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QUANTIFYING AND REDUCING THE CARBON FOOTPRINT OF AZIMUTH THRUSTER MARINE PROPELLER

Master’s Thesis
Faculty of Engineering and Natural Sciences
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ABSTRACT

Liisa Jaakkola: Quantifying and reducing the carbon footprint of azimuth thruster marine propeller
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Carbon footprint is term which is defines the global warming potential (GWP) of the company or the product. It indicates the amount of greenhouse gases (GHG) proportioned to the GWP of carbon dioxide and it is expressed in kilograms per carbon dioxide equivalents. Quantification of GHG emissions is the key to reducing the emissions. In this study, the carbon footprint of azimuth thruster marine propeller was calculated using life cycle assessment (LCA). The calculation was conducted for two thrusters with different nozzle mounting types and the results were compared. The system boundary was cradle-to-gate.

Emissions in manufacturing industry are generated in raw material extraction and material processing phase, in manufacturing phase and in transportation phase. The emissions are generated when the energy is produced, so the most energy intensive processes generate the most emissions. The LCA study included the six heaviest components of the thruster, and the result was 68,700 kg CO_2 eq for the thruster with welded nozzle type. The thruster with bolted nozzle type accounted 1,800 kg CO_2 eq less than the thruster with welded nozzle. The lower emissions were results of shorter delivery distance of the nozzle.

The emissions can be reduced by using materials which are produced via electric arc furnace (EAF) process instead of blast furnace–basic oxygen furnace (BF-BOF) process. The EAF process uses scrap metal as the main raw material and electricity as energy source whereas the BF-BOF process uses iron ore and coal as raw material and energy source. The emissions can be reduced also by making smart design solutions such as developing lighter structures, avoiding long transportation distances, and using less emissions intensive transportation options.

Keywords: Carbon footprint, azimuth thrusters

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TIIVISTELMÄ

Liisa Jaakkola: Ruoripotkurien hiilijalanjäljen määrittäminen ja pienentäminen
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Hiilijalanjälki (engl. carbon footprint) on termi, jolla kuvataan yhtiön tai tuotteen lämmityspotentiaalia (engl. global warming potential, GWP). Se ilmaisee tuotteen kasvihuonekaasupäästöjen (engl. greenhouse gas emissions, GHG emissions) määrää suohteutettuna hiilidioksidin lämmityspotentiaalin yksikössä kilogrammaa hiilidioksidiekvivalenttia. Kasvihuonekaasujen määrittäminen on avainasemassa päästöjen vähentämiseen. Tässä työssä laskettiin ruoripotkurien hiilijalanjälki hyödyntämällä elinkaariarviointia (engl. life cycle assessment, LCA). Laskenta suoritettiin kahdelle potkurille, joilla on erilainen suulakkeenasennustapa ja näitä tuloksia vertailtiin. Tutkimuksen rajattiin kehdosta portille (engl. cradle-to-gate).

Valmistavassa teollisuudessa päästöjä syntyy raaka-aineiden hankinnan ja prosessoinnin vaiheessa, valmistusvaiheessa sekä kuljetusvaiheessa. Päästöjä syntyy, kun energiaa tuotetaan, joten kaikkein energiaintensiivisimmät prosessit tuottavat eniten päästöjä. Elinkaariarviointi sisälsi potkurin kuuden painavimman komponentin elinkaaren arvioinnin ja tulokseksi saatiin 68 700 kg CO_2 eq laitteelle, jonka suulake asennetaan hitsaamalla. Laitteen, jonka suulake asennetaan pulttaamalla, päästöt olivat 1 800 kg CO_2 eq vähemmän verrattuna hitsatulla suulakkeella varustettuun laitteeseen. Pienemmät päästöt johtuivat pultattavan suulakkeen lyhyemmästä toimitusmatkasta.

Päästöjä voidaan vähentää käyttämällä materiaaleja, jotka on tuotettu valokaariuunissa (engl. electric arc furnace, EAF) masuuni-happipuhallusuunin (engl. blast furnace–basic oxygen furnace, BF-BOF) sijasta. EAF-prosessi käyttää pääraaka-aineenaan kierrätettyä terästä ja energialähteenään sähköä. BF-BPF-prosessi sen sijaan käyttää rautamalmia ja hiiltä pääraakaaineena ja energianlähteenä. Päästöjä voidaan vähentää myös tekemällä viisaita valintoja jo suunnitteluvaiheessa, esimerkiksi kehittämällä kevyempiä rakenteita, välttämällä pitkiä kuljetusmatkoja sekä käyttämällä vähempipäästöisiä kuljetustapoja.

Avainsanat: Hiilijalanjälki, ruoripotkuri

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This Master’s Thesis was commissioned by Kongsberg Maritime Finland Oy. I want to thank Joni Keski-Rahkonen for offering me the possibility to write a thesis related to this interesting topic. I also want to thank Ari Vehanen for his support throughout the whole thesis process. I am thankful also for my examiners at Tampere University, Hannele Auvinen and Henrik Tolvanen, for their guidance and support.

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Tampere, 7 November 2022.

Liisa Jaakkola

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LIST OF SYMBOLS AND ABBREVIATIONS

CE	Circular economy
CFP	Carbon footprint of products
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCT	Life cycle thinking
LLGHGs	Long-lived greenhouse gases

1. INTRODUCTION

Climate change caused by anthropogenic activity is identified as one of the most pressing challenges facing the world. It can cause serious threats to both natural and human systems. It could affect to future development and lead to significant impacts on economic activity, resource availability and human wellbeing. (Wu et al. 2015; SFS-EN ISO 14067:2018) The pressure of limiting the global temperature rise to 1.5 °C has increased in recent years (Slaboch et al. 2021).

To fight against climate change and global warming, it is important to mitigate greenhouse gas (GHG) emissions. Globally, the atmospheric mixing ratio of CO_2 has increased from about 280 ppm in the pre-industrial era to 379 ppm in 2005 (IPCC 2007, p. 137). Carbon footprint is the total amount of the greenhouse gases generated through the whole life cycle of a product or service (Wiedmann & Minx 2007). Calculation of carbon footprint quantifies product's potential contribution to global warming. The quantification, monitoring, reporting and verification of GHG emissions and removals are the key initiatives to mitigating the GHG emissions. Quantification of the carbon footprint of a product (CFP) helps in understanding the GHG emissions and assists in increasing GHG removals over the whole life cycle of the product. (SFS-EN ISO 14067:2018)

International Maritime Organization (IMO) conducted a study in 2020 concerning GHG emissions from international shipping. According to the study (International Maritime Organization 2020, p. 1) the GHG emissions of total international shipping were 1 076 million tons CO_2 eq in 2018. The study considers emissions on the use stage. In 2019 one containership generated on average 24,400 t CO_2 eq GHG emissions per year and one bulk carrier on average 4,700 t CO_2 eq per ship. (European Commission 2021) As the mitigation of the emissions starts from the beginning of the life cycle of the product, it is important to assess the GHG emissions right from the design stage of the product.

The aim of this study is to focus on the GHG emissions in the phases before the use stage. More accurately the study considers the carbon footprint of one type of marine propellers, US type azimuth thrusters. The goal is quantifying the carbon footprint of the thruster and study the possibilities to reduce the footprint.

The research questions for this thesis are the following:

1. Of which factors does the carbon footprint consist of in manufacturing industry?
2. What is the carbon footprint of the examined azimuth thrusters?
3. How does the mounting type of the propeller nozzle affect to the thruster's carbon footprint?
4. How can the carbon footprint of the examined thruster to be decreased?

Chapters 2 and 3 consider literature review. Chapter 2 presents the life cycle thinking and principles of life cycle assessment (LCA) and how it can be used in calculating carbon footprint. Chapter 3 provides information about GHG emissions in manufacturing industry, and economic impacts of greenhouse gas emissions. After the literature review, Chapter 4 describes the materials and methods of the research. First there is study overview and introduction of azimuth thruster. Next is goal and scope definition, life cycle inventory analysis and sensitivity analysis. Chapter 5 introduces the results of the study. The results are then discussed and recommendations for reducing carbon footprint are given. Finally, the conclusion can be found in Chapter 6.

2. LIFE CYCLE ASSESSMENT IN QUANTIFYING CARBON FOOTPRINT

This chapter discusses the principles of life cycle assessment. The point of view is on carbon footprint, and the greenhouse effect and gases are introduced.

2.1 Life cycle thinking

Linear philosophy has been adopted by the economy for long time. Linear economy is based on short term consumption of material resources. First, raw material is taken from the nature, then the product is made, used, and finally disposed. This model has resulted in several environmental issues such natural resource loss, climate change and health problems. Today, circular economy (CE) philosophy is starting to replace linear one. In CE, raw materials and products are designed to be reusable. This maintains and enhances natural resources and minimizes the risk by managing renewable loops and limited resources. (Amahmoud et al. 2022)

Life cycle thinking (LCT) consists of three aspects: social, environmental, and economic aspects. Keeping all these aspects in balance is the key in making sustainable materials and products (*Figure 1)*. The fundamental purpose of LCT is to enhance the socio-economic and environmental performance throughout the whole life cycle.

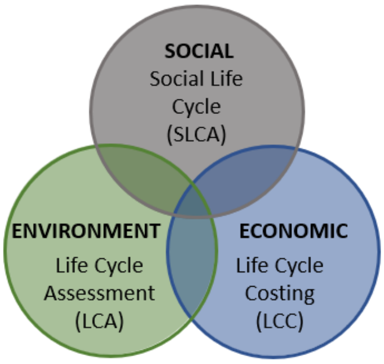

Figure 1. *Life cycle thinking key to every three aspects of sustainability (adapted from Azapagic 2010)*

Its aim is to help customers and companies to be more aware of the impacts of their decisions to the environment and to make better substitute decisions to reduce environmental impacts. (Amahmoud et al. 2022)

2.2 Principles of life cycle assessment and carbon footprint

The international Organization (ISO) has defined a method called LCA, that is a part of the ISO 14000 family of standards related to environmental management (SFS-EN ISO 14040:2006). The international standards ISO 14040 and ISO 14044 has been created to analyze environmental impacts and aspects of product systems (Klöpffer & Grahl 2014). ISO 14040 defines life cycle assessment as preparation and evaluation of the inputs and outputs of a product system and its potential environmental impacts throughout its life cycle (SFS-EN ISO 14040:2006).

Life cycle assessment (LCA) is a commonly used method to identify the environmental impacts of products. LCA helps industries to quantify emissions, such as greenhouse gas emissions (GHG), in different phases of product's life cycle. (Zadgaonkar & Mandavgane 2020) The calculation of carbon footprint of the product has the same requirements as LCA and is based on calculating the global warming potential (GWP) of a product during its life cycle (SFS-EN ISO 14067:2018).

LCA is just one environmental management technique among others, such as risk assessment and environmental auditing, and may not be the most suitable technique in all situations. LCA for example does not address the social and economic aspects and impacts of a product, but for more extensive assessment LCA can be combined with other tools. (SFS-EN ISO 14040:2006)

Calculating carbon footprint enables recognizing the life cycle stages where the emissions are generated and how the emissions can be reduced. After carbon footprint is calculated it is possible to make further studies and for example calculate the carbon handprint of the products. As opposite to carbon footprint, the carbon handprint refers to the positive impact (VTT 2018).

2.3 Greenhouse gases and greenhouse effect

Greenhouse effect is a natural phenomenon which is caused by the greenhouse gases in the atmosphere (Ilmasto-opas 2022). These gases absorb energy and decrease the rate at which the energy gets out from the atmosphere, inflicting earth warming (Vallero 2019). The most important greenhouse gases that occur naturally in the atmosphere are water vapor (H_2O) and carbon dioxide (CO_2). These gases cause most of the natural greenhouse effect and the natural heating on the earth. Other naturally occurring greenhouse gases are methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). (Ilmasto-opas 2022) Due to human activities the atmospheric concentrations of carbon dioxide, methane and nitrous oxide are increasing, making these the most important greenhouse gases (Ilmatieteenlaitos 2022). Other long-lived greenhouse gases (LLGHGs) are halocarbons, such as CFCs, HFCs and PFCs, and sulphur hexafluoride (SF_6). (Muneer et al. 2005; IPCC 2007, p.131).

CO_2 is produced mainly when fossil fuels are used for energy generation. Deforestation also releases CO_2 emissions. Methane is produced when organ material degrades in anaerobic conditions. Methane emissions are caused mainly by agricultural activities, such as in rice fields and farming cattle, changes in land use and combustion of fuels. About 2/3 of methane emissions are anthropogenic. Nitrous oxide emissions are also mostly anthropogenic and are caused by agricultural activities and changes in land use. Halocarbons and SF_6 are released in industrial processes. (Muneer et al. 2005; IPCC 2007, p. 1–19)

Greenhouse gases have various radiative efficiencies, which means that their ability to absorb energy differ. Their atmospheric residence times differ also. Each greenhouse gas has a specific global warming potential (GWP). GWP factor relates the amount of energy which one ton of greenhouse gas will absorb over a time horizon, usually 100 years, compared with the energy which one ton of CO_2 absorbs. (Vallero 2019) The GWP factors for different greenhouse gases and residence times can be found in *Table 1.*

Table 1. *Greenhouse gas residence times and GWP at 100-year time horizon (Vallero 2019)*

Compound name	**Residence time in the atmosphere**	**GWP**
Carbon dioxide (CO_2)	Thousands of years	1
Methane (CH_4)	About 12 years	28–36
Nitrous oxide (N_2O)	About 100 years	265–298
SF_6	-	22,800
C_6F_{14}	-	9,300
CH_2F_2	-	679

Greenhouse Gas Protocol (2015) has defined three scopes to categorize the emissions. Direct emissions are internal and generated at sources that the reporting company owns and controls. These direct emissions are considered scope 1. Indirect emissions are external and generated at sources that another company owns and controls but are caused by the processes of the reporting company. When accounting indirect emissions, it is important to avoid under counting and double counting of the emissions. These indirect emissions include scope 2 and scope 3 emissions. Emissions from energy acquired or purchased and consumed by the reporting company are included in scope 2. Upstream and downstream value chain emissions are included in scope 3. (Wiedmann & Minx 2007, Greenhouse Gas Protocol 2015)

2.4 Phases of life cycle assessment

Life cycle assessment consists of four phases, which are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation (SFS-EN ISO 14040:2006). These stages and their relations are illustrated in *Figure 2.*

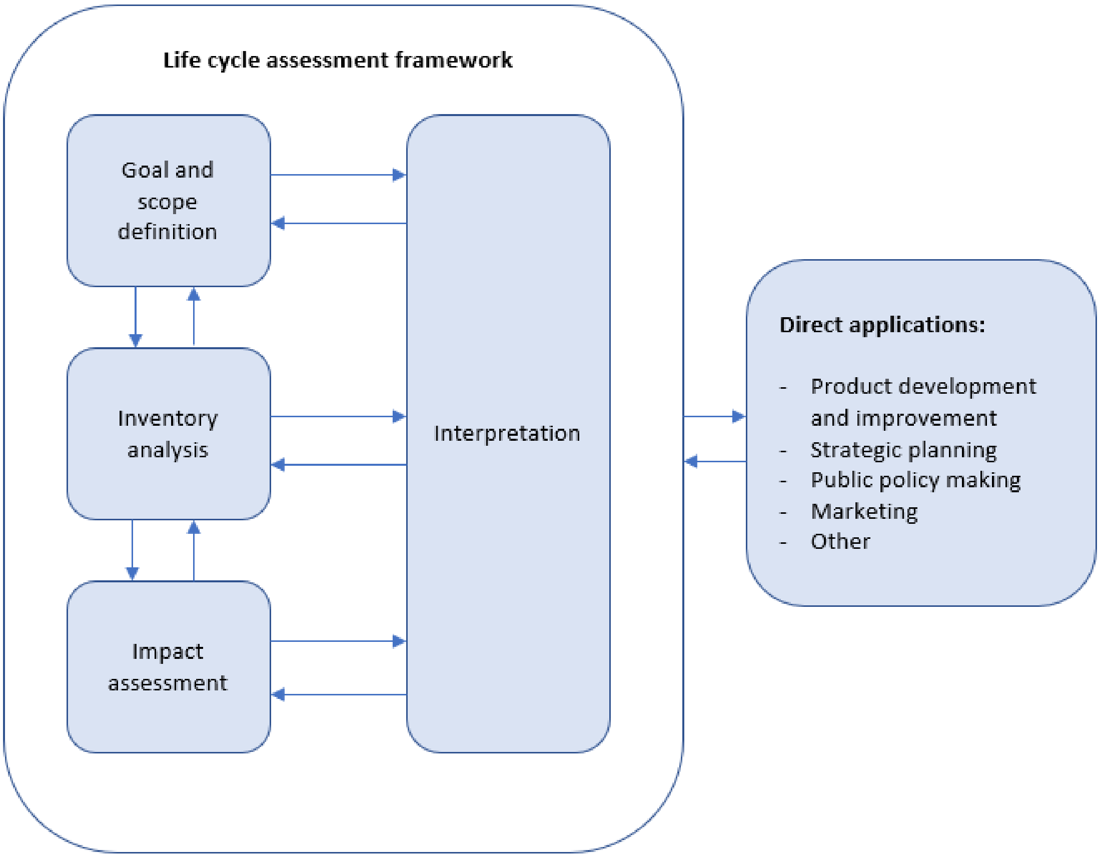

Figure 2. *Stages of LCA (adapted from SFS-EN ISO 14040:2006)*

LCA is also iterative technique where all the individual results are used consequently in the other phases. This relation is seen in *Figure 2.* Transparency is important in LCA to ensure a decent interpretation of the results, since LCA has inherent complexity. LCA covers aspects and attributes of natural environment, resources, and human health. This way potential trade-offs can be identified and evaluated. In decision making within LCA, the priority is scientific approach, preferably natural science. International conventions may be referred to, or other scientific approaches may be used if natural scientific approach is not possible. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006) These can be used for example if the input data is not comprehensive enough to calculate. As appropriate, if any of these is not possible, decisions can be based on value choices (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006).

2.4.1 Goal and scope

The goal of an LCA study defines the intended application and the reasons for carrying out the study. In LCA direct applications are for example product development and improvement, strategic planning, public policy making and marketing. The goal also defines the intended audience of the study results and whether the results are disclosed to the public in comparative assertions. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006) For example, in the study conducted by Maritime CleanTech (2020), the goal was to estimate the GHG emissions of various propulsion systems and compare the results.

The scope of an LCA includes defining the system boundary which means defining which unit processes are included in the LCA study and in which levels of detail. The selection of system boundary must be consistent with the study goal. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006) There are some variations of setting the system boundary and these are illustrated in *Figure 3.* Cradle-to-grave variation presents a full life cycle assessment from raw material extraction to the final disposal of the product and every phase in between. Cradle-to gate method presents a partial life cycle assessment from raw material extraction to production gate, that is the phase where the product leaves the factory. Third variation is gate-to-gate which focuses only to one chosen process, for example manufacturing. The last introduced variation is cradle-to-cradle. This method considers not only a full life cycle assessment but also the refurbish, re-use and recycle after the end of products life. (Tomková & Vilčeková 2019)

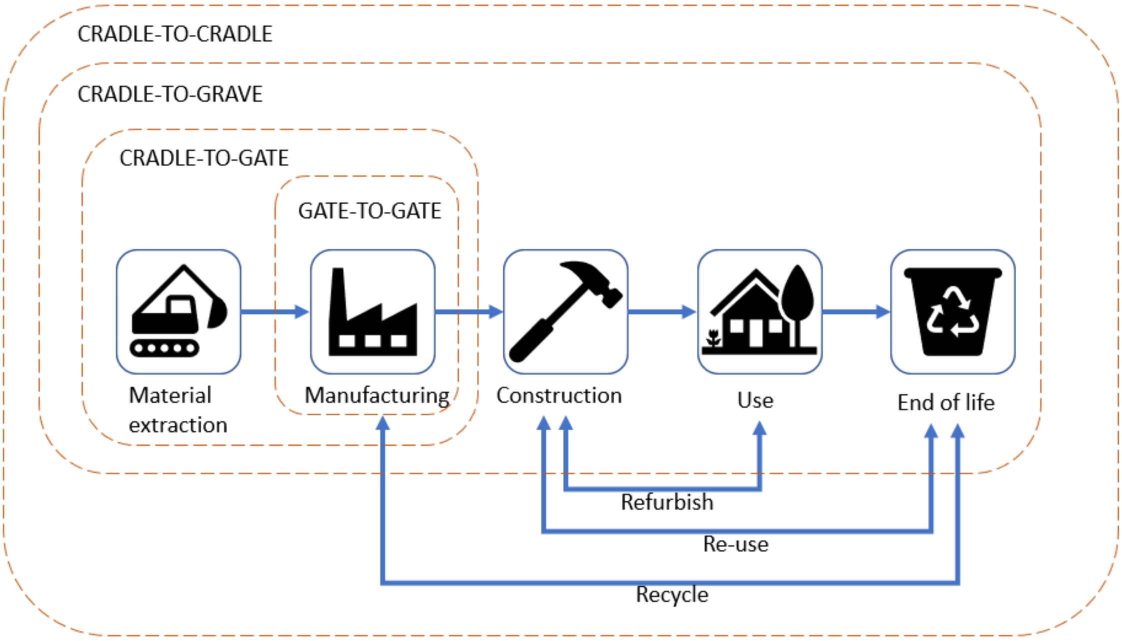

Figure 3. *System boundaring; gate-to-gate, cradle-to-gate, cradle-to-grave and cradle-to-cradle (adapted from Simonen, 2014)*

The scope depends on the use of the study and the extent can differ depending on the goal of the study. In scope definition is presented the studied product system or systems and the functions related to them. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006) The carbon footprint of a product takes account the materials, manufacturing, transportation, use and final disposal in every stage of the product's lifetime and considers the emissions that are generated both directly and indirectly (Wiedmann & Minx 2007).

LCA is structured around a functional unit which defines what is being studied. The functional unit provides a reference to which the inputs, for example energy and materials, and outputs, such as emissions to air and soil, are related. This reference ensures the comparability of the LCA results and that comparisons are made on common basis, which is critical particularly assessing different systems. That is why LCA is a relative approach, and all the following analysis and phases are relative to the functional unit. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006) The functional unit can be for example the production of 1 ton of steel or 1 MW of power.

Each unit process should define where the process begins, the nature of the operations and transformations and where the unit process ends. Ideally the inputs and outputs are elementary and product flows. It is an iterative process where other processes' outputs are used as inputs in other processes. The goal is to identify the considerable inputs. To decide which inputs will be included in the assessment, several cut-off criteria are used. Cut-off criteria is a specification of the amount of energy or material flow or environmental significance that is associated with product system but will be excluded from the LCA study. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

Other things to be considered in the scope phase are introducing allocation procedures, LCIA methodology and types of impacts, interpretation to be used, data requirements, assumptions, value choices and optional elements, limitations, data quality requirements, type of critical review (if any) and type and format of the report. The goal and scope can be revised for example due to unforeseen limitations or because of additional information. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

2.4.2 Life cycle inventory

The LCI phase considers data collection and calculation procedures of a product system. The aim of this phase is to quantify relevant inputs and outputs, such as energy and raw material inputs, products and waste, emissions to air, water and soil and other environmental aspects. The process is iterative, and the more data are collected the more is learned about the product system. After the data collection the calculation procedures are needed to make the results of the inventory of the modelled product system. The calculation procedures include validation of the data and relating data to unit processes and to the reference flow of the functional unit. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

Inventory analysis also includes allocation procedures. Often industrial processes produce more than one product, and the processes recycle discarded or intermediate products as raw materials. In these cases, the need for allocating flows and releases to these several products is necessary. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

2.4.3 Life cycle impact assessment

The aim of the life cycle impact assessment phase is to evaluate the significance of potential environmental impacts. LCIA is conducted using the results of life cycle inventory and will provide information for the next, life cycle interpretation, phase. LCIA phase involves mandatory and optional elements. Mandatory elements involve the selection of specific environmental impact categories, category indicators and characterization models. Examples of different impact categories are global warming potential, stratospheric ozone depletion and acidification potential. There are necessary components of LCIA for each impact category. These are identification of the category endpoint or -points, definition of the category indicator for these endpoints, identification of LCI results that can be classified to the impact category taking into consideration the defined category indicator and identified category endpoints, and identification of the characterization model and factors. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

Next mandatory element is classification, which means the assignment of LCI result and then characterization, which means calculation of category indicator results. As a result, is LCIA profile which contains category indicator and LCIA results. Examples of these terms related to carbon footprint calculation are presented in *Table 2.* The optional elements, normalization, grouping and weighting, can be done after that. Normalization means calculation of the magnitude of category indicator results relative to reference information. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

Table 2. *Examples of terms (SFS-EN ISO 14044:2006)*

Term	**Example**
Impact category	Climate change
LCI result	Amount of a GHG per functional unit
Characterization model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change
Category indicator	Infrared radiative forcing (W/m^2)
Characterization factor	GWP_{100} for each GHG (kg CO2 eq / kg gas)
Category indicator result	Kilograms of CO_2 eq per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radiative forcing is a proxy for potential effects on the climate, depending on the integrated atmospheric heat absorption caused by emissions and the distribution over time of the heat absorption.

The main goal for quantifying the carbon footprint of a product is to calculate its potential contribution to global warming (SFS-EN ISO 14067:2018, p. 21). The carbon footprint is expressed with kg CO_2 equivalents. This means that the mass of the greenhouse gas is multiplied with the GWP factor for the gas. This makes the different greenhouse gases comparable for each other. (Galli et al. 2012)

Uncertainty analysis and sensitivity analysis are additional data quality analysis of LCIA. The aim of the uncertainty analysis is to determine how assumptions and uncertainties in data progress in the calculation and how uncertainties affect the reliability of the LCIA results. The aim of sensitivity analysis is to determine how changes in methodological choices and data affect the LCIA results. (SFS-EN ISO 14044:2006)

LCIA is not a complete environmental assessment, since it considers only the potential environmental impacts specified in the goal and scope definition phase and it does not predict the absolute environmental impacts (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006). There are various software for evaluation of LCA, such as SimaPro, GaBi and OpenLCA (Zadgaonkar & Mandavgane 2020).

2.4.4 Life cycle interpretation

The results of LCIA are summarized in the life cycle interpretation phase. The results are discussed as a basis for conclusion and decision making in compliance with the goal and scope definition. In life cycle interpretation phase the impact assessment and inventory analysis' findings are considered together. The phase comprises of several elements. The first element is significant issues identification based on the findings. The aim of this element is to parse the results from LCI and LCIA phases to help determine the significant issues, in compliance with the goal and scope definition and interactively with the second element, evaluation. The objective of this interaction is to incorporate for example the implications of the assumptions made, and methods used, in the previous phases such as cut-off decisions, allocation rules and selection of impact categories. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

The second element is evaluation that includes completeness, sensitivity and consistency checks, and other validation that may be required to meet the goal and scope. The aim of this element is to establish and enhance reliability of the results of the LCA study. The evaluation includes the significant issues identified above. Also, the evaluation needs to be undertaken in compliance with goal and scope. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

The aim of the completeness check is to make sure that all the relevant data and information are available and complete for the interpretation. If any relevant data or information is missing or deficient, the need for such information must be considered to meet the goal and scope definition. There are two possibilities; to revise the preceding phases or adjust the goal and scope. Next step is sensitivity check. The aim of the sensitivity check is to evaluate the reliability of conclusions and the final results. This is done by determining how uncertainties in the data, calculation, allocation methods, etc. are affecting the final results and conclusions. In consistency check the aim is to determine whether the data, assumptions and methods are in line with the goal and scope. (SFS-EN ISO 14044:2006)

Third element comprises conclusions, limitations, and recommendations. The first aim of this element is to draw conclusions from the study together and iteratively with other elements in interpretation phase. Second aim is to identify limitations. Third aim of this element is to generate recommendations based on the final conclusions and which reflects reasonable and logical consequence of the conclusions and relate to the intended application. (SFS-EN ISO 14040:2006; SFS-EN ISO 14044:2006)

3. GREENHOUSE GAS EMISSIONS IN MANUFACTURING INDUSTRY

This chapter discusses the factors of which the carbon footprint consists in manufacturing industry. For reference, first is introduced the amount of GHG emissions globally and in Finland. Then the possibilities of reducing the emissions are discussed and the economic impact of the emissions.

3.1 GHG emissions globally and in Finland

Major part of the GHG emissions is globally generated in the production of energy (Erkayaoğlu & Demirel 2016). In *Figure 4* is presented the annual CO_2 emissions from industry and fossil fuels by major countries. It can be seen that in 2018 the global emissions were approximately 37,500 Mt CO_2.

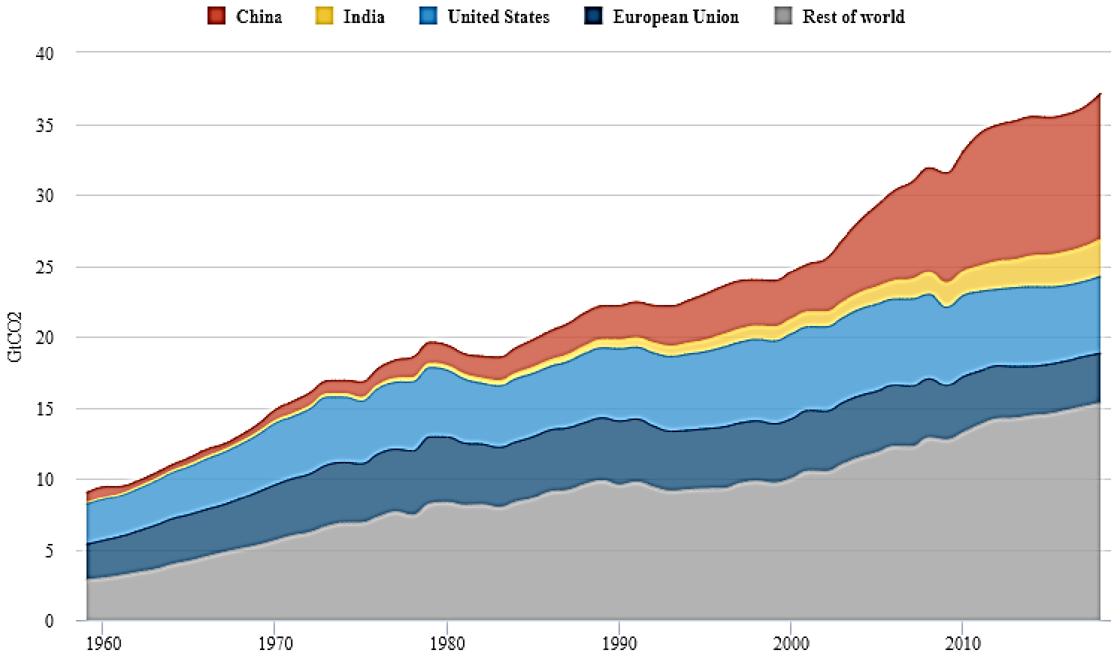

Figure 4. *Annual CO_2 emissions from fossil fuels and industry by country from 1959-2018, in Gt CO_2 per year (Carbon Brief 2018)*

In Finland the total emissions without LULUCF (land use, land use change and forestry) were 53 Mt of CO_2 eq in 2019. The emissions in energy, industrial processes and product use were 45 Mt of CO_2 eq, from which transport accounted for 11 Mt of CO_2 eq in 2019. (Tilastokeskus 2022) Therefore, this industry covers over 80 % of Finland's GHG emissions.

3.2 GHG emissions by each life cycle stage

The life cycle of machinery and industrial equipment can be roughly divided to seven phases: design, sourcing, manufacturing, delivery, product use & service, end of use and reverse logistics. All these phases have an impact on the GHG emissions of the product, some more than others. (Lacy et al. 2020) To discover the phases which cause the most GHG emissions it is important to recognize the most energy intensive processes. In *Figure 5,* is presented different factors which affect to each phase's waste production and energy usage.

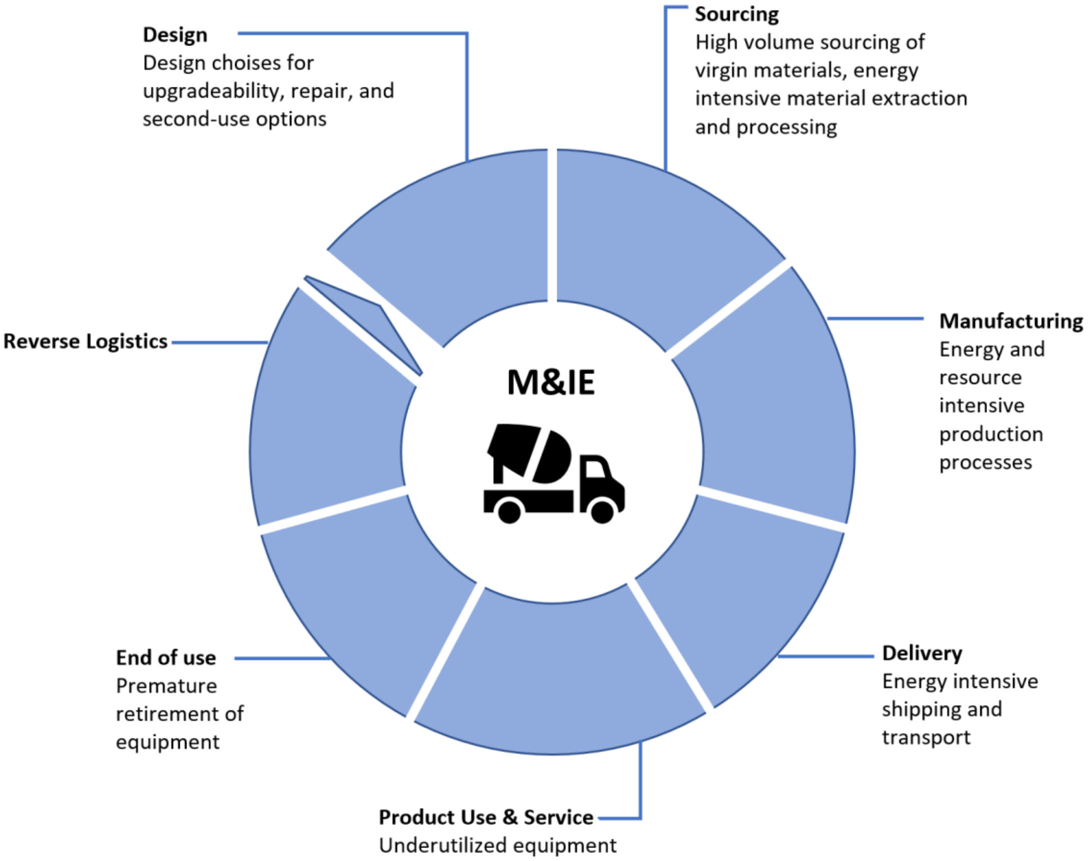

Figure 5. *Life cycle of Machinery & Industrial Equipment (M&IE) (adapted from Lacy et al. 2020, p. 131)*

The design phase itself does not generate GHG emissions. However, in this phase the opportunities to impact the future emissions of the product are high. (Lacy et al. 2020)

3.2.1 Material extraction and processing

The volume of virgin material extraction is high, and the material sourcing and processing are energy, resource- and pollution-intensive. (Lacy et al. 2020) Major part of the carbon dioxide emissions of mining is generated at the power plant during the combustion of for example coal or lignite (Erkayaoğlu & Demirel 2016). This energy was used by the belt conveyors as electricity. Using trucks had lower GHG emissions compared to belt conveyors. Excessive electricity and diesel oil consumption leads also to other air emissions, such as SO_X emissions. The rate of emissions is highly dependent of electricity generation method, which is dependent of the location and the available resources. (Erkayaoğlu & Demirel 2016)

Steel is a basic material for different industries. Despite the fact, that iron and steel recycling industries are common all over the world, the demand for virgin steel material has not fallen. (Morfeldt et al. 2015) Iron and steel production are very energy intensive and generate a considerable amount of CO_2 emissions. Especially traditional steel production relies on fossil fuels. In 2010 the iron and steel manufacturing produced 6 % of total global CO_2 emissions and 16 % of total industrial CO_2 emissions. (van Dijk et al. 2018)

Crude steel can be produced in blast furnace–basic oxygen furnace (BF-BOF) which is based on the use of iron ore and coal, or in electric arc furnace (EAF), which is based on the use of scrap metal and electricity (Gielen & Moriguchi 2002). The first thing in BF-BOF is processing iron ore into iron, also known as pig iron or molten iron. Second process is converting the molten iron into steel in a converter. The steel is ready to deliver after the refining, casting and rolling processes. (He et al. 2020) In *Figure 6* is illustrated the stages of energy intensive casting process and the energy consumption and waste production by stage. The iron ore accounts 70-100 % of the raw material used in BF-BOF process. Other materials such as pig iron, scrap and hot-pressed steel can be added. (He et al. 2020)

In EAF process the required chemical composition can be achieved by adding additives, such as alloys and injecting oxygen into the EAF during the steelmaking. The downstream processes are similar to BF-BOF process. In EAF process the recycled steel generally accounts over 70 % of the raw materials. Other sources such as metallic iron can be used depending on the availability of scrap metal and the plant configuration. (He et al. 2020) The chemical composition of scrap steel includes alloys such as Cu, Sn, Cr, Ni and Mo (Ecoinvent Database 3.8). A problem with using scrap metal is that the impurities cannot be fully avoided. Certain part of the impurities is introduced during melting process but there are no effective methods to eliminate them from the liquid steel. (Lipiński & Wach 2015)

Compared to other materials, metal is relatively well recycled material and steel is the world’s most recycled material. Still only about 40 % of global steel is made from recycled material. (Lacy et al. 2020) Compared to primary steel production, steel recycling

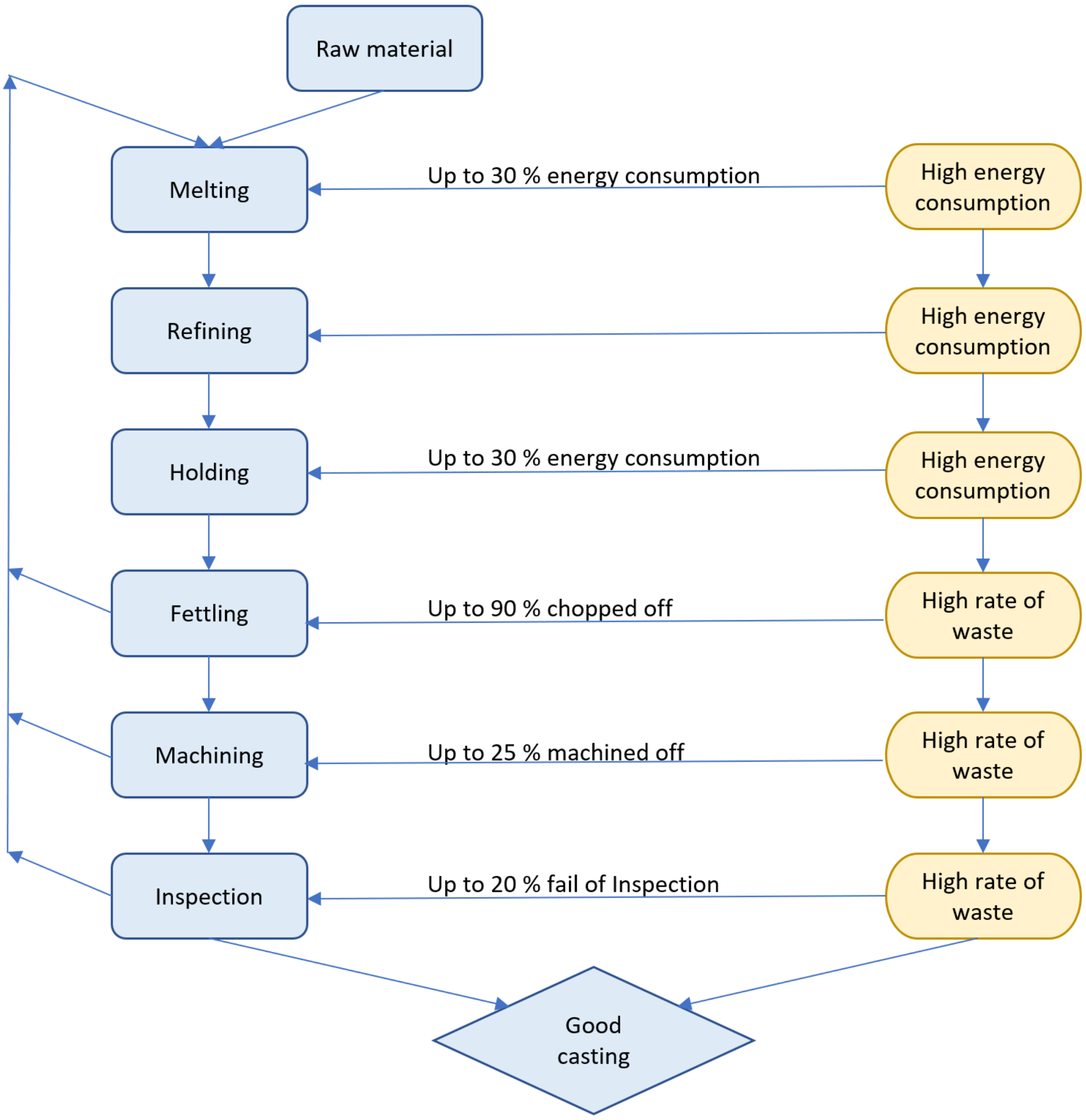

Figure 6. *Material and energy flow chart of a conventional sand-casting process (adapted from Salonitis et al. 2016)*

reduces GHG emissions significantly. The CO_2 emissions from BF-BOF steel production account about 2 t/t whereas EAF steel production accounts only about 0.3 kg/t when using 100 % scrap metal. The limitations are related to the availability of scrap metal. However, the increasing steel consumption also makes more recycled material available later on. Other limitations are related to material losses because of steel oxidation, and scrap quality. (Gielen & Moriguchi 2002)

China is a major steel producer in the world. Other major steel producing countries are listed in *Table 2.* In China's steel enterprises coal accounts about 80 % of the energy consumption structure and the use of scrap metal is far below world's average. In 2016 China's scrap ratio was only 11.2 % when the world's average was 37 %, and for example in United States the ratio was 75 % and in EU 55-60 %. This means that steel industry in China uses mostly iron ore as the main raw material. (He et al. 2020)

Table 3 *Top 15 global steel producers (He et al. 2020)*

Country	**2017**	
	Ranking	**Production (Mt)**
China	1	831.7
Japan	2	104.7
India	3	101.4
United States	4	81.6
Russia	5	71.3
South Korea	6	71.0
Germany	7	43.4
Turkey	8	37.5
Brazil	9	34.4
Italy	10	24.1
Taiwan, China	11	22.4
Ukraine	12	21.3
Iran	13	21.2
Mexico	14	19.9
France	15	15.5
World		1,689.4

In *Table 3* is listed the crude steel production by process by major steel making countries. When the information from *Table 3* is compared to information in *Table 4* the two biggest steel production countries use mostly the environmentally worse BF-BOF technology. Instead, in India, Turkey and U.S. the usage of EAF technology is used more than BF-BOF.

Table 4 *Crude steel production by process in 2017 (He et al. 2020)*

Country	**BF-BOF (%)**	**EAF (%)**	**Open-Hearth (%)**
China	90.7	9.3	-
Japan	75.8	24.2	-
United States	31.6	68.4	-
India	44.2	55.8	-
Russia	66.9	30.7	2.4
South Korea	67.1	32.9	-
Germany	70.0	30.0	-
Turkey	30.8	69.2	-
Brazil	77.6	21.0	-
Ukraine	71.8	6.8	21.5
World	71.6	28.0	0.4

3.2.2 Manufacturing of components

The manufacturing stage includes different processes. Machining is a process where the material is cut to a final shape and size. These days parts of machinery and equipment are manufactured as sequential processing. First, the product undergoes roughing to give the blank the shape and dimensions close to the desired ones. At the following stages are performed semi finishing and finishing. Significant part of the workpiece is removed. The excess material can be reprocessed such as remelted. However, the remelting requires high temperature that requires high rate of energy and large amount of the energy gets wasted during the machining process. Additive technologies are alternative processing methods for traditional machining, but they are not as common in large scale industry. (Pimonov et al. 2021)

Welding is the most significant joining technology in manufacturing, and it has applications in automobile, construction and shipbuilding industries. Welding processes require great amounts of energy and produce metal waste. Products like ships are built from structural steel plates. Different welding processes are automatic laser arc-hybrid welding (LAHW), manual metal arc welding (MMAW) and gas metal arc welding (GMAW) (Sproesser et al. 2015) Other joining processes used for example in propeller manufacturing is shrink fit. In this technology the hub is heated so as the oversized shaft fits the hub and letting it cool back down. The shaft can also be cooled to ease the fitting. (Lopes & Hills 2020) This process requires heating energy.

3.2.3 Transportation phase

Transportation occurs in many stages in life cycle. Transportation is needed every time the material or component moves within the supply chain or even within the same supplier’s premises. In the EU transport sector accounts about 32 % of total energy consumption and is the second largest emitter of GHGs (Fries & Hellweg 2013). Freight can be transported via road, sea, rail, or air (Pizzol 2019).

The emissions of the transportation depends of the transportation type, distance and the used fuel. For example rail transport can be categorized by the fuel which can be either electricity or diesel, depending on the country. (Ecoinvent 2022)

3.3 Reducing carbon footprint

To control the GHG emissions, one of the most effective ways is saving energy and reducing emissions (Fang et al. 2013). Reducing CO_2 emissions in steel industry can be done in the production side or in consumption side. The first stage where the reduction of carbon footprint starts is the design stage. The choices for upgradability, repair and second-use options are done in the design stage. (Lacy et al. 2020)

The changes in production side include increased recycling, fuel substitution, increasing energy efficiency and CO_2 removal and storage. Fuel can be switched from coal to for example natural gas, waste plastics or electricity. (Gielen & Moriguchi 2002) For example the emission factor for electricity from renewable energy sources is 0 t CO_2 eq / MWh and for natural gas 0.202 t CO_2 eq / MWh whereas for sub-bituminous coal it is 0.346 t CO_2 eq / MWh (IPCC 2006). The customer companies can affect to the reduction of CO_2 emissions by favoring suppliers who have taken these aspects in practice.

In the consumption side the changes include increased efficiency of materials use. By improved design the weight of components can be reduced. The demand for trade-offs exists when it comes to energy consumption and steel requirements of the product. (Gielen & Moriguchi 2002)

When it comes to transport, the possibilities of reducing carbon footprint exist. Shifting the traffic to low-emission traffic from high-emission vehicles, for example shifting truck to ship or train lowers the emissions. Also optimizing and reducing transport distances is important. (Fries & Hellweg 2013)

3.4 Economic impacts of GHG emissions

Reducing carbon footprint has its effects to the economy of the organizations. The problems are related to how to harmonize the relations between carbon emissions, economic growth, and energy consumption (Fang et al. 2013).

GHG emissions permit trading schemes are comprised of mechanisms which permit the trade of emissions at the local, national, and international scale between organizations. (Nguyen et al. 2019) The combination of LCC and LCA can enhance the correlation between economic benefits and environmental impact. Trading price of GHG emission quota needs to be considered in the economic assessment using LCC analysis. The LCA results can be the base for the LCC calculation. (Liu et al. 2020)

According to the study performed by Zhang et al. (2016), the carbon intensity could be reduced by 19.8–25.2 % in China with provincial carbon trading. The study shows that in a country like China, the changes towards lower carbon emissions is more profitable than paying emission allowances. This could mean that there is potential to simple changes and that major investments aren’t compulsory. For example, partial fuel substitution to waste plastic is viable.

One of the most efficient economic measures could be carbon tax. It’s an effective measure to control carbon emissions and will reduce GHG emissions ensuring both ecological and global economy. (Fang et al. 2013) Internationally the carbon tax would affect for example to energy structure all over the world. For example, in China it forces the change from coal to low carbon fossil fuels, such as natural gas or even renewable energy to reduce the cost. (Dong et al. 2017) As discussed in chapter 3, the energy consumption in the beginning of the supply chain has the most affects to the carbon footprint of the company. For implementing carbon tax in China, the key sectors for GHG emissions and reducing the emissions, are metal smelting, electricity, and chemicals (Dong et al. 2017).

The damages of emissions are complex and even more complex to estimate in money. The social damages are estimated to be for example from \$7.50 / t CO_2 to even \$85 / t CO_2. (Hsu 2011)

4. MATERIALS AND METHODS

This chapter describes the conditions of the study. First is given the overview of the study and then presented the object to be examined. Next is described the conditions of the LCA study, which include the goal and scope definition and life cycle inventory.

4.1 Study overview

The goal of the study was to quantify the carbon footprint of azimuth thruster and compare the impact of nozzle mounting type to the result. The goal was also to search ways to lower the carbon footprint and to evaluate the economic value of the emissions.

The first phase of the study was collecting information from the literature to carry out the literature review. As a result, was received information about greenhouse gas emissions in generally and in manufacturing industry. The literature review also considers the method for calculating the carbon footprint. In this study the best practice to calculate it was LCA.

The LCA study was conducted using International Standards ISO 14040 and ISO 14044 as framework. The study includes all the four phases of LCA: goal and scope definition, life cycle inventory, life cycle impact assessment and life cycle interpretation. The life cycle inventory phase included a questionnaire survey conducted for the suppliers. The calculation was conducted with SimaPro® 9.3.0.3 software with the ReCiPe 2016 midpoint characterization method with hierarchist perspective.

The results were given in kg CO_2 eq. To analyze the uncertainties of the study, a sensitivity analysis was conducted. Lastly, recommendations for future to decrease the carbon footprint, utilizing the results were given.

4.2 Overview of Azimuth Thruster and nozzle mounting types

Kongsberg Maritime’s thrusters are applicable for propulsion, steering and position control. In an azimuth thruster the propeller rotates 360° around the vertical axis making good maneuverability possible. The different designs suit practically for any application and the units have either diesel or electric drive and remote-control system. (Kongsberg, 2022) In *Figure 7* is illustrated US type azimuth thruster and the heaviest components are marked in the picture. The unit consists of three major parts: upper gear, intermediate part and lower gear.

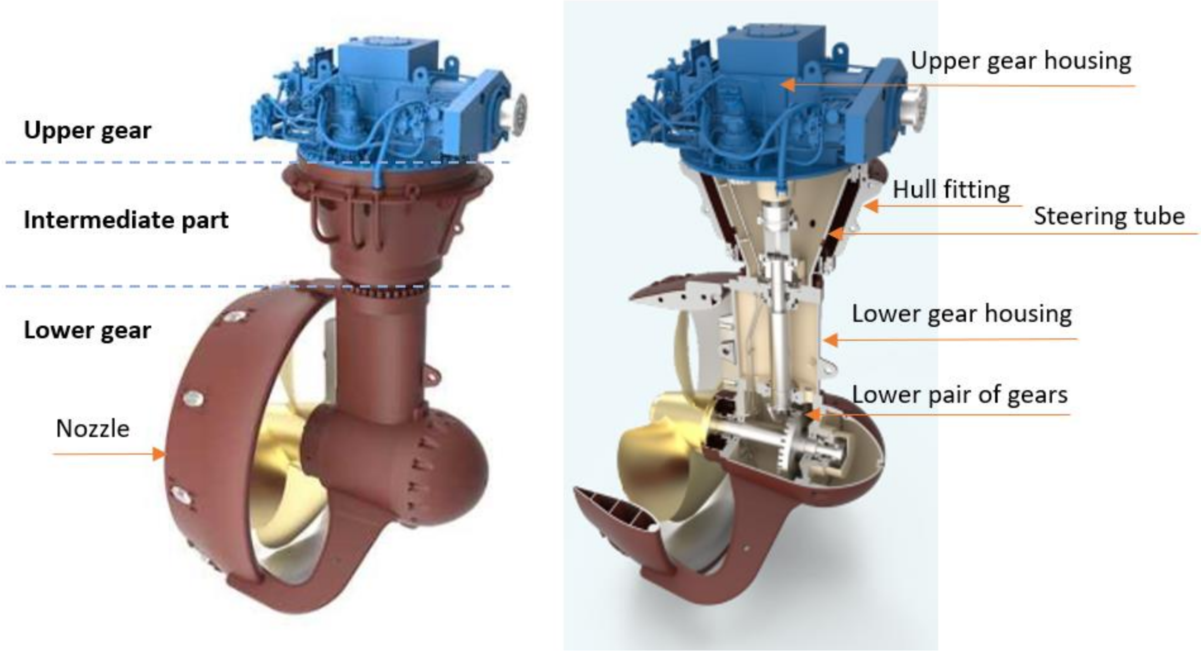

Figure 7. *US type azimuth thruster and the major parts (Kongsberg Maritime 2022)*

The unit consists of mechanical, hydraulic, and electrical parts. The mechanical parts can be divided into housing parts and components that are part of the power transmission line. Housing parts are for example gear housings, hull fitting and propeller nozzle. These parts are made of structural steel and are large and heavy. The power transmission line consists of shafts, gear pairs, couplings and bearings. Lower pair of gears is along with the housing parts one of the biggest components. Depending on whether the unit has a nozzle or not, it can be open or ducted. In most of the cases, two thrusters are mounted to one vessel.

The materials used in the thrusters are mostly different steels, cast iron and aluminum. Different iron alloys can contain small amounts of carbon (C), chromium (Cr), silicon (Si), manganese (Mn), phosphor (P), sulfur (S), nickel (Ni), molybdenum (Mo), copper (Cu), and nitrogen (N).

US type azimuth thruster is a common design used in tugs. Other ship types where it is applicable are ferries, platform supply vessels and anchor handling vessels. Depending on the type of US thruster, the maximum power can vary from 350 kW to 5,500 kW and the propeller diameter can vary from 1,050 mm to 4,000 mm (Kongsberg Maritime 2022).

The thrusters have two different types depending on the nozzle mounting solution. The first type of thruster has a welded nozzle. Its nozzle is mounted at the same time as other components in Rauma. This means that the nozzle is first transported from supplier, typically from China to Finland. Then it is welded to the unit and the whole unit is delivered to the shipyard located in Asia.

The second type of thruster has a bolted nozzle. The bolted nozzle can be mounted in the shipyard. This means that the nozzle is transported from supplier straight to the shipyard in Asia without having to be transported first to Finland like the welded one.

4.3 Goal and scope definition of the study

The goal of this study was to find out the carbon footprint of Azimuth Thruster’s and estimate the company’s climate impact. The intended application of this LCA study was strategic planning and marketing. It was also important to find out ways to lower the impact and compare different technical solutions’ climate impacts. The intended audience was the company, but the results can be utilized as support for sales. This study helps the employees to pay attention in climate aspect in decision making. The results were intended to be disclosed to a limited extent to the public.

Nedreberg (2021) conducted a study regarding carbon footprint calculation for different azimuth thruster type, Azipull. The results were compared to each other to check wheatear they are in line with each other, even though the units differ from each other. Pasanen (2021) conducted a study concerning a different kind of propulsion product, waterjet’s, carbon footprint. Both studies were conducted without using any commercial software. This thesis utilized a commercial calculation software, SimaPro, to enlarge the perspective to the results.

The system boundary’s type was from cradle to gate. This means that the study considered all the life cycle phases from the raw material extraction to the phase where the finished unit is ready to be assembled to the vessel. The system boundaries are illustrated in *Figure 8.* The use and final disposal were excluded from this study since the estimations regarding these phases would distort the results.

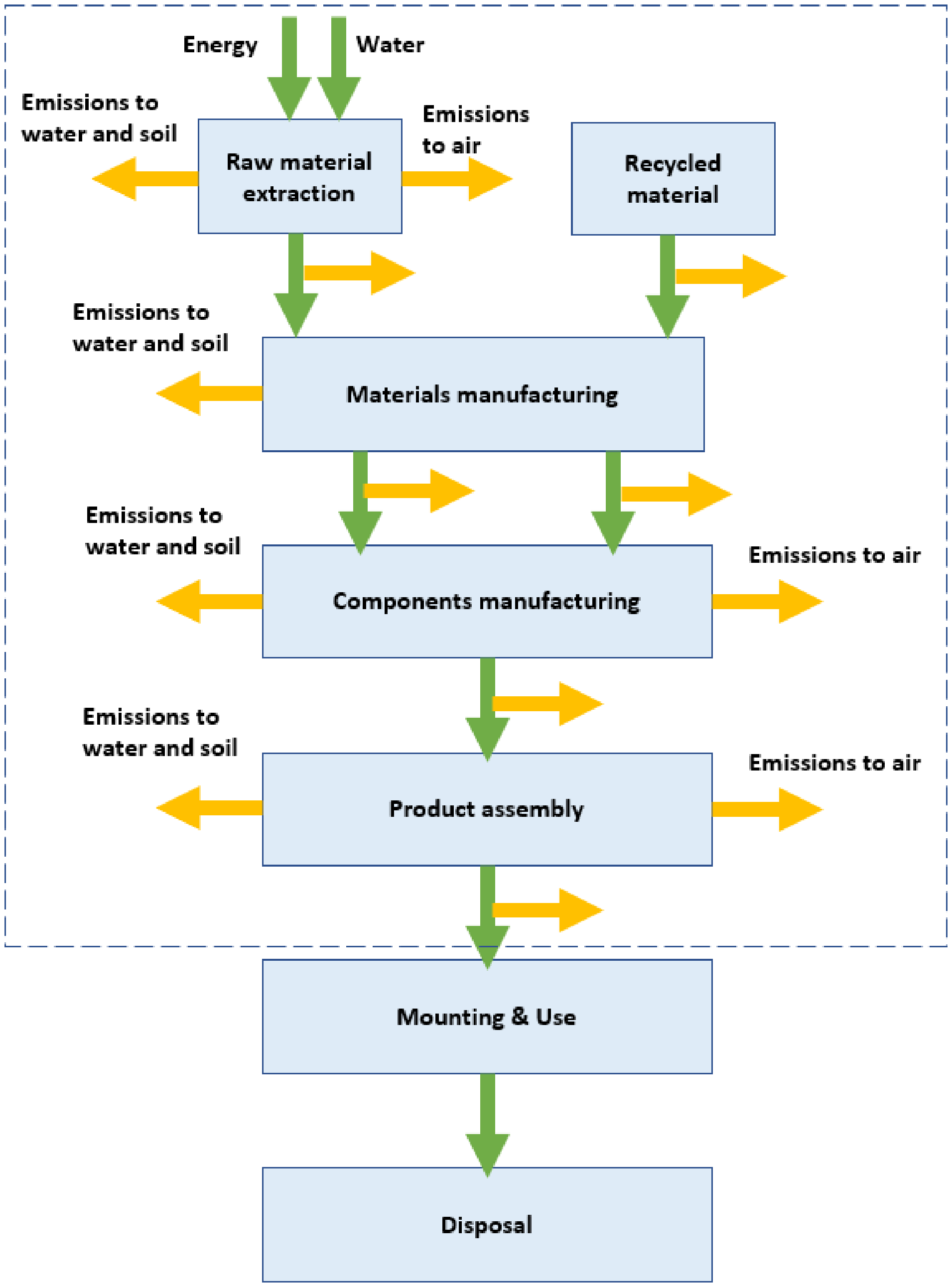

Figure 8. *System boundaries and process flow*

The functional unit was one US azimuth thruster, and the study included the mechanical parts of the thruster. This unit has two different technical solutions in the nozzle mounting which may affect to the carbon footprint of the unit. The product system in Kongsberg Maritime contains the component assembly and test drive. The study included also the functions conducted by suppliers. The functions contain the raw material extraction, material and components manufacturing, product assembly and transportations.

The focus of this study was on the heaviest components of the unit, which account over 5 % of the total weight of the thruster. The manufacturing type for these components is engineering to order, so the component is the main product and there are only a few or none co-products. Therefore, all the energy and material needed was allocated to the production of the component.

In this study the intention was to focus on the carbon footprint analysis. The aim was to calculate the carbon footprint of two different units with different nozzle mounting types and compare these global warming potentials to each other. Potential environmental impacts were calculated using the SimaPro® 9.3.0.3 software with the ReCiPe 2016 midpoint characterization method with hierarchist perspective. In this study, the aim was to calculate carbon footprint, so the only impact category assessed was climate change which' characterization factor is global warming potential (GWP). As characterization model was used IPCC baseline model of 100 years. As category indicator was used infrared radiative forcing (W/m^2) and the result were reported as kilograms of CO_2-equivalents per functional unit.

Production and use of fuels, electricity and heat were included in the study to the extent they are included in Kongsberg Maritime Rauma electricity consumption and in district heating data, and in SimaPro software, as well as manufacture of the ancillary materials.

4.4 Life cycle inventory of azimuth thruster

The first procedure in life cycle inventory is collection and validation of data (SFS-EN ISO 14044:2006). The data collected and used have a significant impact on the LCA study and its results as it is the base for the next phases. The data collection included primary and secondary data collection.

One thruster consists of hundreds of components. In this case, the cut off criteria of 95 % mass contribution of components was applied according to ISO 14040. The information of the product, such as its components and their mass, materials and quantities were obtained from bill of material (BOM). Heaviest components, that accounted over 5 % of the total weight of the unit, were identified. For these suppliers was commissioned an inquiry to collect primary data. Secondary data was obtained from Ecoinvent 3.8 Database or from literature sources. In *Table 5* is specified the data source and quality by each life cycle stage used in the study. The data quality and accuracy varied between the data sources and some data was more recent than others. Even though the primary data is favorable, the databases include more comprehensive data and take account even hundreds of factors and are in some cases even better source of information than primary data.

Table 5 *Data quality and sources by every life cycle stage*

Life cycle phase	**Data quality and source**
Raw material extraction	- Primary data: data from suppliers - Secondary data: data from literature and Ecoinvent 3.8 Database
Materials manufacturing	- Primary data: data from suppliers - Secondary data: data from literature and Ecoinvent 3.8 Database
Components manufacturing	- Primary data: data from suppliers - Secondary data: data from literature and Ecoinvent 3.8 Database
Product assembly	- Primary data: data managed by Kongsberg Maritime
Transport	- Primary data: data managed by Kongsberg Maritime - Secondary data: data from literature, estimations based on data managed by Kongsberg Maritime and Ecoinvent 3.8 Database

After data collection and validation, the data was related to the functional unit. Raw material extraction stage includes the acquisition of the raw materials needed for the processed materials.

In SimaPro, the Ecoinvent 3.8 Database includes ready datasets for different materials, and these were used. These materials also contain the next phase, material manufacturing processes so this phase was not considered separately. The used materials were market activities, that represents the consumption mixture of a product in given geography, connecting consumers of the same product in same geographical area with suppliers. The producers and imports of the product are grouped by markets within the same geographical area. Consumers are also accounted for transport and for losses during that process by the market. (Ecoinvent Database 3.8)

Depending on the amount of the alloy material, the used materials were categorized to unalloyed, low-alloyed and chromium steel. Major part of the components was made from structural steel, which can contain really small amounts of alloys, but were assumed as unalloyed steel. As low-alloyed steel was considered for example 18 CrNiMo7-6, which contains small amounts (under 1 % of each alloy) of carbon, silicon, manganese, and molybdenum and about 1.6–1.8 % of chromium and about 1.4–1.7 % of nickel (Ovako 2022). In *Table 6* is listed the masses and materials of the largest components studied. Global geography was chosen for all the component materials since more accurate geographical area was not available. The mass of the whole unit was 19,699.8 kg.

Table 6 *Materials and masses of the largest components.*

Component	**Mass of the component (kg)**	**Material**	**Mass-% of the component**	**Mass (kg)**
Propeller nozzle	4,198	Unalloyed steel Chromium steel	80 20	3,344 854
Hull fitting	2,255	Unalloyed steel	100	2,255
Steering tube	1,323	Unalloyed steel	100	1,323
Thruster lower gear housing	1,970	Unalloyed steel	100	1,970
Lower pair of gears	1,050	Low-alloyed steel	100	1,050
Upper gear housing	1,183	Unalloyed steel	100	1,183

Components manufacturing process began from the transportation of the materials from material manufacturers to the component manufacturers. Primary data of the material manufacturing countries was received from the suppliers. The transportation distances were estimated based on this information. The freight type was estimated based on the locations and distances. The unit for transportation activities is ton-kilometer (tkm). The unit means delivering the service of transportation of one metric ton across the distance of 1 km (Ecoinvent Database 3.8). It can be calculated by multiplying the weight in tons with distance in kilometers. In material transportation must be considered the losses during the next phase, component manufacturing, to ensure the material sufficiency for the next phase. The primary information for the wasted material in each component's manufacturing process was received from the suppliers. The chosen transport methods were, as well as materials, market activities. In *Table 7* is presented the required mass of the material transported, freight type and transportation distance for each component.

Table 7 *Transportation distances and freight types for each component's materials.*

Materials for the component	**Wasted material (%)**	**Required amount of material (ton)**	**Freight type**	**Transportation distance (km)**	**Transportation (tkm)**
Propeller nozzle	8	4.53	Truck	500	2,267
Hull fitting	35	3.04	Truck	500	1,522
Steering tube	35	2.19	Truck	500	1,093
Lower gear housing	35	2.66	Truck	500	1,330
Lower pair of gears, wheel	17	0.79	Rail Sea Truck	671 1,367 179	531 1,083 1,412
Lower pair of gears, pinion	48	0.55	Truck	450	248
Upper gear housing	40	1.66	Truck	60	99

Next step in studying component manufacturing stage was the manufacturing process itself. The process contains many different subprocesses. Because of the many multiphases and complex processes for each component, all the site-specific data was not available. Therefore, in the scope of this study the data from Ecoinvent 3.8 Database was used. The used process was metal working factory, and it concludes the estimated amount of energy and auxiliary inputs based on average consumption of factories. The source of heating was estimated based on the country specific energy mixes. Also, the estimated data was based on the geographical area, and it was used average data either from Europe (RER) or from the rest of the world (RoW) depending on the country the component was manufactured. For components manufactured in Finland it was used metal working average process and for hollow bars, it was used a process called drawing of pipe, which produces a seamless pipe (Ecoinvent 3.8 Database).

The next phase was transportation of the ready components to the assembling factory of Kongsberg Maritime in Rauma, Finland. The transportation distances were estimated utilizing Google Maps, Routescanner and Roma2rio websites. The information can be found in *Table 8.*

***Table 8** Components transportation to Rauma.*

Component	Weight (ton)	Freight type	Transportation distance (km)	Transportation (tkm)
Propeller nozzle	4.198	Truck Sea	510 22,093	2,141 92,746
Hull fitting	2.255	Truck Rail	400 11,150	902 25,143
Steering tube	1.323	Truck Rail	400 11,150	529 14,751
Thruster lower gear housing	1.970	Truck Rail	400 11,150	788 21,966
Lower pair of gears, pinion *)	0.373	Truck Sea	488 1,162	167 433
Lower pair of gears (whole component)	1.050	Truck	150	158
Upper gear housing	1.183	Truck	140	166

**) The ready pinion (smaller gear) is first transported to supplier*

The last stage before delivering was product assembly, which was done by Kongsberg Maritime in its own factory. The primary data was received from a study conducted by Seniors&Sons (2021). The data from the study included general use of electricity, light fuel oil and district heating consumption in 2021 from the whole functions conducted in Rauma premises. The data included for example the processes such as welding, forklift truck fuel and electricity used in the office. The primary data was allocated to all the delivered units from Rauma in 2020 to estimate the energy needed to produce one thruster, which was the functional unit in this thesis. After the assembly of the thruster, the unit was delivered to the shipyard in Asia. The transportation information can be found in *Table 9.*

***Table 9** Transportation of the azimuth thruster to shipyard in Asia.*

	Weight (ton)	**Freight type**	**Transportation distance (km)**	**Transportation (tkm)**
Azimuth thruster with welded nozzle	19.7	Truck Sea	260 19,970	5,122 393,410

To collect as reliable data as possible, an inquiry was conducted to the suppliers. The survey was conducted to the suppliers who supply components that weight more than 5 % of the total weight of the unit.

4.5 Sensitivity analysis

Sensitivity analysis was used to assess the uncertainties of the data. The most uncertainties considered the raw materials extraction, supply chain processes and the chosen data from Simapro processes.

The impact of the material used in the calculation was assessed by comparing the GWP of the chromium steel which' chemical compositions has 68.6 % Fe, 19.0 % Cr, 9.3 % Ni and 0.08 % C (Ecoinvent Database 3.8) to the actual used steel which chemical composition has 22.5 % Cr, 4.5 % Ni and 2 % Mn. The comparison was made with material, which chemical composition did not competely correspond to the definition of the data in Ecoinvent Database. As it can be seen, the chemical composition of the material differed over 3.5 percentage points for some elements.

The impact of material manufacturing process was assessed by comparing the steel produced via BF-BOF and EAF processes in Europe and the average steel manufacturing process globally. The comparison was made with lower pair of gears, the component made with low-alloyed steel. This was because the unalloyed steel is mainly made from pig iron and manufactured through BF-BOF process and because the chromium steel is mainly made of recycled steel through EAF process. The comparison was made by component so that it does not take a position on whether the other components made of unalloyed steel could be made of low-alloyed steel.

The components in this study have different rates of wasted material, as for example the rate of wasted material for propeller nozzle is about 8 % and for pinion of lower pair of gears about 48 %. The amount of needed raw material during manufacturing process was analysed by reducing and increasing the amount by 10 percentage points to assess the impact of wasted material to the final results. The process regarding the component manufacturing in Ecoinvent already containes the average material loss during the process so the change was unable to do within the process.

The impact of the transportation distances were also assessed. The sea and rail routes were easier to estimate than the road distances. In sea and rail transport both origin and destination was specified in primary data. The road kilometers were based on estimation. The impact of road transportation distances was assessed by doubling all the road kilometers. All the aspects of uncertainties and used sensitivity analysis methods are listed in *Table 10.*

***Table 10** Aspects of uncertainties and used sensitivity analysis methods.*

Aspect of uncertainty	**Sensitivity analysis method**
Material choices	Comparing the actual material composition to the used material in Ecoinvent Database 3.8
Material manufacturing process	Comparing the impact of steel produced via BF-BOF and EAF processes and global average.
Amount of needed raw material	Comparing the impact of 10 % more and 10 % less needed raw material
Transportation distances	Comparing the impact of doubled road kilometers.

The results for sensitivity analysis are presented in chapter 5.2. The results include the assessment of the significance of each aspect of uncertainty according to ISO 14044.

5. RESULTS AND DISCUSSION

In this chapter the results are reviewed to accomplish the goal of the study. The chapter includes the results of carbon footprint, sensitivity analysis and comparison between two thruster types. In the end is recommendations in reducing the carbon footprint.

5.1 Carbon footprint of azimuth thruster

As a result, a carbon footprint of the six heaviest components of a thruster with welded nozzle is 68,700 kg CO_2 eq. The results by components can be found in *Table 11.*

Table 11 *Carbon footprints of the components and whole thruster unit*

Component	**Carbon footprint (kg CO_2 eq)**
Lower gear housing	8,960
Lower pair of gears	5,320
Propeller nozzle (welded)	22,800
Upper gear housing	4,450
Steering tube	6,790
Hull fitting	11,600
Thruster	68,700

The result is well in line with previous Kongsberg studies (Nedreberg 2021; Pasanen 2021), even though the results are not completely comparable due to the relative nature of LCA. This means that the choices made in the study affect inevitably to the results. According to Pasanen (2021), one waterjet unit weighting about 2,000 kg generates 12,400 kg CO_2 eq of emissions, which is about 6,200 kg CO_2 eq per ton of unit. In this study the number is 5,700 kg CO_2 eq per ton of unit.

In *Table 12* the results are presented in categories, and of which factors the carbon footprint consists of. The same information is presented in Annex A in network diagram.

Table 12 *Factors of which carbon footprint consists of (cut-off 0.01 %)*

Category	**Of which carbon footprint consists of**	**Carbon footprint (kg CO_2 eq)**
Material	Steel, unalloyed	17,970
Material	Steel, low-alloyed	2,060
Material	Steel, chromium steel	4,240
Energy	Electricity	2,540
Energy	Heat, district or industrial	1,640
Transport (forklift)	Light fuel oil	22
Transport	Lorry 16-32 metric ton, Euro6, Europe	1,400
Transport	Lorry, unspecified, Rest of the World	1,190
Transport	Train, Europe	24
Transport	Train, China	908
Transport	Train, Rest of the World	2,050
Transport	Sea, container ship, Global	4,580
Processing	Metal working, average for steel product	24,400
Processing	Energy and auxiliary inputs, metal working	4,359
Processing	Metal working, average for metal product	1,270
Processing	Drawing of pipe, steel	101

The metal working causes the biggest impact, and the second largest impact is on the raw material extraction and material processing. The product assembly, which contain the use of light fuel oil, electricity, and district heat, are relatively small, only about 6 % of the total carbon footprint of the product. These emissions represent the scope 1 and 2 emissions. The percentage of carbon footprint of each life cycle stage is presented in *Table 13.*

Table 13 *Carbon footprint percentage of different life cycle phases.*

Life cycle phase	**Factors included**	**Percentage of the carbon footprint**
Raw material extraction and materials manufacturing	Materials, Materials processing	44 %
Components manufacturing	Metal processing	35 %
Product assembly	Electricity, district heating, light fuel oil for forklifts	6 %
Transport	All transport (exc. Forklift)	15 %

The production of propeller nozzle has the biggest impact to the carbon footprint from the components (22,800 kg CO_2 eq). To better understand the factors of which carbon footprint consists of, here is example of the carbon footprint of the nozzle. The biggest impact (45 %) to carbon footprint of the nozzle is the raw material manufacturing. The second biggest impact (41 %) is on metal working of the component. After these comes material processing (7 %), which consists of energy and auxiliary inputs, and total transportation (6 %). The network diagram for these results is shown in *Figure 9*.

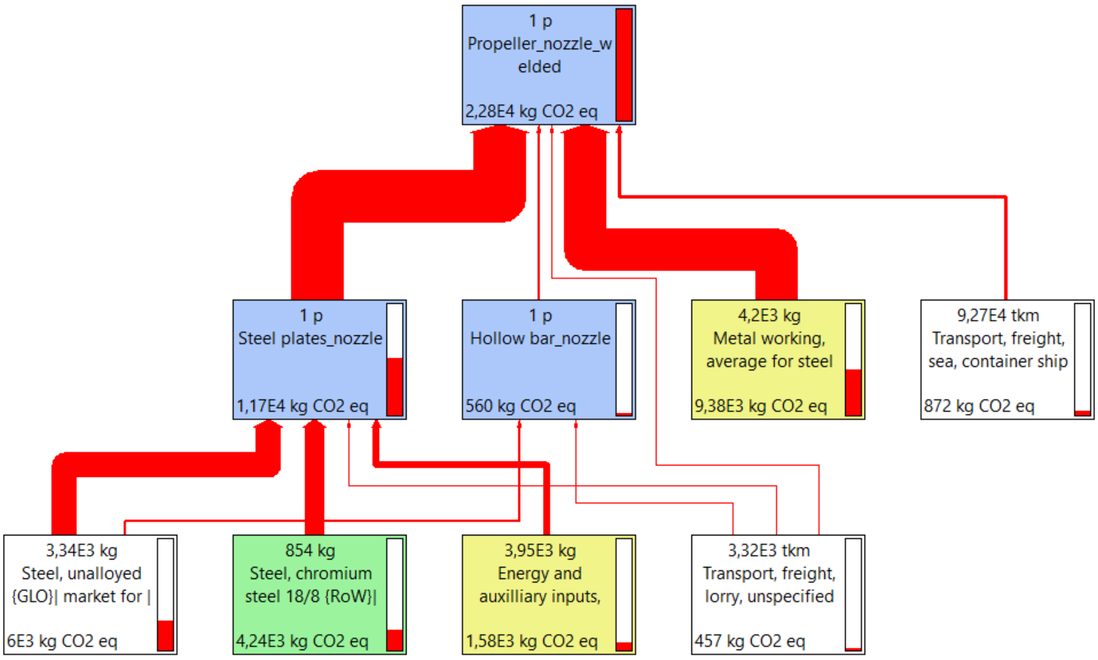

Figure 9 *Network diagram of carbon footprint for nozzle with welded mounting type (cut-off 1 %). The red arrows implement the impact; the thicker the arrow is, the bigger GHG emissions.*

The emissions are generated along the supply chain. Both the materials manufacturing and the component's manufacturing have a huge affect to the component's carbon footprint.

5.2 Results of sensitivity analysis

This chapter discusses the results of the sensitivity analysis. The analysis was made to assess the reliability of the LCA. The analysed aspects were material choises, material manufacturing process, amount of needed raw material and transportation distances. The results can be found in *Table 14.*

***Table 14** Results of sensitivity analysis and the significance according to ISO 14044 annex B. Ranking criteria: significant influence (contribution > 50 %), relevant influence (25 % < contribution < 50 %), some influence (10 % < contribution < 25 %), minor influence (2.5 % < contribution < 10 %, and negligible influence (contribution < 2.5 %)*

Aspect of uncertainty	**Deviation to original carbon footprint**	**Significance**
Material choices	0 %	Negligible influence
Material manufacturing process - BOF - EAF	 3 %* -28 %*	 Minor influence Relevant influence
Amount of needed raw material	4 %	Minor influence
Road transportation distances	4 %	Minor influence

* The deviation to carbon footprint of the lower pair of gears

The comparison of material choices resulted that the chemical composition of the steel has a negligible influence to the GWP of the component. This supported the choice to use the categorization of the materials to three categories already existing in Simapro rather than creating the materials with exact chemical composition but lacking the other exact data.

The comparison of material manufacturing process resulted that if the components were made through BOF or BF-BOF process, the result was 3 % higher. If the components were made through EAF process the influence would be relevant, 28 % lower. The comparison was made by component, because the low-alloyed material can be done both through BF-BOF process and EAF process.

The amount of increasing or decreasing the amount of needed raw material by 10 % had minor influence to carbon footprint. The impact of the transportation distances were also assessed. The sea and rail routes were easier to estimate than the road distances. In sea and rail transport both origin and destination was specified in primary data. The road kilometers were based on estimation. The impact of road transportation distances was assessed by doubling all the road kilometers. As a result the impact accounted 4 % higher.

5.3 Comparison between two different thruster types

The aim of this study was to compare the carbon footprints of two units, which have a different nozzle mounting type. For reference it was used two units which were otherwise identical.

The first type of thruster has a welded nozzle, and its carbon footprint was calculated earlier on this study. The 4.198 tons nozzle is first transported 22,603 km to Finland and then as part of the unit back to Asia for 20,230 km. As a whole the nozzle travels for 42,833 km.

The second type of thruster has a bolted nozzle. The bolted nozzle can be mounted in the shipyard. The 4.198 tons nozzle is transported from supplier straight to the shipyard travelling only 5,292 km which is 37,541 km less than the first type of nozzle. The aim was to concentrate how much it lowers the carbon footprint when the nozzle is delivered straight from the supplier to the shipyard and mounted there. As a result, the bolted nozzle type of thruster shortens the transportation distance and with it reduces the carbon footprint of the thruster by 1,800 kg CO_2 eq. This is the same amount of GHG emissions as an average Finnish person's yearly carbon footprint of food in 2018 (Sitra, 2018).

5.4 Recommendations for reducing the carbon footprint of azimuth thruster

The study showed that major part of the GHG emissions (44 %) are generated in the raw material extraction and material processing phases. According to literature review, calculation, and the sensitivity analysis there are four relevant methods for reducing the emissions in this phase. These methods are using less material, using more recycled material, using material, which is produced via EAF process, and using cleaner energy in the mining and processing the material.

As over 40 % of the emissions are generated in this phase the less material is needed in the thruster the less the material needs to be extracted and processed. This means that less energy is needed in all phases. Kongsberg could invest in the increased efficiency in material use and design lighter structures. All the processes in the calculation use weight as a parameter, so the emissions can be reduced in same ratio as the weight is reduced.

Using more recycled steel and using material produced via EAF process are parallel. According to the sensitivity analysis the material manufacturing process has relevant influence on the carbon footprint. Using material produced via EAF process could reduce the emissions by 28 %. According to the literature the limitations are related to the availability of recycled material and the chemical composition of the material produced from recycled steel. The steel that is produced via EAF process uses recycled steel as raw material and uses electricity as source of energy. Nowadays the impurities are still impossible to remove from the material. The impurities affect in the quality of the material, for example in the yield strength of the structural steel used in the thruster. In this study it was noticed that unalloyed steel is a major material in Kongsberg components. To reduce GHG emissions in the production, it should be investigated whether a part of the unalloyed steel could be replaced with low-alloy steel or chromium steel. This requires finding the components which quality requirements are not so high and suppliers who use this kind of material as input. The more scrap metal is used as raw material, the more likely the final material is produced via EAF process. As stated earlier, the EAF process generates much less GHG emissions than the traditional BF-BOF process. The environmental impacts of EAF are the better the more electricity from renewable sources is used during the process. According to the sensitivity analysis the chemical composition of the metals does not affect much to the carbon footprint of the product.

The results showed that the second most emissions generating phase is the components manufacturing phase which accounted 35 % of the total emissions. In this phase Kongsberg could favor suppliers using cleaner energy in their processes which have lower emission factor. According to literature the best is favoring electricity from renewable energy sources over other, and for example favoring natural gas ovel coal. Using renewable electricity, the emissions are 0 t CO_2 eq / MWh.

According to sensitivity analysis the amount of raw material needed has a minor influence which means that the wasted material during the component manufacturing process does not affect much in the whole picture. This means that Kongsberg could encourage its suppliers to reduce the generation of wasted material during the processing, but the rate of wasted material does not need to be a criterion choosing suppliers.

The transportation phase accounted 15 % of the total emissions. This study showed that the carbon footprint could be reduced by 1,830 kg CO_2 eq if hull fitting, steering tube and thruster lower gear housing were delivered to Finland via sea instead of rail. This is even more, than the effect of the mounting type of the nozzle. The problem is that the transportation via rail takes about 6 days (Rome2rio 2022) and via sea about 32 days (Routescanner 2022). If there is enough delivery time, the sea route should always be the priority in choosing freight from Asia to Finland to reduce the emissions.

Kongsberg could lower the carbon footprint of its products by favoring the suppliers that pay attention to higher rate of recycling, fuel substitution to greener alternatives, increased energy efficiency and removal and storage of CO_2 and takes these aspects into practice. As Kongsberg designs major part of the thruster itself, the company could reduce the emissions in the design stage by making choices for the upgradability and repair options. Also designing lighter structures and favoring recycled materials to the extent of not affecting the durability of the product.

Product assembly accounted 6 % of the total emissions. These scope 1 and 2 emissions of Kongsberg were relatively low compared to the scope 3 emissions. This means that the company itself cannot reduce much the carbon footprint by reducing its own emissions (scope 1 and 2). To lower the emissions more significantly the focus is in lowering the scope 3 emissions.

Now that the carbon footprint of the thruster is calculated, Kongsberg could use the results in further studies. In addition to reducing company's carbon footprint, Kongsberg could utilize the results in assessing the positive effects of their actions calculating the carbon handprint of their thrusters. When it comes to the whole life cycle of the thruster, that way Kongsberg could reduce the emissions of their customers by developing the thrusters and in that way be part of reducing the high emissions of the use stage of the vessels. This means that the company could search for solutions to increase the energy efficiency of the thrusters so that the fuel consumption diminishes.

5.5 Economic impacts of carbon tax

The effects of permit trading are hard to assess as it would need an LCC study to better understand its economic impacts to company like Kongsberg. Instead, the impacts of carbon tax related to reducing carbon footprint can be assessed.

The carbon tax would affect the most to the phases where the emissions are the highest: raw material extraction, material processing and components manufacturing. If carbon tax was \$7.50–\$85 / t CO_2, the carbon tax of producing one thruster would cost \$515–\$5,840. The carbon tax of the thruster with bolted nozzle would be \$13.5–\$153 less. The tax for a thruster which material is produced via EAF process would be \$370–\$4,205. If Kongsberg delivered 190 units per year the total carbon tax per year would be \$97,850–\$1,109,600, which is 0.2–2.3 % of the company's profit in 2021 (Kauppalehti 2022).

6. CONCLUSIONS

The first goal of the study was to discover of which factors the carbon footprint consist of in manufacturing industry. The lifecycle of a product was divided to seven phases, which were design, sourcing, manufacturing, delivery, product use & service, end of use and reverse logistics. The study focused on the first four stages since they were relevant in the next stages of the study. The design phase itself do not cause emissions, but the chances to affect the emissions in following phases are high. The most emission intensive phases are the material extraction and processing. These phases demand a lot of energy, both heat and electricity. In the transport phase the amount of the emissions depends on the transportation method and distance.

The second goal of the study was to calculate the carbon footprint of one azimuth thruster to better understand the climate impact of the product's manufacturing process. The calculation process was made according to an LCA study phases. The results were 68,700 kg CO_2 eq for thruster with welded nozzle. Of this footprint, the raw materials extraction and materials manufacturing accounted for 44 %, components manufacturing 35 %, product assembly 6 % and the transportation 15 %.

The next goal was to calculate how much the mounting type of the thruster's nozzle affects to the carbon footprint. The result was that the thruster with bolted nozzle accounted 1,800 kg CO_2 eq less emissions than the thruster with welded nozzle. The difference was a consequence of the possibility of direct delivery of the nozzle as the mounting of the nozzle can be done on the shipyard.

The fourth goal was to study how the carbon footprint can be decreased. As Kongsberg designs the thrusters, much can be done in this phase. Kongsberg can concentrate on developing lighter constructions and pay attention to utilizing materials which are made partly or completely of recycled materials. When more recycled material is used, one criterion for the suppliers is the use of material made via EAF process. The use of EAF produced steel would have a relevant influence in the emissions. One concrete way to lower the footprint is to change the transportation of the biggest components from China to Finland from rail to sea transportation. According to the calculation, by changing the delivery method of hull fitting, steering tube and thruster lower gear housing, the carbon footprint could be lowered by 1,830 kg CO_2 eq. By favoring suppliers who are using electricity produced from renewable sources, the emissions of the processing could be lowered close to the minimum. Whether the carbon tax would apply, the costs could vary from tens of tons of dollars to million dollars per year. The higher the emissions are, the higher is the carbon tax.

REFERENCES

Amahmoud, A., El Attar, M. M., Meleishy, A. (2022). The Evolution of Life Cycle Assessment Approach: A Review of Past and Future Prospects. IOP conference series. Earth and environmental science. Vol. 992 (1).

Azapagic, A. (2010). Assessing Environmental Sustainability: Life Cycle Thinking and Life Cycle Assessment. Sustainable Development in Practice: Case Studies for Engineers and Scientists. pp. 56–80.

Carbon Brief. (2018). Analysis: Fossil-fuel emissions in 2018 increasing at fastest rate for seven years. Available (referenced: 23.4.2022): https://www.carbonbrief.org/analysis-fossil-fuel-emissions-in-2018-increasing-at-fastest-rate-for-seven-years

van Dijk, H. A. J. (Eric) et al. (2018). STEPWISE Project: Sorption-Enhanced Water-Gas Shift Technology to Reduce Carbon Footprint in the Iron and Steel Industry: An introduction to the project, its aims and its technology. Johnson Matthey technology review. Vol. 62 (4), pp. 395–402.

Dong, H., Dai, H., Geng, Y., Fujita, T., Liu, Z., Xie, Y. (2017). Exploring impact of carbon tax on China’s CO2 reductions and provincial disparities. Renewable & sustainable energy reviews. Vol. 77, pp. 596–603.

Ecoinvent. (2022). Webpage.

European Commission. (2021). 2020 Annual Report on CO2 Emissions from Maritime Transport.

Erkayaoğlu, M., Demirel, N. (2016). A Comparative Life Cycle Assessment of Material Handling Systems for Sustainable Mining. Journal of environmental management. Vol. 174, pp. 1–6.

Fang, G., Tian, L., Fu, M., Sun, M. (2013). The impacts of carbon tax on energy intensity and economic growth – A dynamic evolution analysis on the case of China. Applied Energy. Vol. 110, pp. 17–28.

Fries, N., and Hellweg, S. (2013). LCA of Land-Based Freight Transportation: Facilitating Practical Application and Including Accidents in LCIA. The international journal of life cycle assessment. Vol. 19 (3), pp. 546–557.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S. (2012). Integrating Ecological, Carbon and Water footprint into a “Footprint Family” of indicators: Definition and role in tracking human pressure on the planet. Ecological Indicators. Vol. 16, pp. 100-112.

Gielen, D. and Moriguchi, Y. (2002). CO2 in the Iron and Steel Industry: An Analysis of Japanese Emission Reduction Potentials. Energy policy. Vol. 30 (10), pp. 849–863.

Greenhouse Gas Protocol. (2015). GHG protocol Scope 2 Guidance. An amendment to the GHG Protocol Corporate Standard.

He, K., Li, W., Xiaoyan, L. (2020). Review of the Energy Consumption and Production Structure of China’s Steel Industry: Current Situation and Future Development. Metals. Vol. 10 (3), pp. 302–.

Hsu, Shi-Ling. (2011). The Case for a Carbon Tax Getting Past Our Hang-Ups to Effective Climate Policy.

Ilmasto-opas.fi. (2022). Kasvihuonekaasut lämmittävät. Available (referenced: 23.4.2022): https://ilmasto-opas.fi/fi/ilmastonmuutos/ilmio/-/artikkeli/3a576a6e-bec5-44bc-a01d-11497ebdc441/kasvihuonekaasut-lammittavat.html

Ilmatieteenlaitos. (2022). Greenhouse gases research. Available (referenced: 23.4.2022): https://en.ilmatieteenlaitos.fi/greenhouse-gases-research

Kauppalehti. (2022). Available (referenced: 17.10.2022): https://www.kauppalehti.fi/yritykset/yritys/kongsberg+maritime+finland+oy/1007628-7

Klöpffer, W. and Grahl, B. (2014). Life Cycle Assessment (LCA): A Guide to Best Practice. John Wiley & Sons, Incorporated.

Lacy, P., Long, J., Spindler, W. (2020). The Circular Economy Handbook : Realizing the Circular Advantage.

Lipiński T, Wach A. (2015). Dimensional Structure of Non-Metallic Inclusions in HighGrade Medium Carbon Steel Melted in an Electric Furnace and Subjected to Desulfurization. Solid State Phenomena.

Liu, J., Huang, Z., Wang, X. (2020). Economic and environmental assessment of carbon emissions from demolition waste based on LCA and LCC. Sustainability (Basel, Switzerland). Vol. 12 (16), pp. 6683–.

Lopes, J.P. and D.A. Hills. (2020). The Axisymmetric Shrink Fit Problem Subjected to Torsion. International journal of engineering science. Vol. 150, pp. 103259–.

Maritime CleanTech. (2020). LCA of marine propulsion.

Morfeldt, J., Wouter, N., Semida, S. (2015). The Impact of Climate Targets on Future Steel Production – an Analysis Based on a Global Energy System Model. Journal of cleaner production. Vol. 103, pp. 469–482.

Muneer, T., Asif, M., Munawwar, S. (2005). Sustainable Production of Solar Electricity with Particular Reference to the Indian Economy. Renewable & sustainable energy reviews Vol. 9(5) pp. 444–473.

Nedreberg, M. L. (2021). CO2e Footprint Calculations. Kongsberg Maritime. Internal material.

Nguyen, D. H., Chapman, A., Farabi-Asl, H. (2019). Nation-wide emission trading model for economically feasible carbon reduction in Japan. Applied energy. Vol. 255, pp. 113869–.

Ovako. (2022). Steel navigator – find the right steel for your needs. Steel grades. 18CrNiMo7-6. Available (referenced 8.6.2022): https://steelnavigator.ovako.com/steel-grades/18crnimo7-6/

Pasanen, T. (2021). Best practices to analyse carbon footprint on propulsion product value chain, Case: Waterjet. Master of Science Thesis.

Pimonov, M. V., Romanov, D. A., Chen, H. (2021). The Structure of the Surface Layer of 0.4C–1Cr Structural Steel after Finishing Stages of Machining by Cutting. Inorganic materials : applied research. Vol. 12 (3), pp. 707–717.

Pizzol, M. (2019). Deterministic and Stochastic Carbon Footprint of Intermodal Ferry and Truck Freight Transport Across Scandinavian Routes. Journal of cleaner production. Vol. 224, pp. 626–636.

Rome2rio. (2022). Available (referenced 11.6.2022): https://www.rome2rio.com/map/Shanghai/Saint-Petersburg-Russia#r/Train

Routescanner. (2022). Available (referenced 11.6.2022): https://www.routescanner.com/

Salonitis, K., Zeng, B., Mehrabi, H. A., Jolly, M. (2016). The Challenges for Energy Efficient Casting Processes. Procedia CIRP. Vol 40, pp. 24–29.

SFS-EN ISO 14040. (2006). Environmental management. Life cycle assessment. Principles and framework. Helsinki: Finnish Standards Association SFS. 20 p.

SFS-EN ISO 14044. (2006). Environmental management. Life cycle assessment. Requirements and guidelines. Helsinki: Finnish Standards Association SFS. 46 p.

Simonen, K. (2014). Life cycle assessment.

Sitra. (2018). Carbon footprint of the average Finn. Available (referenced 11.6.2022): https://www.sitra.fi/en/articles/carbon-footprint-average-finn/

Slaboch, J., Hálová, P., Laputková, A. (2021). Development and Structural Changes of Carbon Footprint in EU28. Sustainability 2021. Vol 13(9).

Sproesser, G., Chang, Y-J., Pittner, A., Finkbeiner, M., Rethmeier, M. (2015). Life Cycle Assessment of Welding Technologies for Thick Metal Plate Welds. Journal of cleaner production. Vol. 108, pp. 46–53.

Tilastokeskus. (2022). Statistics Finland’s free-of-charge statistical databases. Available (referenced: 23.4.2022): https://pxweb2.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__khki/statfin_khki_pxt_121z.px/table/tableViewLayout1/

Tomková, Ž., S Vilčeková. (2019) Analysis of Current Situation in Field of LCA. IOP Conference Series: Materials Science and Engineering. Vol. 566 (1).

Vallero, A. (2019). Air Pollution Calculations: Quantifying Pollutant Formation, Transport, Transformation, Fate and Risks.

VTT. (2018). Carbon Handprint Guide.

Wiedmann, T., Minx, J. (2007). A definition of ‘carbon footprint’. Ecological Economics Research Trends. Pp. 1–11.

Wu, P., Bo, X., Wang, X. (2015). The Contribution of ISO 14067 to the Evolution of Global Greenhouse Gas standards—A Review. Renewable & sustainable energy reviews. Vol 47, pp. 142–150.

Zadgaonkar, L., Mandavgane, S. (2020). Framework for calculating ecological footprint of process industries in local hectares using emergy and LCA approach. Clean Technologies and Environmental Policy. Vol. 22, pp. 2207–2221.

Zhang, C., Wang, Q., Shi, D., Li, P., Cai, W. (2016). Scenario-based potential effects of carbon trading in China: An integrated approach. Applied energy. Vol. 182, pp. 177–190.

APPENDIX A: NETWORK DIAGRAM OF CARBON FOOTPRINT FOR THRUSTER WITH WELDED TYPE OF NOZZLE (CUT-OFF 1%)