Høgskolen i Østfold

Master Thesis Report

# Life Cycle Assessment for Environmental Impact Reduction and Product Improvement of Offshore mooring solutions for SEA SYSTEMS AS

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August 15 2023

# Acknowledgement

I am privileged to have an opportunity to write this master's thesis as core work done as a part of my master's in green energy technology carried out in spring 2023. I sincerely thank Prof Gunnar Andersson, the main supervisor and co-supervisor Lars Gunnar Furelid Tellnes for supporting me with the best supervision methods throughout writing the thesis. I acknowledge that this master thesis project on LCA couldn't be easy without the support of the many others who helped me in gaining knowledge in masters GET. A special thanks to Catherine Holm, HR Manager of SEA SYSTEMS AS, and Lars even Nilssen, Director of Sales providing good support and a warm welcome at the Sea Systems office regarding the master thesis project work. Again, I dedicate this thesis work to all the above-mentioned people for their great assistance and continuous support.

# Abstract

The term sustainability has emerged as an important factor in every industry in the present day. The need to reduce resource consumption and corresponding emissions in the supply chain has become an important task in achieving industrial sustainability. There are very limited works of literature and research is available on this specific topic where the environmental impacts of mechanical mooring equipment in FPSO.

The main goal of this master's thesis is to identify and evaluate the environmental impacts of the product in its life cycle from the raw material stage till its final assembly which is called Cradle to gate LCA analysis. This LCA case study is carried out as per the international standards ISO 14040 / 14044. The sources of data input for this case study are taken from the Eco invent database available in Sima Pro 9.4.2 Pre sustainability software. The primary focus of this case study was to experiment with how the LCA tool can be effective in quantifying the environmental impacts and helpful in highlighting the major impact category against which solution can be taken. The results of the study revealed that the different parameters in a product's life cycle decide its sustainability aspect. Starting from the raw material stage until final assembly all the possible sources of emissions are identified and highlighted with the corrective actions to be implemented by the organization.

Helping the organization to improve its product sustainability with the LCA method, this case study was also an opportunity to apply the academic lessons learned in Master green energy technology. The conclusion of this LCA study suggests the client with certain important parameters that help reduce their carbon footprint in the product supply chain and use this study as a reference tool for their future projects to improve the sustainability of the products.

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## Abbreviations

| | |
|---|---|
| LCA | Life cycle assessment |
| UNSDG | United Nations Sustainable Development goals |
| FPSO | Floating Production and storage offloading |
| EPD | Environmental product declaration |
| $CO_2$ e | Carbon dioxide equivalent |
| CE | Circular economy |
| EPD | Environmental Product Declaration |
| $CO_2$ | Carbon Dioxide |
| LCIA | Life Cycle Inventory Analysis |
| Tkm | Ton kilometer |
| IPCC | Intergovernmental panel on climate change |
| GWP | Global Warming Potential |
| KWh | Kilowatt hour |
| GET | Green Energy Technology |
| DACS | Dual Axis Chain Stopper |

# 1. Introduction

The study says that iron and steel contribute a value of 25 % of the greenhouse gas emissions in the industrial sector and 7 % of the total direct emissions in 2018[2]. Therefore, the emissions produced by the manufacturing industries play a vital role in the environmental impacts caused starting from the raw material processing till the end-of-life phase. Raw materials play a vital role in the environmental impacts caused by a product throughout its life cycle. Some of the major emissions resulting in the offshore industry emerge from oil drilling and processing, Offshore materials and structures used in the marine industry. It is a serious matter to reduce the $CO_2$ emissions in the industry to achieve sustainable and climate action goals in the next upcoming years preferably before 2030[3]. Process optimization and resource efficiency management are highly important to obtain a high degree of high-degree level in every production unit. When considering sustainability as an important factor in a product development industry, environmental impacts are the most challenging phases to be evaluated. Since the depletion of natural resources is increasing day by day, it is very important to consume raw materials responsibly and maintain sustainability in every production sector. A sustainable pattern of production in industries is the only solution to this problem and thus taken as a core motivation for performing this master project. Identification of major emissions areas in the industry supply chain and Integration of material circularity principles in the production process reduces the consumption of virgin materials thereby helping the manufacturers to reduce their emissions and maintain a sustainable pattern for resource consumption. It is good if the same functional unit of a product can be achieved with the least resources and corresponding emissions.

# 2. FPSO and the mooring solutions

An FPSO (Floating production storage offloading) is a widely used vessel in the offshore industry for the production, storage and transportation of oil and gas produced in the deep-sea region. They have been in use for many offshore locations across the countries for the oil and gas industry. And China has more than 70 % of FPSOs installed in their national offshore production capacity[4]. The FPSO floating systems highly helps the offshore petroleum industry to reduce the complications in oil extraction and further storage/transportation. The design and development of mooring solutions vary with the application of different FPSO units. The mooring lines are made with different materials such as synthetic ropes, polyester, and certain other reinforced materials to keep the more tough and strong[5].

## 2.1. Common materials for mooring solutions

Mooring equipment is an important part of an FPSO in holding the vessel safely and providing stability in offshore shallow/deep seawater. According to the type of vessel and offshore water depth conditions mooring types can be classified into many types such as Spread mooring, Tower yoke, Articulated column type etc. [6]. Spread mooring is the type manufactured and supplied by sea systems for the FPSO in Brazil project on which this LCA is carried out. Steel and steel alloys are mainly used in the fabrication and assembly of this project where manufacturing is carried out in Bosnia and transported to China by lorry and ship. Some of the other materials used in the fabrication of the product are bronze, Polyethylene and composite materials.

# 3. Problem statement

Since resource utilization and its environmental effect highly influence sustainability in the industry, more attention and careful analysis are required to build up an eco-friendly supply chain portfolio. Though several factors come in a product life cycle, this thesis work especially focuses on product improvements and environmental impact reduction of mooring solutions manufactured and supplied by a marine supplier company named Sea Systems AS located in Norway. This research is also a key work done as a part of the company's sustainability targets. As a product life cycle consists of various stages from mining to landfill in a linear economy, the resulting environmental emissions are the major challenges in a product development chain. To keep the product development sustainable and well-optimized, there always demands a well-planned design and execution throughout the product's life cycle. Mooring solutions are equipment used in FPSO systems to control the movements of floating structures in the offshore oil and gas industry. The mooring solutions used in such a system demand good material characteristics to gain a longer life span and ensure reliable performance. On the other side, the emission developed during the different stages of product development is the major challenge that is experienced by the manufacturers. So, for optimizing the product characteristics and reducing the emissions least as possible in the product life cycle, a deep environmental impact assessment is vital and taken as a major objective to be addressed through this master project. The key motivation of this master's thesis is not only performing an LCA analysis for a product but also taking the opportunity to implement emission reduction in the offshore sector deploying the knowledge gained from the master's program and keeping the UNSDGs goal indicator number 12.5 stating the target of reducing material consumption and the emissions wherever possible in the supply chain[7]

The existing issue in the project is to reduce the material consumption for the mooring equipment and supporting structures thereby reducing the corresponding emissions minimum as possible to achieve the thesis goal. This master thesis will cover and evaluate the product optimization ways of mooring solutions with a sustainability software called Sima Pro and other material assessment tools, such as Granta covering from cradle to gate product life cycle including the recycling options available ensuring maximum circularity in the production process. The project also targets identifying all possible methods to keep the environmental impacts and material consumption least as possible in the product life cycle stages. The research keenly aims to develop an LCA model that describes the typical design/production choices that can be developed for the manufacturer to develop a sustainable supply chain model with the clients and stakeholders.

# 4. Research questions

Norway has committed to reducing GHG emissions by 50% by 2030 and has already started implementing the required measures in almost every sector of work. Some of the key measures adopted are the circular economy action plan, green deal, Decarbonization in industries etc. The manufacturing industry contributes to the major $CO_2$ emissions resulting in climate change and serious environmental impacts [8]. Therefore, a sustainable action plan framework is required to reduce resource consumption and resulting emissions in industries [9]

**This master thesis investigates and evaluates the research question of**

1. **How LCA can be an effective method for mapping the major environmental impacts in a manufacturing industry?**
2. **Do sustainable initiatives in the supply chain help industries reduce resource consumption and corresponding emissions?**

## 5. Academic motivation for the thesis

The motivation for this master's thesis is purely based on the intention of implementing theoretical academic knowledge gained from the master's degree & aiming sustainable goal target number 12.5 ( Reduced waste generation through Prevention, reduction, recycling and Reuse https://sdg-tracker.org/sustainable-consumption-production#12.5 implemented in the industry taking SEA SYSTEMS AS as case study company performing an LCA for their product

The EU Commission states that LCA is a powerful tool to assess and measures the environmental impacts of a product/service throughout its life cycle stages used by most sustainable companies and institutes in the current scenario[10].

## 6. Theoretical position in master thesis

As a student of master's in green energy technology and a mechanical engineer experienced in manufacturing specialization, there was a great interest in exploring and experimenting with the knowledge, I have gained in my master's academic curriculum in the real-life industry. Hence, a master's thesis in LCA case study would be a great initiative to start learning what sustainability is and how it can be deployed in industry. Simapro Pre-sustainability software is an efficient tool for measuring the environmental impacts of a product/service and optimizing them with appropriate sustainable measures. The previous experience in manufacturing was a great advantage in understanding the technical sides of a product while taking this LCA initiative for making the product more environmentally friendly or sustainable.

# 7. Company background and project expectations

## Sea systems AS

A marine equipment supplier located in Vest by, Oslo. The manufacturing units are in various parts of Europe such as Bosnia, Tallinn, and Estonia. As per the requirement of the company in connection with sustainability reporting, an interest has been communicated with the Department of Engineering and Innovation at Østfold University for an environmental assessment of SEA products and thus the same has been taken as a master thesis project. The expectations of the project were -

- Reduced material consumption for the same functional unit of mooring equipment.
- The scope of including moulded/recycled materials in the LCA model.
- Reducing $CO_2$ emissions least as possible in the supply chain.

# 8. Literature review

Sustainability has turned out to be a key solution in industries contributing to climate action and resource minimization targets. The concept of circular economy and renewables are the most focused areas encouraged by the current society to achieve a green transition. Developing a sustainable practice framework in companies including SMEs would create a great impact in achieving the best results in terms of both resource consumption and reduced waste generation[11]. The concept of CE has existed since long back but still, a large gap is found in the industries to put them into practical situations. The interconnection between the environment and industry has a great influence on the sustainable performance of an organization. The more sustainable practices in an industrial supply chain, the higher the key performance indicators it has in terms of business models. This literature review aims in analyzing the major challenges faced by the manufacturing industry in waste reduction and related emissions in their supply chain[12].

The offshore industry is one of the most developing business sectors in Norway with new perspectives towards $CO_2$ reduction and transitioning towards a net zero goal. To make this happen soon, resource consumption should be very responsibly done which helps in reducing unnecessary emissions and waste generation. Iron and steel are the two common and highly consumed materials in the offshore industry for structural buildings and marine applications[6]

This master thesis work analyzed different articles and journals that say how circular economy principles in an organization help in developing a sustainable supply chain for their customers and stakeholders. Measuring the environmental impacts of a product is the initial step in quantifying its performance towards the environment and society. And this can be made possible with the most efficient available sustainability software in the market where SIMA PRO LCA software is used in this case study.

The circular economy can be defined as a closed-loop system where the products are reused or recycled after the end of life without scrapping them but utilizing them as raw materials again. Research says that circular economy can be made possible only if they are considered from the design stage itself but not in the middle of the process, since it is difficult to plan the process accordingly[13]. The scope of including better sustainability tools in the organization management not only improves the environmental standards of the products or services delivered but also contributes to the UN SDGs in the long run.

Innovation and technology like 3D printing and low-carbon solutions can help industries to construct a better business model by introducing sustainable manufacturing design and methods that hugely reduces waste generation and improves environmental performance. Beginning from raw material procurement until the dispatch of the product to the customer, there has a great scope for optimizing the product in every stage of its life cycle[14].

When coming to LCA analysis, the collection of required data is the most challenging stage, and it happens mostly in different life cycle phases. But since LCA is an iterative study, the freedom to go back to the previous stages and redefine the goal and scope of the study is always a perfect advantage in case of unsatisfied results in the interpretation stage. Industrial ecology defines that LCA measures the inventory of a system and injects the results that are required for the process optimization which is quite acceptable. The linear model is the system followed by many industries until the concept of a sustainable approach came in. But now a great change can be witnessed from the activities of different organizations that a responsible initiative taken towards recycling and high interest in environmental impact control in the supply chain.

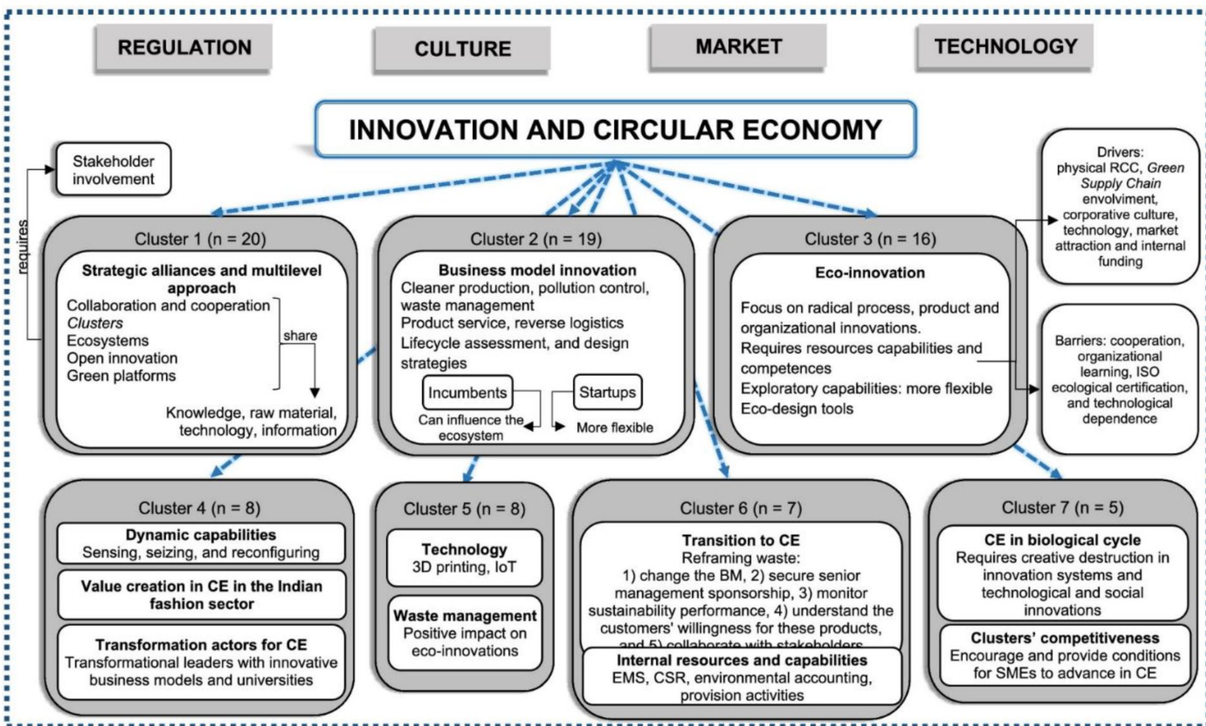



*Figure 1. indicates the framework for understanding sustainable innovation in the Circular economy [11]*

# 9. The LCA Methodology

LCA (Life cycle assessment) is an early existing tool available since long back for quantifying the environmental impacts of products in the industry, but the awareness of implementing sustainability in industries has been witnessed only in recent times and is expected to grow higher in future[15]. The scenario can be observed from Figure 2 which represents the response of industry towards environmental issues.

| | Pre 1970s | 1970s-80s | 1990s | 2000s |
|---|---|---|---|---|
| **General Approach** | **Reactive** | **Compliant** | **Proactive** | **Progressive** |
| Environmental Awareness | Very limited | Limited to particular manager or department | Heightened environmental awareness in all sectors and levels of organization | Environmental concerns are well-established in all sectors and levels of organization |
| Legislative Controls | Few regulations | Controls on emissions and waste | Integrated pollution control<br>Product take-back legislation | More and more environmental policy<br>Integrated product policy |
| Management Controls | Remediation | Inspection | Environmental standards and audits | Development of large concepts (Design for Environment, Eco-efficient manufacturing, Industrial ecology) |
| Pollution & Waste | Waste not an issue | End of pipe controls | Process innovation<br>Life Cycle approach (LCA) | Generalization of LCA, development of integrated tools for environmental design and evaluation of industrial processes |

*Figure 2.The improvement in industrial response to LCA & sustainable approach [12]*

As per the international organization for Standardization ISO 14040, the LCA methodology has been divided into four stages of assessment such as defining the [16]

- Goal and scope of the study - PHASE I

Defining the goal of the study is very important, which determines the system boundaries and the further scope of the project. The scope definition acts as a solid reference for interpreting system boundaries and functional units of the product.

- Life cycle Inventory analysis – PHASE II

This stage defines the input of resources and the information of emissions developed in the environment associated with the whole life cycle product cycle. This phase of the study includes the details of raw materials, transportation and assembly information in a products process flow[17]

- Impact assessment - PHASE III

This phase represents the effect of environmental loads caused by the emissions and resources utilized in product development stages which has the potential that leads to environmental threats such as eutrophication, global warming, and so on in terms of kilogram / metric ton of carbon dioxide equivalent.

- Interpretation – Phase IV

This final phase of the LCA framework allows the presentation of the conclusions drawn from the previous stages of assessment. Since LCA is an iterative process to measure the environmental impacts of a product within the defined boundaries, if one feels unsatisfactory with the functional unit, LCA allows the freedom to adjust the functional unit in stage one and again perform an assessment from stage 2 to stage 4. The uncertainty of the data quality is reviewed continuously throughout the assessment process.

## 10. The ideal structure of a Life cycle assessment

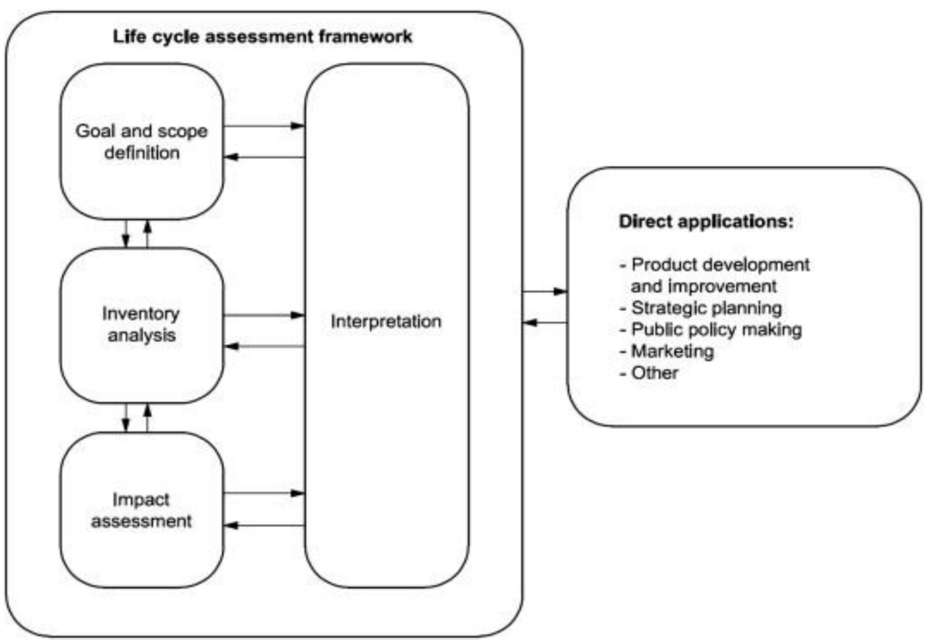



*Figure 3.Represents the framework of a Life cycle assessment methodology [15]*

# 11. Product Overview

Mooring equipment is a mechanical device that controls the movement of floating vessels used in offshore applications. They can be classified according to their nature of construction and working mechanism concerning the applications[6]. The design characteristics of the mooring solutions depend on the weather condition and the type of water depth where the FPSOs are operated[18]

The technical specifications and the bill of raw materials obtained from the company are evaluated. The mooring system consists of four clusters that include 24 DACS (Dual Axis chain stoppers) with a balcony and chain box included for each cluster unit.

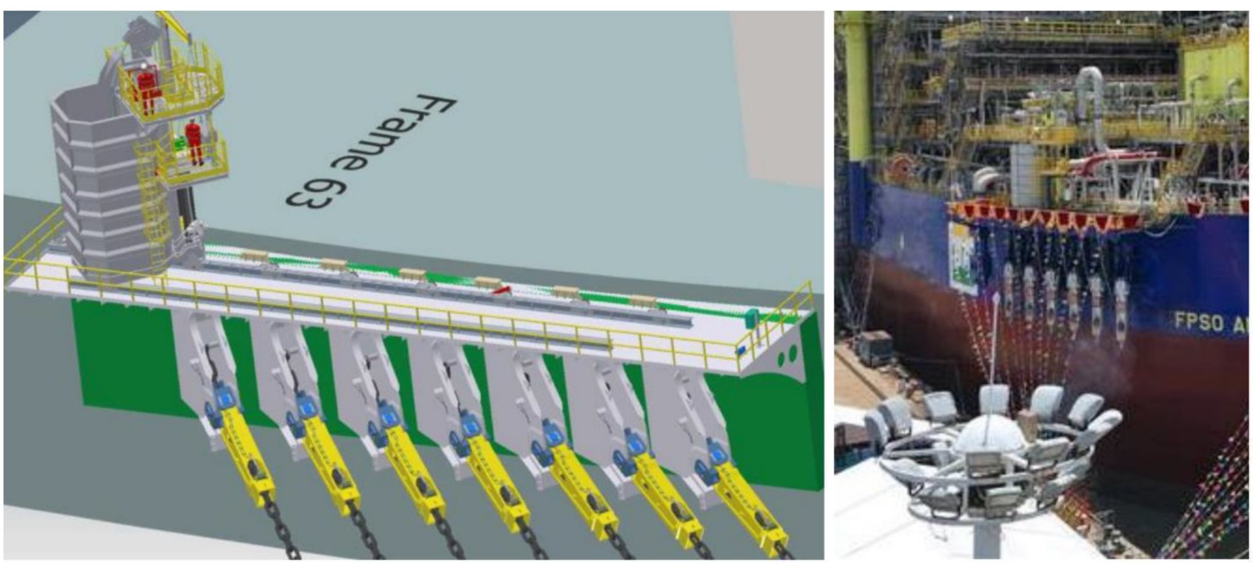



*Figure 4. represents the DACS assembly animated view (Left) and actual view (right) in FPSO. Image source – Sea systems AS*

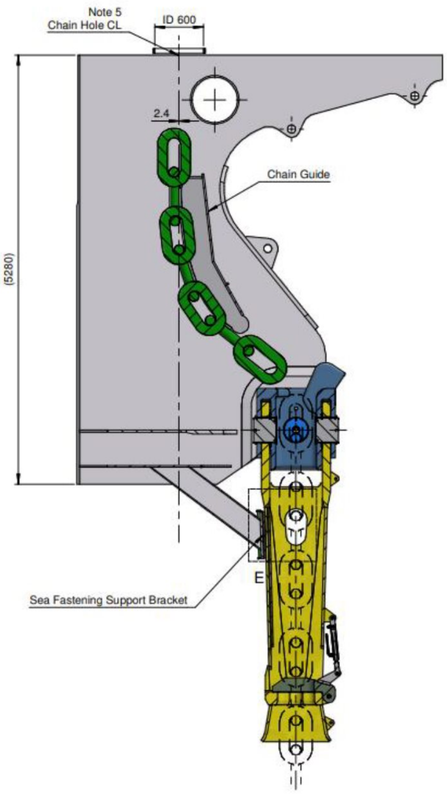



*Figure 5.The cross-sectional view of the Dual axis chain stopper. Image source – Sea systems AS*

## 12. The method of LCA (Cradle to Gate) deployed in this case study and how it was performed.

## 12.1. The goal and scope

The goal of this LCA study is to assess the environmental impacts and reduce the emissions from the product life cycle stage by optimizing the product development methods associated with the design, production, and installation of mooring equipment assembled in FPSO in China and operated in Brazil. The project is named MARLIM II ANNA NERY FPSO Project.

## 12.2. Functional Unit

The functional unit of the mooring equipment can be defined as a Mooring system that has four clusters, with 6 DACS in each cluster. The average final weight of a DACS is 7035 kg each and the total weight of an assembly is 21909 kg including the operational facility of chain box, Balcony, and a hull bracket to which the DACS is mounted and operated in shallow water depth below 1000 feet designed for the mooring of an FPSO with an average storage capacity of 16,00,000 Barrel and a service life of 34 years. The mooring equipment is designed in such a way as to withstand the Brazilian ocean load & weather conditions considering all the HSE requirements.

The LCA study is carried out as per EN 15804 and the phases are evaluated from cradle to gate of products life cycle. The system boundaries include the raw material stage (A1) till the assembly of the system in China (A5)[19]

# 13. Scope and system boundaries of the project

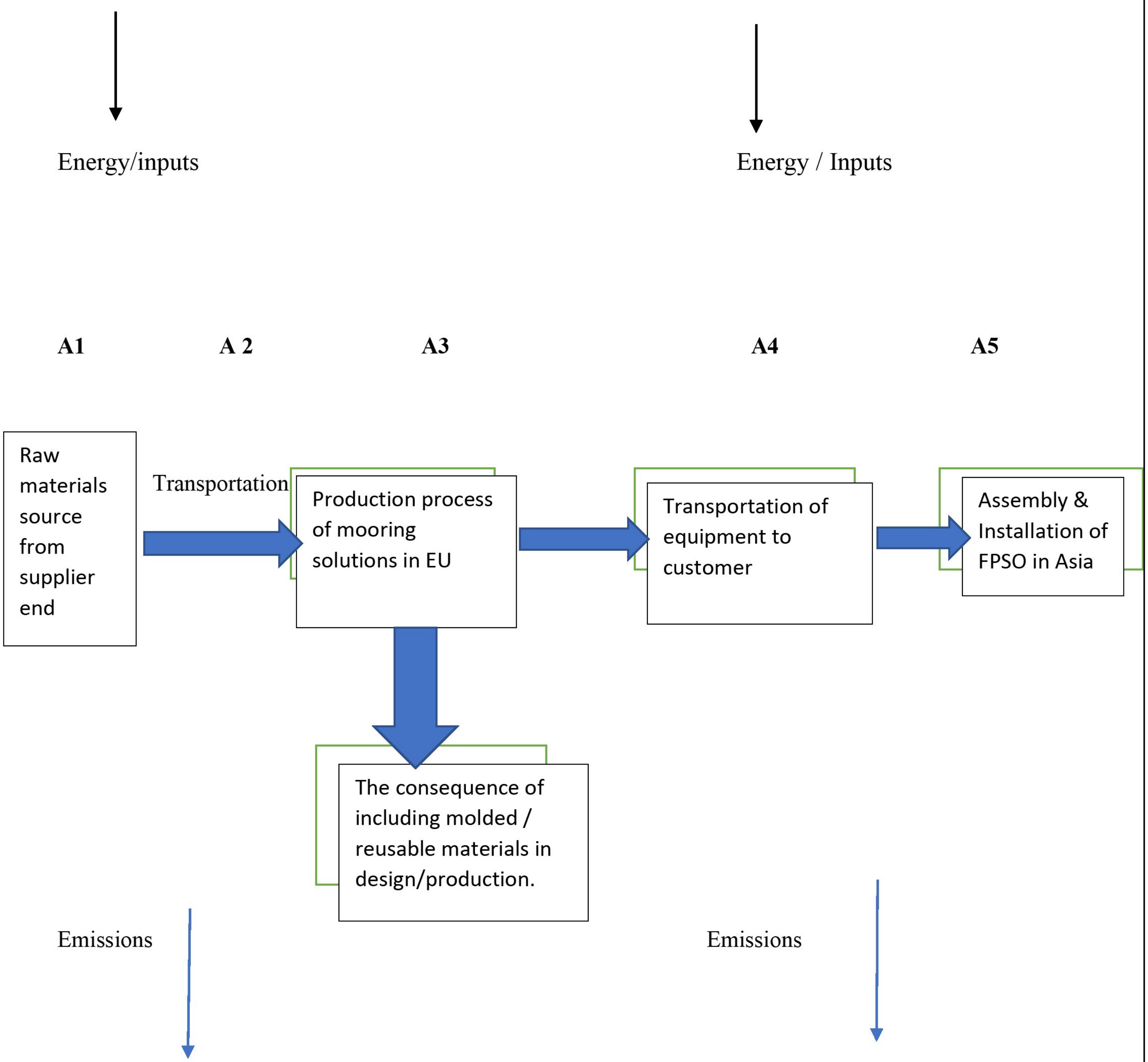



Figure 6 indicates the system boundaries of the LCA case study.

## 13.1. Scope of the study

The scope of this study will include the following stages:

The system boundary of the study will also focus on identifying opportunities to reduce the material consumption rate of the mooring equipment by reduction/optimization of design/production methods from the cradle to gate phase considering the scope of reuse/recycling of materials simultaneously lowering the emissions within the defined system boundaries.

### A1 - Raw Material

This stage includes the Procurement of raw materials such as steel, plastic, and other materials used in the production of mooring equipment at the manufacturing plant in Bosnia.

### A2 - Transportation of materials to the factory

The transportation of the raw materials from the steel suppliers to the factory in Bosnia with an exception for cardan joint since it is manufactured at the location itself in a foundry. The materials are assumed to be transported to the production site using the truck by road.

## A3 -Manufacturing

The manufacturing of the DACS is carried out in the factory and includes cutting and welding as the primary process. Bur the cardan joint in the DACS assembly is manufactured by casting in a foundry located in Bosnia.

## A4 - Transportation to the customer

The transportation of finished product assembly from the production site to the customer located in China is carried out in two phases. The first transportation is from Bosnia to Croatia by lorry and then to Shanghai by freight ship.

## A5 - Installation / Assembly in FPSO

The assembly phase includes the installation of the mooring equipment on the vessel with the necessary structures at the yard in China.

The scope of using recycled or reused materials is included within the production phase. However, the results of this study can still be used to identify areas where improvements can be made to reduce the environmental impacts of the mooring equipment throughout its defined life cycle, including its end-of-life and broad recycling phases beyond the system boundaries with a sensitivity analysis study.

# 14. LCI Phase (Life cycle Inventory)

## Raw material (A1)

The raw materials data for a single DACS is obtained from the bill of materials collected from sea systems AS for the Marlim II project and listed below.

*Table 1. Bill of Materials provided by Sea Systems AS for the manufacturing of a single DACS.*

| **Materials** | **Weight** | **Unit** |
|---|---|---|
| Steel, S355J2+N | 625 | Kg |
| Rubber | 25 | Kg |
| Steel, NVE36 | 2968 | Kg |

| | | |
|---|---|---|
| Steel, VL E36+Z35 | 575 | Kg |
| Super-Duplex SS2328 | 48 | Kg |
| Super-Duplex | 309 | Kg |
| Composite | 4 | Kg |
| Bronze | 9 | Kg |
| Polyethylene | 0,15 | Kg |
| PUR – 70 Shore | 0,4 | Kg |
| Cast steel, G24Mn66+QT | 2411 | Kg |
| AISI 316L | 11 | Kg |
| A4-80 | 0,16 | Kg |
| Paint | 34 | Kg |
| Welded material | 14,5 | Kg |
| | | |
| **Final weight** | **7036 Kg** | |

## Transportation A2

Since the data about the distance of raw materials supplier to the manufacturing unit are unknown, a medium-haul distance of 500 kilometres is applied for all raw materials and the mode of transportation is assumed by a truck as per the European sources. An exception for transportation is provided for the Cardan joint as it is manufactured at the location itself in a Bosnian foundry.

## Manufacturing A3

The manufacturing of the DACS is carried out in the Bosnian factory that involves processes such as Cutting, welding and assembly of the product. The energy use and electricity source are important in calculating the total emissions also including the loss of waste materials during manufacturing. The uncertainty in this stage is about the unavailability of exact data regarding the manufacturing process and the producer information. But the process is assumed based on the generic data available on the Eco invent database.

The Cardan joint that is used to couple the DACS Arm as shown in Figure 8 to the Hull bracket is manufactured in a Bosnian foundry. Hence no transportation is required for this component, unlike other materials. The impact assessment to produce cardan joints is calculated based on certain EPDs available for similar kinds of products. The energy use is also taken from similar kinds of manufacturers as specific data was not available regarding this.

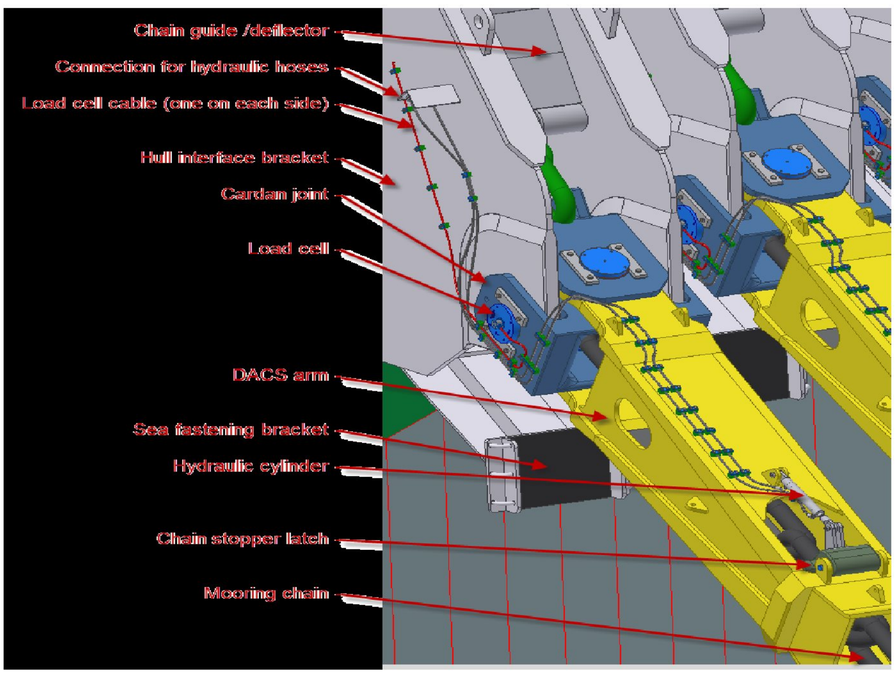



*Figure 8.The sectional view of the DACS in the final assembly Image source – Sea systems AS*

## Transport to construction site / Assembly site A4

The manufactured DACS are then transported to the customer in China by different modes such as by road and Freight ship. The first transportation mode is by truck from Banja Luka, Bosnia to Croatia with an average distance of 300 km and then from Croatia to Shanghai by fright ship around 15000 km[20]

## Assembly phase A5

The assembly is carried out in the yard in China. The assembly of DACS in the FPSO contains certain additional structures as well that include a Hull Bracket to which the DACS are mounted, A Balcony and a chain box to operate the movement of Mooring DACS. It is acknowledged that the maximum emissions are observed in the assembly phase since it requires a huge amount of additional material structure and additional energy for material handling and assembly purposes as shown in Figure 9.

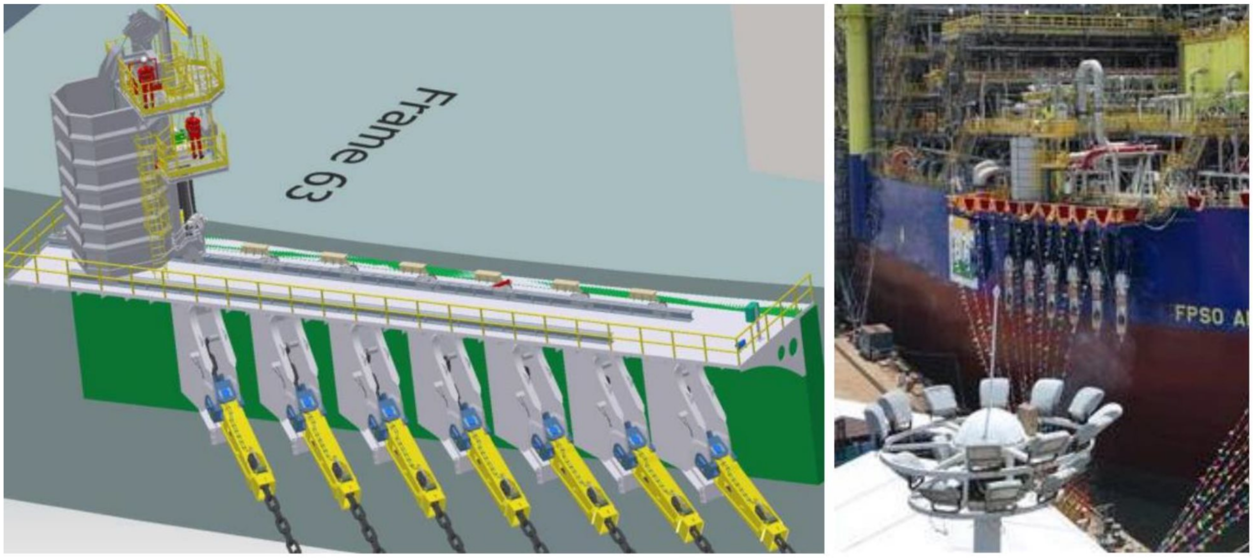



*Figure 9.The animated design of the final assembly (Left) and the actual view (Right) in FPSO. Image source – Sea Systems AS*

## 15. Emission factors used for the impact assessment and the quality of data sources.

**Note:** Most of the data is collected from the Eco invent database available on Sima Pro sustainability software and certain standard assumptions are taken wherever the uncertainty of data is observed during the assessment.

*Table 2. The emission factors for raw materials*

| Material | Description | Emission Factor in Kg | Unit | Data source Eco invent – Sima Pro |
|---|---|---|---|---|
| NVE36 | Construction steel | 2.5 | $CO_2$ e / Kg | Converter hot rolled steel |
| S355J2 + N | Thick steel | 2.5 | $CO_2$ e / Kg | Converter Hot rolled steel |
| VL E36 + Z 35 | Thick steel | 2.5 | $CO_2$ e / Kg | Hot rolled steel |
| Super Duplex SS2328 | Stainless steel | 4.2 | $CO_2$ e / Kg | Construction steel |
| Super Duplex | Stainless steel | 4.2 | $CO_2$ e / Kg | Construction steel |
| Bronze | Bearing Bush material | 6.9 | $CO_2$ e / Kg | GLO market |
| Composite | Thrust washer | 2.4 | $CO_2$ e / Kg | Glass fibre GLO market |
| Polyethylene | Clamping material | 5.3 | $CO_2$ e / Kg | High-density polyethene |

| | | | | |
|---|---|---|---|---|
| PUR 70 - Shore | Bushing material | 5.01 | $CO_2$ e / Kg | Polyurethane flexible foam RER market |
| Rubber | Hydraulic hose | 2.7 | $CO_2$ e / Kg | Synthetic rubber GLO market |
| AISI 316 L | Steel plate | 4.4 | $CO_2$ e / Kg | Steel 18 / 8 Hot rolled GLO |
| A4 - 80 | Socket screw | 5.2 | $CO_2$ e / Kg | Steel 18 / 8 Hot rolled GLO |
| Paint | Dry paint | 5.3 | $CO_2$ e / Kg | Alkyd paint without solvent (Dry paint) |

## 15.1. Emission factors for transportation

*Table 3. The emission factor details for transportation.*

| Mode of Transportation | Emission | Unit |
|---|---|---|
| Intercontinental ship / Long haul | 0.006 | Kg $CO_2$ Equivalent per tkm |
| Lorry medium | 0.165 | Kg $CO_2$ Equivalent per tkm |
| Lorry large | 0.09 | Kg $CO_2$ Equivalent per tkm |
| Air freight long | 0.75 | Kg $CO_2$ Equivalent per tkm |

## 15.2. Emission factors for energy and electricity use.

*Table 4. represents the data for electricity use by country mix and energy required for material handling.*

| **Processing** | **Description of product** | **Emission factor** | **Unit** | |
|---|---|---|---|---|
| Electricity use in Bosnia | Electricity at Medium voltage | 0.235 | Kg $CO_2$ Equivalent / Kwhr | |
| Electricity use in China | Electricity at Medium voltage | 0.686 | Kg $CO_2$ Equivalent / Kwhr | |
| Metalworking, Europe | Per kg of Final product | 1.64 | Per kg of the final product | |
| Welding Europe | Per meter of Final product | 0.184 | Per meter length | |
| Diesel energy use in machines at the work site | Amount of diesel used in machines | 0.0957 | Per MJ of fuel used | |

# 16. Environmental Impact assessment

The impact assessment is carried out based on all the parameters that have been included in the scope and life cycle inventory of the LCA study. This phase addresses and evaluates the potential human and environmental impacts based on the input energy and emissions developed in the inventory stage [21]. While evaluating the impact assessment of the inventory, certain important factors need to be considered such as midpoint and endpoint characters in the LCIA stages of the study as shown in figure 10.

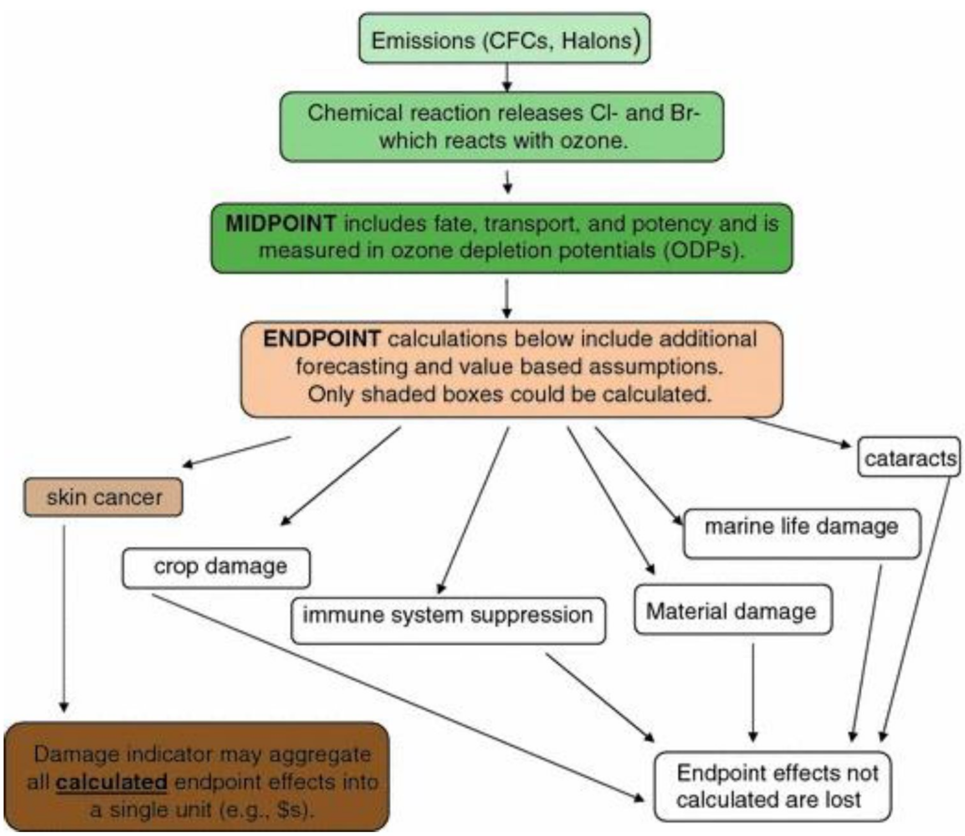



*Figure 10.The relationship between the midpoint and endpoint characters in the Impact assessment stage in LCIA [16].*


*Figure 11.The major impact categories in LCIA [1]*

As described in above figure 11. The major environmental impact categories in an LCA study can be broadly classified into three sections Human, Ecosystem and Resource depletion. The environmental impact of a product/service depends on the nature of the inventory used in the analysis[1]

The method used in this LCA study to quantify the environmental impacts of the product is based on IPCC GWP 100 including $CO_2$ intake from Sima Pro. The impact assessment is carried out in every life cycle phase from raw material extraction until the final assembly phase based on the life cycle inventory data.

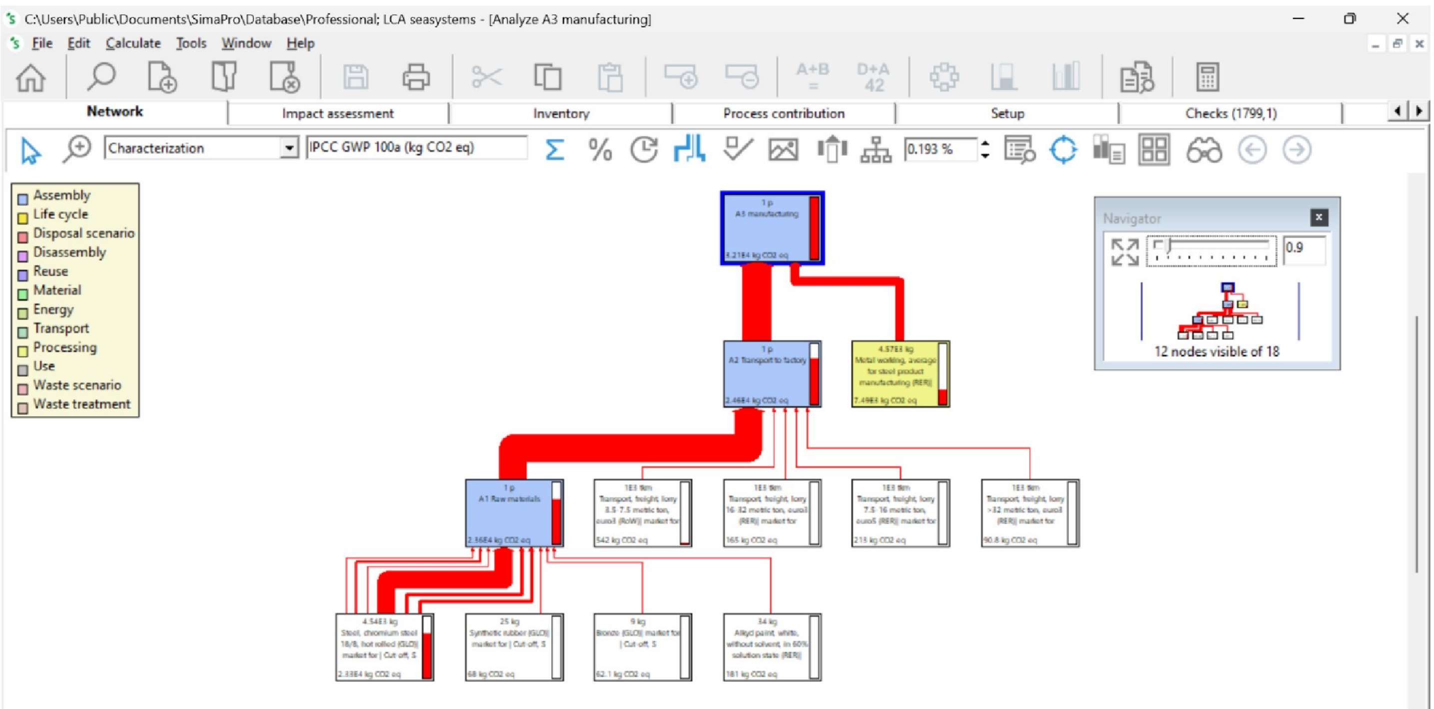
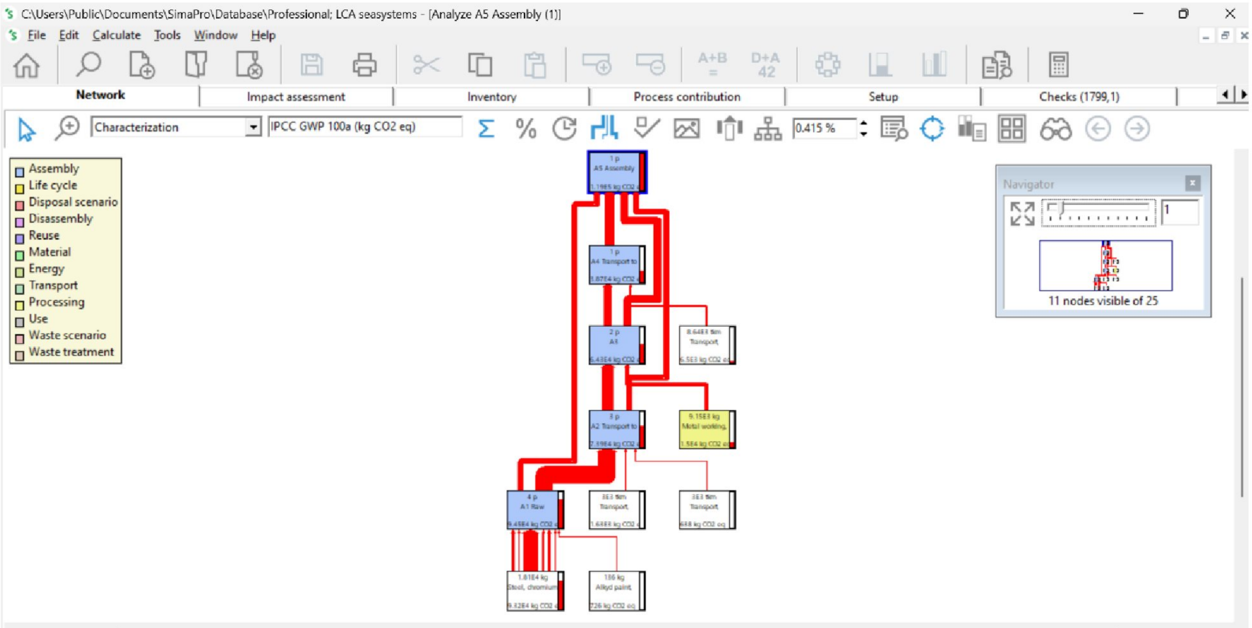



*Figure 12.The network of impact assessment from the A1 to A3 phase. Image source – Sima Pro*

Figure 12. above shows the network of impact assessment from the raw materials stage to the manufacturing phase to produce one DACS simulated in Sima Pro software. It is noticeable that the emissions from the raw materials and transportation phase contribute to little high footprint since the emission factor for the steel alloys is quite high due to their high material mass, which results in a high material consumption rate[22]



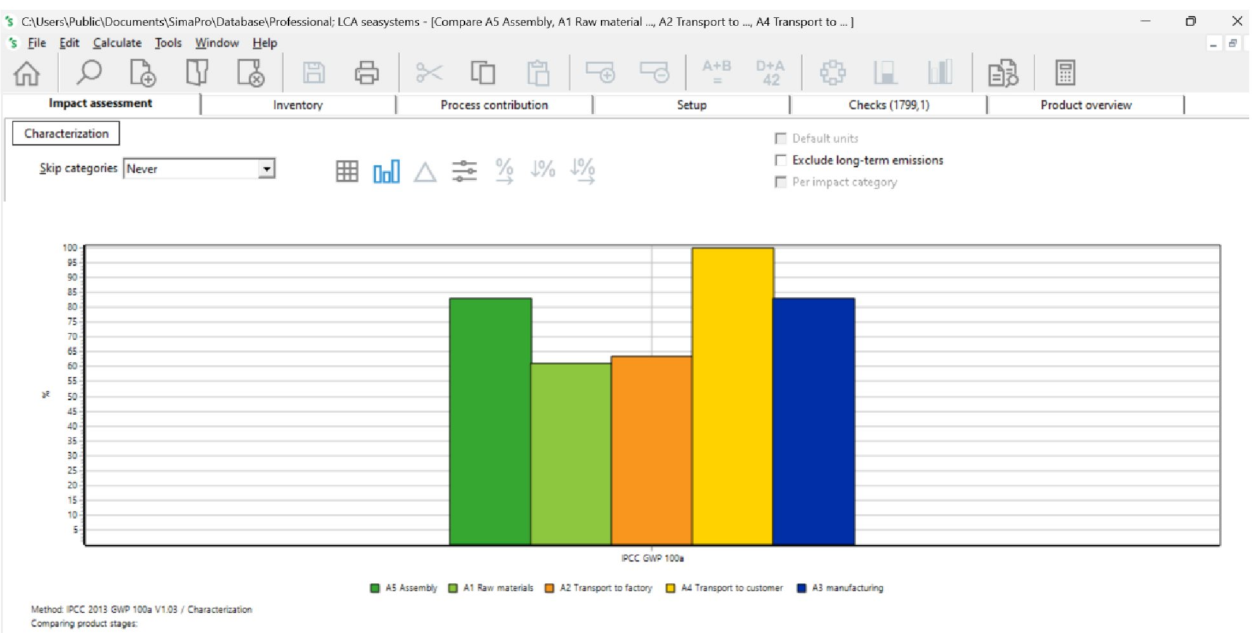




*Figure 13.The comparison of the different phases in terms of environmental impacts.*

*Image source – Sima pro*

Figure 13. shows the comparison of environmental impacts in different product stages. The transportation and assembly Phase (A4 & A5) has a high impact as the transportation is sometimes carried out by air freight to the customer which contributes to a huge potential for higher emissions in the product's life cycle stages. And the number of additional materials used in the supporting structures for assembly also has a high Carbon footprint due to high material consumption.

# 17. Interpretation

The interpretation phase in the LCA analysis is the final stage of the study in evaluating the results obtained in the previous stages such as impact assessment and highlighting the uncertainty factors in the study. While interpreting the LCA results, the results obtained must be well evaluated and confidently initiated concerning the previous stages from the life cycle inventory, impact assessment and goal and scope. If the interpretation of the results is not convincing, then the LCA methodology provides freedom to reframe the goal and scope of the study in such a way that the best results can be interpreted.

The results show the environmental impacts from the different phases of the product life cycle. The objective of the LCA study was to identify the important parameters that affect the $CO_2$ equivalent in the product development cycle. The parameters in the different life cycle phases that affect the emissions of the product are identified and corrective actions are suggested how to reduce the emissions of the product.

## 18. Results of the LCA study

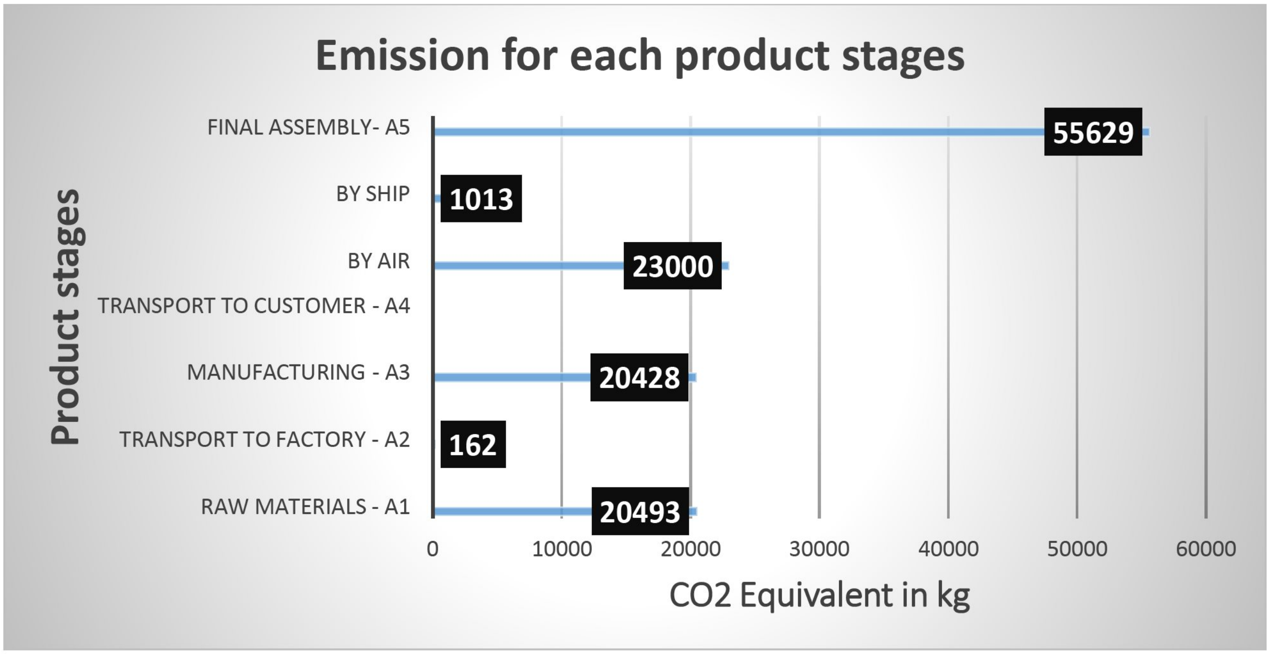



*Figure 14.The results of CO2 emissions developed in different product development phases.*

From the above figure 14, major emissions are developed in the assembly phase due to the high mass of materials used for the additional structures of the assembly. Most of the material used here for the assembly is construction steel which has an emissions factor of 2.5 kg $CO_2$ e per kg. The next high emissions are observed in A4, the transportation phase where the products are shipped to the customer by air freight which has a huge emission factor of 0.38 kg $CO_2$ per km, whereas transporting a single DACS through intercontinental ship has a very low emission factor of 0.009 kg $CO_2$ per tkm. The difference in carbon footprint value in the A4 phase is huge between the two mediums of transportation and it has been clearly stated in the above graph. In A3 the carbon footprint is mainly constituted by the metalworking process which consists of cutting welding and mechanical operations. The emissions from electricity by country are also considered while calculating the emissions from the eco invent database available in Sima Pro.

The energy used for the material handling operations and electricity used for the manufacturing operations plays a vital role in quantifying the emissions in different countries. The emission per Kilowatt-hour of electricity in the country of manufacturing (Bosnia) and the country of assembly (China) and the diesel usage for the material handling are stated in Table 4. When coming to phase A2 the raw materials to the factory are transported by truck which has an emission of 0.165 kg $CO_2$ per tkm and the distance for all materials is assumed as 500 kilometres since the actual distance is unknown in this case. The emission value in Raw material phase A1 is calculated with the help of the Bill of Materials obtained from Sea systems and specified in Table 1.

Based on the results obtained in the LCA study, certain alternative solutions / Key findings were suggested to the manufacturer to reduce the carbon emission from different stages, and they are listed below.

- Integrating Low carbon or recycled material alloy options in the product design stage itself reduces the overall CO2e in the raw materials stage.

- Reducing the material weight in the product development by choosing low-mass alloys with the same mechanical properties but with a low emission factor.

- Medium distance suppliers, Transportation through waterways has very little emission factor of 0.006 kg $CO_2$ Eq per tkm compared to air freight which Reduces $CO_2$ in the transportation phase.

- Choosing manufacturing companies that use power and energy from renewable energy sources can highly reduce the impact of $CO_2$ footprint in the manufacturing phase of the product.

- For example, In China - The emission from electricity is 0.686 Kg $CO_2$ e per KWh.

- Bosnia - 0.711 Kg $CO_2$ e per KWh,

- Sweden 0.036 Kg $CO_2$ e per KWh

- Norway 0.018 Kg $CO_2$ e per KWh

**Note - The above emission factors are taken from the SIMA PRO software database.**

- Sustainable country selection for manufacturing improves the environmental performance of the product.

- The country selection for the manufacturing & Assembly plays a vital role in the Carbon footprints of the supply chain.

- Science-based target tool - Helps set goals towards the Paris Agreement goal & helps in improving ESG reporting and sustainability of the company.

- Carbon emission reduction tool - https://sciencebasedtargets.org/resources/files/SBTi-target-setting-tool.xlsx helps in monitoring the organization's emission level and plotting them for easy reference.

## 18.1. Solutions to the Research Questions.

The master thesis also had the objective of answering two research questions after the interpretation of the results. The questions were.

1. **How LCA can be an effective method for mapping the major environmental impacts in a manufacturing industry?**

From the case study, it was clearly understood that the LCA method can provide effective results in identifying the major environmental impacts in the product cycle life stage with an evidence-based approach. The Eco invent database in the LCA software called Sima Pro has the best allocation methods to identify the input resources for product development and assess their corresponding impact categories. Although the software has certain limitations in finding out some impact categories for some parameters, it is highly helpful in making sustainable decisions regarding product/service development. LCA tool helped assess my case study helping to find out the major environmental emissions in the product development stages of the product I have chosen for the analysis.

2. **Do sustainable initiatives in the supply chain help industries reduce resource consumption and corresponding emissions?**

After the interpretation phase in the LCA case study, it was acknowledged that integrating sustainable practices such as choosing low-emission factor materials in the design stage, choosing a sustainable country for product manufacturing, reducing emissions through water transportation rather than air etc. can highly influence the reduction of carbon footprint in the supply chain. The circular economy method of production by reusing the materials after the end of life helps in reducing resource depletion and optimizing pollution. Hence it is clear that shifting to sustainable practices in the industry has many benefits in reducing the overall carbon footprints of the products/services.

## 19. Uncertainties and challenges faced in the study.

Some of the uncertainties that were observed in this case study are stated below.

- Lack of data in the manufacturing phase regarding the loss of waste materials and specific metal working processes.

- The emission from welding couldn't be stated in terms of kg, but available in terms of length in Sima Pro which is quite challenging to calculate the welding emissions in without solid data available from the manufacturer.

- The amount from loss of waste materials during manufacturing is unknown in the case study where those emissions are excluded in the impact assessment.

- The scope of using recycled materials in manufacturing needs to improve in further study with more data collection in the manufacturing phase.

- Since the lack of manufacturing data available, the reference of certain EPDs (Environmental Product Declarations) was useful in identifying the material composition and impact categories of steel materials and their respective alloys.

# 20. Conclusion and further research on the project.

The LCA method of evaluating a product life cycle is highly efficient and effective in quantifying the environmental impacts throughout the product life cycle. This case study was an experiment to identify the level of emissions that is associated with product development in a manufacturing industry. As a master in green energy technology, this life cycle analysis conducted in the industry provided good exposure to understanding the practical sides of sustainability happening in a real industry. The academic knowledge gained from the master's program was the core fundamental for initiating this Master thesis case study at Sea Systems AS. The main goal of the LCA case study was to identify the major parameters that result in the high carbon footprints in the product life cycle. Some of the key observations to conclude this case study are as follows.

a. The reduced material consumption by the industries for product development helps in waste reduction and the corresponding emissions.

b. Choosing sustainable manufacturing & Transportation options in the supply chain helps in reducing emissions to a large extent as shown in this case study.

c. Planning the project with a sustainable point of approach from the design phase itself helps the product to be more environmentally friendly.

d. The alternative suggestions provided to client Sea Systems AS to improve the environmental performance of the product in this case study shall be used as a reference for their further projects in improving the sustainability of the products.

The scope of further sensitivity analysis for the improvement of study results is highly appreciated. The interpretation can be improved in the phase of manufacturing with more accurate data inputs that help to evaluate the impacts more precisely. This LCA case study has more to do with sustainable development goal number 12 which aims in reducing waste generation and corresponding emissions in the manufacturing industry.

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