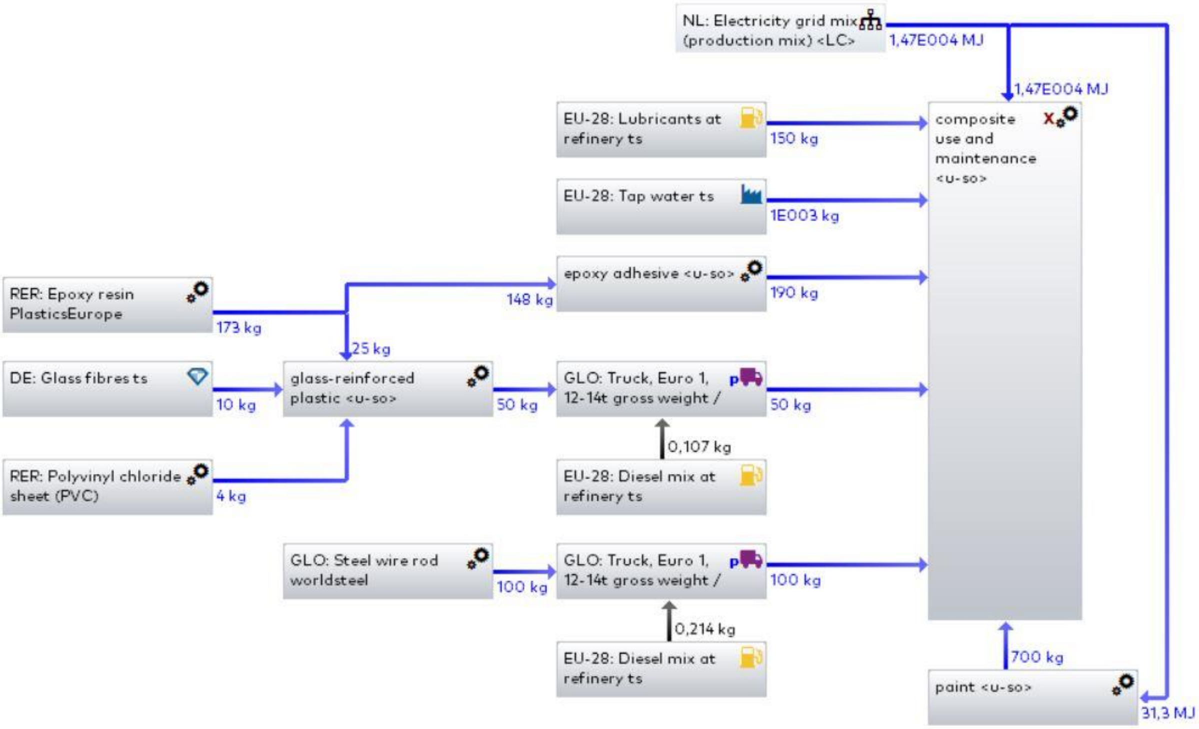


Figure 9: Composite use and maintenance plan

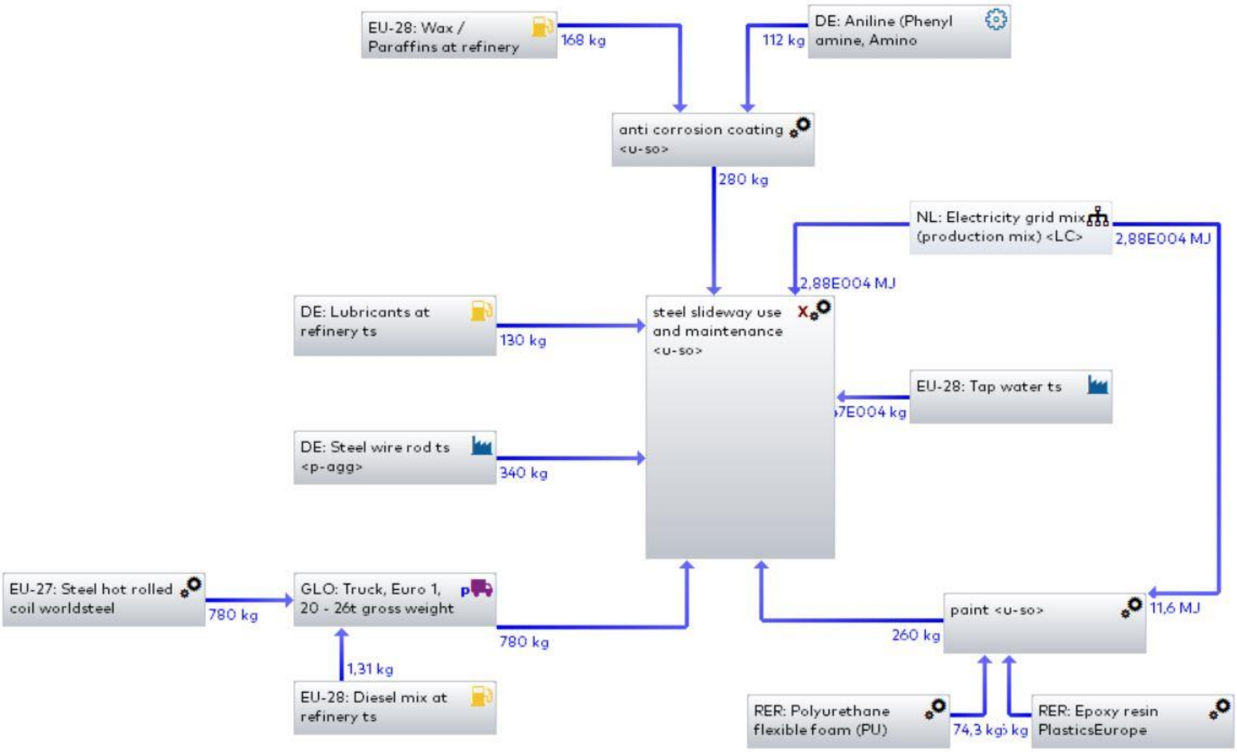


Figure 10: Steel use and maintenance plan

3.5.3. End of life phase

The EOL phase includes the dismantling of the system and distributing them to be processed. Within GaBi model, I created different scenarios for the EOL of both slideways. i.e. recycling, disposing (e.g. in landfills) or incineration.

The EOL of steel structures has been studied intensively in the previous decades. The American iron and steel institute postulates that steel is 100% recyclable into the same materials of same quality or into different materials. In his study "steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy" Clare Broadbent also proved that steel is 100% recyclable (Broadbent, 2015). For this reason, all materials made of steel are recycled and used as input for the system process again.

The EOL of composite structure is quite different. The recyclability of glass-fibre reinforced plastic has not been accurately established yet. In his study titled "A sustainable and viable method to recycle fibreglass", Andrew Bubb concluded that there is significant challenges in recycling of fibreglass due to problems that arise from separation and infusion of fibreglass into plastic sheets. Yet another study by (Yang Y. , et al., 2011) concluded that the recycling of composite structures is associated with lack of markets for recycled materials, high cost of recycling and lower quality of the recyclates compared to the virgin material. These bottlenecks hinder further use of recycled composites in aerospace and other engineering fields.

A recent study by (Oudheusden, 2019) indicated that even though there has been reduction in composites ending up in landfills, a more sophisticated recycling method and technology for composites is needed.

For these reason and reasons including absence of recycling database within GaBi, the EOL of composite processes are distributed into incineration and landfills and the outcome is explained under the discussion section.

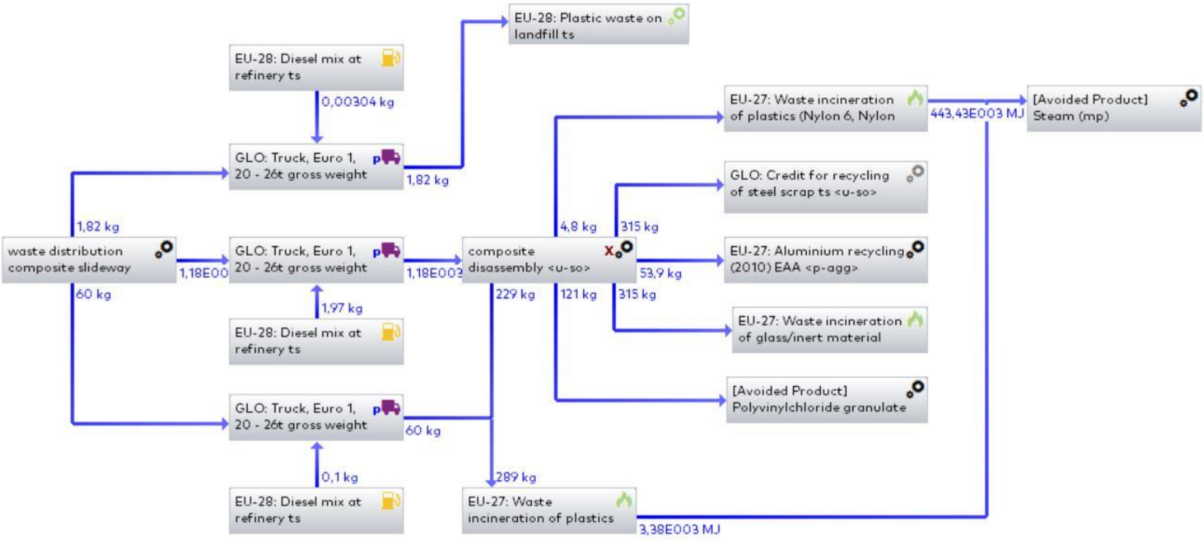


Figure 11: EOL of composite plan

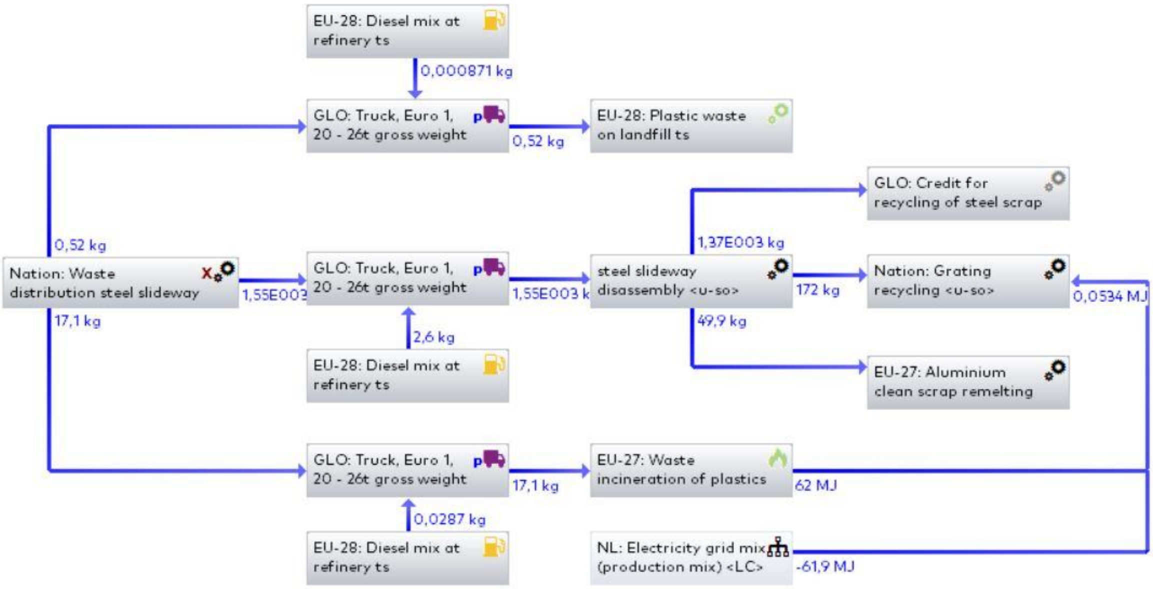


Figure 12: EOL of steel plan

4. Life Cycle analysis results

In this chapter, the outcome of the life cycle impact assessment is presented for the production, assembly and use of 1 slideway of each material. The LCIA includes methodologies for combining different emissions into a metric for the life cycle inventory. As mentioned in chapter 3.4, the impact assessment is carried out using ReCiPe 1.08 Midpoint (H) methodology. The result is displayed per slideway production.

4.1. Impact categories

as mentioned earlier, four impact categories are used in this report to analyse the environmental impacts of the slideways i.e. GWP, EP, AP and OD which are briefly explained here.

Greenhouse gases contribute to climate change by “absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the earth” (EPA, 2020). The lifetime of these gases in the atmosphere and their ability to absorb energy is also different and can cause confusion in comparing their impact on the environment (EPA, 2020). For this reason, global warming potential allows us to compare and contrast specific impacts of these gases. GWP achieves this comparison by calculating “how much energy the emissions of 1 ton of gas will absorb over a given period, relative to the emissions of 1 ton of carbon dioxide (CO_2) over that period which is usually 100years.” (EPA, 2020)

The GWP uses CO_2 as the reference substance and all the quantities are therefore converted to kgCO_2equivalent.

Acidification potential indicates factors that lead to acid rain such as sulphur dioxide (SO_2), Nitrogen monoxide (NO), nitrogen dioxide (N_2O) and other substances. Whenever there is combustion of fuel, these substances are released to the atmosphere and may lead to varying intensity of acid formation (Dincer & Abu-Rayash, 2020). AP uses SO_2 as the reference quantity and the results are recorded in kgSO_2-equiv.

On the other hand, the ozone layer blocks harmful UV rays, however, when CFCs are released to the atmosphere, they form chlorine through a chain reaction with UV rays in the ozone. This makes the ozone layer thin and thus more UV rays pass through and can cause detrimental effects on long exposure (Dincer & Abu-Rayash, 2020). GaBi uses the CFC-11 molecule as the reference unit to measure ozone depletion, and hence all quantities are recorded in KgCFC-11 equivalent.

4.2. Effects of slideways on different impact categories

Table 13 shows the overall performance of the slideways over a 10-year period. All the impact categories except acidification potential (AP) indicate that the GRP composite has the least total environmental burden.

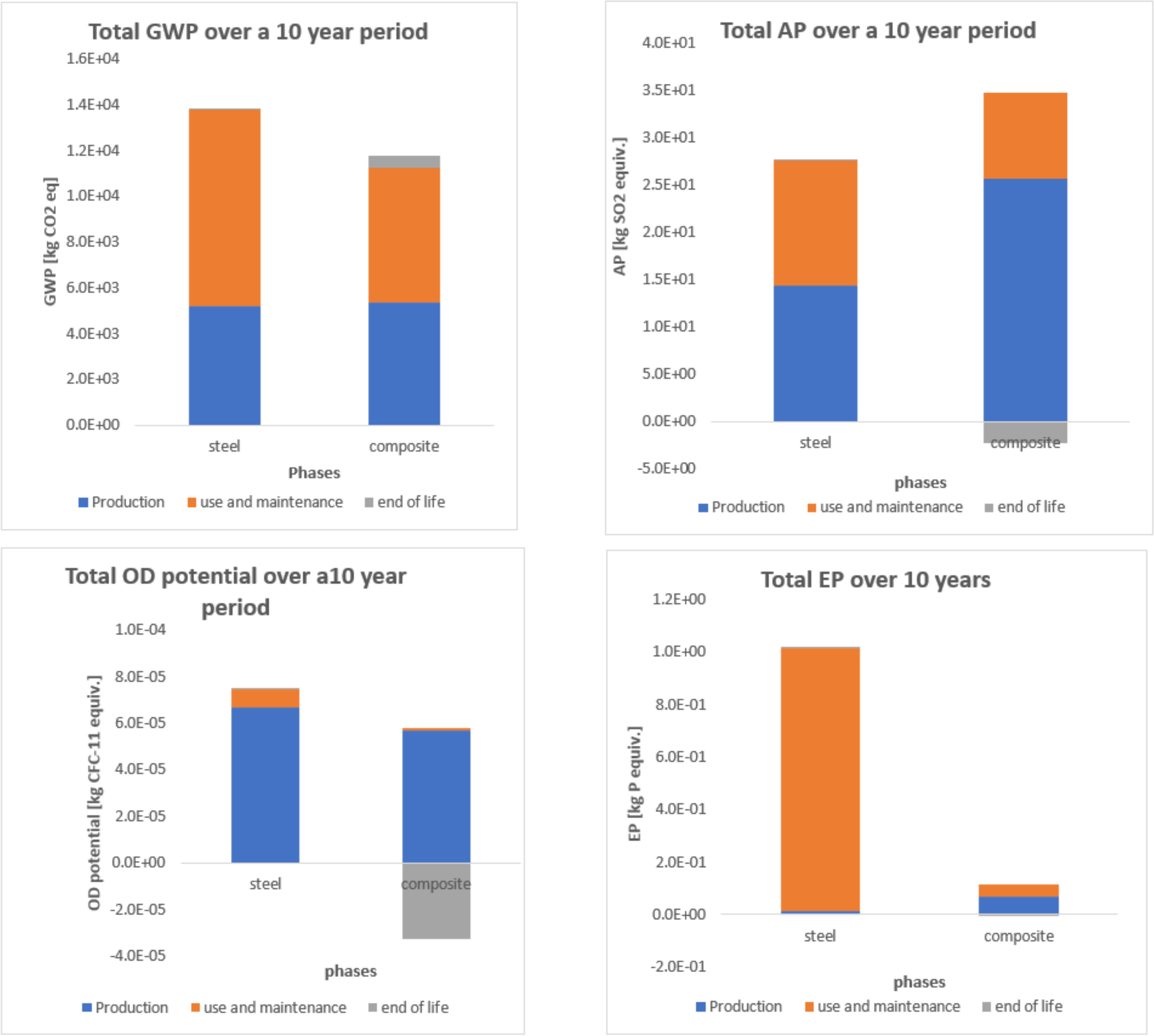


Figure 13: Total impact of slideways on the environment

A breakdown of the performance of both slideway at different life cycle phases is shown in Figure 14. The production phase of the composite slideway has the highest impact on the environment for the all the categories except the ozone layer depletion (OD) (5,623.89 kgCO_2 equivalent) compared to steel (5,221.63 kgCO_2-equivalent). The absolute emission is largest in the use and maintenance phase for both slideways. This is attributed to the lifespan (10 years) compared to the one-time construction and disposals. This holds not only for the indicator related to global warming potential but for all the other indicators.

For the use and maintenance phase, I observed that steel has the most environmental impact. this is mainly due to the lifespan of the slideways in which materials, electricity, transportation and energy are invested into the project togther with the limited parts that require replacement in the composite slideway. Steel strucutres generally tend to require constant spare parts, welding or anti-rust coatings to be applied, on the other hand, the composite requires minimal parts for its maintenance, mainly in terms of adhesives, since the structure itself is glued and moulded in place.

a counter intuitive scenario occurs when comparing the end-of-life cycle of the materials, it can be seen that the impact of the end-of-use of composite on its EOL phase is negative. This is attributed to the fact that the composite structure doesn't contain any chloride or fluoride components that would have been responsible for a chain reaction with UV rays which implies that the product is absorbing rather than releasing those emissions.

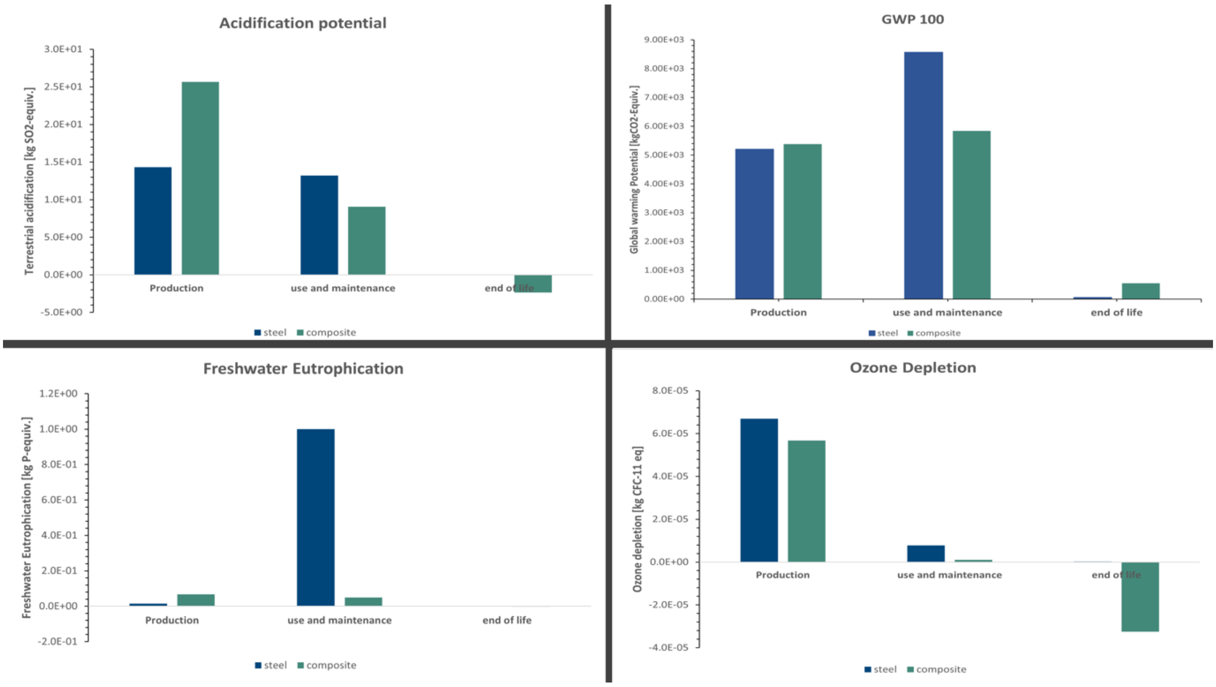


Figure 14: Environmental performance of the slideways at different phases

The graph of ozone layer depeltion does not have any similarities with the other categories. This graph shows that the production of steel has higher impact on the ozone than the composite slideway. This shows that the resources used in the production and assembly of composite doesn't not contain any controbuting factos to ozone depletion such as chlorides or fluorides. However, the effect of steel (7.23e-5 kgCFC-11 equiv.) on ozone is overwhelming outweighed by the effect of composite on global warming (865.23E+03).Freshwate eutrophication indicates the seepage of nutrients into the soil or freshwater bodies and the increase of nutrients in these water bodies. The graph shows that the composite slideway has highest impact on water eutrophication in all phases, with the use phase generating the most impacts.

For the composite slideway, the LCIA resulted in a GWP of 5,623.89 kgCO$_2$-equivalent for its production with the significant parameters being epoxy resin (accounting for 38% of the direct emissions), electricity (accounting for 22%) and glass fibre (which accounted for 11% of direct emissions). In the end-of-life phase, the most contributing factor to GWP emissions was the incineration of PVC foam which accounted for 38.5% of the total emissions and waste incineration of glass fibre which produced 34.5% of the emissions. Other processes like steel, was recycled while polytetrafluoroethylene (PTFE) components were converted into steam.

For the steel slideway, the LCIA resulted in 5,221.63 kgCO$_2$-equivalent for its production, 8,569.98 kgCO$_2$-equivalent during its 10-year operation phase and 57.2 kg CO$_2$-equivalent in its EOL phase. The significant parameters for the production and use phases were electricity which accounted for 50% of the emissions with hot-rolled steel components emitting a combined 19.0% of the emissions. 100% of the steel components were recycled while the GRP grating and incinerated producing a total of 57.2kg CO_2-equivalent emissions.

Table 10: Results for different impact categories

	Production phase				***Use & maintenance***				***EoL***		
	GWP100	*AP*	*EP*		*GWP100*	*AP*	*EP*		*GWP100*	*AP*	*EP*
Material/units	kgCO$_2$-eq	kgSO$_2$-eq	kgP-eq		kgCO$_2$-eq	kgSO$_2$-eq	kgP-eq		kgCO$_2$-eq	kgSO$_2$-eq	kgP-eq
GRP composite	5623.69	25.67	0.068		5842.78	9.1	0.049		549.25	-21.25	-1.7e-4
steel	5221.45	13.212	0.014		8569.88	14.33	1		57.4	0.047	5.0e-5

According to table 10 the least environmental impact category for both slideways is Eutrophication potential with a combined negative effect, implying that resources were absorbed rather than emitted or released to the environment. On the other hand, the highest environmental impacts occur with the issue of global warming potential in all stages of the slideways indicating a poor environmental performance for this category.

Close examination of different components of each slideway show that epoxy resin has the most dominant environmental burden for the composite slideway while energy input for steel production contributes to the largest emissions as shown in Figure 15.

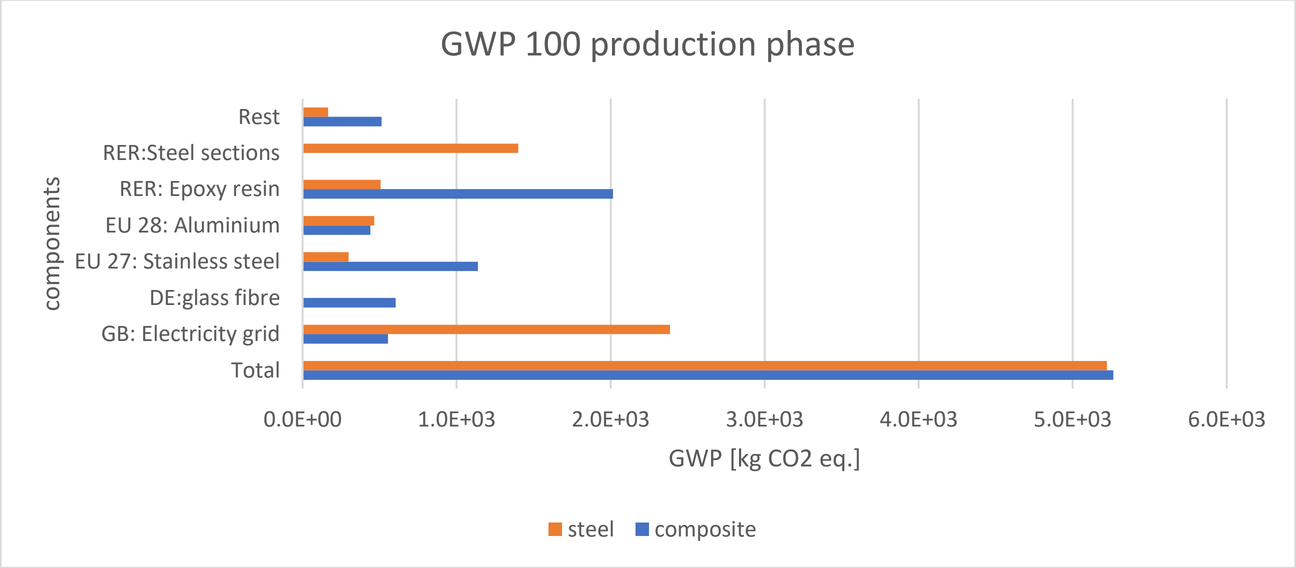


Figure 15: Impacts of different components on GWP 100

Detailed results of the contribution of each component of the slideway can be seen in the appendix.

5. Discussion

Using the inputs and outputs from the LCI stage, the ReCiPe method and four main environmental categories, the environmental performance of a GRP and a steel slideway were compared. First, the limitation of this study is highlighted and its effects are explained. The potential impacts of the slideways as computed with the LCA method might differ from the actual environmental impacts due to several reasons. For example, the program uses standards and formulas based one experiments to assess emissions. These experiments could be different for each case and could only to be extrapolated to a limited extent. Furthermore, environmental data applicable to the slideways were not always available in program, for example, the use of polytetrafluoroethylene (PTFE) was prominent in the composite slideway, but the model flow and the input data were not available, this prompted the use of closely related material as a representation e.g. fluoropolymer brands.

The energy calculation data was also a rough estimate based on efficiency of the operations, production techniques and the time of operation. This could lead to variations from exact values and customizable constraints. The chance of over estimating could create a false input and consequently a false environmental output.

The choice of the impact categories to assess the environmental performance is also subjective matter and could lead to varying results. For example, if an author decided to use human toxicity or depletion of abiotic resources, then the results would be much different than using freshwater eutrophication for example. Therefore, depending on the goal and aim of the study, a same case study may produce varying outcomes which does not render either of them irrelevant.

The composite structure, unlike steel, is heterogenous, making it difficult to separate into its constituent materials. This makes it difficult to either recycle or reuse at the end of its life cycle which in turn forces it into a landfill where it does not decay or into an incineration plant where it emits heavy metals and toxins into the air. (Bratcher, 2017) estimated that manufacturing glass (the primary material of GRP composite) from recycling material can reduce emissions by 20%. Consequently, using recycled glass in the fabrication of the composite slideway would reduce environmental burdens associated with its emissions.

Taking into account the constraints of this LCA study, I compare the impacts of the two slideways on the environment and identify hotspots for improvements. The higher total GWP per kg of the composite is associated with the production and use of epoxy resins which is both energy and material intensive. For example, to produce 1 ton of liquid epoxy, 14.3 tons of abiotic material, almost 300 tons of water, 5.4 tons of air and 150kWh of electricity are needed (Stiller, 1999). Nevertheless, the minimal maintenance and repair requirement increases the longevity of the composite slideway in contrast to the steel which in affected by constant rust in the salty environment of operation. The higher acidification potential for the composite production could be due to acid deposition of sulphur and nitrogen compounds that result from emissions of SO_2, NH_3 and NO_x.

For the steel slideway, most of its environmental impacts are related to the energy consumption and the emission associated with its production. The energy input for this study was estimated based on studies such as (Renzulli, Notarnicola, Tassielli, Arcese, & Capua, 2016) who have studied in detail the production of steel in a similar mill. They estimated that 1 ton of steel production demands 23.2GJ of energy consumption, that includes rolling of steel sections. The steel sections were direct input into the slideway for both decks and frames.

Implementing energy-efficient technologies such as the exploitation of low-grade waste energy reuse could greatly reduce the environmental impacts of the steel slideway.
For all impact categories, the use and maintenance phase of composite slideway performs better but still all the energy consumption takes place in the material production, it is recommended therefore to focus efforts for material recycling strategy.

6. Conclusion

The overall results of this study show that the selection of a GRP composite in the building of the slideways is more environmentally friendly over a 10-year period than the steel slideway. Specifically, the LCA case study, based on the ISO standards for the two slideways indicated slightly better environmental performance for the steel slideway concerning GWP in the production phase but an overall better performance for the composite in the long-term operation period. The production of steel has the lowest environmental burden for the acidification potential and freshwater eutrophication impact categories. Nevertheless, composite performs better in the duration of its use and maintenance phase for all impact categories which contributes the majority of the environmental burden for both the slideways. Furthermore, the EoL phase indicated a negative environmental burden on the ozone depletion from the composite and almost no emissions from the steel recycling and reuse process.
In the case of steel slideway, the most environmental impacts is associated with the energy intensity of its production for all the different impact categories while in the case of the composite slideway, the most emissions for the GWP category are as a result of epoxy resin use during the production phase. The heterogeneity of the composite structure makes it difficult to separate it into its constituents and therefore ends up in landfills and incineration plants. The energy intensity of incineration of the composite slideway generated the most impacts during the EOL of phase.

From a general perspective, the total amount of pollution in various stages of composite was 1.8% more than the steel for the GWP potential and 15% more in the case of ozone layer depletion potential. In the EoL, the steel scrap from the composite (e.g. bolts, wheels) and the steel scrap from the slideway could be recycled and reused, while most of components of the GRP (e.g. glass fibre, epoxy adhesive and PVC foams) were incinerated or ended up in landfills, this has a detrimental impact on the ecosystem.

In order to further reduce effects of composite on climate, I recommend (1) designing for recycling targets by selecting materials with good recycling rates or form recycled products into new products. (2) reducing the weight to improve emissions associated with transportation as well as production (3) extending the life of the composite by creating a fast and cost-effective maintenance and repair operations based on design for assembly and disassembly approaches.

in terms of both further improving material properties and investigating environmental impacts, there is still significant scope for further research. This study was performed with a limited license version of GaBi model, therefore, there is significant database that could not be accessed which would otherwise prove to be important for a solid conclusion.

Overall, the result represent a first step to understanding the environmental impacts of GRP compared with steel, which should be used as starting point for the development of both impact and design control. In future, the current LCA could be extended to include the entire Ampelmann system and compare the results from an integrated view including energy and operation influences of the system to the environment. This would enable to bridge the gap of using composite structures in the built environment.

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8. Appendix

Table 11: Operation hours of the hexapod per day

year	**Start**	**A-24**
2019	Sep	11.8
	Oct	18.9
	Nov	12.7
	Dec	5.3
2020	Feb	7.6
	Mar	10.5
	Apr	6.7
	May	6.6
	Jun	10.4
	Jul	10.8
	Aug	8.9
	Sep	13.5
	Oct	11.4
	Nov	8.7
	Dec	10.2
	Jan	11
2021	Feb	10.4
	Mar	10.2
	Apr	10.9
	May	11.1
	Jun	9.8

Calculation of energy of operation

To calculate the force and hence the energy to move the slideways, the governing formula used is:

$$\mathrm{P} = \mathrm{F} \times \mathrm{V}$$

In which F, the force is derived from the mass and acceleration of the slideway motion. While V, is the maximum velocity of slideway operation. Firstly, since the mass of outer boom of composite slideway is known (732.81kg), and the recorded maximum velocity is 0.5m/s over a period of 10 seconds; then

$$a = \frac{0.5m/s}{10s} = 0.05m/s^2$$

Therefore, the power it takes to operate the composite slideway: -

$$P = maV$$

$$P = 732.81kg \times \frac{0.05m}{s^2} \times 0.5 = 18.32\ W$$

For the steel slideway, the same procedure is followed, but the difference is that only the inner boom is in motion and its mass is 698.93kg

$$P = 698.93kg \times \frac{0.05m}{s^2} \times 0.5 = 17.47\ W$$

Energy required to transport the composite slideway: -

At a fuel economy of 12.6km per 3.8liters of fuel, it would take 150liters of diesel to transport the composite from Airborne to Ampelmann. There are 34.62MJ in a litre of diesel and the payload on the truck being the mass of the composite is 1175.064kg, then the energy to transport the payload is calculated as: -

$$E_{transportation} = \frac{150 \times 34.62}{1175.064} = 4.419MJ$$

Table 12:Steel database used for inventory modelling

Material	Data source	Year	Type of data	comments
Truck global, Euro 1	GaBi model	2018-2021	Input parameters, payload	Heavy or light duty for road transport, Sulphur content of fuel and drive sharing
Diesel at refinery	GaBi model			
GLO credit for recycling of steel scarp	GaBi LCA model	2018-2021	Literature, generic to GLOBAL	Auxiliary process
Steel sections	GaBi model	2014-2020	Industry data, generic to Global	Based on global coke, sinter, pellet, dry and hot metal production at worldsteel consistency checks
Aluminium profiles	GaBi LCA model			
NL electricity grid mix	GaBi LCA modelling	2016-2021	Literature, generic for NL	Data set represents average country electricity supply to consumer.
NL electricity from wind power	GaBi model	2016-2021	Literature, generic to NL	Foreground system with winder driver turbines. Operational lifetime of 60 years.
Lubricants	Maintenance guide	2020-2021		Permatex lithium grease base
Anti-corrosion coating	Maintenance guide	2020-2021		
Water	Maintenance guide	2020-2021	Primary	
Glass fibre	Design guide	2020-2021		Form part the gratings
Polyamides	Design guide	2020-2021		Form part of the gratings

Table 13: Composite database used for inventory modelling

Material	Data source	Year	Type of data	comments
RER. Epoxy resin Plastic Europe	Design docs.	2018-2021	Industry data	
Diesel at refinery	GaBi model			
GLO credit for recycling of steel scarp	GaBi LCA model	2018-2021	Literature, generic to GLOBAL	Auxiliary process
DE: glass fibres	GaBi model	2014-2020	Industry data, generic to Global	
RER: polyvinylchloride sheets (PVC)	GaBi LCA model			
NL electricity grid mix	GaBi LCA modelling	2016-2021	Literature, generic for NL	Data set represents average country electricity supply to consumer.
GLO: truck, Euro 1	GaBi model	2016-2021	Input parameters, payload	Heavy or light duty for road transport, Sulphur content of fuel and drive sharing
GLO: steel wire rod worldsteel	GaBi model	2018-2021		
EU-28: Lubricant at refinery		2018-2021		
Paint	Airborne doc			
EU-27 stainless steel white hot rolled coil	GaBi model	2020-2021	Hot furnace industry data	
RER: Polyurethane flexible foam	Design docs.	2020-2021	Generic for EU	
Polyamide fibres	GaBi model	2020-2021		
EU-28Aluminium ingot mix	Design docs.	2020-2021	Metal production industry, generic for EU	
GB Electricity grid mix (production mix)	GaBi model	2020-2021	Literature, generic to NL	

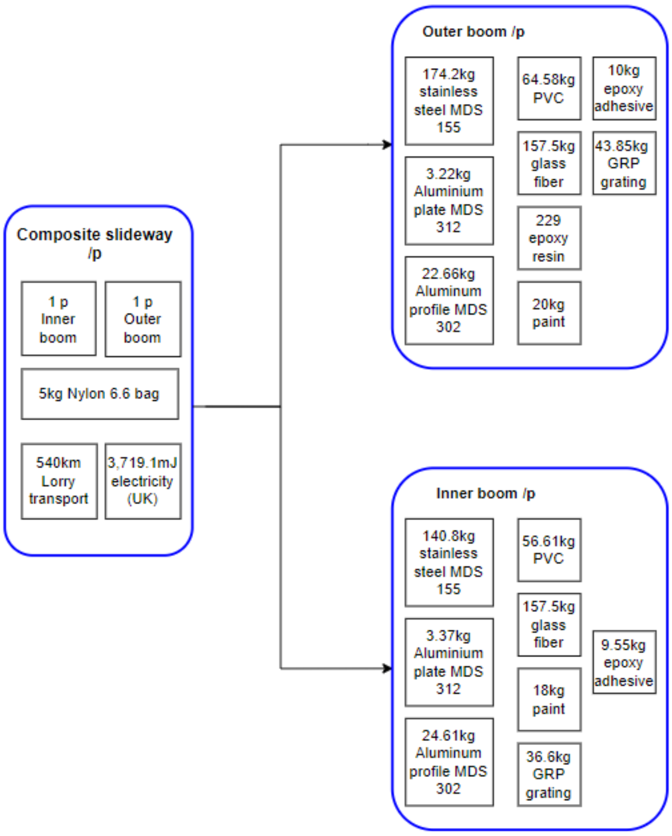

Figure 16: Assembly process of the composite slideway

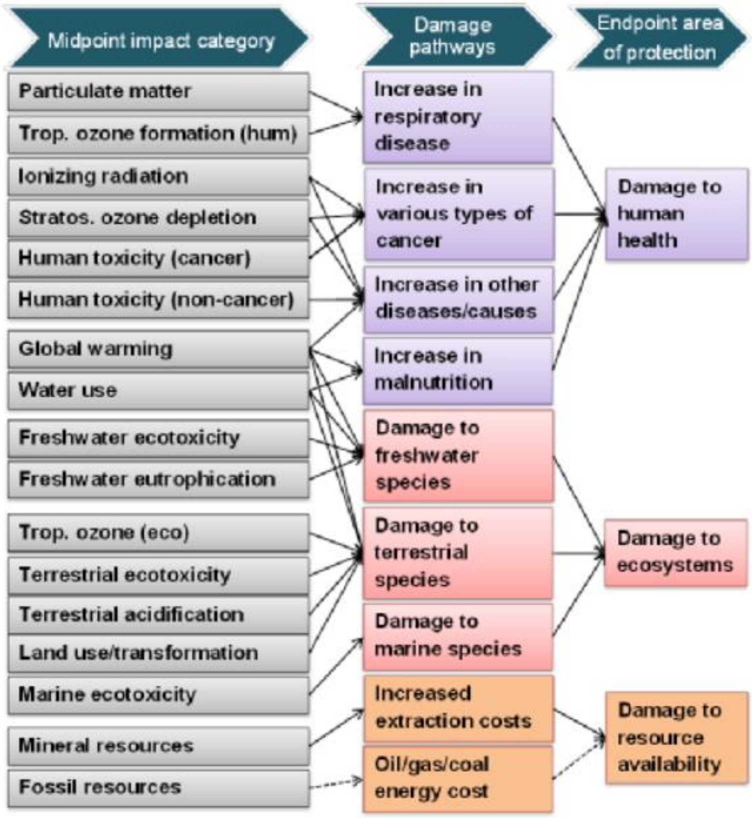

Figure 17: Overall structure of ReCiPe method (RIVM, 2011)

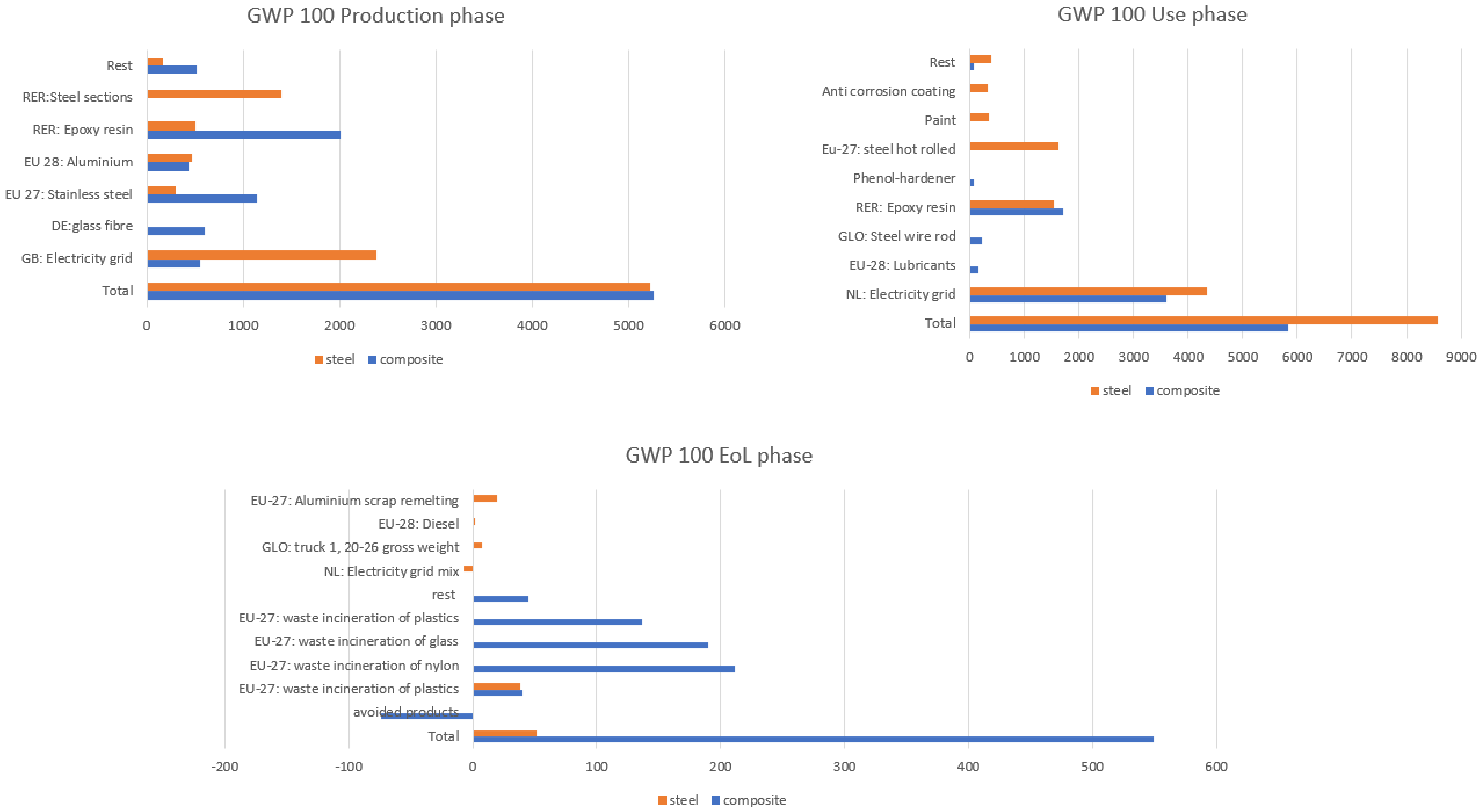

Figure 18:Comparison of impacts of different components on GWP100

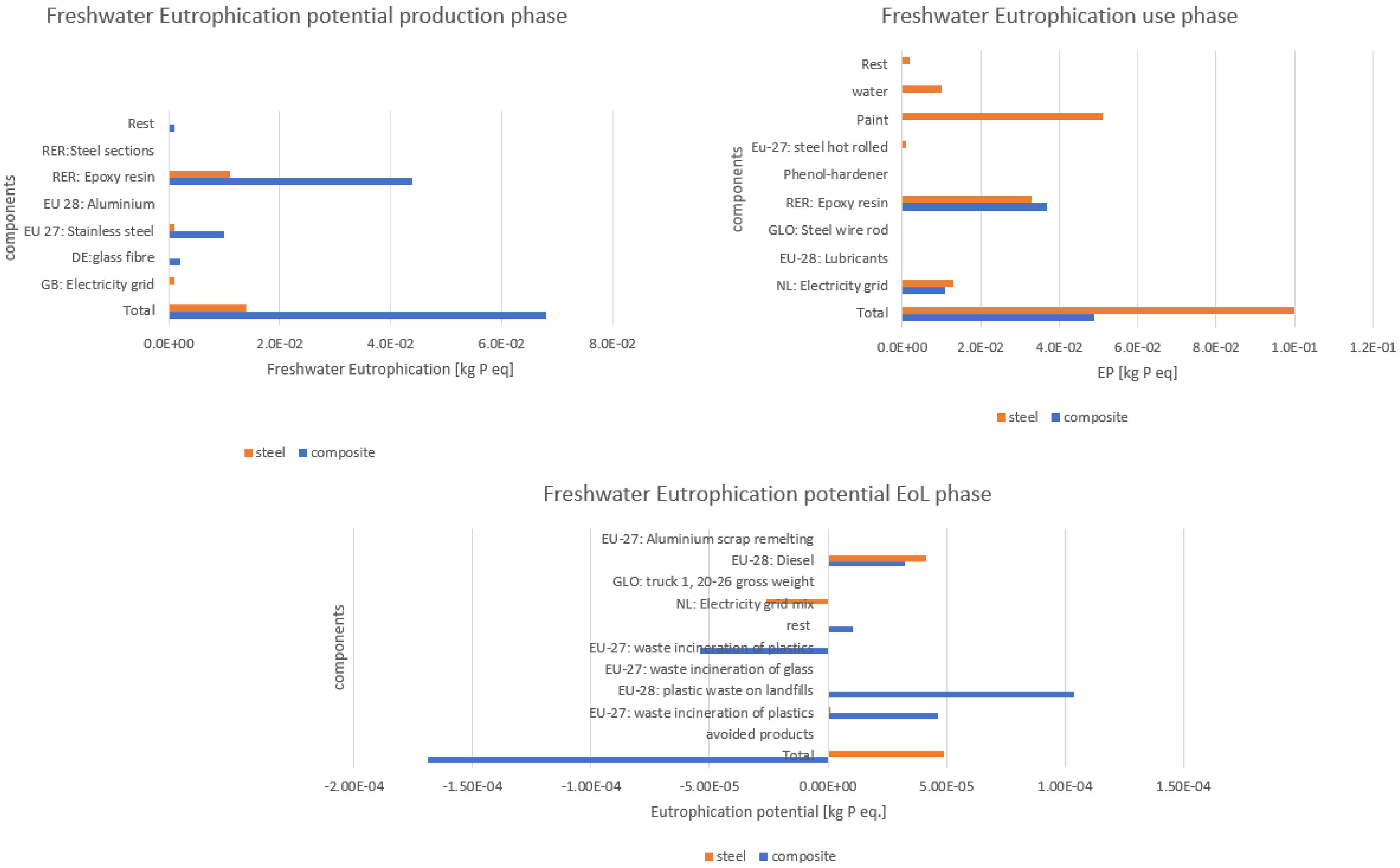

Figure 19: Eutrophication potential of different components

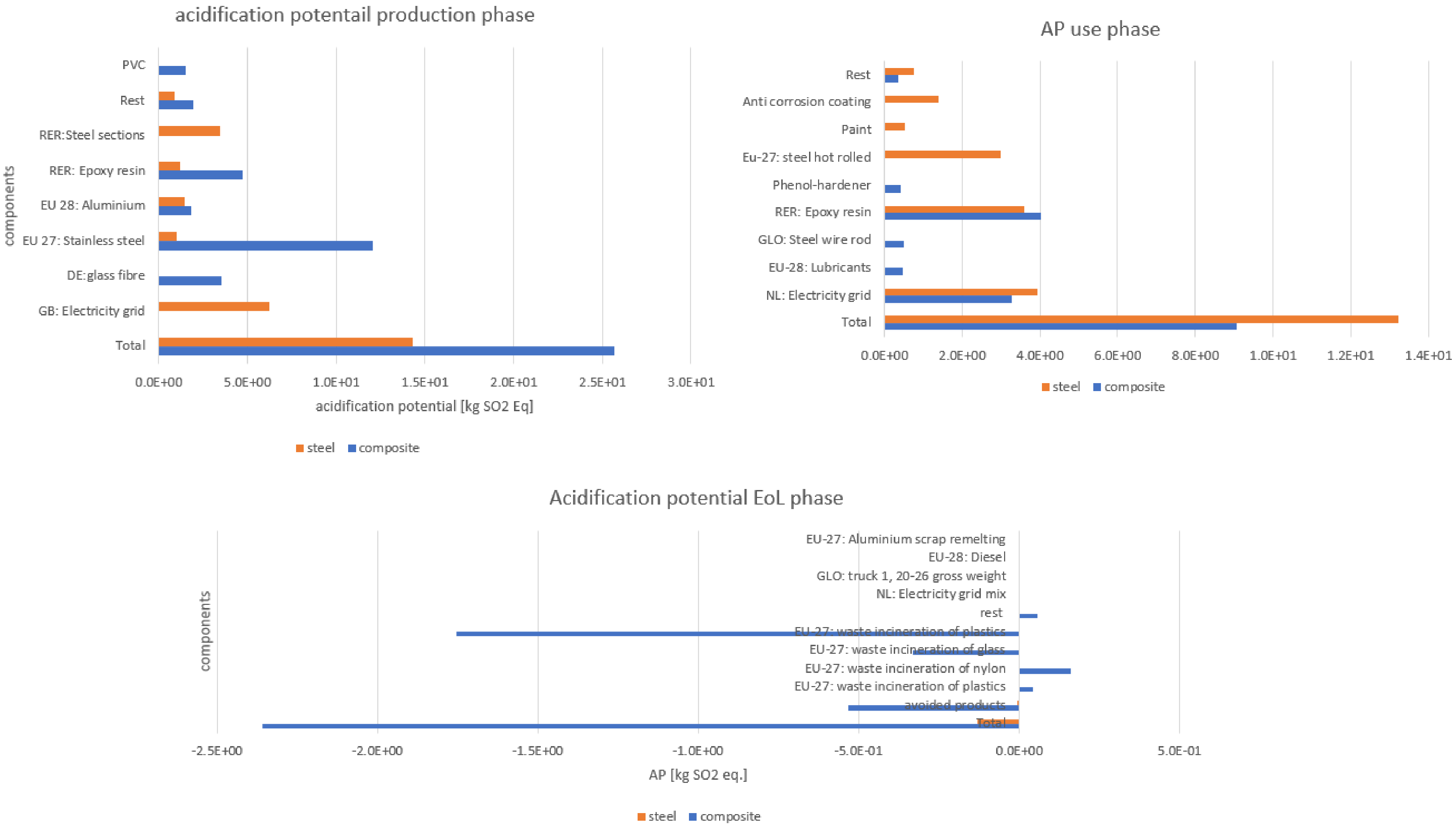

Figure 20: Acidification potential of different components of the slideways

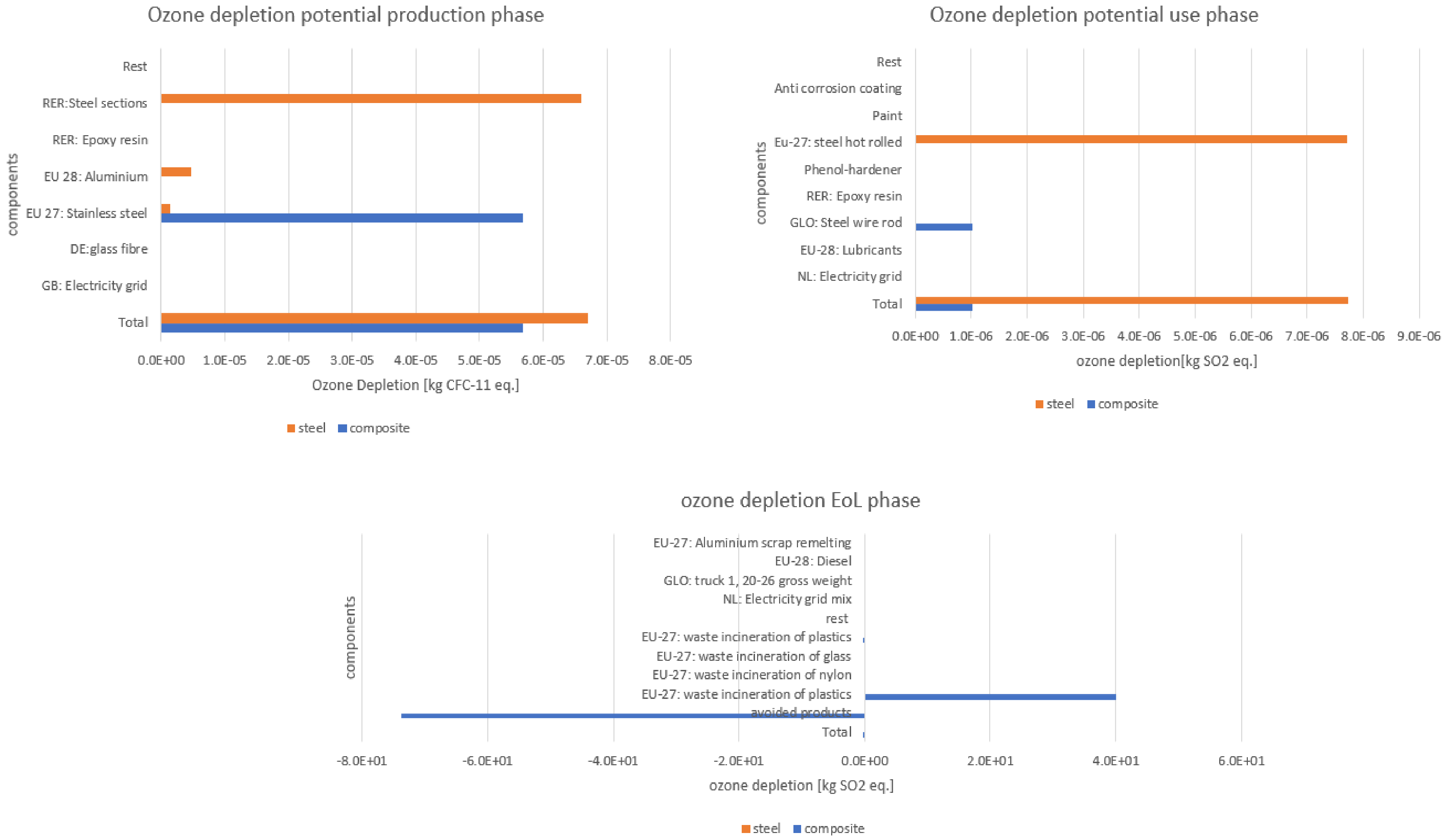

Figure 21: ozone depletion potential of different components