Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

Thomas André Gundersen

Applying Material Flow Analysis to develop Circular Economy strategies for improved resource efficiency at OneSubsea

Master's thesis in Safety, Health and Environment
Supervisor: Paritosh Deshpande
June 2022

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Trondheim, 9. June 2022

Thomas André Gundersen

Summary

This master thesis is a case study investigating steel flows for flowmeters at OneSubsea, using Material Flow Analysis (MFA) to further assess, evaluate and recommend Circular Economy (CE) strategies to improve overall resource efficiency of steel and achieve sustainable resource management.

OneSubsea, owned by Schlumberger, is a multinational company delivering subsea systems, services, and solutions to the oil and gas industry. The oil and gas industry is under immense pressure from the community and other stakeholders to reduce their emissions and become more sustainable. While multiple efforts are made to reduce the carbon footprints of the process, little or insignificant attention is given on reducing material consumption. OneSubsea has historically not considered the sustainability aspect of the established processes or services they provide to the petroleum sector in Norway. There are most likely multiple processes that could be investigated in the search for sustainability improvement.

The objective of this thesis will be to investigate and analyze the life cycle of flowmeters to create a holistic understanding of their steel resource management by mapping the life cycle flows of steel for flowmeters in OneSubsea. The analysis is further used to identify how OneSubsea can increase resource efficiency to ensure sustainable resource management throughout the life cycle. Therefore, the principle problem statement defined for this thesis is "*Which Circular Economy strategies can be implemented for sustainable management of steel used in flowmeters produced at OneSubsea, Norway?"*. CE focuses on achieving sustainable resource management by moving from the traditional linear economy consisting of usage and disposal to minimizing waste and exploiting the residual value of a product or material and turning these into resources rather than waste. The scope of the analysis is limited to the flowmeter, which is only one of many products OneSubsea delivers.

The thesis contains a literature study and an MFA to answer the problem statement. The literature study was carried out to identify relevant CE strategies, which is further discussed on how they could benefit OneSubsea. The MFA is used to generate evidence across the life cycle stages of the steel in the production and use of flowmeters produced at OneSubsea. Further, the analysis documents existing CE strategies and forms a foundation to assess strategies to improve resource efficiency and reduce valuable material loss. Data collection for MFA was done by questionnaires, interviews, and document reviews.

Results show that several CE strategies exist despite OneSubsea not focusing on sustainability. For instance, repair and maintenance to extend the products lifetime, take-back systems, partnerships for waste management, and more are currently practiced and are part of their routines. However, these are limited to OneSubseas processes, and they lack a holistic understanding of what happens across the supply chain. In addition, there is room to improve the resource efficiency by implementing various CE strategies. For example, OneSubsea is advised to consider closed-loop recycling and exploit the residual value of the products through strategies such as remanufacturing, refurbishing, and reusing. Doing this can result in both economic and environmental savings.

Sammendrag

Masteroppgaven er en casestudie som undersøker materialflyten av stål for strømningsmålere hos OneSubsea ved bruk av materialstrømanalyse, for å videre vurdere, evaluere og anbefale Sirkulær Økonomi (SØ) strategier for å forbedre ressurseffektiviteten og oppnå en bærekraftig ressursforvaltning.

OneSubsea er et multinasjonalt selskap som er eid av Schlumberger. OneSubsea leverer undervannssystemer, service og løsninger til olje og gass industrien. Olje og gass industrien er under press fra samfunnet og andre aktører for å redusere utslippet og bli mer bærekraftige. Mens mye ressurser og innsats har blitt lagt ned for å redusere karbon fotavtrykket for prosessene, har det derimot vært mindre eller ubetydelig fokus på å redusere materialforbruket. Historisk sett har ikke OneSubsea vurdert bærekrafts aspektet av de etablerte prosessene og tjenestene de tilbyr til petroleumsindustrien i Norge. Derfor er det mest sannsynlig flere prosesser som kan undersøkes med mål om å gjøre dem mer bærekraftige.

Formålet med denne oppgaven er å undersøke og analysere livssyklusen til strømningsmålere for å danne en helhetlig forståelse av OneSubsea’s ressursforvaltning av stål for strømningsmålere. Dette gjøres ved å kartlegge stålbehandlingen i alle faser av livsløpet. Videre blir det sett på hvordan Onesubsea kan øke ressurseffektiviteten for å sikre en bærekraftig ressursbehandling gjennom hele livssyklusen. Problemstillingen er derfor definert som «*Hvilke Sirkulære Økonomi strategier kan bli implementert for en bærekraftig ressursbehandling av stål brukt i strømningsmålere produsert hos OneSubsea, Norge?*». SØ fokuserer på å oppnå en bærekraftig ressursbehandling ved å gå vekk fra den tradisjonelle lineære økonomien som består av bruk og avhending, til å minimalisere avfall og utnytte restverdien av et produkt eller materiale ved å gjøre dette om til ressurser istedenfor avfall. Oppgaven er avgrenset til strømningsmålere, som kun er et av mange produkter OneSubsea leverer.

Oppgaven inneholder en litteraturstudie og en materialstrømanalyse for å besvare problemstillingen. Litteraturstudiet er utført for å identifisere relevante SØ strategier, som blir diskutert for å se på hvordan de kan hjelpe OneSubsea. Materialstrømanalysen er brukt for å få generere bevis på tvers av stålets livssyklusfaser ved produksjon og bruk av strømningsmålere produsert av OneSubsea. Analysen blir og brukt for å dokumentere eksisterende SØ strategier og danner et grunnlag for å videre vurdere strategier for å forbedre ressurseffektiviteten og redusere verdifullt materialtap. Datainnsamling for materialstrømanalysen ble gjort ved hjelp av spørreskjemaer, intervjuer og dokumentgjennomganger.

Resultatene viser at flere SØ strategier eksisterer selv om OneSubsea ikke har hatt bærekraft som et fokusområde. For eksempel reparasjon og vedlikehold av produkter for å forlenge levetiden, systemer for å ta tilbake produkter på slutten av livssyklusen, avtaler med avfallshåndteringsfirmaer og flere andre strategier blir i dag praktisert som en del av rutinene deres. Strategiene er derimot begrenset til OneSubsea sine prosesser, og de mangler en helhetlig forståelse av hva som skjer gjennom hele forsyningskjeden. I tillegg er det også rom for å forbedre ressurseffektiviteten ved å implementere ulike SØ strategier. For eksempel kan OneSubsea vurdere resirkulering med lukket sløyfe og utnytte den gjenværende verdien av produktet gjennom strategier som oppussing, gjenbruk av produkter og gjenbruk av deler. Dette kan føre til både økonomiske og miljømessige besparelser.

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1 Introduction

Climate changes are already affecting every country and disrupting national economies. Today, consequences from climate change have occurred in rising sea level, more extreme weather events and changes of weather patterns [1]. United Nations (UN) claims that "*greenhouse gas emissions from human activities are driving climate change and continue to rise"* [1]. UN has adapted 17 Sustainable Development Goals (SDGs) and 169 targets in 2015 [2] which are a blueprint towards achieving a more sustainable future. These goals are aimed towards the global challenges such as climate change, environmental degradation, poverty, peace and justice, and inequality [3]. A commonly used definition for sustainable development is a '*development that meets our needs without compromising the future generations possibility to meet their needs*' [4].

The oil & gas industry is under considerable pressure from the community and other stakeholders to reduce their emissions and become more sustainable. As more oil platforms are electrified from onshore, the focus is shifting to other potential hotspots for environmental pollution, such as cement, steel, and fluids. Schlumberger, like other companies, must reduce its emissions and become more sustainable. The Norwegian oil and gas industry intend to achieve a 40 percent reduction in absolute greenhouse gas emissions by 2030 and near-zero by 2050 [5]. New ideas, technologies, and solutions need to be picked up and adopted to realize these goals.

SDGs are becoming a part of the oil & gas industry, and several companies are implementing these as goals in their organization. The SDGs have industry specific goals such as SDG number 12, *Responsible Consumption and Production* [6], with targets such as 12.2, achieve sustainable management and efficient use of natural resources by 2030; and 12.5, reduce waste generation through prevention, reduction, recycling, and reuse substantially by 2030 [7]. This SDG is for securing a sustainable consumption and production pattern. Nowadays, much more is consumed than what is sustainable for the earth [6]. The traditional economy is linear and consists of take, make, use and dispose of resources, resulting in unnecessary waste and damage to the environment [8]. Naturally, it is not sustainable to consume more than what is sustainable for the earth.

Circular Economy (CE) is a principle that uses several strategies to achieve sustainable resource management by closing loops, minimizing waste, and turning goods at the end of their life cycle into resources [9], with a goal to continuously reuse the resources, achieving no net effect on the environment [8]. CE can be defined as "*an economic system where stakeholders collaborate to maximize the value of products and materials, and as such contribute to minimizing the depletion of natural resources and create positive social and environmental impact*" [10]. CE applies to SDG number 12, *Responsible Consumption and Production*, because it focuses on sustainable consumption and production by prolonging the life of materials and doing more with fewer resources.

The CE concept has evolved differently. For instance, in Germany, the concept was introduced to address the issue related to raw and natural material use for sustained economic growth [11]. In China, it was used to upgrade equipment, improve industry management, new technology development, and profitable product development [12]. It has been used for waste management in the UK, Denmark, Switzerland, and Portugal [13]. Furthermore, in the past decade, approaches have emerged to include CE and tools for quantitative assessment of new CE initiatives, for instance, Material Flow Analysis (MFA) [11].

CE is also becoming more known in the subsea industry. Recently, a Norwegian company was given an innovation foundation from Innovation Norway for an idea in Sharing- and Circular Economy [14]. A quick search also lists other companies fronting CE in the subsea industry. Subsea structures and products contain a large amount of high-grade steel due to the harsh environment and pressures it needs to restrain. Steel is one of the few materials that sustain its properties when recycled. Steel is 100% recyclable any number of times, without loss of quality [15]. Therefore, steel is well-fitting for the CE concept.

OneSubsea is one of several companies which delivers subsea systems to the oil & gas sector. Subsea systems are important for many reasons. For instance, they can help with flow assurance, improving the flow of the reservoir, maximizing recovery, and reducing energy consumption, emissions, and costs [16]. In addition, transporting, controlling, and monitoring both liquid and gas, and more [17]. OneSubsea has historically not considered the sustainability aspect of the established processes or services they provide to the petroleum sector in Norway. And as the environmental focus is rising companies that can account for a reduced environmental impact is likely to have a significant advantage over competitors. As steel is becoming one of the hot spots, this study will apply an MFA to develop CE strategies for OneSubsea to work against UN´s SDG number 12, *Responsible Consumption and Production*.

1.1 Schlumberger and OneSubsea

With employees representing over 160 nationalities, Schlumberger is providing leading digital solutions and innovative technologies to enable performance and sustainability for the global energy industry, with an endless and enduring purpose to create industry-changing technologies for cleaner and safer access to energy for every community [18]. OneSubsea, created in 2013, is a multinational company owned by Schlumberger. OneSubsea delivers integrated solutions, products, systems, and services to the subsea oil and gas market, optimizing the entire production system through the lifetime of the field. With Schlumberger, OneSubsea delivers tailored end-to-end solutions from the reservoir to the surface [19].

OneSubsea operates in the following areas: processing systems, control systems, swivel & marine systems, production systems, services, and integrated solutions [19], as listed in **Table 1**.

Table 1 OneSubsea operating in 6 areas [19]

Processing systems (Figure 1) • Single- and Multiphase Pumps • Multiphase Compressors • Multiphase and Wet Gas Meters • Sampling • Separation OneSubsea offers pumps, meters, and subsea processing systems for development and technology projects, covering all aspects of subsea separation and processing. In addition, providing a wide range of technical solutions to help increase efficiency in subsea oil and gas developments with subsea multiphase boosting, subsea wet gas compression, and multiphase metering.	 Figure 1 Processing systems
Control Systems (Figure 2) • Tree and Manifold Controls • Multiphase Pump Controls • Multiphase Flow Controls • Topside and FPSO Controls • Wet-Mateable Diamould Connectors Control systems provide the needed control and enables feedback on process information. In addition, all current and future devices can be connected.	 Figure 2 Control *Systems*
Swivel & Marine Systems (Figure 3) • Swivel Stacks • Turrets • Submerged Loading Systems • Offshore Cryogenic Transfer In rough weather, swivels ensure that all fluids, controls, and power are transferred safely from the wells, flowlines, manifolds, and risers to the rotating vessel and its process plants.	 Figure 3 Swivel & Marine Systems

Production Systems (Figure 4)

- Trees
- Manifolds
- MARS
- Connection Systems
- Wellheads

Trees, manifolds, connection systems, and wellheads offer fully integrated subsea production systems solutions.

Figure 4 Production Systems

Services (Figure 5)

- Installation and Commissioning
- Life of Field
- Asset Management

OneSubsea offers services throughout the life cycle of the subsea field – from discovery to abandonment.

Figure 5 Services

Integrated Solutions (Figure 6)

- Field Development Planning
- Petro Technical Services
- Flow Assurance Consulting
- Early Engineering Engagement
- One-System Approach

This area focuses on delivering technologies and expertise to optimize the entire production system.

Figure 6 Integrated Solutions

Figure 7 shows the facility of OneSubsea Processing AS at Horsøy. The facility is mainly for assembly and testing products. Processing systems such as pumps and compressors, swivel and marine systems, and flowmeters are the main products on Horsøy. The area is around 26 thousand square meters and has about 200 employees. First, parts are received and registered at the warehouse before internal delivery for assembling and testing. Then, a full-scale test is performed in a subsea test pool of the complete system before the product is shipped from the quay for transport and installation. Horsøy contains two subsea test pits, test loops, and hyperbaric chambers to simulate the depth.

Figure 7 OneSubsea facility at Horsøy. Photo; OneSubsea

1.1.1 Flowmeter

Figure 8 shows a picture of the Vx Omni multiphase flowmeter. The flowmeter is used for subsea well testing, monitoring the production continuously, fiscal allocation and custody transfer, an evaluation of well performance, and production measurement for heave oil to gas condensate [20]. OneSubsea also offers other flowmeters, called F-type, E, and B type. In addition, these products also come in varying sizes depending on the operating depth/pressure. The VX Omni shown in Figure 8 is the newest flowmeter. The design has improved over the years, focusing on standardizing and reducing the complexity. As a result, the product is 95 % standardized, a reduction of 66% parts, and a reduced footprint. **Figure 9** shows how the design has improved over the generations. The figure shows that reliability, durability, footprint, and delivery time have improved.

Figure 8 Vx Omni multiphase flowmeter (OneSubsea, 2022)

The venturi is the main steel body component with an approximate weight of 1200 to 2300 kg, depending on the size. The venturi is accountable for around 2/3 of the flowmeters weight. OneSubsea procures the steel for the venturi in the form of a blank, a blank is just a larger piece of steel. Then it is sent to a supplier which machines out the venturi from this blank. The flowmeter's total weight typically ranges up to 4000 kg. The flowmeter also has a radioactive barium source with a half-life of 10 years, and in the newest flowmeter, it is designed to last for 35 years.

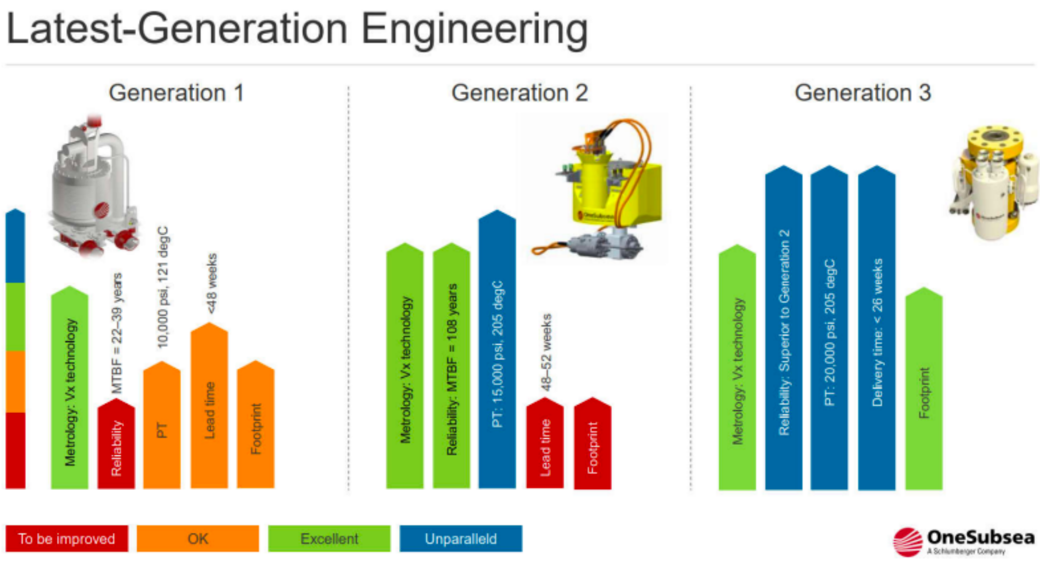

Figure 9 Improvement of flowmeter design (OneSubsea, 2022)

Figure 10 shows the main steps in delivering a flowmeter from OneSubsea's perspective. At first, the client requests a quotation for the product. If this is accepted, a purchase order is received. Next is the engineering phase. This includes drawings, specifications, and a bill of material. As often, this phase is not necessarily as the product is standardized. However, sometimes OneSubsea is required to design some customized parts/components for some customers. The next phase is procurement. Here, a bill of material is released for all components not already present in stock. These components are produced and manufactured at OneSubsea's suppliers. Each component has a different supplier because of the specific competence needed. This means that all components are pre-fabricated when they arrive. Therefore, the next phase is assembly. After the assembly, a pressure test and flow test are performed. After these, a factory acceptance test is carried out, and the product is then packed and ready for delivery.

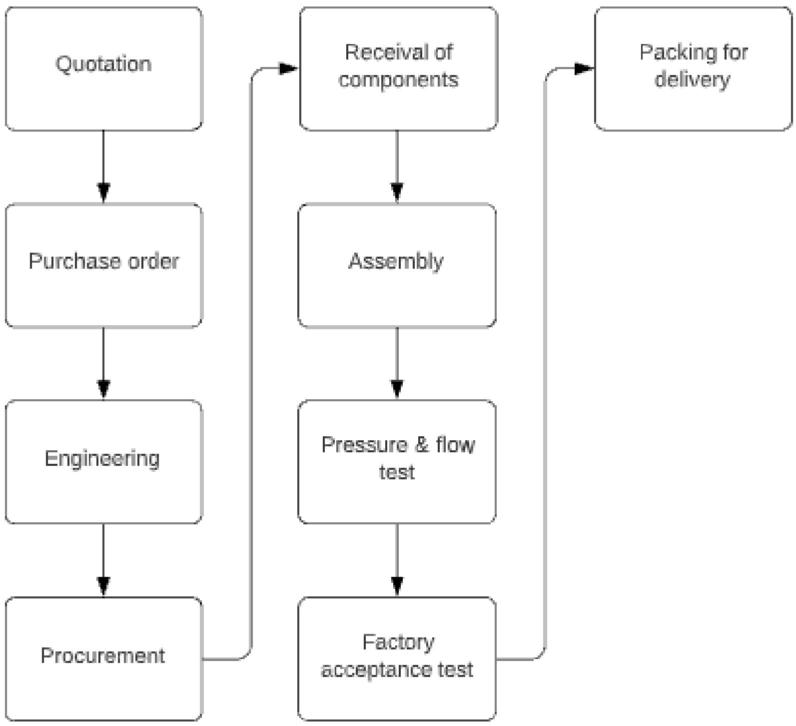

Figure 10 Flowchart for flowmeter

Some flowmeters are retrievable, and some are not, depending on how the customers install them. If a not retrievable flowmeter fails, a new one must be produced. The retrievable ones can come in for repairs and maintenance. When a flowmeter comes in for repair, the customers are responsible for retrieving and shipping the product. Next, the product is inspected, and components are categorized for either reuse, repair, or replacement. After the maintenance and repair are finished, the product is packed and ready for delivery. Products sometimes need repair due to damage or failure. Other times, the flowmeter is returned for maintenance and upgrades during scheduled maintenance at the oil field. Typically upgrades could be the transmitter, computer, and the barium source is often replaced during maintenance and repairs to secure optimal measurements.

Waste occurs at OneSubseas facility during repair and maintenance and end-of-life collection. As the product contains a radioactive source, OneSubsea must accept the product back at end-of-life for proper disposal. When retrieved at end-of-life, all the flowmeter's components are sorted out for disposal. The sources are stored and frequently sent for disposal. OneSubsea has different contracts for waste management. Heavier and bigger steel parts to be scrapped are stored outside the facility. When this area is filled up, a waste management company is contacted and will collect and pay for the material. Minor parts such as bolts and small flanges are placed in a container and sorted between low carbon steel and stainless steel. When filled up, the material is collected by a waste management company, and OneSubsea gets paid for the different material types. There is also a system for nonmaterial waste handlings such as electrical waste, transmitter cards and electric cables.

Figure 11 shows the typical process flow diagram for steel used in the flowmeter from the OneSubseas perspective. As mentioned, OneSubsea procures the steel for the venturi production, which occurs at suppliers. For the rest of the components, OneSubsea does not procure the steel. These flows then combine into the assembly at OneSubsea. The next phase is the use phase at the customers. When the flows re-enter OneSubsea, it is either for repair & maintenance or for products returned at end-of-life. All waste that occurs at OneSubsea is delivered to waste management companies. What customers do with the product at end-of-life is unknown unless it is returned and described as not defined. It is also not unknown what happens with the waste at the suppliers, other than the venturi production. Here, the waste is delivered to a waste management company.

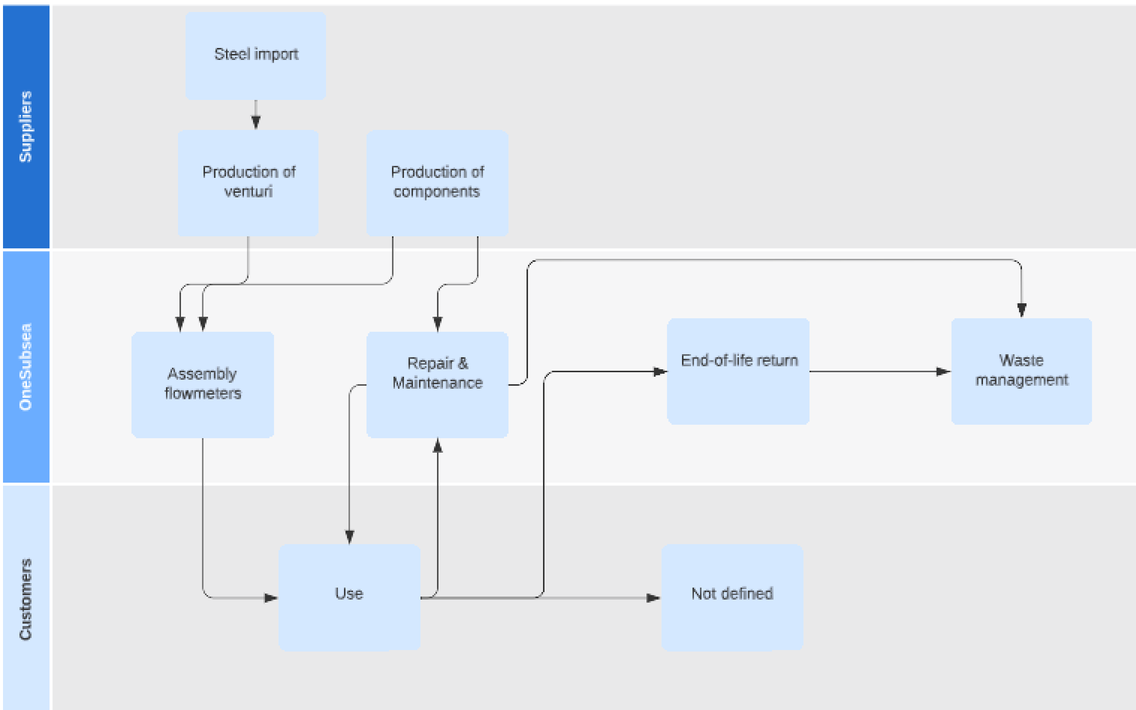

Figure 11 Typical flows of steel for flowmeter life cycle

1.2 Steel

Steel is an alloy of iron and carbon and is the world´s most important engineering and construction material [21]. Steel characteristics such as high yield strength, excellent weldability, and good resistance to brittle fracture make it work in harsh environments and reduce the risk of failure [22]. Production of steel leads to emissions of carbon dioxide, methane, and nitrous oxide [23].

There are two main production routes for steel. Route one is the “primary” one, or “integrated” one, and is based on a blast furnace (BF) and a basic oxygen furnace (BoF). This route uses raw materials including iron ore, coal, limestone, and recycled steel (also called scrap steel). To produce 1,000 kg of crude steel, the integrated route uses on average 1,370 kg of iron ore, 780 kg of metallurgical coal, 270 kg of limestone, and 125 kg of recycled steel [24]. Route two, “secondary” steel making, uses an electric arc furnace (EAF) and uses recycled steel and direct reduced iron or hot metal and electricity [25]. To produce 1,000 kg of crude steel, the recycled steel EAF route, on average, uses 710 kg of recycled steel, 568 kg of iron ore, 150 kg of coal, 88 kg of limestone, and 2.3 GJ of electricity [24]. All steel production uses scrap. In BF/BOFs, up to 30% are used, and in EAFs, up to 100%. All collected scrap is recycled, and the recycling rate is estimated to be around 85%. Therefore, the scrap availability will variate by demand, while raw materials can flex with the demand [24]. The price for scrap steel can variate due to demand.

Figure 12 shows the different steel production routes, respectively, the BOF route on the left and EAF on the right through either a combination of direct reduced iron (DRI) and recycled steel or only recycled steel. Open heart furnaces are shown on the left, which is less common. In 2003, BOFs accounted for around 63 percent of the production, EAF for 33 percent, and the remaining 4 percent for OHF [23].

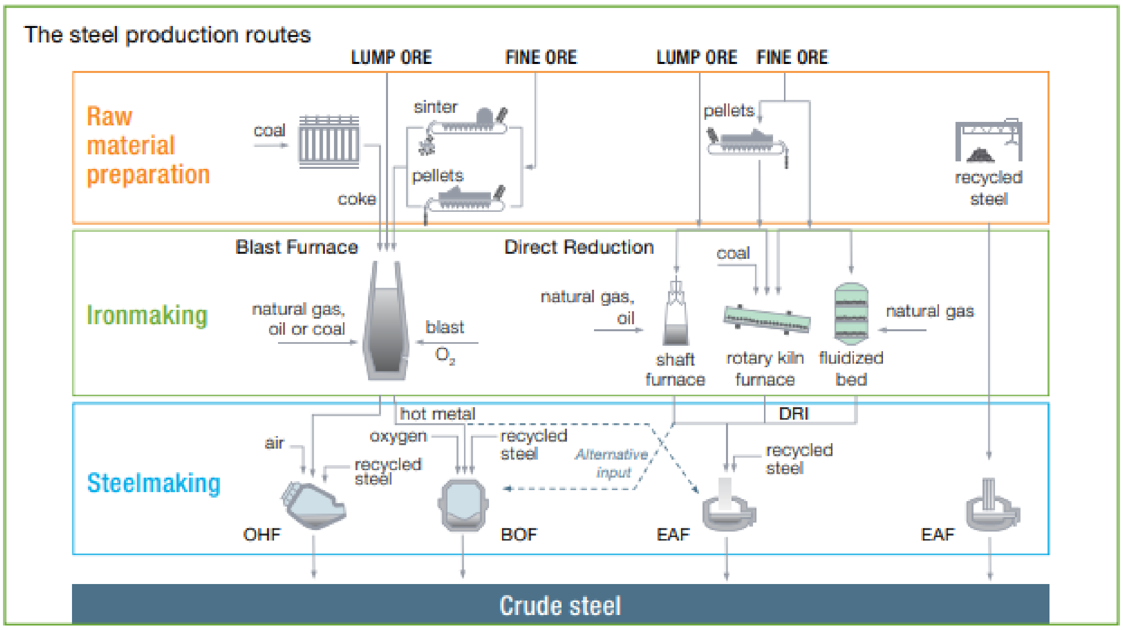

Figure 12 Steel production routes [26]

There are more than 500 steel production sites across the EU member states [27]. For instance, in Sweden, two production sites operate with BOFs, and six production sites use the EAF route [28].

1.2.1 Circular Economy Perspectives for Steel

Figure 13 illustrates potential strategies for CE with steel. First, all raw materials needed to produce steel are extracted and transported to a steel production plant. Then it is melted to a requested steel grade and sent to manufacturing. Steel scrap or steel waste from these processes is again used in production. After the product is manufactured, it enters its use phase. The next step is to prolong the life span of the product. Thus, reuse and remanufacturing are used to *slow* the loop. Finally, it is sent to recycling at the end of the product use phase. The steel is then recycled to close the loop by shutting or reducing the need for raw material extraction.

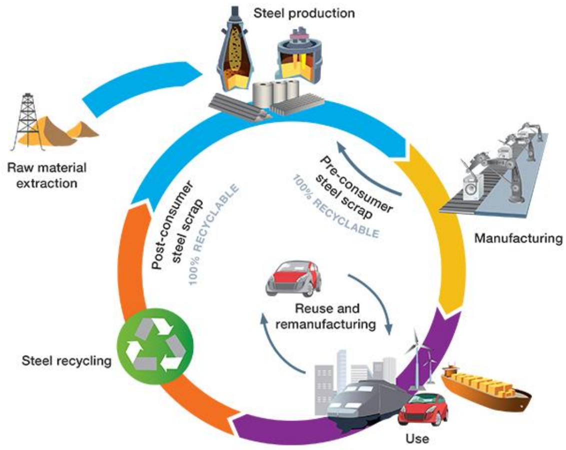

Figure 13 Steel in a Circular Economy [29]

Reduce

One way to narrow the loop is to reduce the amount of steel in the products. A higher grade can be utilized to use less steel and reduce weight. Over the past decades, high-strength steel has led to a 25-40% weight reduction, with a corresponding decrease in emissions and energy use [30].

A case study performed by World Steel in construction shows a CO_2 reduction of around 30% in steel columns and 20% in steel beams by substituting high-strength steel for regular steel. Whether construction or business, replacing with high-strength steel means less steel is required to provide the same strength and functionality [30]. Furthermore, reducing the amount of steel in the products makes the loop narrower due to less raw material use. In addition, there are reduced impacts due to transport, reduced energy use, and reduced CO_2 emissions [30].

Reuse

Reuse of steel is possible because of its durability. Reusing leads to slowing the loop by extending the lifespan of the steel. Compared to recycling, reducing emissions and impact will be accomplished by avoiding transport for re-melting. Therefore, the environment has the advantage of reusing and maximizing the use of resources [30].

Remanufacture
As already mentioned, steel has high durability. Remanufacturing (here restoring products) takes advantage of this. Remanufacturing steel components guarantees that energy used in the manufacturing is preserved. Steel applications are well suited for remanufacturing because the needed technology is widespread, and the tools are inexpensive. Once the steel or product is recertified, the application is "as-new" [30].

Recycle
Steel can be recycled endlessly without losing its properties, making it optimal for a CE to close the loop. On the one hand, the steel can maintain the inherent properties of the original steel. However, these properties also can be modified to create many thousands of steel grades available. In addition, it is also possible to improve the quality of the steel during recycling [30].

Recycling steel accounts for significant energy and raw material savings. For every tonne of scrap steel used, the consumption of 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone are saved, and 1,5 tonnes of carbon dioxide emission is avoided [24].

Around half of the steel produced in Europe comes from recovered secondary sources. However, around 20% of the scrap from Europe is exported to international markets [27]. In criticizing existing ways of implementing Circular Economy strategies, where waste is collected and transported to low-income regions, the authors [31] propose the need to find localized ways for closing the loop for resources. Accordingly, the Small Circles approach argue that the negative externalities caused by the export of waste also should be considered in circularity and sustainability targets, as targets nowadays exclude the impact generated due to transport. The Small Circle approach aims to keep and manage the waste within a smaller geographical area of its origin. As a result, environmental burdens due to exporting waste are reduced. Additionally, the regions producing waste are responsible for the generation and management [31]. The European Steel Association says the steel scrap should stay within the loop in Europe [27].

1.3 Problem Statement

OneSubsea has historically not considered the sustainability aspect through the dimension of resources conservation for the established processes or services they provide to the petroleum sector in Norway. There are most likely multiple processes that could be investigated in the search for sustainability improvement.

Therefore, the objective of this thesis is to investigate the life cycle of flowmeters, to create a holistic understanding of the steel resource management by OneSubsea. The evidence through mapping the life cycle flows of steel will be applied to identify how OneSubsea can increase the resource efficiency throughout the life-cycle to ensure sustainable steel management.

Therefore, the **overall research goal** for this thesis is summarized as "*Which Circular Economy strategies can be implemented for sustainable management of steel used in flowmeters produced at OneSubsea, Norway?*"

To identify a potential to improve resource efficiency, first, the current system life cycle steel flows of the flowmeter must be mapped out and documented. As a result, the **first research question** is defined as "*How to generate evidence across the life cycle stages for steel used by OneSubsea?".* Material Flow Analysis is chosen as the method and is explained in chapter 3, research design and methods.

The **second research question**, which the main problem has been broken down into, is "*Which Circular Economy strategies are already existing at OneSubsea?".* This question is natural, as to increase resource efficiency and recommend CE strategies, the existing strategies must be identified and documented. This research question is addressed in the discussion and is demonstrated by the results.

The **last research question** to fulfill the main problem is defined as "*Which Circular Economy strategies are relevant for OneSubsea?*". To recommend CE strategies, all relevant ones must first be identified and addressed further. These are listed in chapter 2, theoretical foundation.

At last, to answer the main problem, the strategies identified in research question 3 are addressed in the discussion, as well as identifying potential improvements to the existing strategies identified in research question 2.

1.4 Limits

OneSubsea is a multinational company operating in several areas delivering many products. Therefore, the scope must be limited as a factor of time. The study will be limited to the steel flows from OneSubseas perspective on the flowmeter produced in Norway. However, results and recommendations are most likely relevant for other steel flows in the company.

1.5 Structure

Figure 14 shows the structure of the thesis. The thesis follows the standard format, an introduction, theoretical foundation, method, results, discussion, and conclusion.

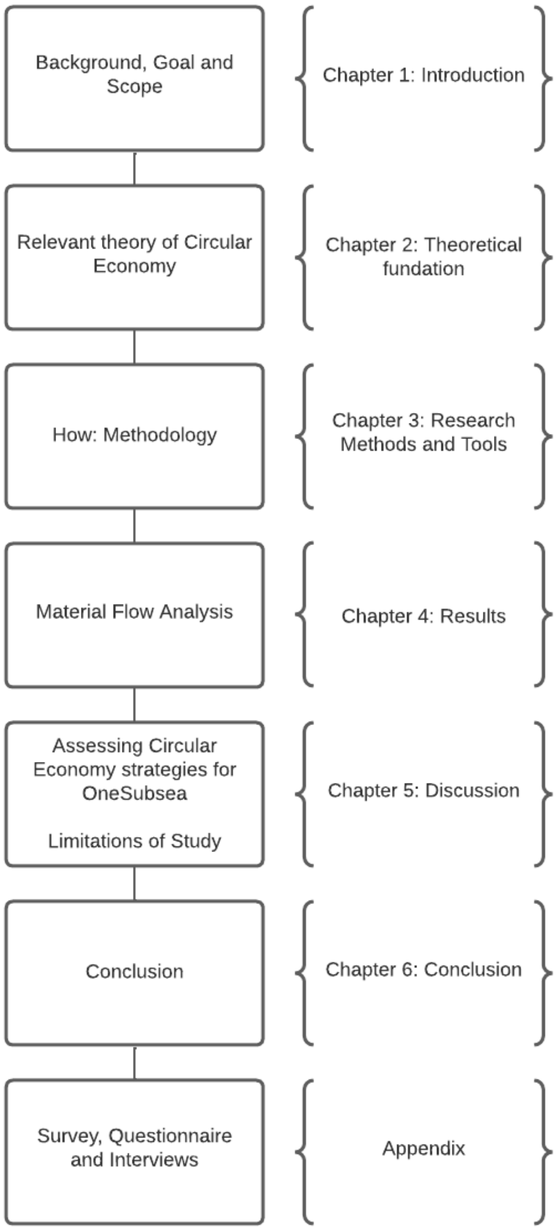

Figure 14 Thesis structure

The *first chapter* introduces the topic, the case company, and relevant information about the product, supply chain, and steel, which will be further evaluated through the thesis. In addition, the problem and research question are described, along with the scope and limitation of the thesis.

In the *second chapter*, theoretical foundation and relevant theory are provided about the topic so the reader can fully understand the discussion. This chapter includes pertinent information about Industrial Ecology and CE.

The *third chapter*, methodology, seeks to explain how the author has completed the thesis. This includes the research design and how the data has been collected and analyzed. Introductory theory about the research methods is also presented.

The *fourth chapter,* the relevant collected data and results are presented and illustrated in the form of an MFA. Finally, these results are discussed against the theoretical foundation in the following part discussion, focusing on answering the research *questions «Which Circular Economy strategies are already existing at OneSubsea?»* and discussing research question 3, «*Which Circular Economy strategies are relevant for OneSubsea?»* in order to answer the main problem, " *Which Circular Economy strategies can be implemented for sustainable management of steel used in flowmeters produced at OneSubsea, Norway?"* There also is a subchapter with clear recommendations that concretizes how OneSubsea can work with CE moving forward. In addition, the limitations of the study are discussed.

The Conclusion reflects on the journey and the authors experience of the process. Additionally, future research for OneSubsea is recommended.

All references are listed in the latter part of the thesis, followed by an appendix, including the request for information regarding the Material Flow Analysis, survey, and interview questions.

2 Theoretical Foundation

2.1 Industrial Ecology

Industrial Ecology (IE) is also often called the "science of sustainability" [32] and is the field of study which focuses on the production processes from a natures point of view, trying to mimic natural systems but conserving and reusing resources and materials [33]. It is challenging to have a uniform definition and understanding of the term with a multidisciplinary nature. IE might be explained as to how humanity can approach and maintain sustainability, given continued evolution within economics, culture, and technology. The concept is given that the industrial ecosystem is not only evaluated as isolated from the surrounding systems. It is a system that focuses on the total material cycle from virgin material to disposal and seeks to optimize the cycle by optimizing resources, energy, and capital [32]. The IE concept is developed to improve environmental management by seeking to balance industrial processes and environmental sustainability by minimizing waste and pollutants in the material cycle [34].

The evolution of CE would not be possible without the tools and concepts of IE. Material Flow Analysis, Cleaner Production, and Eco-design are tools used to support CE. IE, therefore, contributes to CE in many ways, such as studying material and energy flows, providing Material Flow Analysis, strategies such as reuse, recycling repair and remanufacturing, using waste as by-products, and more [35].

2.2 Circular Economy

As shown in **Figure 15**, a linear economy focuses on extraction, production, use, and disposal. The opposite, Circular Economy (CE), is shown in **Figure 16**, focuses on closing loops, minimizing waste, and turning goods at the end of their life cycle into resources [9]. Although CE has many definitions listed in the literature, in this thesis we define the CE as "*an economic system where stakeholders collaborate to maximize the value of products and materials, and as such contribute to minimizing the depletion of natural resources and create positive social and environmental impact*" [10].

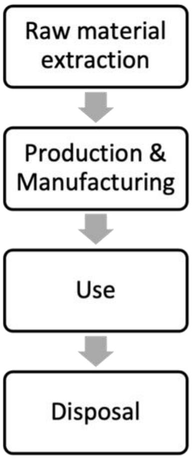

Figure 15 Example of a Linear Economy

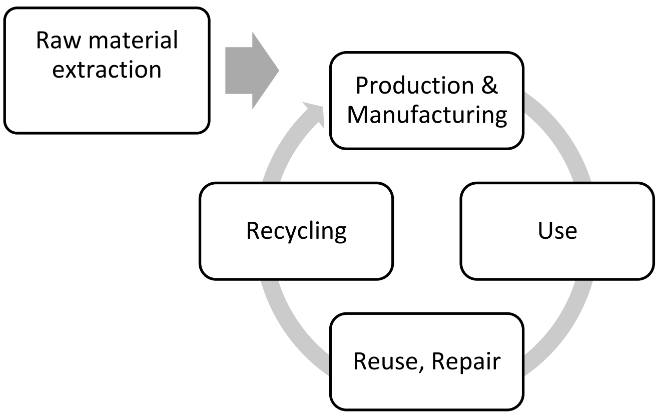

Figure 16 Example of a Circular Economy

Circular business models (CBM) are another upcoming term in the literature broadly based on realizing the CE at an industrial scale. The literature on CBM is divided into two groups, one that focuses on reusing and extending the life of products through repairs, remanufacturing, upgrades, and retrofits. The other focuses on turning old goods into new resources by recycling the materials [9]. Realizing CBM needs the adaption of one or more CE strategies to *slow*, *narrow*, or *close* the resource loop. These main principles and strategies are illustrated in **Figure 18**. By *slowing* the loop, resources are kept in the life cycle for an extended time by maintenance, repair, reuse, refurbishing, or remanufacturing. The need for raw material extraction is reduced by closing the loop with recycling. The loop becomes narrower by reducing the number/amount of resources needed in the product and processes.

2.2.1 Reducing input and use of natural resources

Figure 17 Sustainable Development Goal 12

United Nations sustainable development goals (SDGs) number 12, responsible consumption and production (**Figure 17**), focusing on realizing and mapping the CE through securing sustainable consumption and production patterns for available resources. Nowadays, much more is consumed than what is sustainable for the earth [6]. CE applies to this SDG because it focuses on sustainable consumption and production by prolonging the life of materials and doing more with fewer resources. Targets worth mentioning for the current study are 12.2, *achieve sustainable management and efficient use of natural resources by 2030*; and 12.5, *reduce waste generation through prevention, reduction, recycling, and reuse substantially by 2030* [7].

2.2.2 Strategies for achieving a Circular Economy

Figure 18 lists CE strategies that have been identified as relevant to further elaborate and assess for OneSubsea. Each strategy is described below. Later in the discussion, it is discussed how some of these strategies are already implemented and how some can help increase resource efficiency and reduce valuable material loss.

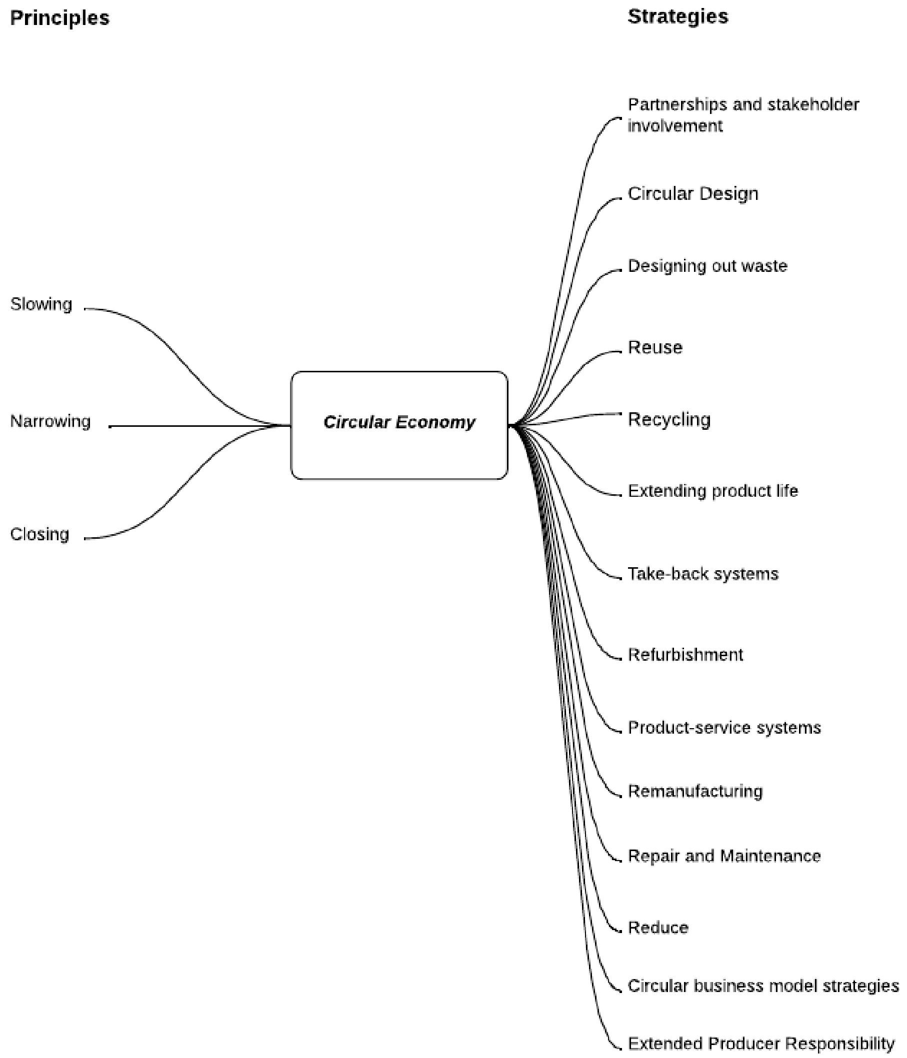

Figure 18 Circular Economy principles and strategies, strategies collected from [36] [37] [38] [39] [40]

Partnerships and stakeholder involvement

Developing partnerships and involving the stakeholders allows for circularity along the value chain. It is recognized in the literature that to realize a strong CBM, the relationship between supplier and customers should be firm and close [37].

Circular Design

Designing a product for circularity means a design that allows multiple cycles through principles such as reuse, disassembly, and remanufacturing [37]. Evaluating CE at the design phase is essential, as only minor changes are possible after the product specifications are made. To prolong a product´s lifetime, a product should be designed for maintenance and repairs, which enables the product to be in top condition. Another strategy is that the product is designed to allow future expansion and modification later. In addition, the product should be designed for standardization and compatibility, meaning the parts or interfaces also fit other products. By designing the product for disassembly and reassembly, the product can be separated and reassembled quickly, which could help increase the future rates for reusing components. The product also should be designed for durability and reliability as needed. When designing to close the loop, recycling should be taken into consideration. Design for disassembly could also be important here as materials potentially could enter different cycles [36].

Designing out waste

Increasing resource efficiency by avoiding and reducing waste and ensuring proper waste treatment [37].

Reuse

Extends the life cycle by second-hand use of a product or components [40]. The product is still in such a condition that it can operate and fulfill its original function.

Recycling

By recycling, the product/resource can serve another use cycle with the same or a new purpose [37]. Materials can maintain the exact grade, lower or higher quality when recycling. When a material is recycled, it is referred to as secondary material. Upcycling is when the recycled material is subjected to a higher quality than previously, and downcycling is for a poorer quality [38]. Closed-loop recycling is when a secondary material replaces the primary material input in an earlier process in the same system, replacing the need for that primary material. Open-loop recycling is when a share of the secondary material is used in a different system [39].

Extending product life

Making a product last longer in its life cycle by strategies such as “building to last," the possibility for repair and maintenance, refurbishment and reconditioning, and offering upgrades [37].

Take-back systems

Take-back systems (TBS) are systems that ensure that the product is recovered from the consumer at the end-of-life [40], which gives the producer the responsibility [37].

Refurbishment

Refurbishment, equivalent to reconditioning [38], aims to renew the status and condition to a minimum of when new. This could be fulfilled by replacements or restorations [37].

Product-service systems

Product-service systems (PSS) go away from traditional sales, where clients buy and own the product. Instead, strategies could be renting/leasing where the producer/supplier remains ownership over the product [37].

Remanufacturing

Remanufacture is also called second-life production, which implies using parts/components of a used product in a new, retaining the same quality as a brand new one when using used spare parts [38]. To facilitate reusing of parts, the products need to be built for disassembly and to reduce disassembly time [38].

Repair and Maintenance

Extending the product's lifetime by scheduled maintenance and repairs [37]. Repair is when a defective is fixed for a product to be operative again with its original function. Maintenance is upholding a product in its working condition. Maintenance could also include refurbishment, remanufacturing, and repairs [38].

Reduce

Reduce means using fewer natural resources, which leads to less raw materials extraction, waste, and fewer energy inputs [38].

Circular business model strategies

Also, the way an organization does business can be changed to a circular model. Different business models for slowing the loop are *Access and performance model*, *Extending product value*, *classic long-life model*, and *encouraging sufficiency*. The *Access and performance model* includes strategies such as PSS, where the user does not need to own the product. The value proposition in this model is delivering access and performance rather than ownership. This model can result in financial benefits, such as additional life extension costs. *Extending product value* focuses on exploiting the residual value of products. The value proposition, in this case, is built around remanufacturing and repairs. This model requires strategies such as TBS. *Classic long-life model and encourage sufficiency*. Here, the value proposition is built around high-quality and long-lasting products supported by design for durability and repair. The last one, *Encourage sufficiency*, also is about long-lasting products. However, here solutions seek to reduce end-user consumption to make products that last and allow users to hold on to them as long as possible and with a high level of service [36].

Extending resource value and *industrial symbiosis* are business model strategies that focus on closing loops. Strategies for closing the loop are about capturing value from what in linear business models are considered waste and by-products. The first one is about collecting or sourcing the “waste” materials and turning these into value. Here, value is created by exploiting the residual value of the waste and resources. In the latter, *Industrial symbiosis*, waste from one process is input for another feedstock [36].

Extended Producer Responsibility

Extended Producer Responsibility (EPR) is another action that means the producer's responsibility is extended to the post-consumer stage of the product's life cycle [40].

3 Research Methods and Tools

Figure 19 illustrates the context and structure of the thesis and the methods used to achieve a result for the research questions and main problem. First, the research question *How to generate evidence across the life cycle stages for steel used by OneSubsea?* is done by data collecting thru surveys, interviews, and questionnaires. These results are used in an MFA and illustrate the life cycle flows of steel, also showing the status of CE today, which is research question two and forming the basis to identify areas of improvement. Then, research question three, *Which Circular Economy strategies are relevant for OneSubsea?* is identified through a literature study. At last, these appropriate strategies are discussed against the result from MFA on how to improve the resource efficiency, answering the main problem, *Which Circular Economy strategies can be implemented for sustainable management of steel used in flowmeters produced at OneSubsea, Norway?*. The research methods selected and their respective application in this thesis is elaborated below.

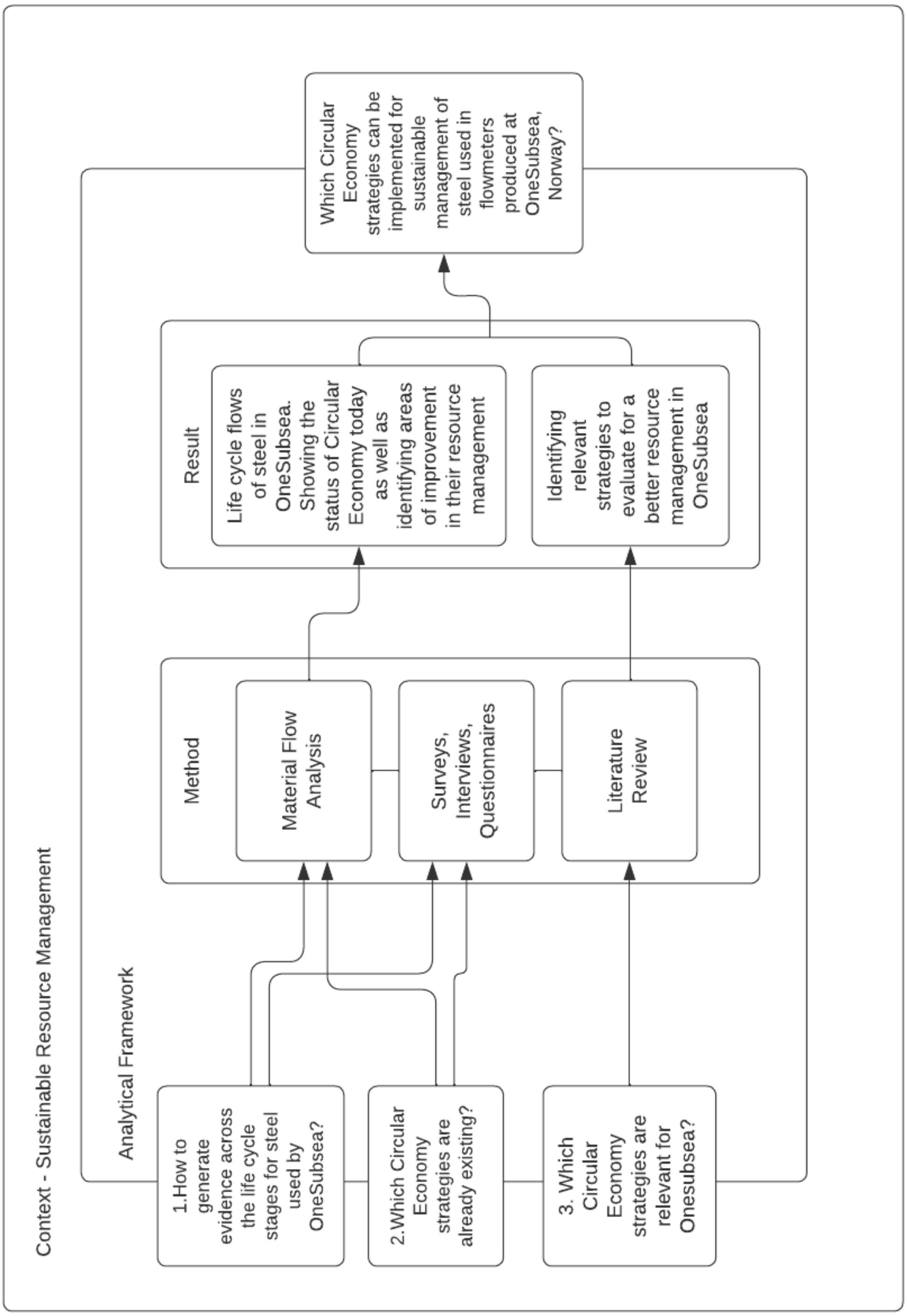

Figure 19 Context and structure of the thesis

3.1 Case Study

A case study is a research method within social science and is often used in situations where the main research question is "how" or "why" to explain some present circumstances. A case study is an empirical inquiry that investigates a case in depth and within its real-world context. A case study design could be a single-case or a multiple-case, combined with either a holistic or embedded design [41]. A case study can be associated with developing detailed information on a specific business phenomenon or with a specific case. Several methods are used for data gatherings, such as observations, experiments, interviews, questionnaires, and document analysis [42]. Potential single-case designs for case studies are *critical*, *unusual, common*, *revelatory*, *or longitudinal* [41].

Here, OneSubsea is chosen as a single-case study for sufficient access to data for steel flows, to use MFA to gather evidence of steel treatment at all life stages, and to further evaluate how CE strategies can improve resource efficiency. The design of the case study can be identified as *common*. A *common* case is used when the objective is to capture the circumstances and conditions of an everyday situation [41]. The case study can be seen as an embedded design, as we delimit ourselves to a particular steel flow of the case company with further limitations.

There are several criteria for judging the quality of research design, *construct validity, internal validity*, *external validity*, and *reliability*. *Construct validity* relates to the data collection part and is about identifying operational measures for the concepts studied. Tactics are using multiple sources of evidence, establishing a chain of evidence, and having key informants review drafts [41]. Several different personnel have reviewed the draft before delivery. While performing the interviews, two attendees were present. For the data collection for MFA, a questionnaire was sent out. The respondents had open communication with the author throughout the whole process. In addition to the interviews and questionnaires, documents also have been provided. The *Internal validity* mainly emphasizes the data analysis part and is only for explanatory and casual studies. This step seeks to establish a causal relationship if some conditions are believed to lead to other conditions. Tactics here include pattern matching, explanation building, addressing rival explanations, and using logic models [41]. This step is evaluated as not relevant for this study. *External validity* focuses on the research design and is about defining the domain to which a study´s findings can be generalized. In single-case studies, a common tactic for *external validity* is using theory [41]. However, the objective of this thesis is not to generalize any data for the industry. The thesis is delimited to one of OneSubseas facilities and one of the products, which are finalized here. Therefore, based on the findings, the identified and recommended strategies can be generalized to OneSubseas other products and locations and other related Schlumberger-owned companies. The last one, *reliability,* occurs in the data collection part and is about demonstrating that the study's operations can be repeated with the same results. Strategies for this are to use case study protocol and develop a case study database [41]. Therefore, the method is well elaborated, and questionnaires and interview questions are added in the appendix. The data collected for the MFA and the transcripted interviews are stored in an online database.

3.2 Literature Review

A literature review is a research method where the researcher critically reviews existing literature about a subject [43]. There are several review methods, such as systematic and traditional reviews, and sub-categories such as conceptual review, state-of-the-art review, scoping review, and more [44]. Therefore, the correct method must be chosen accordingly for the study.

A literature review is sometimes described as a traditional narrative review due to its narrative style of presentation [43]. Traditional reviews allow for flexibility and exploring ideas, as well as they can be insightful and original [44]. Narrative reviews are chosen when the purpose is to identify a few studies that describe the problem or topic of interest. The review is performed by first searching relevant databases, whereas in this case, most searches have been performed in Orcla and Google/Scholar. The next step is to identify keywords in the relevant articles and use in in the search. Then the abstracts are reviewed and thrown out unless relevant. When doing the narrative approach, it is unnecessary to include every article on the topic [45].
Critics of the narrative approach arise reasoning no formal methodology, thus lacking transparency and no academic rigor. In addition, there could be a biased selection when not including every article, and the review is only small. With no formal standardized method, the review cannot be replicated. It is also mentioned that incorrect interpretations may result as there is no quality assessment for the material. At last, contrary views might not be identified or included in the review [44].

A literature study is performed to provide a theoretical background and complements the discussion part of the results leading to the recommendations/conclusion. A narrow literature study was performed. Searches were performed with keywords such as:

- "Circular Economy"
- "Circular Economy Strategies"
- "Material Flow Analysis"
- "Steel"
- "steel" AND "circular economy"
- "Recycling" AND "steel"
- "Eco-design"
- "Circular Economy" AND "Subsea"
- "Industrial Ecology"
- "Industrial Ecology Tools"
- "Industrial Ecology" AND "Circular Economy"

For steel, most of the literature has been collected from World steel association, which represents steel producers, national and regional steel industry associations, and steel research institutes. The association represents around 85% of global steel production [46].

Document review is a way of collecting data by looking through documents. Here, a random selection of nine sales orders for the flowmeter was picked out to identify the typical lifespan of the flowmeters.

3.3 Interview

Interviews are viewed as one of the most important sources of evidence in a case study [41]. There are three main types of interviews, varying in their content and degree of structure. Conventional unstructured interviews, structured conventional interviews, and structured behavioral interviews [47]. The most used personnel interview method is the conventional unstructured interview. This method is an informal conversation between the candidate and interviewer [48]. Conventional unstructured interviews differ from the structured by being unscripted, and the questions are formulated according to the course of the conversation [49]. Structured conventional interviews are scripted, and the interviewer follows guidelines and asks predefined questions about the information which must be obtained [50]. Interviews in case studies can remind of guided conversations rather than structured interviews, this type of interview is also called intensive, in-depth, or unstructured interviews [41].

Here, a semi-structured interview has been conducted to understand and present the supply chain and processes of the product described in the thesis, and as described above, can remind of a guided conversation. The interview was performed over Microsoft Teams, with two attendees from OneSubsea.

3.4 Material Flow Analysis

Material Flow Analysis (MFA) assesses flows and stocks of materials within a system defined in space and time [51]. MFA is used to describe and further evaluate the flow of goods or materials through the defined system. MFA is attractive as a decision-support tool in resource management, waste management, and environmental management. It follows the law of the conservation of matter, which makes the results easily controllable. By performing an MFA, the flows of waste and loadings will be illustrated, and one can identify potential sources of accumulations [51].

Figure 20 is remodified from [52] and shows the steps in assessing a CE strategy. At first, the processes to be monitored must be identified. This could be a single process, multiple, or a whole supply chain. CE strategies that could positively impact should be identified in the next step. These are listed in 2.2.2. In the third step, the focus of the analysis is to be defined, and CE requirements to be chosen. This choice leads to a methodology to assess the circularity of a strategy [52]. In this thesis, MFA is used to measure the steel flow of OneSubsea, looking into the material input, design, and end-of-life resource management, to identify opportunities to reduce input and use of natural resources by reducing valuable material losses with CE strategies.

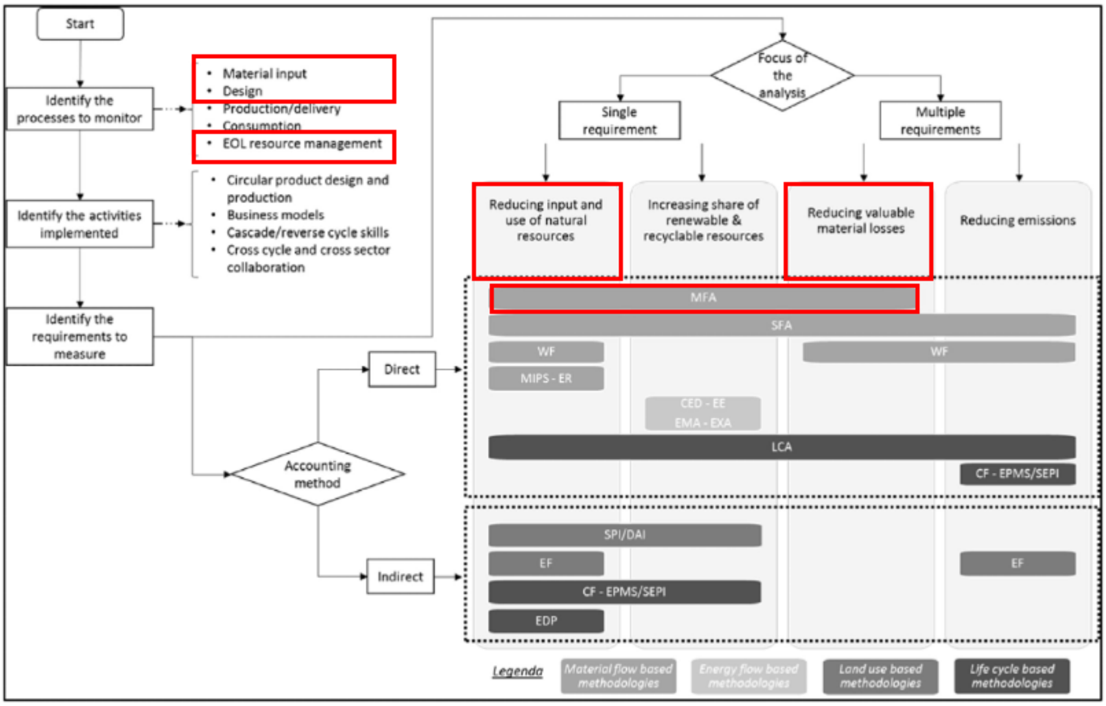

Figure 20 Steps in assessing a CE strategy, remodified from [52]

3.5 Data collection overview

Table 2 lists the data collectors, which data they provided, the date the request was sent, and the data received. Before starting the master thesis, one of the identified challenges was the time-consuming data collection. Therefore, the request was sent out to the case company as early as the end of November (thesis starting in January). However, OneSubsea was not able to provide data at this point. This is because the scope was still not fully determined. In addition, OneSubsea had to locate contact persons who had the time and motivation to work to gather detailed data. Nevertheless, it is important to show when the data was received as time further can influence the thesis, which is discussed later in the discussion chapter.

Table 2 Overview over data collection

Stakeholder	Activity	Request sent (date)	Data received (date)
OneSubsea employee Supply Chain Materials Advisor	• Data collection for machining the venturi • Data collection for flowmeter assembly	26.11.2011	04.04.2022
OneSubsea employee Project Manager Subsea Services - Processing	• Data collection for flowmeter repair and maintenance • Data collection for flowmeter retrieval	26.11.2011	29.03.2022
OneSubsea employee Sales Manager – Subsea Meters	• Data collection for flowmeter usage time	17.03.2022	25.04.2022
Customers of OneSubseas flowmeter	• Data collection for end-of-life	-	Not received

A questionnaire was created to gather information for the MFA and is shown in **Appendix A**. In addition, the author has had continuous contact with the data gathering team. As OneSubsea lacked some of the requested data, an additional survey was created. The survey consisted of one question, shown in **Appendix B**, with the intention to send it out to 5 customers to generalize the end-of-life data for the products.

However, OneSubsea was unable to provide contact persons. Thus, this data was not made available.

Table 3 shows the position of the interviewees, date, and purpose. Subchapter 1.1.1 is mainly based on the information received in the interview. Mentioned this was a semi-structured interview. Questions for the interview are listed in **Appendix C**.

Table 3 Interview information

Attendees	Date performed	Purpose
OneSubsea employee Supply Chain Materials Advisor	22.02.2022	Gather information and understand the processes and activities for the whole life cycle of a flowmeter
OneSubsea employee Project Manager Subsea Services - Processing		

4 Results

Figure 21 shows the MFA, which illustrates the steel flows for the flowmeters in the period 2019-2021 (February 2022 for repair & maintenance). This does not follow the law of conservation or input equals output, as the use phase contains steel from previous years. All numbers are in kg.

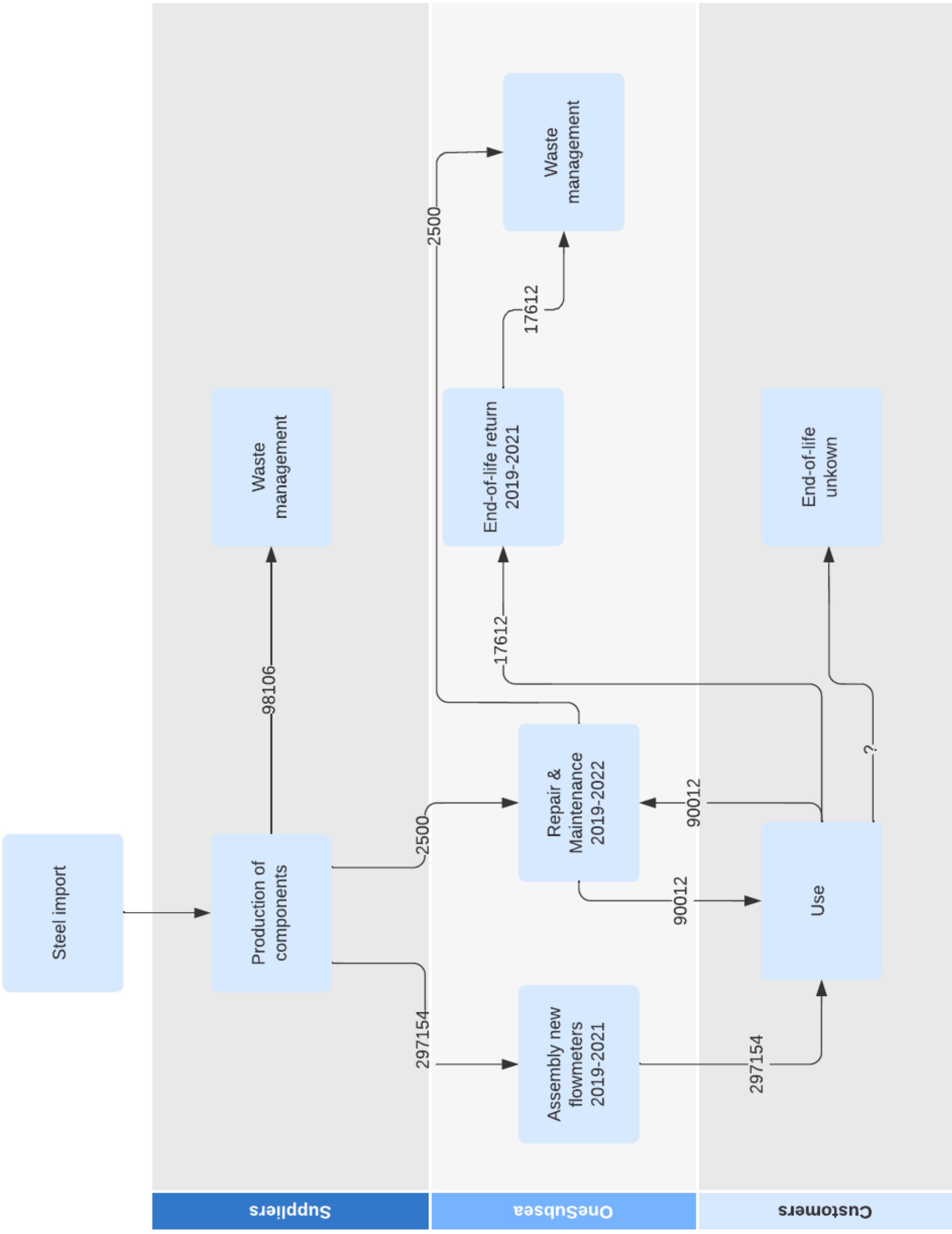

Figure 21 Material Flow Analysis

Table 4 lists the assumptions, simplifications, and limitations related to the MFA.

Table 4 Assumptions, simplifications, and limitations of the Material Flow Analysis

Assumptions and simplifications	Limitations
• Input = output at maintenance and repair • Steel delivered to waste management companies is assumed to be recycled (open-loop recycling) • No waste occurs at assembly	• Steel treatment at suppliers where OneSubsea does not procure steel is excluded • Steel treatment at waste management companies excluded • Does not divide input from scrap steel and virgin materials • Does not include standard deviation • Does not include end-of-life data from users

At first, the steel is imported to suppliers who produce all the components. Steel treatment at suppliers is excluded. However, the machining of the venturi is included. The reason is that the venturi is the largest proportion of the product. During the interview, it was mentioned that a significant amount of waste is generated during this process, and OneSubsea procures the steel. **Table 5** lists the number of flowmeters, total waste which occurs during the machining of the venturi, and the average waste per venturi in 2019, 2020 and 2021, as well as the sum.

Table 5 Waste from venturi machining

Year	2019	2020	2021	Sum
Total Qty.	75	108	72	255
Total Waste (kg)	25 501	45 789	26 816	98 106
Average waste per venturi (kg)	340	423	372	

Figure 22 shows the percentage of waste that occurs when machining the venturi compared to the total weight of the complete flowmeter. The data is from 2020 and 2021. Each column represents the machining waste from one venturi to the product's total weight. The blue columns are for the venturis for the Omni flowmeter, and the red represents the other types. In some cases, the number is over 100%. This is because older blanks have been used instead of procuring new ones and disposing of the elder. The graph illustrates that the waste percentage from machining the venturi for the Omni is higher than the elder flowmeters. The graph is sorted by the waste percentage for a better overview.

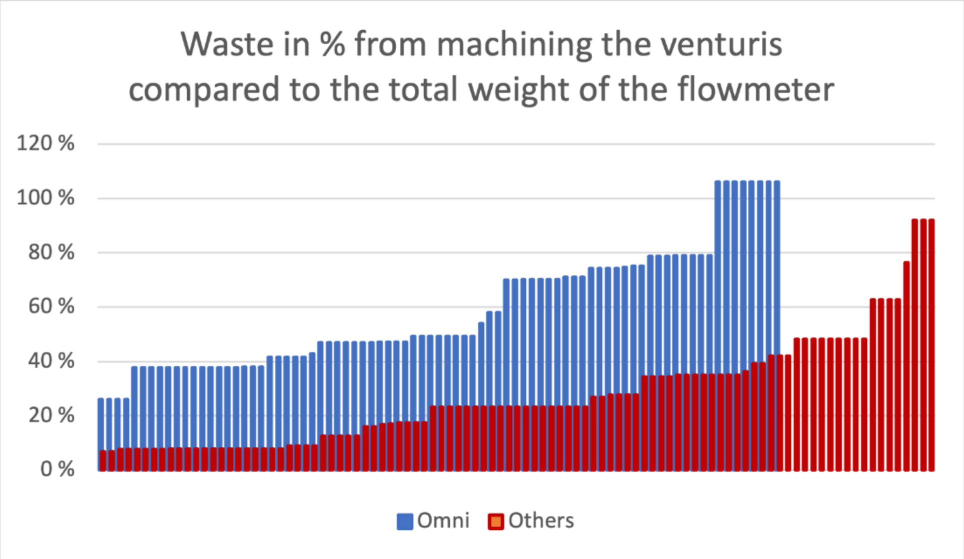

Figure 22 Waste compared to total product weight

The next phase is the assembly at OneSubsea. Here, input equals output to the next phase, use. There is no waste during assembly, as the only process is the assembly of pre-fabricated components.

During 2019-2021 OneSubsea handled approximately 45 service orders to repair flowmeters. As a result, 43 meters have replaced approximately 2500 kg of steel material. The total weight of those 43 meters is 90012 kg, including non-steel components. The venturi is the main component and contributes to a total weight of 64157 kg. The percentage of steel replaced during repair and maintenance compared to the total weight of different flowmeters spans from 0% to around 9%, which **Figure 23** illustrates. Each point represents one service. Most of the higher values are due to an upgrade of the transmitter, and one is because of a replacement due to failure. The total steel replaced compared to the total weight of the flowmeters is approximate 3%.

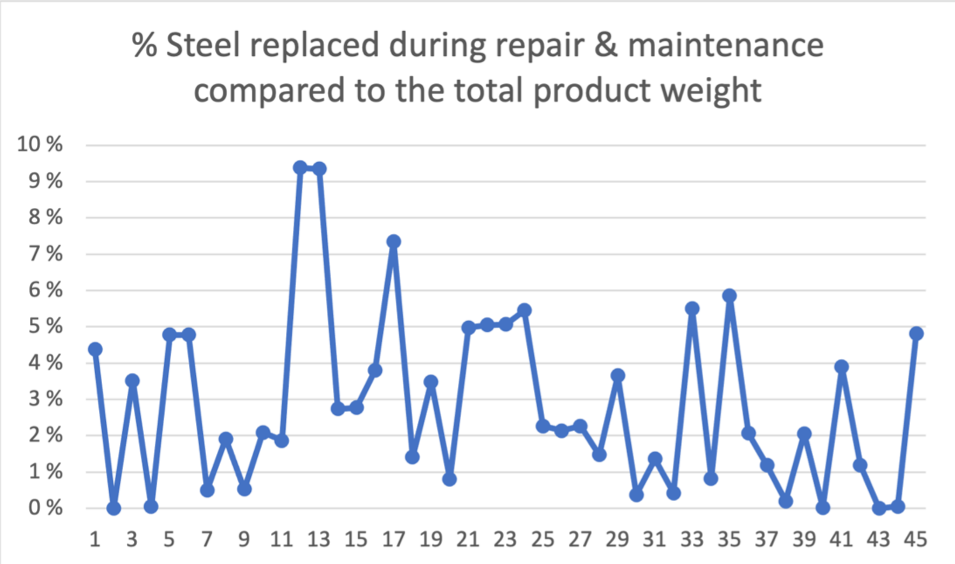

Figure 23 Graph of percentage steel replaced in the flowmeter compared to the total product weight

Between 2019 and 2021, nine flowmeters have been returned at end-of-life for disposal. This sums up to a total of 17612 kg, which is all delivered to waste management companies.

4.1 Document review

A document review has been completed in the sales orders to determine how long the flowmeters stay in operation. **Table 6** lists the planned years in operation for nine projects and the quantity entitled of Omni flowmeters to the project. The average alone with the years in production is 21 years, including the quantity of the flowmeters brings it to 22,5 years per flowmeter.

Table 6 flowmeters usage time

Usage (Years)	21	30	21	8	28	12	30	25	15
Quantity	1	4	1	2	1	12	15	7	1

5 Discussion

5.1 Evaluating Circular Economy for OneSubsea

Table 7 summarizes the status of the different CE strategies at OneSubsea, if there is room for improvement, and how they should be prioritized and divided into long-term or short-term focus. Additionally, the identified CE strategies are discussed against the results from the literature study and the MFA. In 0 is a summarization of the ideas discussed below that relate to the needs improvement column. These ideas are also illustrated in **Figure 24**.

Table 7 Evaluation of Circular Economy Strategies

Strategy	Implemented	Needs improvement	Relevant	Priority
Partnerships and stakeholder involvement	No	Yes	Yes	Short term
Circular design	Yes	No	Yes	Ok
Designing out waste	No	Yes	Yes	Long term
Reuse	No	Yes	Yes	Long term
Recycling	Yes	Yes	Yes	Long term
Extending product life	Yes	No	Yes	Ok
Take-back systems	Yes	Yes	Yes	Short term
Refurbishment	No	Yes	Yes	Long term
Product-Service systems	No	No	No	None
Remanufacturing	No	Yes	Yes	Long term
Repair and Maintenance	Yes	Yes	Yes	Long term
Reduce	Yes	No	Yes	Ok
Circular business model strategies	No	Yes	Yes	Long Term
Extended Producer Responsibility	Yes	Yes	Yes	Short term

What is the current status of the Circular Economy in OneSubsea?

Repair and maintenance are already existing CE strategies at OneSubsea and are well documented in the MFA. The result yields that even if the product is in for repair, only a small number of parts are replaced. This is illustrated in Figure 23, which shows how much steel is replaced on every repair in terms of percentage of the total product weight. And only a total of 3% steel has been replaced compared to the total weight of the flowmeters. The main focus is to repair components if there are defects. All the waste at *repair and maintenance* is delivered to waste management companies. This is expected in this case, as the focus is to repair defective components. If the component is not usable or repairable, the part needs to be replaced, and the old is delivered to a waste management company. However, sometimes components must be replaced due to the pressure of time. The MFA shows equal input and output of material in *repair and maintenance*. On the one hand, this is not accurate. A simplification was made. The input is higher than the output from modifications such as upgrades with heavier equipment. However, the importance lies in identifying these strategies and what happens to the old components.

Discussing the product's design and how it has developed over the years shows that the product has been standardized and *reduced* in size. The *reduction* in size narrows the loop as less material is needed. In *Circular Design*, it is described that the product should be designed for *repair and maintenance* to *extend product life*. Here, the MFA documents the availability for *repair and maintenance*. Another parameter is to allow for future expansion and modification, which is also documented by the upgrades of new transmitters. The flowmeter is designed to last 25 years. Consequently, it can be argued that it is designed for durability and reliability, which also are parameters for *Circular Design*. Design for disassembly is another parameter that allows for disassembly, in that case, the materials could enter different cycles. This is also documented as flowmeters have been returned, disassembled, sorted, and delivered to a waste management company. Therefore, it could be argued that the flowmeter has a *Circular Design*.

In the theoretical foundation, the *CBM's strategies* were described. How OneSubsea operates with the flowmeters today draws several parallels to the classic *long-life model and encourages sufficiency,* which is for slowing the loop. As mentioned, the value proposition here is built around high-quality and long-lasting products supported by design for durability and repair.

OneSubsea also has a *take-back system*, as they are obligated to ensure proper disposal due to the barium source, which also relates to the strategi *extended producer responsibility*. Throughout 2019-2021, OneSubsea had nine flowmeters returned for disposal. When the product is returned after use, steel is sorted out and sold to waste management companies. In general, all steel waste at OneSubsea is sorted out and sold to waste management companies.

Venturi production has also been a target. The result shows that the waste generated per venturi spans from 340 to 425 kg over the last three years. Suppliers do this process, and the generated waste is delivered to a waste management company.

If all waste delivered to waste management companies is recycled means that there is a current *open-loop recycling* strategy to close the loop.

As a result of the discussion above, it can be argued that the steel treatment is very efficient when looking at OneSubsea and its processes isolated. However, there is room to improve resource efficiency by implementing and improving various CE strategies, which is elaborated below.

Which Circular Economy strategies can be implemented for sustainable resource management of steel in OneSubsea?

As illustrated in Figure 22, the waste from machining the venturi for the Omni was significantly higher compared to other flowmeters. Omni is also the latest flowmeter design. As mentioned previously, the Omni flowmeter has been standardized and had a size *reduction*. However, the percentage of waste generated from production of the venturis for Omni flowmeters, has increased. This might be explained by a higher focus on fast delivery and cost-optimizing, rather than *designing out waste*, which is another strategy to narrow the loop. Hence, there might be a potential to increase resource efficiency by reducing waste. However, this might be a challenge, as cost is an important criterion for being competitive as a supplier. Having a new blank designed for each venturi could be too expensive. Figure 22 illustrates that the waste has been significantly lower. Thus, there could be a potential to standardize new blanks to reduce waste. But there are some uncertainties according to the figure, despite it being displayed in percentage of the complete product. As the Omni flowmeter has a reduced footprint/size, it does not mean that the different venturis have had a size reduction. The figure illustrates that 25 Omni flowmeters have waste above 70% from machining the venturi (excluded the meters above 100%). These 25 venturis are machined out from three different blanks. Moreover, these blanks have not been used on any other venturis, under 70% waste. Therefore, one might assume this blank is designed for this venturi with that waste. For that reason, OneSubsea should consider designing or having more blanks standardized to reduce waste. There could also be potential savings as less material is required.

All steel waste generated at OneSubsea is sorted out and sold to waste management companies. Waste is generated when flowmeters are returned for repair or at end-of-life. The status today is considered to be *open-loop recycling*. This means the steel is transferred to another life cycle after being *recycled*, which could also result in downcycling of the material. As described in theory, *designing out waste* is also about ensuring proper waste treatment. OneSubsea has not included waste management companies in their contractor management processes. Consequently, OneSubsea doesn't know what happens to this waste. However, the steel is valuable and endlessly recyclable without losing its properties and thus is most likely a part of the waste management companies income. Because of that, the steel waste is not considered high environmental risk and is therefore not included in their contractor management process. As mentioned in theory, around 20% of the steel scrap is exported from Europe to the international market. According to the Small Circle approach, it is argued that negative externalities caused by export should be considered in circularity and sustainability targets. The European Steel Association claims that recyclable materials should stay in a constant loop within European Society. OneSubsea should request reports and perhaps perform audits to ensure the waste is adequately treated and scrap steel stays within Europe. Ensuring the fate of generated waste is a key step in circularity. In addition, OneSubsea should deliver procedures to the customers describing how they should properly dispose of the product.

A potential strategy for OneSubsea is *closed-loop recycling*. Recycling accounts for significant energy and raw material savings. Every tonne of scrap steel equals an approximate reduction of 1,5 tonnes of carbon dioxide emissions. Instead of disposing damaged venturis, it can be sent back to a steel producer and be re-smelted as a part of the following blank for the next venturi. This secures the quality of the steel and reduces the need for raw materials. Additionally, OneSubsea can request the steel waste from the venturi machining. With enough scrap, OneSubsea can make an agreement with a steel producer using EAF, which may allow for a 100% recycled venturi. Furthermore, the emissions that would have occurred during the primary steelmaking can be substituted away, which could be included in sustainability reporting. OneSubsea could also purchase recycled steel directly for the venturi. The other steel components for the product are ordered directly from suppliers. OneSubsea can use the customer power to request the parts to be manufactured from 100% recycled steel. OneSubsea can also reach out to these for possible *closed-loop recycling*. This brings another strategy which is *partnerships and stakeholder involvement*, which is essential to achieve circularity along the supply chain. Furthermore, *closed-loop recycling* can be advantageous as OneSubsea can account for what happens to the steel at all times. Versus in *open-loop recycling*, the steel can be downcycled or eventually lost. Therefore, the ideal solution that OneSubsea should seek is *closed-loop recycling*.

OneSubsea could approach an EAF producer and ask if they accept obsolete scrap for closed-loop re-melting, with the intention to form a partnership where the recycled steel is then purchased back cheaper than directly procuring recycled steel. The European Steel Association list several steel producers using EAF in Europe; for instance, six exist in Sweden. However, *open-loop recycling* also closes the loop. Therefore, for the short term, it is recommended that OneSubsea follows up with the waste management companies to ensure correct waste treatment.

Environmental product declarations should be made for the product together with circularity reporting, which further allows customers to compare the product on environmental performance to competitors.

Steel is well known for its durability and therefore is well-fitting for a CE due to its *reuse* potential. Originally, *reuse* as a strategy was excluded, as OneSubsea gave the impression that the products were too worn out to meet the high-quality specifications. OneSubsea have set a standard lifetime expectation of 25 years for the Omni flowmeter. The practical lifetime of the Omni flowmeters was investigated and are listed in Table 6. Results shows that usage time spans from 8 – 30 years. OneSubsea explains that despite the design being for 25 years, this is when the product is facing high pressures, temperatures, corrosive liquids, and vibrations. In most cases, the flowmeters are not exposed to this, and rarely at the same time. Consequently, the lifetime would be higher. Thus, having standard procedures to dispose of complete meters when returned at end-of-life might not be the ideal solution.

OneSubsea can create a database over when flowmeters are supposed to be returned and how long they are still operable, enabling for potential *reuse* of the flowmeters. Direct *reuse* also would save emissions that would have occurred for re-melting in the case of recycling and transport as well as manufacturing. Naturally, barriers must be discussed as the customers might not want to purchase a used product. OneSubsea could consider performing a market investigation, evaluating the potential market for second-hand sales. Additionally, fair and transparent pricing and a good reputation of quality might increase the customers willingness for second-hand sales. This could have substantial environmental and economical savings, increasing the profits by reducing material and energy costs. Other factors also must be evaluated, such as reuse might not be that attractive, as the product is rapidly outdated, and existing components can also be taken off the market, affecting the *repair and maintenance* program. It should also be mentioned that the average usage time over the nine investigated projects is 22,5 years close to the mentioned lifetime of 25 years. However, as only nine projects are investigated, there is high uncertainty. Furthermore, the result shows that some flowmeters only are used for eight years, and with a barium source designed for 35 years, there should be some *reuse* potential.

OneSubsea should not automatically dispose of the product when it is returned at end-of-life. For instance, the product can be inspected and categorized for *reuse*, *refurbishment*, *remanufacturing*, or disposal. If the flowmeter cannot be directly *reused*, some of the other components might still be usable at end-of-life. Therefore, strategies such as *remanufacturing* and *refurbishing* should be relevant. *Remanufacturing* implies using these components in a new product. On the other hand, *refurbishment* focuses on renewing the product's condition to as new or better by restorations and/or replacements. Therefore, *refurbishment* could be a good strategy when the product is not directly reusable and *remanufacturing* when only a few components are usable. Reduction in carbon emissions as a result of *reusing, refurbishing* or *remanufacturing* would benefit the customers as a sustainable choice and could be included in their sustainability reporting.

Normally, *refurbishing* is cheaper than acquiring new components, which results in savings for both companies. OneSubsea should consider these options instead of disposing of the complete product when returned at end-of-life. However, an end-of-life collection is crucial to move forward with these options. To increase the collection, *take-back* or *buy-back* agreements can be agreed upon with the contract. OneSubsea should therefore implement incentives to maximize end-of-life collection. Agreeing at the early stages if the product is to be returned allows OneSubsea for future planning of *reuse, refurbishment*, or *remanufacturing*. In addition, spare parts could be saved from products returned at end-of-life which could be incorporated into products delivered to *repair and maintenance*. This could save time and costs related to ordering a new component and reduce environmental burdens associated to these processes.

OneSubsea explains that components must sometimes be replaced when they come in for repair, as it is quicker to acquire a new component than to repair the same component. However, there were no data to track the further fate of these replaced parts, and it was likely believed that they were disposed of as waste. There might be a potential for OneSubsea to investigate the option to improve the exploitation of replaced components in these cases. For instance, they can be fixed and saved as spare parts.

PSS is another CE strategy to consider. With *PSS*, the asset will be owned by the supplier and offered to a client as a service, for example, through leasing. *PSS* has both advantages and disadvantages, which must be addressed. PSS could increase sales positively as purchasing the service would be cheaper than procuring and owning the product, which could be more competitive. Additionally, it would secure OneSubsea the product at end-of-life, which opens for *reuse, remanufacturing, refurbishing,* and ensuring proper waste disposal. However, the major consideration which must be addressed is a risk. Changing the business method to *PSS*, the supplier would take on the risk, which previously was the customers. Meaning, that if the flowmeter fails, OneSubsea would potentially have to pay for retrieval and shipping of the product and shipping and installation of the new or fixed one. These operations would be quite costly and could result in a negative income. Although *PSS* ensures that OneSubsea ends up with the product, a *buy-back* solution seems safer.

Based on findings in this thesis, there is an opportunity for OneSubsea to focus their *business model* in a CE direction. Despite the existing business model drawing parallels, it needs to be a focus, and a target needs to be implemented. OneSubsea can incorporate goals from the UN´s SDGs. For example, SDG number 12, *responsible consumption and production*, with the targets achieve sustainable management and efficient use of natural resources, and reduce waste generation through prevention, *reduction*, *recycling*, and *reuse* substantially by 2030. The discussed CE strategies could be used to accomplish these targets. Furthermore, CE strategy is a holistic approach, which needs to include suppliers and contractors. Therefore, to realize these CE strategies, OneSubsea must explore SDG number 17 *Partnerships for the goals*, and OneSubsea must collaborate with internal and external stakeholders to successfully implement CE strategies.

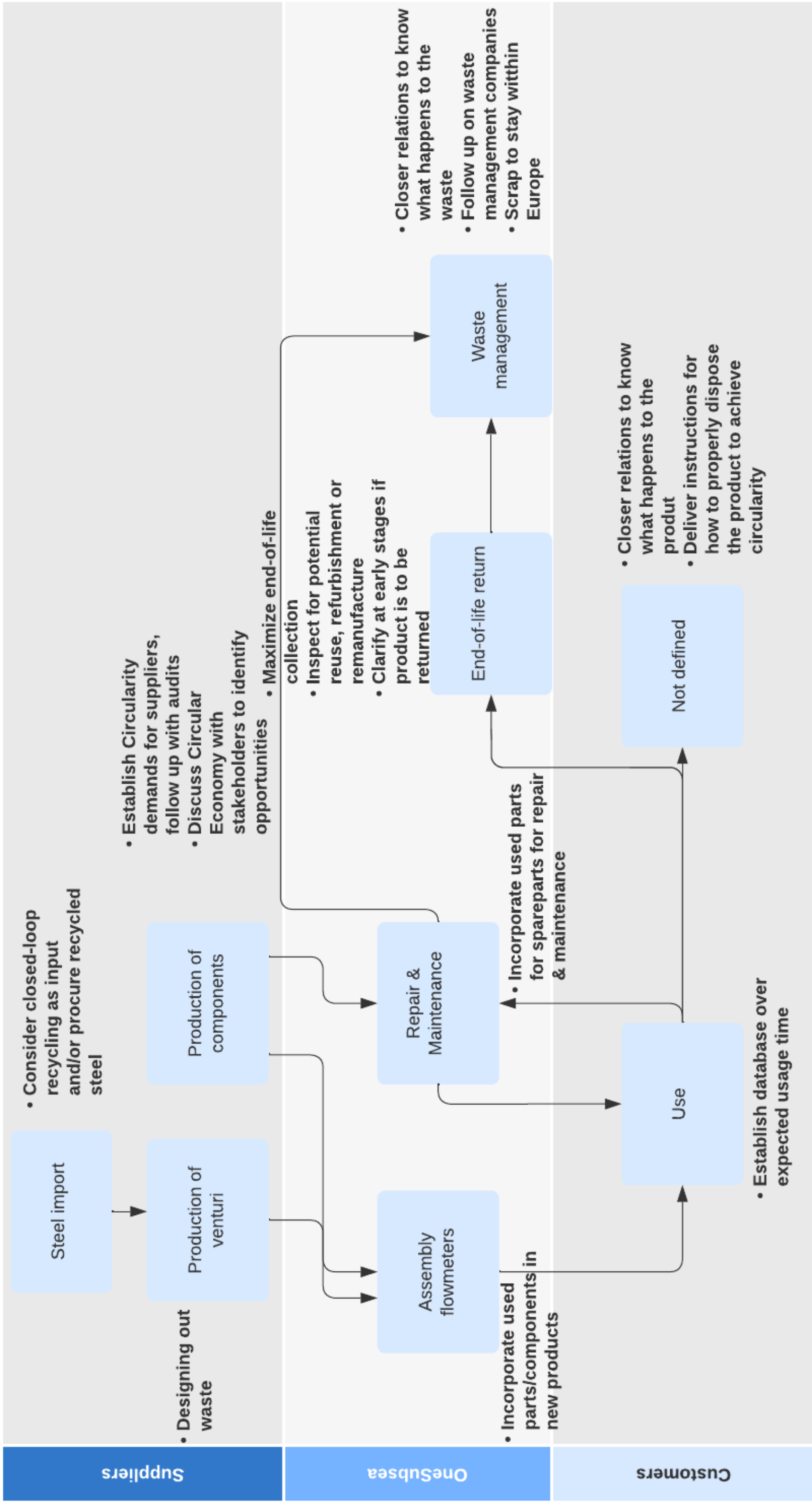

Figure 24 Illustration of how strategies should be used over the supply chain

5.2 Recommendations for OneSubsea

- OneSubsea should have closer relations with stakeholders across the supply chain. For instance, knowing what happens to the waste delivered to waste management companies, what happens to the product at end-of-life, how the suppliers treat their waste, etc.
- OneSubsea should consider reuse for products by second-hand sales when possible. For instance, two identified flowmeters will only be used for eight years.
- OneSubsea should focus on designing out waste when designing products.
- OneSubsea should consider closed-loop recycling.
- OneSubsea should consider procuring recycled steel for all components.
- OneSubsea should maximize the end-of-life collection.
- OneSubsea should investigate the opportunity to refurbish products at end-of-life for resale (renew status and condition by replacements or restorations).
- OneSubsea should consider remanufacturing (using parts/components of used products in new ones).
- OneSubsea should consider saving spare parts from used products, which could be used in repair and maintenance.
- OneSubsea should consider changing its business strategy to work for a CE.
- OneSubsea should deliver instructions on how to dispose of the products properly.
- Achieving a circular supply chain also relies on other stakeholders. Environmental demands, therefore, need to be incorporated in the selection process of suppliers and procurement, which also needs follow-up. For instance, environmental audits at suppliers or waste management companies to follow up on circularity requirements.
- OneSubsea should create an environmental product declaration for the product, allowing customers to compare the product against competitors on environmental performance.
- OneSubsea should clarify early if the product is to be returned at end-of-life and keep a record of expected usage time.
- OneSubsea should discuss CE with stakeholders across the supply chain. For instance, instead of disposing components, the suppliers might be able to refurbish and resell or even refurbish for OneSubsea.

5.3 Limitations of study

The main limitation affecting the study and scope is the timeframe. As this study is a master thesis, it has a deadline, with a total time of approximately five months. Time is crucial as it limits the scope itself, and assumptions and limitations must be made. In addition, it affects the data collection and can affect the validity of the data. However, time does not allow for further research, as gathering the right contact persons and collecting and processing all data is too time-consuming. One of the disadvantages of performing an MFA is that it requires a lot of data to minimize assumptions and derive meaningful mass balance. And in many instances, data collection requires much time, which this thesis reflects. Because OneSubesa could not provide data before April, the time frame for this thesis became significantly reduced, and it affected the possibility for a deeper investigation of the process.

Another limitation is data availability. As the data was not easily available, the contact persons had to complete extensive work to provide the requested data. As OneSubsea did not contain any data for what the customers did with the product at end-of-life, a survey was created to send it out to all customers in the investigated period. However, there occurred difficulties in getting this done. This survey asked how long they were planning to use the product, what they generally do with the product at end-of-life, what they think are the challenges with disposing of the product, and how often they must repair or replace it. As this was not manageable, it was limited to 5 customers, only asking how they dispose of the product at end-of-life. Still, this data was not made available through the thesis. As a result, the MFA lack end-of-life data. As for usage time, nine random sale documents were reviewed where the planned usage time is listed. The limitations increase the uncertainties, and it might not be enough data to generalize appropriately.

Additional limitations are the steel treatment at suppliers, waste management companies, and the other products of OneSubsea. Therefore, it is described as an embedded case study, and the result is not reflecting the wanted holistic approach. Furthermore, the other products of OneSubsea are often project-specific. Therefore, steel treatment may vary, which means that the identified excising CE strategies may not have been implemented generally in the resource management for the other products, such as take-back systems. It also would be interesting to evaluate project-specific products up against circular design, as the process for delivering a flowmeter is much more standardized.

It is also worth mentioning that when presenting the results of an MFA, it is usual to include uncertainties. In this instance, minor errors or deviations would not affect the outcome as the focus of the study was not to report exact quantities of steel flows but to provide insights on the application of CE strategies.

6 Conclusion

Circular Economy (CE) is highly relevant today, and companies that strive for sustainable solutions can gain advantages over competitors. In this thesis, the goal was to identify CE strategies for OneSubsea for sustainable resource management and, as a result, to increase resource efficiency. To accomplish this, the steel flows of the flowmeters were investigated. And for this, Material Flow Analysis (MFA) was the chosen method.

To require data for the MFA, a questionnaire was created. In addition, this was followed up with interviews regarding the processes through the supply chain. By doing this, a holistic understanding was formed of the system and how they operate. Which simultaneously gave a deep understanding while waiting for the data. Although the data collection took most of the time for the thesis, once it was received, it was relatively quick to understand and analyze the data due to MFA's simple representation. Furthermore, after forming this basis, it was straightforward to evaluate how CE strategies could improve the system. This illustrates how Industrial Ecology supports CE.

It was also interesting to learn that a company that has not focused on sustainable development already has several existing CE strategies. Therefore, by inducing CE targets, OneSubsea could improve its sustainability easily as they would not have to start from zero. The reason for this, could be that these strategies need to be implemented for competitiveness and reputation. For example, OneSubsea would not be especially competitive if they could not deliver reliable products or offer a repair if something were to happen. The thesis clearly showed that the most significant shortcoming was the narrow border or scope they operate within, which means they lack knowledge of what happens outside their processes. Communication across the supply chain and exploiting the product's residual value is probably most important for transitioning to a CE.

OneSubsea should periodically use MFA for all their products, not only the flowmeter, to understand the absolute circularity of the industry, then develop strategies for improving the sustainability and circularity of all the product lines, working towards responsible consumption and production by achieving sustainable resource management and reducing waste generation.

Additionally, as the focus is CE, it would be interesting to follow up the study by identifying the percentage of recycled steel procured and used in the product. This could be done by dividing the steel input in the MFA into scrap steel and steel from virgin materials. However, time restrained a follow-up on this theme. Therefore, OneSubsea themselves further should identify and potentially improve this, as one of the main themes in CE is reducing raw material extraction, it is highly relevant.

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Appendix

Appendix A – Material Flow Analysis Information Request

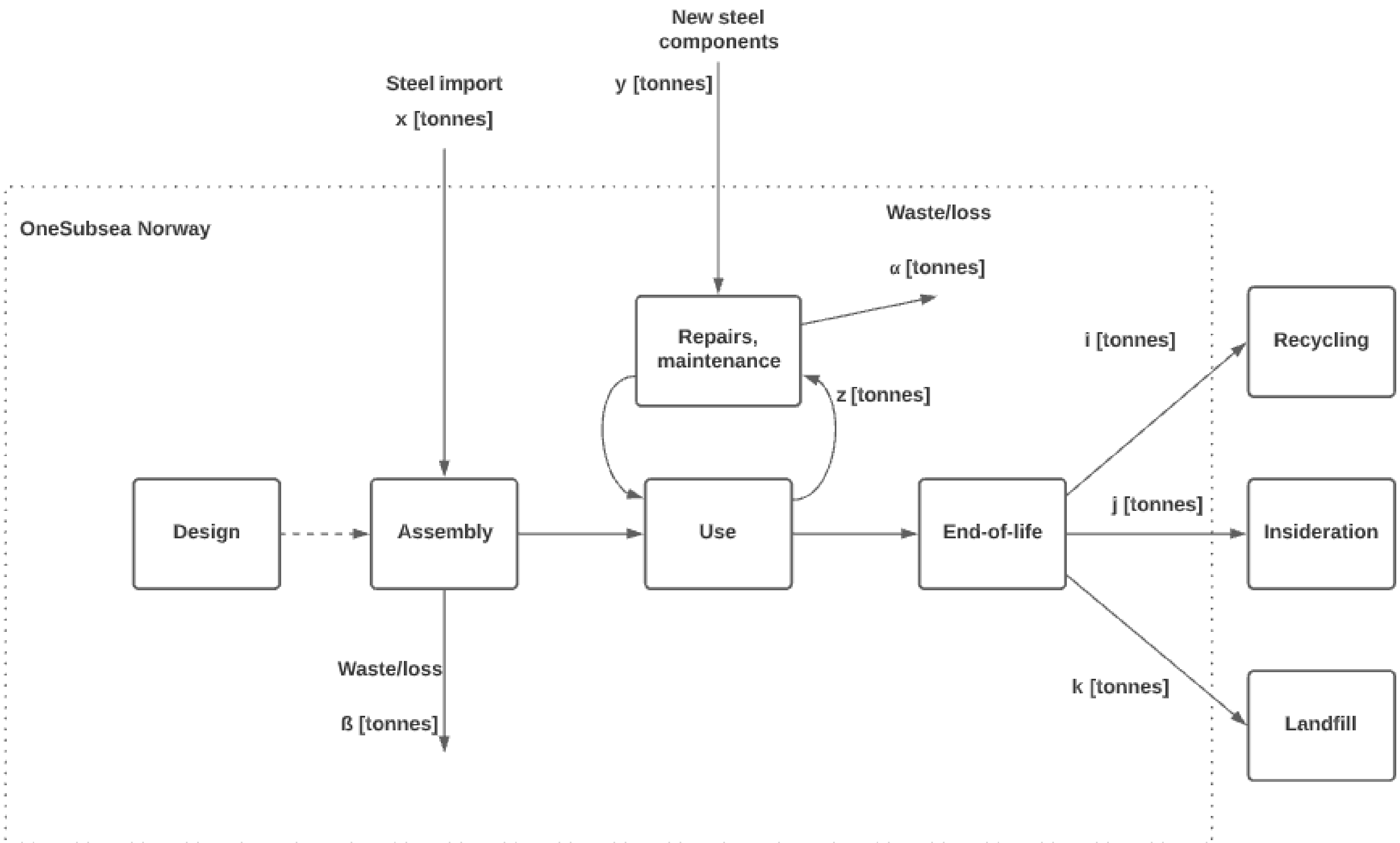
One of the methods in my thesis is Material Flow Analysis (MFA). The purpose of MFA is to identify potential problem areas in the steel management which can be used to make informed decisions on which Circular Economy (CE) strategies to implement, in addition, identifying which CE strategies already exist.

To collect the data for assessing steel flows from OneSubsea, I have created a flowsheet (Figure on next page). Do you think the flowsheet is representing the processes correctly? Or is there anything missing or represented incorrectly?

To perform the analysis, the following data is required for each product back from 2013 until today (figure on next page to clarify):

1. Where are you getting steel from (which country) and the quantity (in tonnes)?
2. What product and amount of steel in every product (marked x in the flowsheet)
    a. How much waste of steel is generated while assembling the product? What happens to this waste? (marked ß in the flowsheet)
3. Maintenance and repair history of every product
    a. How much “new steel” is incorporated in the product (marked y)
    b. How much waste is generated and what is done with the waste (marked α)
    c. Are parts refurbished instead of replaced if possible?
4. End of life treatment
    a. What happened to the product after the use phase? (marked i, j or k)
    b. If the product still is operational in a project, what is the plan for end-of-life treatment? (remember to specify)

Remember to specify the unit (kg, tonnes).
Remember the information is needed per product.


New steel
components
Steel import
x [tonnes]
y [tonnes]
OneSubsea Norway
Waste/loss
α [tonnes]
Repairs,
maintenance
z [tonnes]
i [tonnes]
Recycling
Design
Assembly
Use
End-of-life
j [tonnes]
Insideration
Waste/loss
ß [tonnes]
k [tonnes]
Landfill

Appendix B – Survey for customers

My name is Thomas Gundersen, I´m a student at NTNU in Trondheim. I´m currently doing my master thesis at OneSubsea in Bergen. I will perform a Material Flow Analysis of steel for the flowmeters in the period of 2019-2021 to document the steel treatment at all life stages. Further, it will be discussed how circular economy strategies could lead to better resource efficiency and reduce raw material extraction and loss of valuable material. This could also benefit OneSubsea with a more sustainable production and resource management. Feedback from OneSubsea´s clients is an essential part of the study. Therefore, I hope you can answer the following question below. The data are treated with confidentiality, and no company or personal names is to be released.

How do you dispose the flowmeters at end-of-life?
- Return it to OneSubsea
- Deliver to waste management
- Abandonment (left subsea)
- Other - Please specify

Appendix C – Interview Questions

1. Can you please explain the processes throughout the supply chain, from receiving an order until end-of-life?

2. How is the product´s design improved over the years?

3. What happens to the product at end-of-life?

4. What happens to the waste which occurs throughout the supply chain, and what are the typical waste?

5. Do you have a Life Cycle Assessment and Environmental Product Declaration for the product?

NTNU

Norwegian University of
Science and Technology