CHALMERS
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Life Cycle Assessment and Life Cycle Cost of Heat Exchangers

A Case for Inter Terminals Sweden AB Located in Port of Gothenburg

Master's thesis in Industrial Ecology

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Abstract

Inter Terminals AB store oil products for their costumers and need to store them at a certain temperature with the help of heat exchangers depending on the product. The current heat exchangers at Inter Terminals are old and does not function efficiently in terms of energy and costs. The heat exchangers are used to heat oil products in three caverns and a group of four tanks. The idea is to have heat exchangers for the caverns and for the group of tanks to keep the oil products at the desired temperature. This assessment evaluates and compares new heat exchangers for Inter Terminals, which is located in Port of Gothenburg. The companies responsible for the proposal of the new heat exchangers were Alfa Laval AB, ViFlow AB and GB Tank AB. Two of the heat exchangers were made of carbon steel and one of stainless steel. The comparison and evaluation is done through the methods life cycle assessment (LCA) and life cycle cost (LCC) and three different heat exchangers were compared and evaluated in terms of environmental and economic aspects. The purpose of this evaluation and comparison is to help Inter Terminals decision-making to invest in new heat exchangers which they are in need of. The life cycle assessment was conducted by using OpenLCA, which is a software tool for calculating environmental impacts. The environmental impacts categories considered in the assessment were global warming potential, human toxicity, depletion of abiotic resources and acidification. The weight and the material which a heat exchanger is made of were two major factors contributing to the environmental impacts.

The results of the LCC were analyzed to calculate the payback time for each heat exchanger. This was done by comparing the operating costs for the current heat exchangers and the new ones. This indicated the best alternative of the new heat exchangers for Inter Terminals from an economic point of view.

Sensitivity analyses were also conducted regarding recycling rates, changes in energy prices and the percentage amendments of the energy sources. This lead to changes related to the environmental impacts and the payback time.

The conclusion of this is assessment is that heat exchanger 2, purposed by ViFlow, is best suited for Inter Terminals and is also manufactured by ViFlow in Örnsköldsvik. It is a shell and tube heat exchanger made of carbon steel and has the least environmental impacts and has the shortest payback time compared to the other alternatives.

Keywords: Heat exchanger, Life cycle assessment (LCA), Life cycle cost (LCC), Stainless steel, Carbon steel, Environmental impact.

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Marcus Adolfsson and Shivan Rashid.

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1. Introduction

Inter Terminals is one of the largest independent storage providers of liquid oil products in northern Europe, and the largest in Scandinavia, with more than 4.25 million cubic meters of storage capacity (approximately 27 million barrels) located across 16 terminals. Inter Terminals has four terminals in Sweden along both the east and west coasts, which are important trading routes for petroleum products. The function of the facilities is as strategic storage and mixing for the transshipment of petroleum products. They are also an important part for continental distribution of both petroleum and petrochemical products (Inter Terminals, 2016).

The Gothenburg terminal is located in the port of Gothenburg, Scandinavia´s largest port and has easy access to North Sea, - and the Baltic region. It also has convenient access to rail and road networks and is directly linked via pipelines to three refineries. At Inter Terminals in Gothenburg products such as fuel oil, heavy oil, diesel, jet fuel and gasoline among many other are stored and handled. The oil products are stored in both tanks and caverns depending on the type of the product. These tanks and caverns are using heat exchangers to adjust the temperatures for the different types of oil products to the requested level (Inter Terminals, 2016). A heat exchanger is a device used to transfer heat between one or more fluids. The fluids in the heat exchanger can be single or two phase and are often separated by a solid wall to prevent mixing. This depends on what type of heat exchanger is used, so the fluids may in some cases be in direct contact (Brogan, 2011).

Inter Terminals AB Sweden stores oil product for their customers in order for them to make a business in the oil business. The customers usually buy a large amount of oil for a cheap price and stores the oil at Inter Terminals to sell it later when the demand and price is higher. Since more countries around the world strive for a carbon free society, Inter Terminals are interested in how much emissions their equipment is emitting from a lifecycle perspective. Societies in general wants to make a profit in the oil market, since it still one of the major markets thus the reason for storing oil.

This study concerns heating up oil products in three caverns and four tanks at the Inter Terminals facility in Gothenburg. The three caverns could each contain approximately 50 000 m^3 of oil products and each of the tanks could hold up to approximately 10 000 m^3. The oil products are arriving at the port of Gothenburg with ships and are then pumped to caverns or tanks at Inter Terminals. The oil products are stored at Inter Terminals until the customers want it delivered. The customers also specify which properties the oil products should have. The temperature of the oil products is important when it is time to deliver it to the customers. To obtain the desired outlet temperature of the oil Inter Terminals use shell and tube heat exchangers. The current heat exchangers, which date back to the 70-80s, are not up to date and need to be replaced in order to increase the heat transfer between the fluids, thus becoming more energy efficient. The current heat exchangers that Inter Terminals uses to heat up the oil products are so called water to water heat exchanger and are not constructed to heat heavy oil. The purpose of the heat exchanger was from the beginning to heat the water bed, which subsequently warmed the oil. Using the wrong medium impairs the heat exchangers capability through coatings and fouling on the tubes, along with the high age of the heat exchangers makes the heat transfer from the water to the oil poor. The current heat exchangers cannot handle the products that Inter Terminals is storing at the moment to reach the desired temperature in an effective way without high costs due to long running time. The current heat exchangers are running at a high cost, due to the poor heat transfer from the warm water to the oil products in the caverns. For Inter Terminals this is a problem regarding both economic and the environmental impacts due to inefficient use of energy in the process. This leads to a bigger carbon footprint than necessary.

In order to explore what type of heat exchangers are suitable to replace the current ones, life cycle assessment (LCA) and life cycle cost (LCC) have been conducted. These methods will give detailed information about the environmental and economic impacts and helps Inter Terminals in the decision-making to determine which alternatives is best suited for their process. The geographical boundaries are set for Sweden in this study and the time coverage is set for 30 years for the heat exchangers and 100 years for some of the impact categories.

The aim of this study thus is to review different types of heat exchanger alternatives for Inter Terminals Sweden AB, regarding economic and environmental aspects. The study will serve as a basis for Inter Terminals in terms of decision-making for future investments of new heat exchangers. Therefore, this master thesis will answer these following research questions:

- Using LCA and LCC, which heat exchanger is best suited for Inter Terminals concerning the environmental and economic aspects?

- Is there a trade-off between the environmental and economic aspects?

2. Overview of the Technology

Unfortunately, no previous LCA or LCC on heat exchangers were found. However, there were several LCAs on stainless steel regarding the production and the emissions. According to International Stainless Steel Forum (ISSF), the CO_2 emission is 2,9 ton CO_2/ton stainless steel. This value will be different depending on the chosen electricity mix since it has a major impact. The previous LCA studies about steel production were mainly used in order to understand and model the steel production in this study. Values concerning the energy need in different steps of the steel production was considered, but in this thesis the Swedish electricity mix was used instead.

The heat exchangers that are used for the caverns are stationed above ground and each cavern has its own. The oil in the cavern is pumped up above ground and into the heat exchanger where warm water transfers its thermal energy to the colder oil and heats it. The oil is then pumped down into the cavern again and creates stirring and mixing of the oil inside the cavern, which slightly increases the heat transfer to the surrounding oil. The tanks instead use pipes in the bottom of the tank with warm water flowing inside them to warm the oil.
The caverns at Inter Terminals are unclad, which means that the oil is stored directly to the mountain. This kind of storage builds on the principle that oil is lighter than water and that they do not mix with each other. The caverns are located so that the highest product level is located at least five meters below the natural ground water. The pressure of the groundwater in the surrounding mountain will allow the oil to stay in the cavern and prevents it from leaking throughout cracks in the mountain. Groundwater continuously flows into the cavern through the cracks and forms a water bed that the oil floats on. The water bed is maintained constant just above the bottom of the cavern (Avveckling av oljelager i oinklädda bergrum, 2003). Inter Terminals has its own internal water piping system and they are using municipal drinking water in their pipes. In order to heat Inter Terminals water system, they are buying hot water from Göteborg Energi and use a heat exchanger to transfer the thermal energy from the warmer water to the colder water. When the water within Inter Terminals system has been

heated it is transported through pipes to the heat exchangers at the caverns or to the tubes at the bottom of the tanks to heat the oil products to the desired temperature.

The assumptions throughout the study related to the LCA and LCC are described in the inventory analysis. Assumptions has been made for each process for the LCA and LCC and have been explained.

2.1 Heat Exchanger

A heat exchanger is a device used to transfer heat between one or more fluids. The fluids in the heat exchanger can be single or two phase and are often separated by a solid wall to prevent mixing, but it´s depending on what type of heat exchanger that is used, so the fluids could in some cases be in direct contact. When discussing heat exchangers, it is important to provide some form of categorization. This is mainly done through two approaches. First, to consider the flow configuration within the heat exchanger, and the second approach is based on the classification of equipment type by construction. There are four types of basic flow configurations; counter flow, concurrent flow, crossflow and hybrids. These types of flow configurations depend on the purpose of the heat exchanger. The classification of the heat exchangers is mainly classified by their constructions (Brogan, 2011).

The heat exchangers that are interesting and will be focused on in this assessment are shell and tube heat exchangers (tubular) and plate heat exchangers. They are the most common types of heat exchangers in the industry (Brogan, 2011). The manufacturers contacted in this study have designed the proposed heat exchangers based on the specifications from Inter Terminals and their own knowledge. The type of flow and characterization of the heat exchangers have been designed by the manufacturers individually.

2.1.1 Shell and Tube Heat Exchanger

Shell and tube heat exchanger belongs to the category of heat exchangers called tubular and are popular because of the wide range of pressure and temperature. It consists of a number of tubes mounted inside a cylindrical shell. It functions in the way that two fluids can exchange heat, one fluid flow through the tubes while the other fluid flows outside the tubes. This makes the fluids to exchange heat. There are four major parts in a shell and tube heat exchanger; front end, rear end, tube bundle and shell (Brogan, 2011).

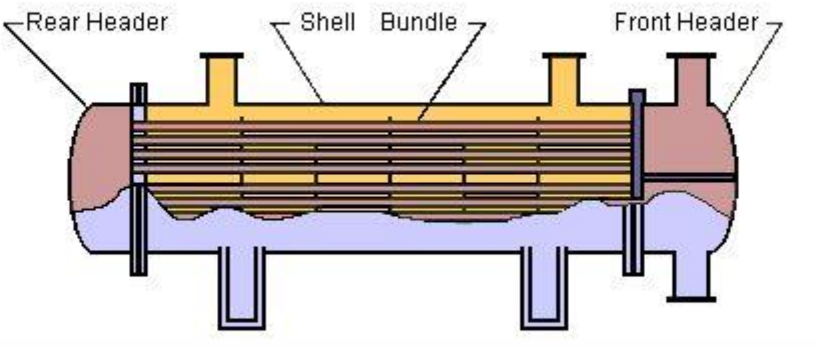

Figure 1. Shell and tube heat exchanger (Brogan, 2011)

A typical shell and tube heat exchanger have the design as in figure 1, with the four major parts included. The front end is where the fluid enters the tube side of the exchanger, the rear is where the subside fluid leaves the exchanger or is returned to the front header. The tube bundle comprises the tubes, tube sheets, baffles and tie rods etc. to hold the bundle together. Lastly, the tube bundle is contained in the shell. Compared to the plate heat exchanger shell and tube are often less expensive to buy and could be used in systems with higher operating temperatures and pressures. Another advantage with tubular heat exchangers is that leaking tubes are easy to locate and plug (Brogan, 2011).

2.1.2 Plate Heat Exchanger

Another popular type of heat exchanger is the plate heat exchanger, which separate the fluids exchanging heat by plates. It is often used in cryogenic and food processing industries, but is also being used in the chemical industries due to its ability to handle more than two streams. This type of heat exchanger consists of two rectangular end members which holds together several pressed rectangular plates with holes in the corners for the fluid to pass through between the plates (figure 2). Plate heat exchangers´ major advantage compared to shell and tube is that they are easier to take apart for cleaning and maintenance. The heat transfer efficiency is also higher for a plate heat exchanger and demands less working space (Brogan, 2011).

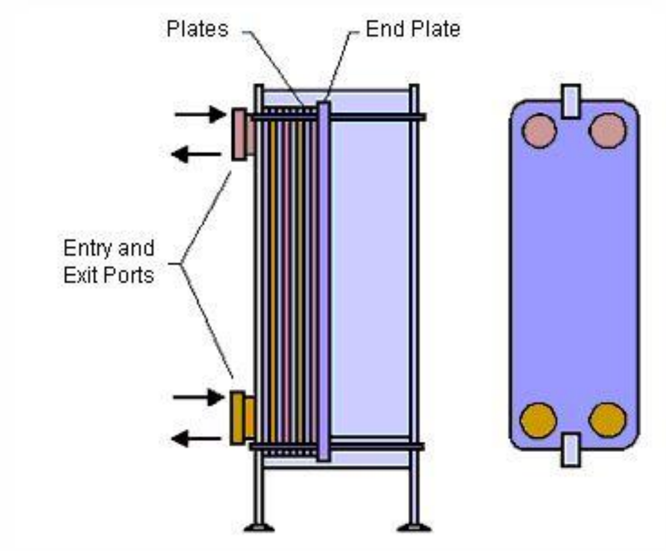

Figure 2. Plate heat exchanger (Brogan, 2011)

2.1.3 Carbon Steel and Stainless Steel

Heat exchangers, whether they are shell and tube or plate, are mainly constructed with variations of stainless steel or carbon steel. Steel is an alloy made of carbon and iron, and depending on the grade of the steel the amount of carbon is varied. Although carbon is the key alloy element for iron other materials are important to add to obtain various desirable properties of the steel. For carbon steel, where carbon as said is the main alloying element, the properties are mainly defined by the amount of carbon that usually is between 0.2% and 2.1% (pearlitesteel, 2015). A higher amount of carbon increases the strength and hardness of the steel. For stainless steel chromium and nickel are important alloying materials, the chromium is used to prevent corrosion and staining. The nickel is added to increase toughness and combined with a reduced amount of carbon the nickel improves the weldability of the steel (Outokumpu, 2016).

The main difference between stainless and carbon steel is that the carbon steel can corrode while stainless steel is protected against corrosion. However, carbon steel has higher thermal conductivity then stainless steel (pearlitesteel, 2015).

3. Method

3.1 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a method to analyze the environmental impacts associated with a product or service throughout its life from cradle to grave. The method studies the energy and material flows for the product and system from raw material extraction, through production and use, to disposal (Baumann and Tillman, n.d.) As seen in figure 3, life cycle assessment is carried out in four different steps, goal and scope definition, inventory analysis, impact assessment and interpretation (UNEP, 2015).

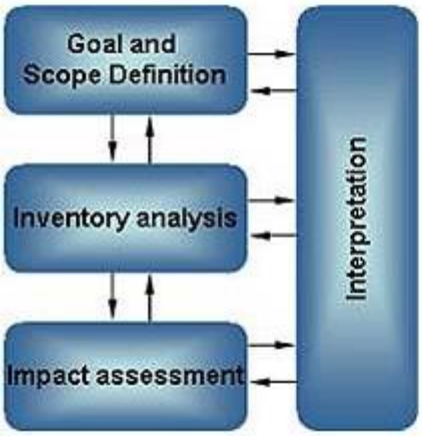

Figure 3. LCA outline with the four steps that is required for a LCA (UNEP, 2015)

A LCA starts with the definition of the goal and scope of the study, which establishes the context of the study and answers the question how and to whom the results are communicated to. This LCA step should include specific information such as functional unit, system boundaries, impact categories, assumptions and limitations, which serve as guidance for the subsequent analysis.

The goal and scope definition is followed by the inventory analysis which contains all the relevant data for the LCA study. An inventory of flows, both from and to the nature for the product system, within the system boundary is created in this step. The inventory includes inputs of water, energy and raw materials and releases of emissions to air, land and water.

Inventory analysis is followed by the impact assessment; which main purpose is to evaluate the potential environmental impacts based on the results of the inventory analysis. Significant impact categories for the product system are selected and all the inventory data are assigned to the specific impact category that it addresses.

The final step in the LCA is the interpretation, where the results are presented in a comprehensive way and evaluated regarding the opportunities to reduce material use, energy and environmental impacts of the product or service that is being studied. The interpretation looks at each step of the products life cycle in order to evaluate, identify and quantify the information from the result (Baumann and Tillman, n.d.).

3.1.1 OpenLCA

OpenLCA is a software that is used for conducting Life Cycle Assessments (LCA) and Sustainability Assessments. The software is developed by GreenDelta, an independent sustainability consulting and software company (Ciroth, 2016). OpenLCA is used to simplify all the calculations that must be made for the life cycle assessment.

3.2 Goal and Scope

The goal of this study is to conduct a LCA and a LCC to serve as a basis for Inter Terminals Sweden AB in Gothenburg, regarding their decision-making replacing their old heat exchangers with new ones. Their current heat exchangers are from the 70-80s and are not efficient enough at the moment in terms of energy efficiency, costs and thermal capacity. Therefore, this study will analyze the current heat exchangers and compare them to the alternatives on the market regarding environmental and economic aspects. The LCA will cover the environmental aspects, while the LCC focus on the economic aspects.
The goals of the two analyses are to:

- Analyze the environmental impact in terms of carbon footprint and other environmental impacts of a heat exchangers lifecycle from cradle-to-grave.
- Conduct a life cycle cost analysis on the proposed heat exchanger alternatives for Inter Terminals Sweden AB.
- Evaluate if there is a trade-off between the environmental and economic aspects for the heat exchangers.

The target audience of this study is mainly Inter Terminals Sweden AB, but it also includes the steel industry and the heat exchanger industry.
The results of this study are intended to assist Inter Terminals Sweden AB decision-making in which heat exchangers to invest in. The results can also be used for the steel industry to locate hot spots in the process concerning energy consumption and environmental impacts.

3.2.1 Functional Unit

The functional unit is used in the LCA study to describe the function of the system under study. The functional unit that will be used in this study is the *amount of energy needed to keep the oil products at the desired temperature over the life time of the heat exchanger*.

3.2.2 System Description

Figure 4 illustrates the processes that are included in the study, the material flow from cradle to grave. The boxes represent different processes and the arrows are illustrating the direction of material flow within the system. Landfill is not included in the calculation. The energy mixes included is first of all the Swedish electricity mix, but if that is not available in OpenLCA global and rest of the world is used. The chemicals, gases and other substances used during the life cycle of the heat exchangers are not included due to lack of data.

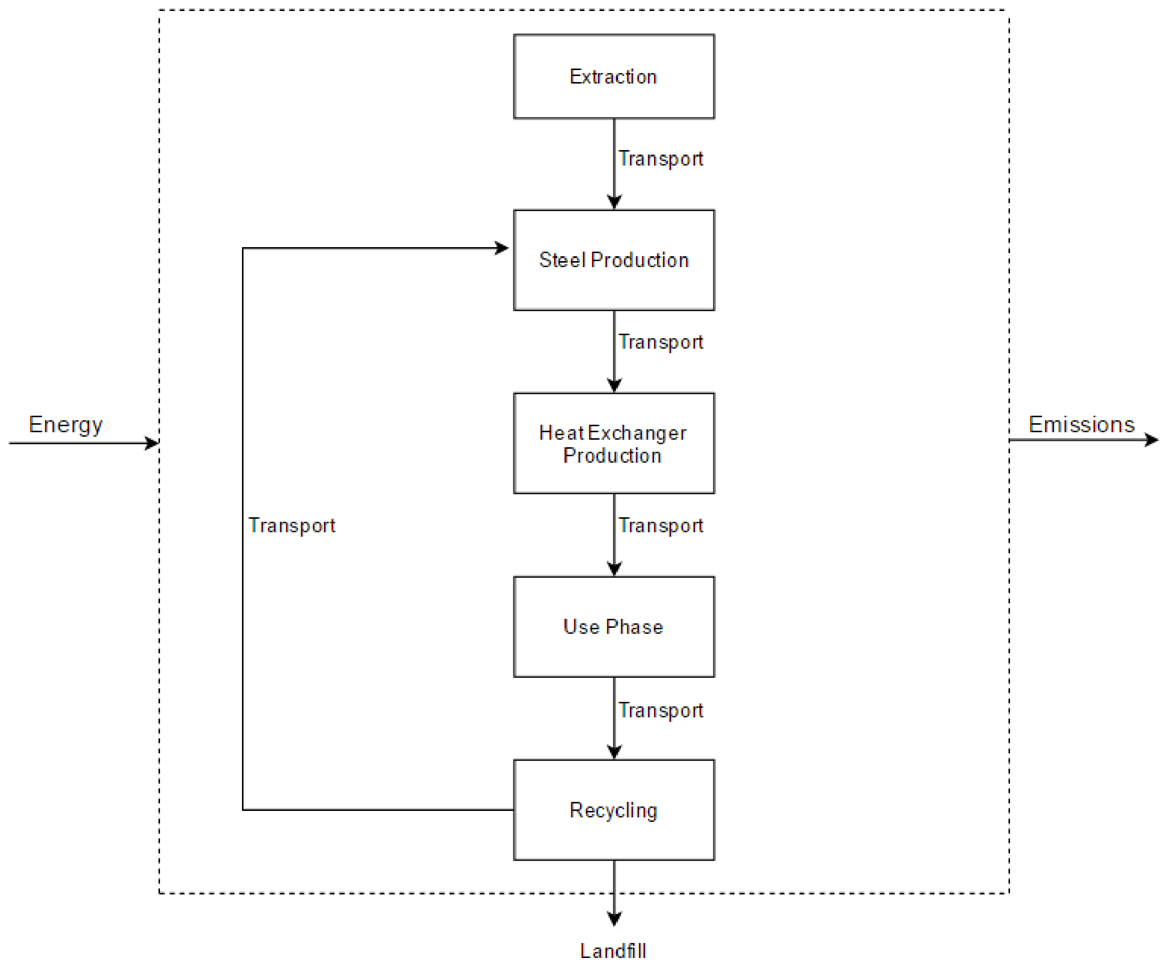

Figure 4. LCA flowchart for a heat exchanger

3.2.2.1 Extraction

The first step in a LCA is the extraction phase, which includes all the flows related to the extraction of the raw materials. This step in this assessment refers to the materials and energy needed to produce stainless steel and carbon steel which will be used in the manufacturing process for the heat exchangers later on in the system.
In the extraction phase, all the materials needed are extracted. This phase will be different depending on the material of the heat exchanger, if it's made of stainless steel or carbon steel. The transports within the extractions site are included in the inputs related to the extraction processes in OpenLCA.

3.2.2.2 Steel Production

Stainless steel and carbon steel are produced in the same way; the only difference is the material composition. Figure 5 below illustrates one route of processes and flows regarding steel production, this route is considered in this study and is the most common one.

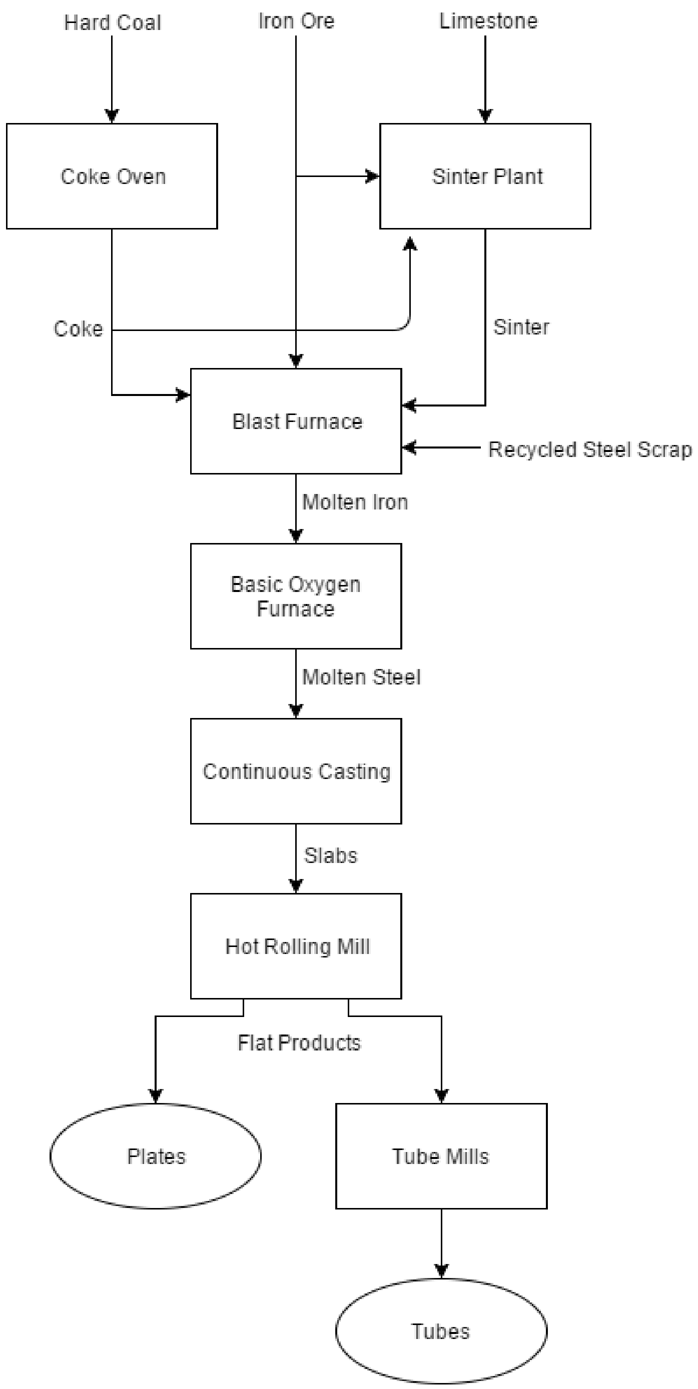

Figure 5. Flows and processes of steelmaking

Coke Making

Coke is one of the key raw ingredients, together with iron, when making steel regardless if its carbon or stainless steel. Metallurgical coal is used in the coke making process, because of its high carbon content (Gccoal.com, 2016). Hard cocking coal that is used in this LCA model forms the best quality coke. The coke is produced by heating the coking coal in absence of oxygen. The absence of oxygen prevents the coal from burning and the volatile compounds are driven off (World Coal Association, 2016). The hard solid matter that remains after the coking process is nearly pure carbon (World Coal Association, 2016). Sulfur and phosphorous are compounds that are undesirable in the coke and after the process is the amount of this compounds significant low.

Sinter Plant
The sintering process is a pre-treatment step for iron making where sinter is produced for the blast furnace step (Ispatguru, 2016). Before the actual sintering process different ferrous containing materials are mixed. These substances can be derived from various ores mainly iron (Sinter plants, 2001). This mix is blended with coke particles, limestone and heated in order to produce a semi-molten mass. This molten mass is solidified to porous sinter pieces that are used in the blast furnace process (Ispatguru, 2016) (Industrial Efficiency Technology & Measures, 2016).

Blast Furnace
Sinter and coke are introduced to the blast furnace where hot air is blasted from the bottom of the furnace. Carbon monoxide is then formed when oxygen in the air is combusted with the coke. The carbon monoxide flows up through the blast furnace and removes the oxygen in the sinter leaving iron. The high temperature in the furnace melts the iron and the liquid iron is tapped into ladles where the iron liquid is transported to the steel furnace also called basic oxygen steelmaking process (EEF, 2016).

Basic Oxygen Steelmaking
The liquid iron from the blast furnace is the main raw material in the basic oxygen steelmaking process, the rest is balanced with steel scrap. The liquid iron and the steel scrap is inserted into the basic oxygen furnace, where nearly pure oxygen at high temperature is blown in (Steel, 2016). Through oxidation unwanted elements are separated from the metal and left is molten steel that is tapped into ladles. Alloys could be added to the molten steel before its goes on to the casting machine where the steel is solidified (EEF, 2016).

Continues Casting
Molten steel from basic oxygen furnace is inserted in the continuous casting machine where the steel passes through a series of rolls and water sprays. This process ensure that steel is rolled into right shape and at the same time fully solidified. The steel is straightened and cut into the required length at the end of the process, forming so called slabs, billets and blooms. These are transported to the hot rolling mill in order to produce steel products (EEF, 2016).

Hot Rolling Mill
The slabs, billets and blooms from the steelmaking process are transported to the hot rolling mill. These semi-finished products can be classified into flat or long products based on their shape. Slabs are used to roll flat products, that are used to manufacture steel components for heat exchangers. The steps that are followed in the hot rolling mill are the use of different finishing steps depending of the desirable shape and dimension of the finished product. Examples of finished products could be plates, large and small tubes that are used in the heat exchanger manufacturing (EEF, 2016).

3.2.2.3 Heat Exchanger Production
The heat exchangers are manufactured in this process, by using either stainless steel or carbon steel and adding energy and transportation. The materials that the heat exchangers are made of depends on the type of heat exchanger and the company manufacturing it. In this assessment only two materials are considered, stainless steel and carbon steel.

3.2.2.4 Use Phase
In the use phase, the products are being used. Some products require energy during their use phase and that needs to be accounted for. Heat exchangers do not require any energy in form of electricity, but the heated water that runs through the heat exchanger is heated by various energy sources. The use phase for this assessment will be the energy that is needed to heat up the water that runs through the heat exchangers in order to keep the oil products at the desired temperature.

3.2.2.5 Recycling
Steel is the most recycled material, even more than all other materials combined, and its properties makes it possible to continually recycle the steel without any degradation in performance and quality (Steel, 2016). Collected metal scrap is transported to recycling facilities where it is checked, sorted and processed to meet the steel producer's quality requirements (Stena Recycling, 2016). Recycled metal scrap is then transported back to the steel production facility were its reintroduced in the steel production.

3.2.3 Time Coverage
The study will take into account a lifetime of 30 years for the heat exchangers, both for the LCA and the LCC. The impact assessment will cover a time of 100 years for the impact categories global warming potential and human toxicity.

3.2.4 Geographic Coverage
The geographical coverage of the assessments is set for Sweden, both for the LCA and LCC. The origin of the oil products heated in the heat exchanger are not taken into account, thus neglected in the study.

3.2.5 Impact Categories
The impact categories that this study includes and are global warming potential, human toxicity potential, acidification potential and depletion of abiotic resources. Inter Terminals is interested in the carbon footprint for the heat exchanger, therefore global warming potential is chosen as an impact category. Global warming potential considers the release of so called greenhouse gases to the atmosphere and is weighted against the effect same amount of carbon dioxide has, thus the unit kg CO_2-equivalent (Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation, 2005).

Depletion of abiotic resources is chosen as an impact category because heat exchangers mainly contains different metals. Depletion of abiotic resources focus on the extraction of scare minerals and metals and the depletion factor is determined by the extraction rate and the remaining reserves. The depletion factor for the studied mineral/metal is compared to the factor for Antimony (Sb), which is used as a reference case. The unit for abiotic resources is hence kg Sb-equivalent (Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation, 2005).

Human toxicity is chosen to evaluate how emissions from substances used throughout the lifecycle impacts human health. The human toxicity potential depends on the fate, exposure and effects of the toxic substance for an infinite time horizon and is expressed by the reference unit, kg 1,4-dichlorobenzene (DCB) -equivalent (Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation, 2005). The reason to include this impact category is to indicate that some products are harmful to humans even though the product itself has no danger to humans directly during its use phase. However, the manufacturing of the products could include processes which are harmful to humans.

Throughout a lifecycle for a heat exchanger a lot of energy and substances are used, which in different ways contribute to acidification. Processes such as road transportation and the energy used are examples of processes that contributes to acidification (SO_x, NO_x and NH_3). Therefore, is this impact category analyzed in this assessment. This impact category uses kg SO_2-equivalent as reference unit (Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation, 2005).

3.3 Life Cycle Cost (LCC)

Life cycle costing (LCC) is a tool that concerns all the costs that arise from an investing decision and can be used to evaluate complete processes, systems and objects throughout its life cycle. LCC is used to assist and improve the decision-making process. LCC is defined as the present value of the total cost of an asset over its operating life, including initial capital cost, installation costs, operating costs, maintenance costs and the cost or benefit of the eventual disposal at the end of its life. That is the total cost that the project will impose throughout the whole of its life (Constanza et.al P 36-37, 2013).

In this assessment LCC will be used to calculate the total costs related to the heat exchangers that are being studied and compared. Since Inter Terminals are also interested in the costs, LCC seemed like a good method to use for this assessment. Inter Terminals wants to become more environmentally friendly, but at the same time increase the economic effectiveness. The LCC will take into account all the costs related to each heat exchanger and compare them to see which alternative is best regarding the economic aspects. Together with the LCA, it will be a guideline for Inter Terminals decision making in the future for the investment of heat exchangers.

The study will include the capital cost, installation cost, maintenance, operating cost and recycling profit of the three heat exchangers. The operating cost for the current heat exchangers at Inter Terminals will also be included to enable comparison of possible operation cost savings if investing in new heat exchangers. This LCC is conducted as a cradle-to-grave. The time coverage for this LCC is 30 years, its estimated in consultation with the three companies and it´s said that the heat exchangers would function well at least for 30 years. In this study Inter Terminals are interested in four heat exchangers, three for their caverns and one for their group of four tanks. This LCC will just consider costs regarding three heat exchangers, thus the heat exchanger for the tanks will be excluded. The heat exchangers proposed by the companies are designed for the caverns volume of approximately 50 000 m^3. The companies designing the heat exchanger did not consider that the volume of the tanks approximately is a fifth of the caverns size. This would have an impact on the size of the heat exchanger for the tanks, thus direct impact on all of the costs. The tanks at Inter Terminals are not using a heat exchanger right now, as said they are using tubes, with hot water, in the bottom of the tanks to heat the oil. The heat exchanger planned for the tanks is intended to only be used to boost the heating in cases of big temperature drops or used to heat the oil in order to simplify emptying of the tanks. Because they do not use a heat exchanger for the tanks today it is difficult to compare the energy used today and the energy consumption after a heat exchanger is installed. It becomes difficult to estimate how many hours per year this heat exchanger would be used, and it is not correctly dimensioned. This would not give a good approximated value of the energy consumption, so it would not make a relevant analysis of the costs for this exchanger and thus not relevant to the LCC analysis. Because of that the fourth heat exchanger is excluded in this cost analysis.

3.4 Sensitivity Analysis

The sensitivity analysis method has been applied to determine the difference in environmental impact using different recycling rates (60, 80 and 100 %) of steel scrap to decrease the extraction and use of virgin metals.

The time coverage for the life cycle assessment is 30 years for the heat exchangers, meaning that the use phase is most likely the primary contributor regarding the environmental impact. Therefore, a sensitivity analysis is conducted on the energy sources for the use phase. This is performed by increasing the amount of energy, in percentage (20 and 40%), for each energy sources separately, which decreases the other energy sources. This was done in order to evaluate how the environmental impacts were affected by the energy sources during the use phase.

A sensitivity analysis was conducted for the life cycle cost regarding changes of the energy price. This will affect the payback time for the analyzed heat exchangers. This is an essential analyze, because the energy price would most likely to change over the next 30 years which is the life cycle of the heat exchangers. This sensitivity analysis is conducted by using the calculated energy price for 2016 as a starting point and then alter the energy price by increasing and decreasing it with 10, 25 and 50%.

3.5 Data Sources

Ecoinvent is one of the most used LCA-databases worldwide and is regularly updated. Ecoinvent is a transparent and consistent life cycle inventory database that provides process data for thousands of products, in order to simplify decision-making based on environmental impact (GmbH, 2016). The inventory data are derived from international industrial life cycles and contains for instance data regarding energy supply, resource extraction, material supply, chemicals, metals, waste management services and transports services (Openlca, 2016). Except Ecoinvent, other data sources were used such as Chalmers database and the companies involved in the assessment (Inter Terminals, Göteborg Energi, Stena Recycling, Alfa Laval AB, ViFlow AB and GB Tank AB).

3.6 Delimitations

Every flow related to the whole process of the LCA is based on Swedish values such as energy and extraction locations, but if it’s not available in ecoinvent then global and rest of the world flows are used for the calculations. Also, the technical details about the heat exchangers are not included in this process, only the materials they are made of. Due to lack of data the chemicals and other substances used in the production of the heat exchangers are not included in this assessment.

4. Inventory Analysis

Three companies (Alfa Lava AB, GB Tank AB and ViFlow AB) were contacted and willing to help with the thermal design and dimensioning of the heat exchangers, in order to suggest one to fit Inter Terminals specifications and facility. In table 1 below the specifications from Inter Terminals are stated, which requirements the proposed heat exchangers had to manage.

Table 1. Technical requirements from Inter Terminals.

Inlet temp. water	90°C
Outlet temp. water	>76°C
Inlet temp. oil	46-65°C
Flow (water)	30 m^3/h
Flow (oil)	350 m^3/h
Type of oil	ISO VG equivalent
Density (oil)	0,9-0,97 kg/m^3
Viscosity (oil) at 50°C	800 Cst
Specific heat capacity (oil)	~1,967 KJ/kg*°C
Volume (caverns)	48 500 -59 355 m^3
Volume (tanks)	9 000 – 11 800 m^3
Dimensional limits	>10m

The heat exchangers are expected to be designed so they manage to heat a volume of 50 000 m^3 oil 1 degree Celsius per day. It is not required that the total volume of 50 000 m^3 oil should pass through the heat exchanger in one day. The oil that is passed through the heat exchanger is heated more than one degree Celsius, then pumped back down into the cavern heating the surrounding oil which leads to an overall heating of one degree Celsius for 50 000 m^3.

This chapter gives an explanation to all processes included in the life cycle assessment and the three heat exchangers that were obtained are analyzed, compared and presented in this chapter. They have been divided and named heat exchanger 1, 2 & 3.

4.1 Heat Exchanger 1

The proposed heat exchanger that Alfa Laval Lund AB provided is a plate heat exchanger of the model T35-PFM and will be referred to as heat exchanger 1 in this assessment. It is mainly made of stainless steel; therefore, the assumption has been made that the whole heat exchanger consists of stainless steel. Other parts of the heat exchanger, like gaskets, that are not made of stainless steel accounts for a very small mass of the heat exchanger. Table 2, gives a short summary the heat exchanger.

Table 2. Heat exchanger 1 (Alfa Laval).

Name:	**Heat Exchanger 1**
Material:	Stainless Steel (304)
Weight:	8810 kg

4.1.1 Extraction

The first process in the life cycle assessment is the extraction. The extraction flows for heat exchanger 1 are from Rest of the World (RoW) and Global (GLO) due to lack of data for Sweden. Stainless steel is mainly made of iron with small percentages of other elements such as coal, manganese, chromium, nickel, ferrosilicon, phosphor, sulfur and the rest is balanced with iron (Table 3). There are many different types of alloys for stainless steel, the one used in this heat exchanger is called alloy 304. The extraction of the materials is assumed to occur in the Swedish city Kiruna in northern Sweden. The amount of energy required and the transports within the extraction site are included in the flows in OpenLCA. Sulfur and phosphor are not included in the calculations in OpenLCA due to lack of data and the small amounts, therefore they have been excluded.

Table 3. The composition of stainless steel (304) in percentages (Rjsales, 2016).

C	Cr	Mn	Ni	P	S	Si
Max		Max		Max	Max	Max
0.035	18.0-20.0	2.0	8.0-13.0	0.040	0.030	0.75

4.1.2 Stainless Steel Production

The second process in the LCA is the stainless steel production. The process to manufacture stainless steel is complicated and requires multiple steps, but the total amount of energy needed for these steps are 52,4 MJ/kg stainless steel. This amount is actually for steel in general and not specifically for stainless steel, since the procedure is the same. Therefore, the assumption has been made that the amount of energy is the same for stainless steel as it is for steel. The energy is coming from the Swedish electricity mix which is available in ecoinvent. The coke making process, which is a part of the process for stainless steel production, requires 1,6 kg hard coal and 5 MJ to produce 1kg of coke. This amount of energy accounts for 10% of the energy demand in the blast furnace and basic oxygen furnace steps which is a part of the stainless steel production (Industrial Efficiency Technology & Measures, 2016). Beside these steps, there is also a hot rolling process which require 2,4 MJ/kg (Industrial Efficiency Technology & Measures, 2016). This means that the energy demand for the whole stainless steel production is 52,4 MJ/kg, while 2,4 MJ/kg is from the hot rolling and 50 MJ/kg from the other process for stainless steel production. It was assumed that only the biggest steps in the production was included, which is; coke making, hot rolling, blast furnace and basic oxygen furnace due to lack of data for the other steps. The iron that is needed to produce stainless steel is sintered iron (Ispatguru, 2016).

4.1.3 Heat Exchanger Manufacturing

As seen in table 2, the heat exchanger weights 8810 kg, and is assumed to be made of stainless steel only. The heat exchanger is manufactured by Alfa Laval at their manufacturing site which is located in Lund. The energy used in their facility is coming from three different sources; electricity, heat district and natural gas. The natural gas and heat district is from RoW, since no data for Sweden was available in ecoinvent. The energy amounts were obtained from Alfa Laval, but it is not precise since they do not have the exact amount of energy for each heat exchanger manufactured. Therefore, the amounts are generic and have been obtained by looking at their annual energy production divided by the amount of steel treated at their manufacturing site. These numbers were the best data that could be achieved, even if it’s not only stainless steel they are working with since there were no specific data for each heat exchanger regarding the energy consumptions (Lundgren, 2016). The lifetime of the heat exchanger is assumed to be 30 years.

4.1.4 Use Phase

Heat exchangers are not electronical devices, meaning that they do not consume any kind of energy or emit emissions during the use phase. However, Inter Terminals are getting hot water from Göteborg Energi to heat up the water in their internal water system to heat the oil products via the heat exchanger. Göteborg Energi uses different kind of energy sources to heat the water to a certain temperature which Inter Terminals then use. By knowing the flow of the hot water, the amount of energy needed to maintain the oil products at a certain temperature can be calculated. The majority of the energy is coming from burning pellets, but also from natural gas and heating fuel. The data were accessed from Göteborg Energi annual production for Skarvik, which Inter Terminal is a part of in Port of Gothenburg. Due to lack of data in ecoinvent, RoW energy mix was used for the calculations in OpenLCA (Lilienberg, 2014).

Göteborg Energi Energy

Göteborg Energi uses three different types of energy sources to heat the water for Inter Terminals; pellets, natural gas and heating fuel (table 4).

Table 4. Energy sources and the energy amount for Göteborg Energi without losses (Lilienberg, 2014).

Energy Source	Amount of Energy	Percentage
E01 (heating fuel)	398 MWh = 1432800 MJ	1,5 %
Natural Gas	8190 MWh = 2948400 MJ	31 %
Pellets	17694 MWh = 63698400 MJ	67,5 %
Total	26282 MWh = 94615200 MJ	100 %

Table 4 describes where Göteborg Energi is getting their energy from and the amounts for each source. The numbers are without losses which occurs later on when the energy is used and it is a 16% loss. The same percentage will be used for the losses for Inter Terminals facility, since the transportation way is similar to Göteborg Energis (table 5). This data is only accountable for Skarvik in Gothenburg Port.

Inter Terminals Energy Demand Calculations

These calculations accounts for the use phase for all the heat exchangers, since the amount of energy needed is the same.

- Göteborg Energi heat up Inter Terminals water from 75 to 90 degree Celsius.
- The water flow rate in the heat exchangers are 30 m^3/h.
- The new heat exchanger has a capacity to heat the oil in the tanks and caverns by 1 degree Celsius per day, while the old ones could only heat 0,1 degree Celsius per day. Therefore, the new heat exchangers require only 10% of the time to heat up the oil products compared to the old ones.
- The current heat exchangers are estimated to operate 30% of the year which is 2628 h/year.

- The energy loss has been estimated to be 16% from pump, valves, pipes etc, which is the same value for Götebrg Energi when they produce the energy.

Heating water from 75-90 degree requires *504 kWh/h = 1814,4 MJ/h*
This is calculated by a calculator on the website Lenntech (Lenntech, 2016).

Operating time for the new heat exchangers: *10% * 2628 h/year = 262,8 h/year*

Amount of energy required to maintain the oil products at the desired temperature without energy losses: 262,8 h/year * 1814,4 MJ/h = 476 824 MJ/year

Taking the energy losses into account: *476 824 MJ/year * 1,16 = 553 116 MJ/year/heat exchanger*

Table 5. Energy required distributed over different energy sources based on data from Göteborg Energi (data for use of one new heat exchanger and one year with 16% energy loss) (Lilienberg, 2014).

Energy Source	Amount of Energy	Percentage
E01 (heating fuel)	8297 MJ	1,5 %
Natural Gas	171466 MJ	31 %
Pellets	373353 MJ	67,5 %
Total	553116 MJ	100 %

For the heat exchanger lifetime (30 years): *553 116 MJ/year * 30 years = 165 934 80 MJ*

4.1.5 Recycling

For the recycling, three different recycling rates were calculated in OpenLCA to see how it affects the result. The recycling rates were 60%, 80% and 100% and it goes back into the steel production. After the lifetime of the heat exchanger, the materials are collected, sorted and processed to be used again. These steps require transport and energy. In ecoinvent, there was a process but it had to be modified to make it suitable for this assessment. All the energy flows related to the process were added together to see how much energy is needed to collect and sort one kg of stainless steel. The Swedish energy mix was used for this. The reason for including a recycling process is that in reality, steel in general has a high recycling rate which is reused in every equipment. The rest that is not recycled has been assumed to go to landfill.

4.1.6 Transport

The metals used to produce stainless steel are assumed to be extracted in LKAB:s mine in Kiruna in northern Sweden, because it is one of the largest mining operations in the world. The extracted metals are assumed to be transported to Outokumpus facility in Avesta. Outokumpu is a leading company in stainless steel production in Sweden, therefore it is assumed that the stainless steel for the heat exchanger is produced by them (Jernkontoret.se, 2015). The transport distance from Kiruna to Avesta is 1 160 km.
The stainless steel is assumed to be transported directly from Avesta to Alfa Laval in Lund where the heat exchangers are manufactured, transports to and from various steel wholesalers are neglected. The stainless steel is transported 630 km from Avesta to Lund. The heat exchanger is then transported 262 km from Alfa Laval to Inter Terminals Sweden AB in Gothenburg.

The heat exchanger is dismantled after its lifetime and is assumed to be transported to Stena Recycling in Gothenburg, this transportation is neglected because of the short distance. Metal scrap from the heat exchanger are sorted and processed at Stena Recycling before it is transported back to the steel production, it is assumed that all the metal scrap goes to Outokumpus steel production in Avesta where it is recycled. The distance between Gothenburg and Avesta is 419 km. All transports are assumed to be carried out with EURO 4 lorries (GLO). The transportations can be seen in table 6.

Table 6. Transportation route for heat exchanger 1.

Transport - Heat Exchanger 1	
Transport Path (EURO 4 Lorry)	**Distance (km)**
Kiruna-Avesta	1160
Avesta-Lund	630
Lund-Gothenburg	262
Gothenburg-Avesta	419
Total	2471

4.2 Heat Exchanger 2 & 3

The other heat exchangers proposed were from two other companies, ViFlow and GB Tank. They are both shell and tube heat exchangers and are made of the same material but has different weights. In this assessment ViFlow´s heat exchanger is referred to as heat exchanger 2 and GB Tank´s heat exchanger 3. Below in table 7 and 8, a brief summary of these heat exchangers can be seen. Both are made of carbon steel, and its assumed that the whole heat exchangers are made of it. The weight for heat exchanger 2 is for two heat exchangers, since ViFlow recommended to use two heat exchangers of the same model in series in order to maintain the oil products at the desired temperature.

Table 7. Heat exchanger 2 (ViFlow AB).

Name:	**Heat Exchanger 2**
Material:	Carbon Steel
Weight:	6400 kg

Table 8. Heat exchanger 3 (GB Tank AB).

Name:	**Heat Exchanger 3**
Material:	Carbon Steel
Weight:	22301,4 kg

4.2.1 Extraction

The modelling for these heat exchanger 2 & 3 were exactly the same in OpenLCA as for heat exchanger 1, except for some different values regarding the extraction. Since these heat exchangers are made of carbon steel, the composition is different from stainless steel, meaning that the extraction phase is different. The composition of carbon steel can be seen in Table 9. As for the stainless steel heat exchanger, phosphorous and sulfur were not included in the extraction phase in OpenLCA due to lack of data.

Table 9. The composition of carbon steel (Ibrahim, 2010)

C	Si	Mn	Cr	Mo	Ni	P	S	Cu	Fe
0,40	0,31	1,08	0,14	0,005	0,104	0,012	0,043	0,169	Balanced

4.2.2 Carbon Steel Production

The production of carbon steel is the same as for stainless steel production since the procedure is identical. Therefore, the amount of energy needed to produce carbon steel has been assumed to be the same as for stainless steel which is 52,4 MJ/kg.

4.2.3 Heat Exchanger Manufacturing

The manufacturing of the carbon steel heat exchangers had different energy values than the one made of stainless steel. It is still assumed that the whole heat exchangers are made of carbon steel, but the energy values required are different. For heat exchanger 1 (stainless steel), Alfa Laval provided data regarding their annual energy consumption and the amount of material treated which made it easy to calculate and estimate an approximate value of the energy required to manufacture one heat exchanger. For heat exchanger 2 and 3, no such data were available, therefore some assumptions were made to calculate the energy needed for the manufacturing of these heat exchangers. According to ViFlow, the energy needed to manufacture a heat exchanger is a small percentage of the amount of energy needed for the carbon steel production. To verify this statement, heat exchanger 1 was analyzed. The energy for manufacturing the heat exchanger 1 was only 1,4% of the energy needed for the stainless steel production and since that amount also accounts for the carbon steel, the statement seemed to be an appropriate assumption (Lindberg, 2016). This value was assumed for GB Tanks manufacture process as well. To calculate the energy required to manufacture heat exchanger 2 and 3, the same amount (1,4%) was used. This is also an assumption since it is not the exact amount of energy needed for the manufacturing of the heat exchanger in reality.

4.2.4 Use Phase

The use phase is exactly the same as for heat exchanger 1, since the energy needed to maintain the oil products at the desired temperature is the same for all three heat exchangers. To see the calculations, see chapter 4.1.4.

4.2.5 Recycling

The recycling for heat exchanger 2 and 3 is also the same as for heat exchanger 1.
The metals goes back into the carbon steel production instead of the stainless steel production. The recycling rates are the same; 60%, 80% and 100%.

4.2.6 Transport

The metals used to produce carbon steel are assumed to be extracted in LKAB:s mine in Kiruna in northern Sweden. The extracted metals are then assumed to be transported to SSABs facility in Luleå, where carbon steel is produced. The distance between Kiruna and Luleå is 343 km. Carbon steel is transported from Luleå to ViFlow in Örnsköldsvik, a distance of 375 km, where the heat exchanger manufacturing takes place. Transports of carbon steel to and from various steel wholesalers ViFlow are neglected. The heat exchanger is transported 873 km from ViFlow to Inter Terminals Sweden AB in Gothenburg.

It is assumed that the heat exchanger after its lifetime are transported to Stena Recycling in Gothenburg, this transport is neglected because of the short distance. All of the sorted and processed metal scrap at Stena Recycling are assumed to be recycled and returned to SSABs steel production in Luleå, a distance of 1 247 km. All transports are assumed to be carried out with EURO 4 lorries (GLO). The transportations can be seen in table 10.

Table 10. Transportation route for heat exchanger 2.

Transport - Heat Exchanger 2	
Transport Path (EURO 4 Lorry)	**Distance (km)**
Kiruna-Luleå	343
Luleå-Örnsköldsvik	375
Örnsköldsvik-Gothenburg	873
Gothenburg-Luleå	1247
Total	2838

The extraction of the materials for heat exchanger 3 also takes place in LKAB:s mine in Kiruna. The extracted metals are assumed to be transported 343 km to SSAB in Luleå, where carbon steel is produced. Carbon steel is transported from Luleå to GB Tank AB in Falun, a distance of 820 km, where the heat exchanger manufacturing takes place. Transports to and from various steel wholesalers are neglected for heat exchanger 3 as well. The heat exchanger is transported 461 km from GB Tank AB to Inter Terminals Sweden AB in Gothenburg.
The heat exchangers are assumed to be transported to Stena Recycling in Gothenburg, this transport is neglected because of the short distance. All of the sorted and processed metal scrap at Stena Recycling are assumed to be recycled and returned to SSABs steel production in Luleå, a distance of 1 247 km. All transports are assumed to be carried out with EURO 4 lorries (GLO). The transportations can be seen in table 11.

Table 11. Transportation route for heat exchanger 3.

Transport - Heat Exchanger 3	
Transport Path (EURO 4 Lorry)	**Distance (km)**
Kiruna-Luleå	343
Luleå-Falun	820
Falun-Gothenburg	461
Gothenburg-Luleå	1247
Total	2871

4.3 Summary of the Heat Exchangers

A summary of the heat exchangers analyzed in this assessment is presented in the table below (table 12). It shows the type of material, weight of the heat exchangers and the energy requirement from each step in the production process. The weight of the heat exchangers alters for the different alternatives depending on the design made by the manufactures. The extraction phase was constructed in OpenLCA and includes several different energy flows which is time consuming to sum up, therefore only the composition of the materials is included. As mentioned earlier, the composition for stainless steel and carbon steel is different. For stainless steel the amount of chromium and nickel is higher than for carbon steel, which can impact the result. The extraction phase is also dependent of the recycling rates, the higher the recycling rate the less energy is needed from the extraction phase. The energy needed for all of the heat exchangers is the same regarding the steel production. This is due to that the procedure is the same for both stainless steel and carbon steel. The different energy values for the heat exchanger production is due to the data collected. With help from Alfa Laval the energy required could be estimated. For heat exchanger 2 and 3, assumptions were made which are explained in detail in section 4.2.3. The energy required for the recycling process is the same for all of the heat exchangers and was obtained through ecoinvent. The difference in the transport is due to different locations of companies.

Table 12. Summary of energy flows, material flows and transportation for the analyzed heat exchangers.

	Heat Exchanger 1 (Alfa Laval)	**Heat Exchanger 2 (ViFlow)**	**Heat Exchanger 3 (GB Tank)**
Material:	Stainless Steel	Carbon Steel	Carbon Steel
Weight:	8810 kg	6400 kg	22301,4 kg
Extraction:	C (0,035%), Cr (20%), Mn (2%), Ni (13%), Si (0,75%), Fe (64,22%)	C (0,4%), Si (0,31%), Mn (1,08), Cr (0,14%), Mo (0,005%),Ni (0,104%), Cu (0,169%), Fe (97,79%)	C (0,4%), Si (0,31%), Mn (1,08), Cr (0,14%), Mo (0,005%),Ni (0,104%), Cu (0,169%), Fe (97,79%)
Steel Production:	52,4 MJ/kg	52,4 MJ/kg	52,4 MJ/kg
Heat Exchanger Production:	0,8028 MJ/kg	0,7336 MJ/kg	0,7336 MJ/kg
Use Phase:	553116 MJ/year	553116 MJ/year	553116 MJ/year
Recycling:	0,144 MJ/kg	0,144 MJ/kg	0,144 MJ/kg
Transport:	2471 km	2838 km	2871 km

4.4 Life Cycle Cost

4.4.1 Capital Cost

The capital costs for the heat exchangers were obtained from the representatively company. Costs are given for one heat exchanger and then multiplied with the number of heat exchangers needed. Alfa Laval and GB Tank proposed one heat exchanger per cavern while ViFlow proposed two heat exchangers in series for each cavern.

4.4.2 Installation Cost

The installation cost for heat exchanger 1 was estimated by ViFlow. For Alfa Laval and GB Tank no costs could be obtained, therefore the installation costs for heat exchanger 2 & 3 were assumed to be the same as ViFlow´s. This assumption was made in consideration with relevant staff at Inter Terminals. Costs for building foundations and operation houses for the heat exchangers are not included in the installation cost, only the actual installation connecting the pipes are accounted for. The capital and installation costs are a onetime cost and is not dependent on the heat exchangers lifetime. These costs are illustrated below in table 13, the number of heat exchangers needed is also given. HX in the tables is an abbreviation of heat exchanger.

Table 13. Capital and installation costs for the different heat exchangers and number of heat exchangers needed.

Capitaland installationcost			
	Alfa Laval	**ViFlow**	**GB Tank**
Capital cost/HX (SEK)	596 082	395 000	927 000
Installation cost/HX (SEK)	40 000	40 000	40 000
Number of HX	3	6	3
Totalcapital cost (SEK)	1 788 246	2 370 000	2 781 000
Total installation cost (SEK)	120 000	120 000	120 000

The installation cost for ViFlow´s alternative of using two heat exchangers in a series is assumed not to have an effect on the installation price, this after consultation with staff at Inter Terminals. It has been assumed that there would be approximately the same costs for installing one heat exchanger to the cavern as for installing to in a series.

4.4.3 Operating Cost

The operation costs depend on the energy use and the cost of the energy needed to heat the oil. The energy requirement for the new and old heat exchangers are calculated and estimated. The calculation steps and assumptions are shown in Appendix C. The energy cost depends on how much energy is used and the return temperature of the water to Göteborg Energi. The energy needed for the pumps to transport the oil from the caverns to the heat exchangers and back again are neglected. Only the energy used to heat up the oil to the desired temperature is taken into account. The operating cost for both the current heat exchangers at Inter Terminals and the proposed ones are calculated to compare and estimate the cost savings during the use phase and payback time.

4.4.4 Energy Price

The energy price model from Göteborgs Energi is shown below in equation 1.

$Price = Energy\ price - Effectivty\ bonus$ (Prismodell-Skarvik, 2015)
Eq. (1)

According to the supply agreement between Inter Terminals and Göteborg Energi for delivering hot water, the tariff should be adjusted annually. Equation 2 is used to calculate the energy price for coming years. In this study the energy price (SEK/MWh) for year 2016 are calculated and this price is used during the lifetime of the heat exchangers. This energy price will give a fairly good approximation of how the operating cost would look like during the heat exchangers lifetime. The energy price is adjusted by consisting of 40% district heating (FV), 40% pellets index (PI) and 20% consumption price index (KPI).

$$Energy\ price\ 2016 = EP2015\left(0{,}4 * \frac{FV_1}{FV_{bas}} + 0{,}4 * \frac{PI_1}{PI_{bas}} + 0{,}2 * \frac{KPI_1}{KPI_{bas}}\right) \quad \text{Eq. (2)}$$

(Prismodell-Skarvik, 2015)

- EP_{2015} = Energy Price (SEK/MWh) for 2015 = 900 SEK/MWh
- FV_1 = Price per MWh of district heating for the current year from Göteborg Energi for the reference house in the rapport Nils Holgersson investigation (Nilsholgersson.nu, 2016) = 782 SEK/MWh
- FV_{bas} = As above with 2014 as base year = 765 SEK/MWh

- PI_1 = Pellets price index bulk (min. 15-ton delivery), annual average calculated from monthly index according to Pelletsförbundet for the year before the current year = 102,0
- PI_{bas} = As above with base year 2013 = 102,0
- KPI_1 = Consumption price index according to Statistiska Centralbyrån (Statistiska Centralbyrån, 2016), the average value of the year before the current year = 313,49
- KPI_{bas} = As above with base year 2013 = 314,06

Insertion of values in equation 2 gives an energy price of 907,7 SEK/MWh for 2016.

4.4.5 Effectivity Bonus

The effectivity bonus depends on the return temperature of the water to Göteborg Energi. The return temperature is on the primary side of the water-water heat exchanger at point B in figure 8.

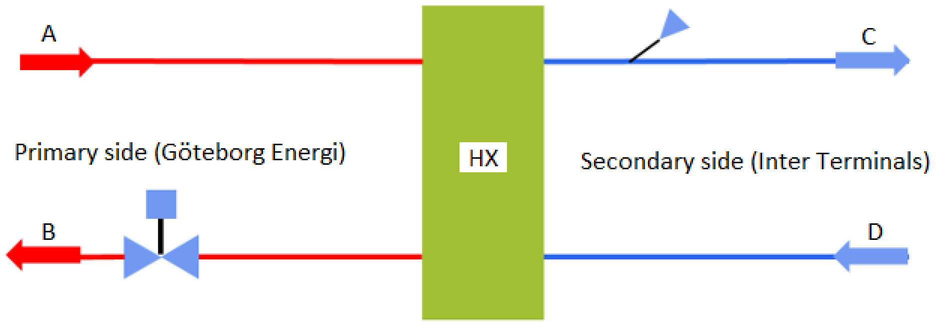

Figure 6. How Göteborg Energi heat the water inside Inter Terminals internal water system.

The new heat exchangers are designed to give an outlet temperature of approximately 75°C, if the inlet temperature of the water is 90 °C and the water flow is 30 m^3/h. After passing through the heat exchanger the water is pumped back to the water-water heat exchanger (point D, in figure 8), where Inter Terminals internal water system is heated by Göteborg Energis hot water. The return temperature (point B) has to be calculated in order to obtain the correct effectivity bonus. The return temperature is weighted against the energy consumption. The energy consumption and return temperature is measured per hour. For the monthly hours, the energy consumption is multiplied by the return temperature, the sum of these values is divided by the month's total energy consumption, giving the energy-weighted return temperature. The data needed to calculate the return temperature were however impossible to obtain, since the data for the current heat exchangers are not valid or possible to relate to the new heat exchangers. In consultation with Inter Terminals the return temperature at the primary side (point B) was assumed to be the same as the return temperature at the secondary side (point D), when looking for a whole month.

The return temperature for the current heat exchangers is needed in order to be able to do a comparison between the operation costs and determine possible cost savings when investing in new heat exchangers. As mentioned earlier, the current heat exchangers are old and do not function well, therefore Inter Terminals is currently running the heat exchanger with an average water flow of 10 m^3/h. The reason for this is to let the heated water stay as long as possible in the heat exchangers and get a higher heat transfer between the water and oil. To be able to compare the operating costs the return temperature of the water for 10 m^3/h must be converted to a return temperature for 30 m^3/h for the current heat exchangers. The inlet and outlet temperature of the water with a flow rate of 10 m^3/h is 94 °C and 75 °C, resulting in a delta temperature of 19 °C. New delta temperature for a flow rate of 30 m^3/h can be calculated with equation 3 and 4 below.

$$\frac{10m3/h}{30m3/h} = 0{,}33 = 33\% \qquad \text{Eq. (3)}$$

$$\Delta T * 0{,}33 = 19 * 0{,}33 = 6{,}33°C \qquad \text{Eq. (4)}$$

The new delta temperature for the current heat exchangers with a flow rate of 30 m^3/h is 6,33 °C, resulting in an outlet temperature of 87,66 °C. As for the new heat exchangers the cost is determined by the return temperature at the primary side (point B). Calculations for the new return temperature are explained in Appendix B.

The price (SEK/MWh) could be calculated using the price model, equation 1 and the energy prices using the current and new heat exchangers are highlighted and shown in table 14. The effectivity bonus for each return temperature can be seen in table 14.

Table 14. Energy prices depending on the return temperature and the effectivity bonus.

Energy price (SEK/MWh)	**Return temp. (°C)**	**Effectivity bonus (SEK/MWh)**
907,7	87	0
877,7	86-85	30
847,7	84-83	60
817,7	82-81	90
787,7	80-79	120
777,7	78	130
767,7	77	140
757,7	76	150
747,7	75	160
737,7	74	170
727,7	73	180
717,7	72	190
707,7	71	200
697,7	70	210
687,7	69	220
677,7	68	230
667,7	67	240

When the energy price is known the operating cost could be calculated, by multiplying the energy price with the energy required per heat exchanger and year. The operating cost is calculated for the required energy with losses (16 %, pipes, pumps etc.) and also without losses to calculate a mean value for the operating cost. This is because of the operating cost would probably lay somewhere in the interval between the required energy with and without losses, therefore is a mean value used in order to get a more accurate value on the operating cost during the lifetime of the heat exchangers. The required energy for the heat exchangers with and without energy loss is shown below in table 15.

Table 15. Required energy for new and current heat exchangers with and without energy loss through the system.

Required energy/HX (MWh/yr)		
	New HX	**Current HX**
With losses (16% pipes, pumps, HX etc.)	153,64	649,33
Without losses	132,45	559,76

The mean operating cost value is calculated for both the new and the current heat exchangers in order to determine the cost savings regarding operating cost when investing in new heat exchangers. This is shown in table 16 below.

Table 16. Operating cost for new and current HX and cost savings.

Operating cost			
Operating cost (SEK)	**New HX**	**Current HX**	**Cost saving**
Operating cost/year/HX	106 955	548 745	441 791
Total operating cost/year	320 864	1 646 236	1 325 372
Total operating cost 30 years	9 625 927	49 387 095	39 761 168

4.4.5 Maintenance Cost

The maintenance costs include cost of cleaning plates/tubes, changing gaskets and the labor itself. The cost of traveling and accommodation for the workers is also included in the maintenance price. It is assumed that the company that manufactures the heat exchangers also maintains them. The maintenance costs for each heat exchanger are approximate numbers estimated in consultation with GB Tank, ViFlow and Alfa Laval. The maintenance costs may differ due to the level of the fouling. The heat exchangers are assumed to be running 30% of the year, therefore down-time costs are neglected. With proper maintenance the plates/tubes would hold and function properly for at least 30 years and the costs for changing plates or tubes are neglected. Maintenance work are assumed to be carried out once a year per heat exchanger in order to decrease the risk of fouling and thus keep a good heat transfer between the fluids. Table 17 shows the assumed maintenance cost per heat exchanger for each company.

Table 17. Maintenance cost for the three heat exchanger alternatives.

Maintenance cost			
	Alfa Laval	**ViFlow**	**GB Tank**
Maintenance cost/year/HX (SEK)	59 608	5 000	8 750
Total maintenance cost of HXs for 30 years (SEK)	5 364 738	900 000	787 500

The maintenance cost for heat exchanger 1 is much higher than for heat exchanger 2 & 3. Heat exchanger 1 is a plate heat exchanger and they are usually cheaper regarding maintenance costs compared to shell and tube heat exchangers. The maintenance costs for the plate heat exchanger in this case is more expensive than the shell and tube, due to plate heat exchangers are not as suited as shell and tube heat exchangers for fluids like the oil products Inter Terminals is handling. Heat exchanger 2 and 3 are as mentioned tubular heat exchangers and the maintenance costs are basically the same for them. Heat exchanger 2 has a little lower cost probably due to extendable tube package.

4.4.6 Recycling

The heat exchangers are recycled after its lifetime and it is assumed that Stena Recycling AB takes care of the recycling. After discussion with Stena Recycling, an estimated price on the carbon steel and stainless steel were obtained (table 18). The profit of recycling the heat exchangers is also displayed in the same table for different recycling rates.

Table 18. Price of carbon and stainless steel per ton and the profit of recycling the heat exchangers for different recycling rates.

Recycling			
	Alfa Laval	**ViFlow**	**GB Tank**
Carbon steel (SEK/ton)	-	500	500
Stainless steel (SEK/ton)	6000	-	-
Weight (ton/HX)	8,8	6,4	22,3
Profit 60% recycling (SEK/HX)	31 716	1 920	6 690
Profit 80% recycling (SEK/HX)	42 288	2 560	8 921
Profit 100% recycling (SEK/HX)	52 860	3 200	11 151
Total profit 60% recycling (SEK)	95 148	5 760	20 071
Total profit 80% recycling (SEK)	126 864	7 680	26 762
Total profit 100% recycling (SEK)	158 580	9 600	33 452

The price depends on how complex the heat exchanger is to dismantle and how clean it is when arriving to Stena Recycling. If it is not easy to dismantle and not properly cleaned, Stena Recycling will require a sanitation fee. The price also depends on how much of the weight is pure carbon steel or stainless steel. In this study, the total weight of the heat exchanger is assumed to be made entirely of carbon steel or stainless steel.

4.4.7 Payback Time

When investing in new products, it is always interesting to determine the payback time. That’s also the case for Inter Terminals, they are interested in the payback time for the heat exchangers that have been analyzed in this assessment. Payback time can be a decisive factor whether or not to invest in these heat exchangers in the future and has a major impact on the decision-making. The payback time is calculated by adding the capital cost, installation cost, maintenance cost during 30 years and the profit of recycling and dividing it with the yearly operating cost saving. The payback time barely changes with altering recycling rate, thus will not have an effect on the payback time.

The energy price from Göteborgs Energi is adjusted annually and affect the operating cost and operating saving. In order to see how the payback time is affected by altering energy price throughout the lifecycle, a sensitivity analysis was conducted on the energy price. The sensitivity analysis takes into account both increase and decrease of the energy price by 10, 25 and 50 %. The operating costs for the current heat exchangers are fixed during this sensitivity analysis and only the energy price regarding the new heat exchangers are changed. The payback time is presented and analyzed in chapter 5.2.

4.4.8 Summary of the Costs for the Heat Exchangers

A summary of all the costs for the heat exchangers that were analyzed in this assessment is presented in table 19 below. The operating costs for the current heat exchangers is also displayed in this table. Other costs for the current heat exchangers were not available.

Table 19. All cost for the three heat exchanger alternatives and operating cost for the current ones.

Operation	Alfa Laval (SEK)	ViFlow (SEK)	GB Tank (SEK)	Current (SEK)
Capital cost/HX	596 082	395 000	927 000	-
Total capital cost	1 788 246	2 370 000	2 781 000	-
Installation cost/HX	40 000	40 000	40 000	-
Total installation cost	120 000	120 000	120 000	-
Operating cost/year/HX	106 955	106 955	106 955	548 745
Total operating cost/year	320 864	320 864	320 864	1 646 236
Maintenance cost/year/HX	59 608	5 000	8 750	-
Total maintenance cost/year	178 825	30 000	26 250	-
Total profit 60% recycling rate	95 148	5 760	20 071	-
Total profit 80% recycling rate	126 864	7 680	26 762	-
Total profit 100% recycling rate	158 580	9 600	33 452	-
Total cost (30 years & 60% recycling rate)	16 803 763	13 010 167	13 294 356	49 387 095
Total cost (30 years & 80% recycling rate)	16 772 047	13 008 247	13 287 666	49 387 095
Total cost (30 years & 100% recycling rate)	16 740 331	13 006 327	13 280 975	49 387 095

5. Results and Analysis

5.1 Life Cycle Impact Assessment

The result from the life cycle assessment are presented in figures. It is for the three heat exchangers and the environmental impacts are included with the different recycling rates. Two of the heat exchangers are made of carbon steel, and one is made of stainless steel. The results for the LCA is for the heat exchangers lifetime which is 30 years. Logically thinking, the lifetime would affect the environmental impacts. A shorter lifetime will result in an increased environmental impact. If the heat exchangers would have a shorter lifetime, more heat exchangers must be manufactured. This will lead to an increased amount of metal that needs to be extracted and more energy is needed for the steel production and heat exchanger production. The impacts categories are global warming potential, depletion of abiotic resources, human toxicity potential and acidification potential.

In figure 9 heat exchanger 1 has the highest impact for 60 % recycling regarding global warming potential followed by heat exchanger 3 and 2. The global warming impact for heat exchanger 1 has a much steeper decrease with a higher recycling rate than the other two alternatives. For 100 % recycling rate heat exchanger 3 has the biggest impact and heat exchanger 1 has decreased to almost the same level as heat exchanger 2. For both the second and third heat exchanger is the reduced global warming barely noticeable for the different recycling rates. Heat exchanger 2 and 3 is made of the same material, but there is still a big difference regarding the global warming impact. The weight of heat exchanger 2 is nearly one fourth of heat exchanger 3. The steel production and the heat exchanger production requires energy and the amount of energy needed depends on the weight of the heat exchanger. This explains the difference between heat exchanger 2 and 3 regarding the global warming potential.

For a recycling rate of 60 %, heat exchanger 1 has the highest global warming potential, even though it does not have the highest weight. The production of steel, manufacturing of the heat exchanger, the use phase and recycling are assumed to be the same for both carbon and stainless steel. Therefore, the extraction of different elements and different amounts of these elements affects the result. This means that the higher amount of chromium and nickel in stainless steel increases the global warming impact. This can be seen in the figures 8-10, which indicate how much the different production processes contribute to global warming with different recycling rates. Since heat exchanger 1 is made of stainless steel, the global warming impact decreases with an increased recycling rate. With higher recycling rates, thus lesser extraction of virgin metals, the impact decreases. When the recycling rate increases, it can be seen that the weight of the heat exchanger starts to influence the global warming potential to a greater extent. As shown in figure 9, the heaviest heat exchanger has the highest impact for 100% recycling rate followed by heat exchanger 1 and heat exchanger 2 which is the lightest one.

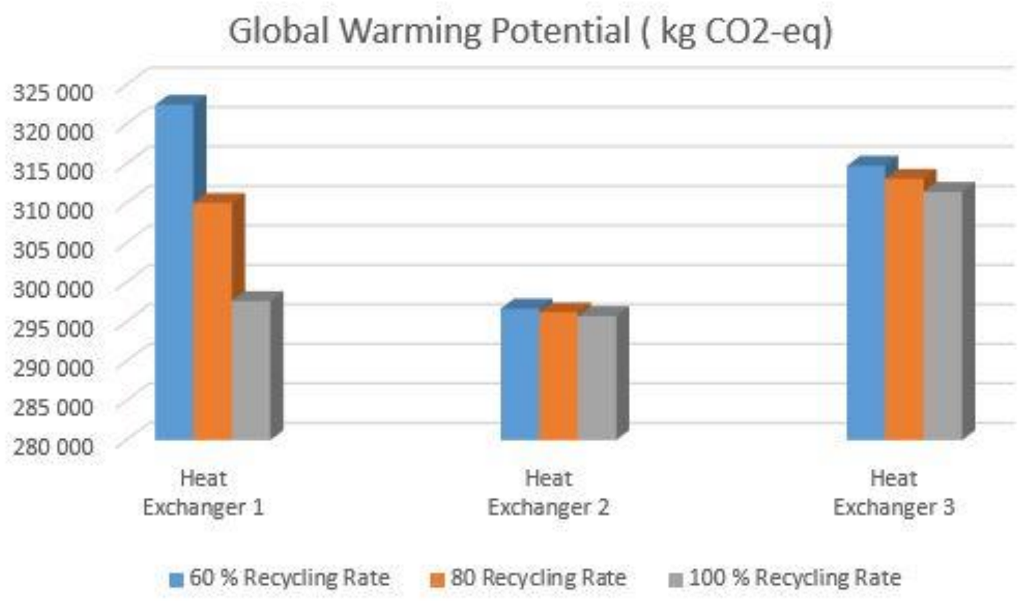

Figure 7. Comparing of the heat exchangers regarding global warming potential with three different recycling rates.

Figures 8-10 shows that the use phase is the dominating process, due to the total amount of energy that is needed to run during their lifetime. The energy is coming from three different sources, in which all of them contributes to global warming.

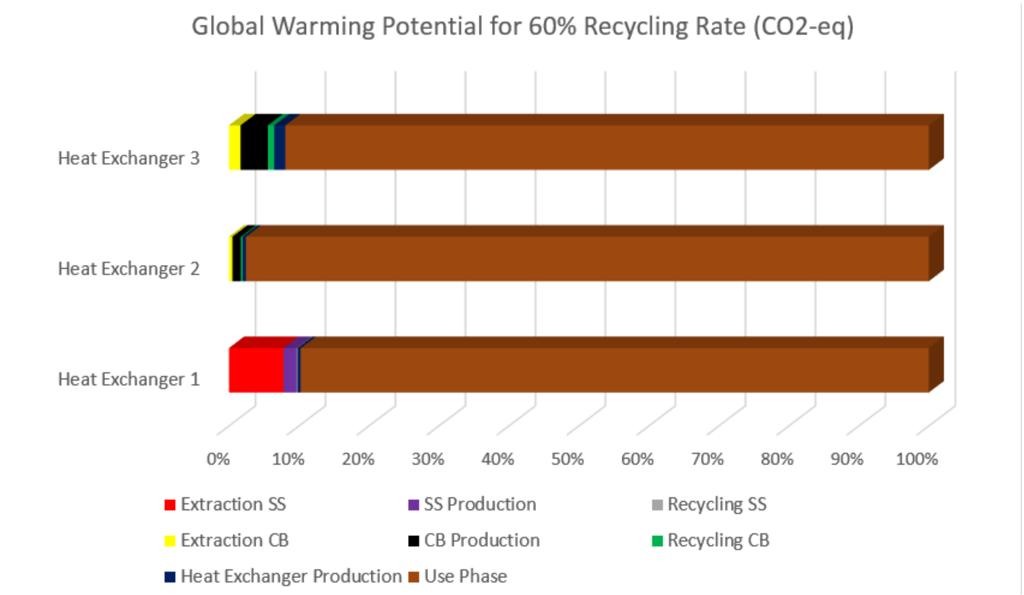

Figure 8. The global warming potential distribution for the process steps of the heat exchangers life cycle with 60% recycling. SS stands for stainless steel and CB for carbon steel.

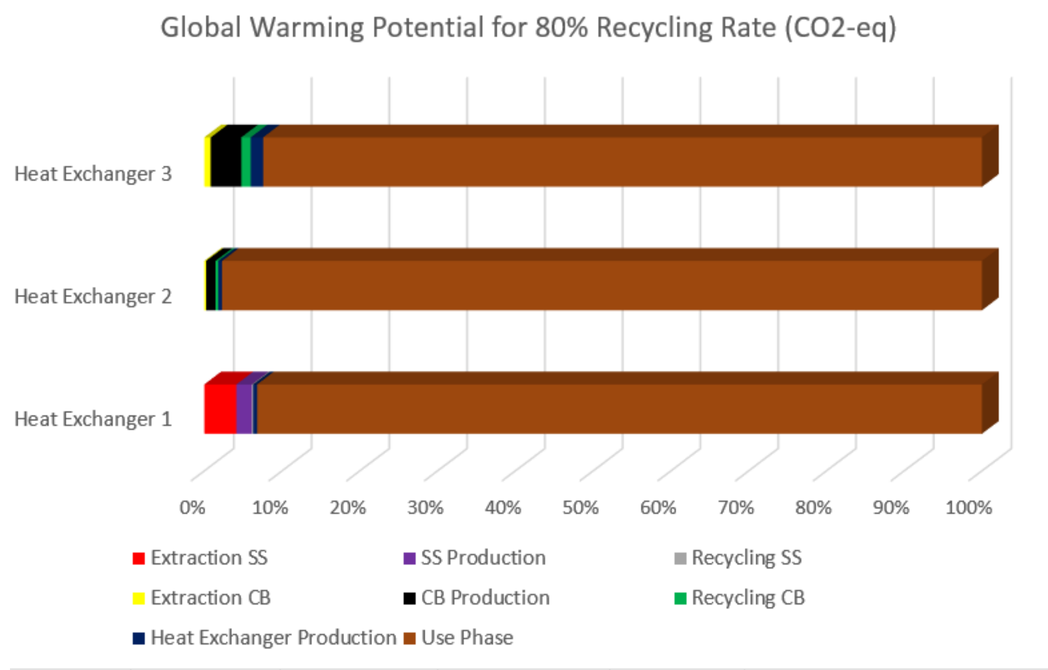

Figure 9. The global warming potential distribution for the process steps of the heat exchangers life cycle with 80% recycling. SS stands for stainless steel and CB for carbon steel.

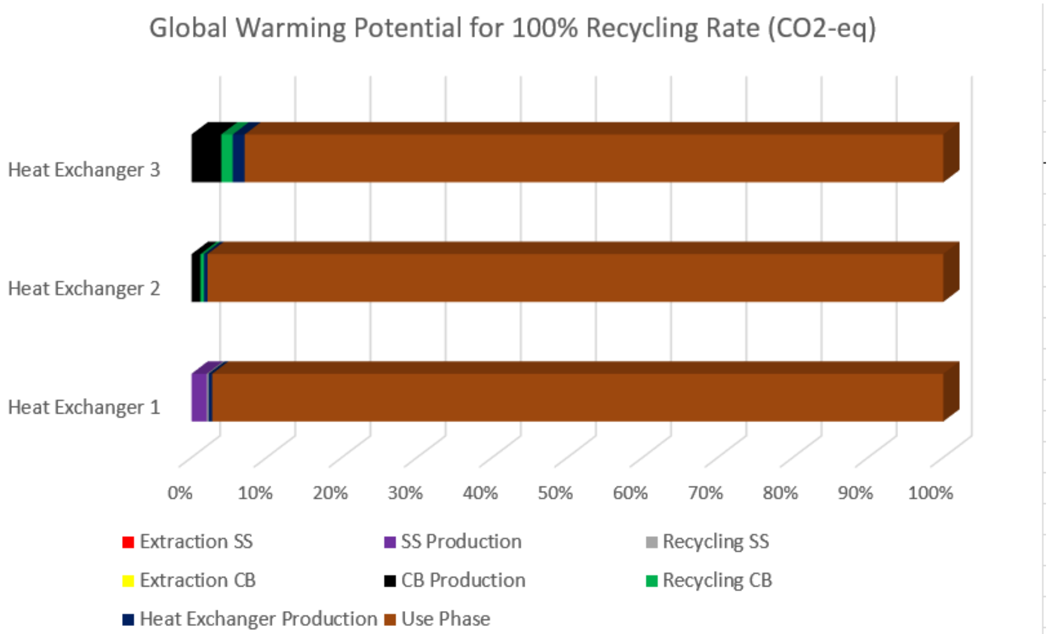

Figure 10. The global warming potential distribution for the process steps of the heat exchangers life cycle with 100% recycling. SS stands for stainless steel and CB for carbon steel.

Figure 11, which describes depletion of abiotic resources looks the same as for global warming potential. Heat exchanger 1 has the highest potential for depletion of abiotic resources at 60 % recycling and the impact decreases with higher recycling rate and for 100 % recycling heat exchanger 3 has the highest contribution.

Nickel and chromium is scarce metals and contains relative high amounts of stainless steel compared to carbon steel. It is the main factor to why heat exchanger 1 has a high impact on depletion of abiotic resources, as seen in the figures 12-14. The higher recycling rate meaning lesser use of chromium and nickel explains the significant decrease for heat exchanger 1. As in the case of global warming, heat exchanger 3 has the biggest impact for depletion of abiotic resources with a recycling rate of 100 %. This is due to the weight of the heat exchanger.

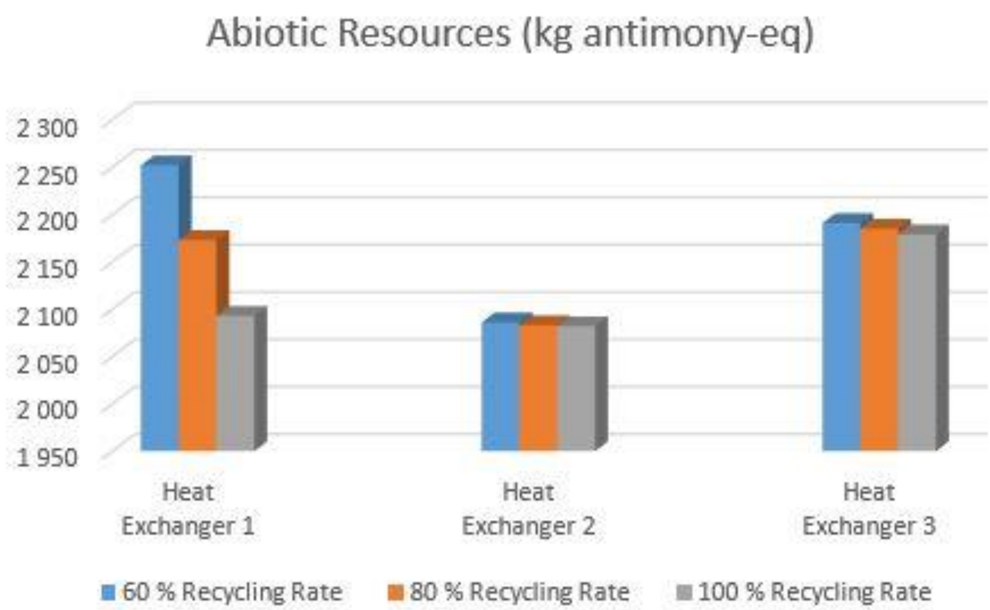

Figure 11. Comparing of the heat exchangers regarding depletion of abiotic resources with three different recycling rates.

Figures 12-14, represent the contribution to depletion of abiotic resources for each production process throughout the heat exchangers life cycle. The use phase is still dominating like for global warming, due to the energy requirements over the lifetime of the heat exchanger. The extraction of stainless steel is the second biggest contributor after the use phase for 60 and 80% recycling rate. With 100% recycling rate, there is no extraction for both stainless steel and carbon steel.

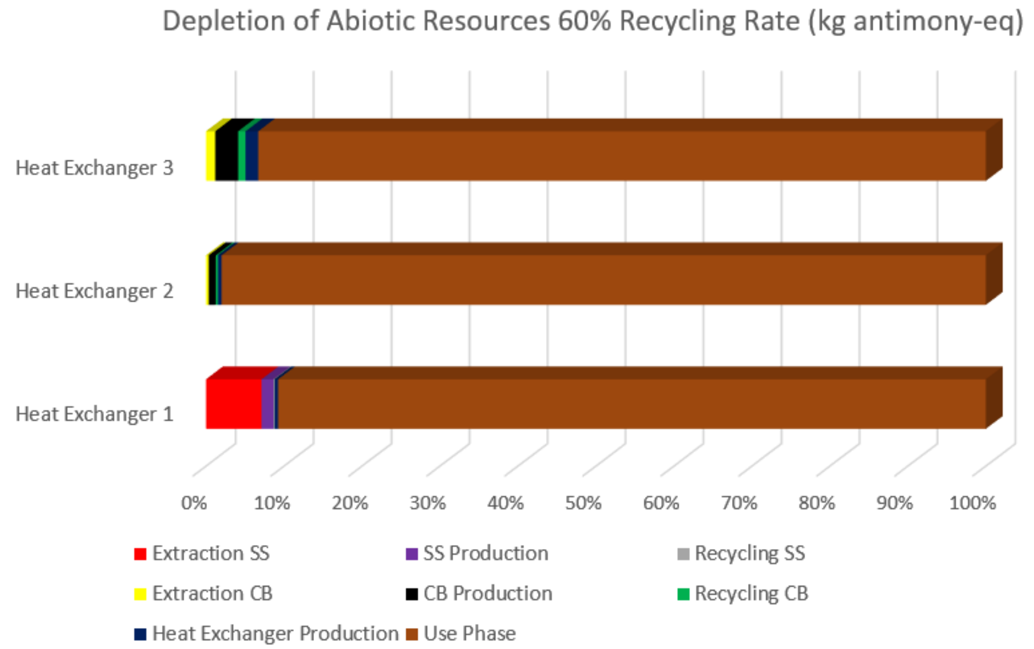

Figure 12. The depletion of abiotic resources distribution for the process steps of the heat exchangers life cycle with 60% recycling. SS stands for stainless steel and CB for carbon steel.

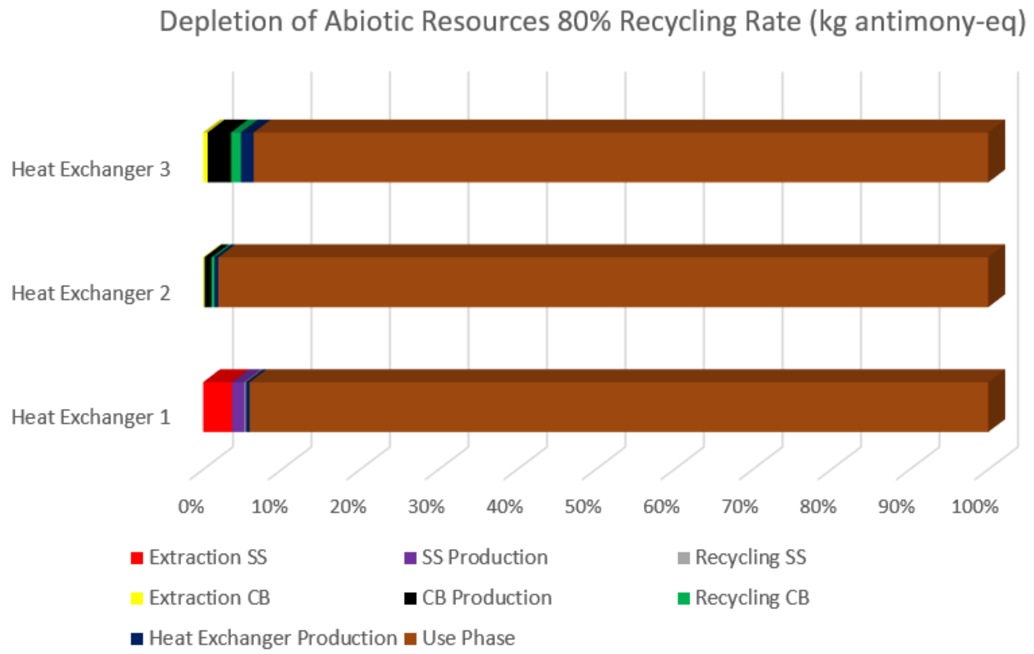

Figure 13. The depletion of abiotic resources distribution for the process steps of the heat exchangers life cycle with 80% recycling. SS stands for stainless steel and CB for carbon steel.

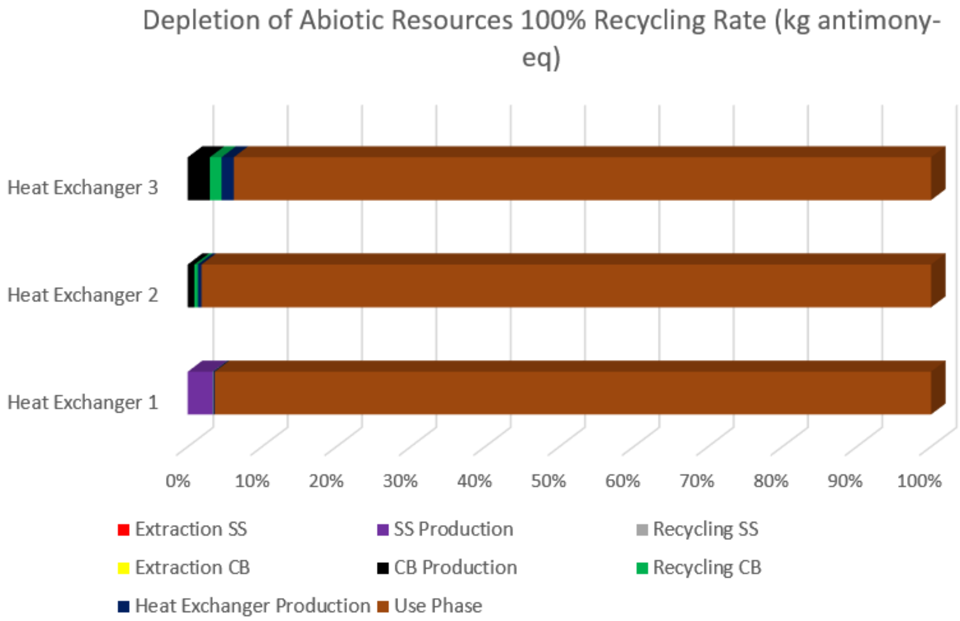

Figure 14. The depletion of abiotic resources distribution for the process steps of the heat exchangers life cycle with 100% recycling. SS stands for stainless steel and CB for carbon steel.

For a recycling rate of 60% heat exchanger 1 has the largest impact regarding human toxicity, meanwhile heat exchanger 2 and 3 has roughly the same (figure 15). When increasing the recycling rate to 80 %, heat exchanger 1 has a more significant decrease than the other two. Once again it shows how the amount of chromium and nickel in stainless steel affects all the impact categories. A tendency can be seen that for all the impact categories, an increased recycling rate for heat exchanger 1 influence the impact categories in a positive way. Heat exchangers 2 and 3 show a slight decrease of human toxicity with higher recycling rate. For these two heat exchangers, the decreased impact is barely noticeable in the interval of 60-100 % recycling rate. The impact for heat exchanger 1 decreases further with 100 % recycling. With that recycling rate all the heat exchangers have roughly the same impact regarding human toxicity. Heat exchanger 3 will have the highest impact for all of the impacts categories with a recycling rate of 100% due to the weight of it, which is by far the heaviest heat exchanger.

Heat exchanger 1 has a greater impact for 60 and 80 %, than heat exchanger 2 and 3, because in those cases the extraction of chromium and nickel are smaller. Chromium and nickel seems to contributes more to human toxicity than the other elements. With no extraction (100% recycling rate) of virgin metals, the heat exchangers have approximately the same impact, which indicates that the weight of the heat exchangers barely have an effect. The kind of steel the heat exchanger is made of is the most important factor regarding human toxicity.

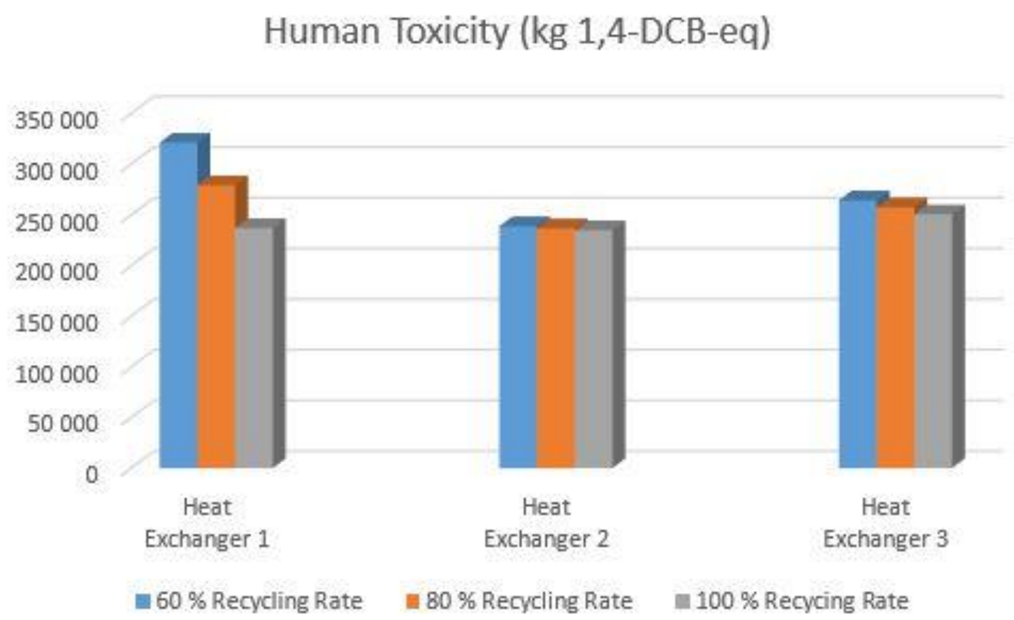

Figure 15. Comparing of the heat exchangers regarding human toxicity with three different recycling rates.

Chromium and nickel seem to contribute a lot regarding human toxicity except for 100% recycling rate, especially during the extraction, as it can be seen in the figures 16-18. Since the amount of chromium and nickel is much higher in stainless steel, heat exchanger 1 contributes much more compared to the other heat exchangers which are made of carbon steel. With 100% recycling, heat exchanger 3 contributes more to human toxicity during the carbon steel production due to the weight of the heat exchanger. The extraction phase has a quite high contribution regarding human toxicity and acidification. This can be related to the modelling in OpenLCA, in which rest of the world and global flows were used during the extraction phase and these flows contains energy. Since the rest of the world and global energy mix is considered to be less environmental friendly than the Swedish energy mix, it will probably have a bigger impact for these categories.

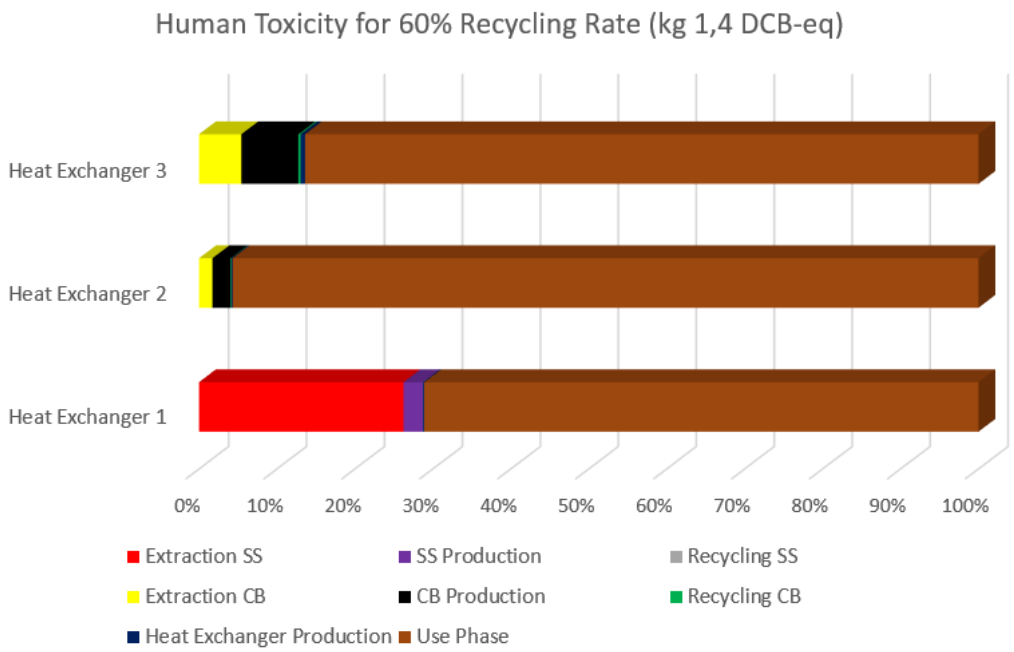

Figure 16. The human toxicity distribution for the process steps of the heat exchangers life cycle with 60% recycling. SS stands for stainless steel and CB for carbon steel.

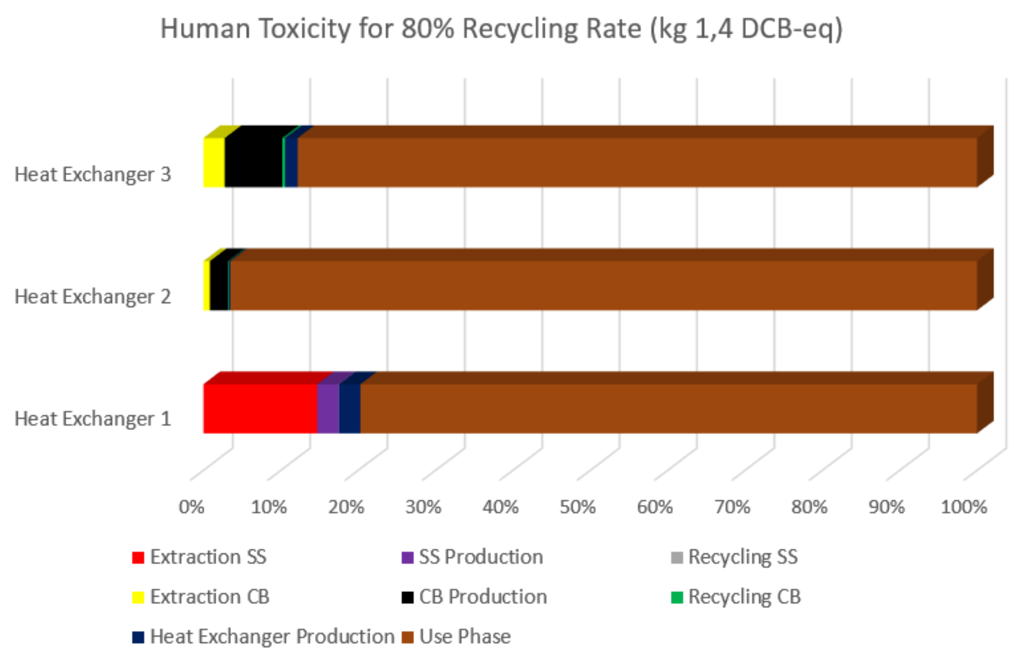

Figure 17. The human toxicity distribution for the process steps of the heat exchangers life cycle with 80% recycling. SS stands for stainless steel and CB for carbon steel.

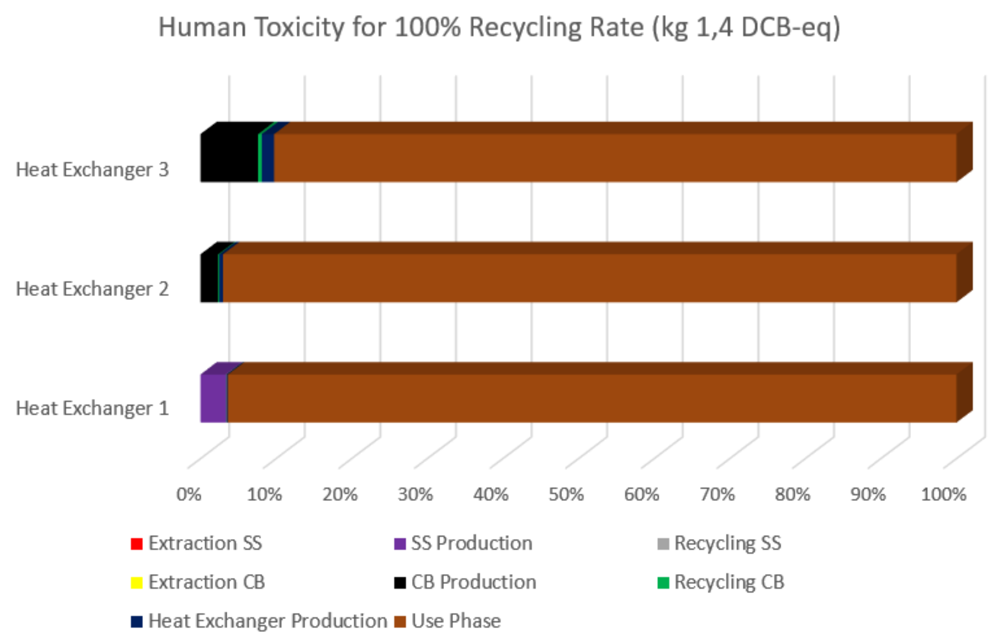

Figure 18. The human toxicity distribution for the process steps of the heat exchangers life cycle with 100% recycling. SS stands for stainless steel and CB for carbon steel.

Figure 19, the acidification looks identical as for human toxicity. The way the three alternatives react with altering recycling rate depends on the same reasons as for human toxicity. Once again, heat exchanger 1 contributes much more regarding acidification but also decrease most with a higher recycling rate.

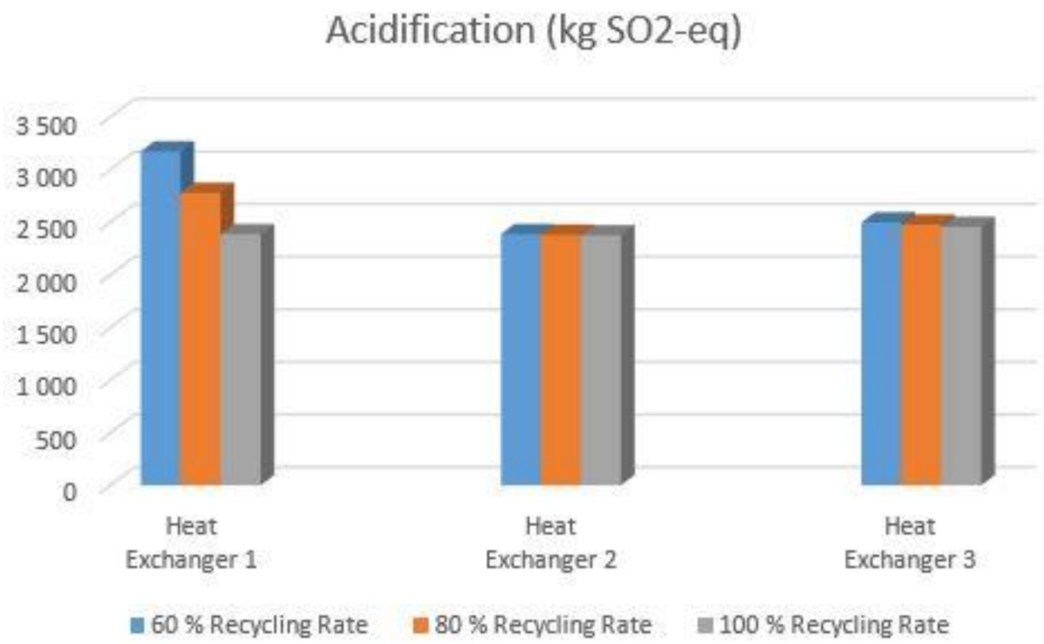

Figure 19. Comparing of the heat exchangers regarding acidification with three different recycling rates.

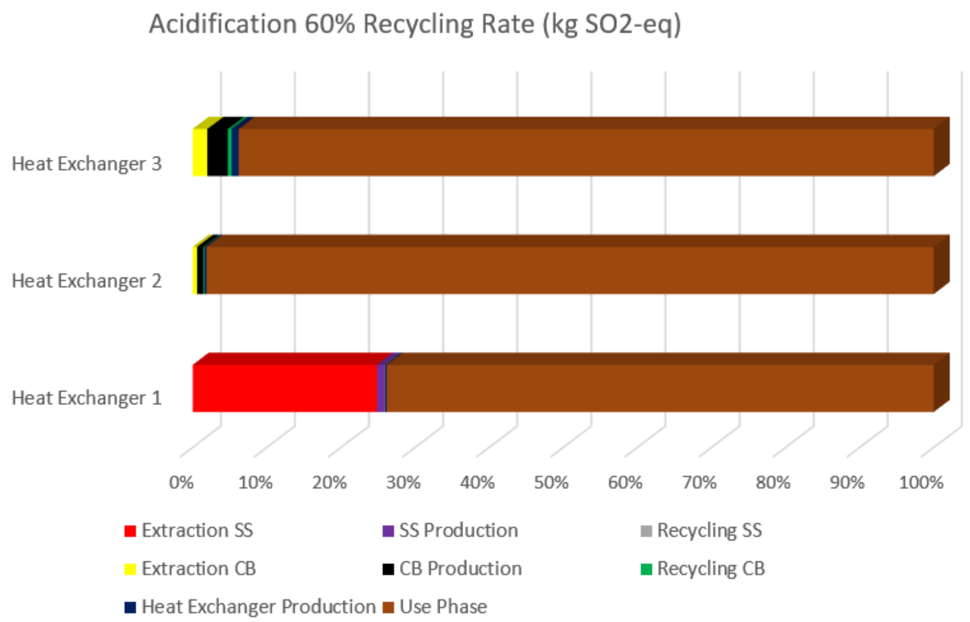

Figure 20. The acidification distribution for the process steps of the heat exchangers life cycle with 60% recycling. SS stands for stainless steel and CB for carbon steel.

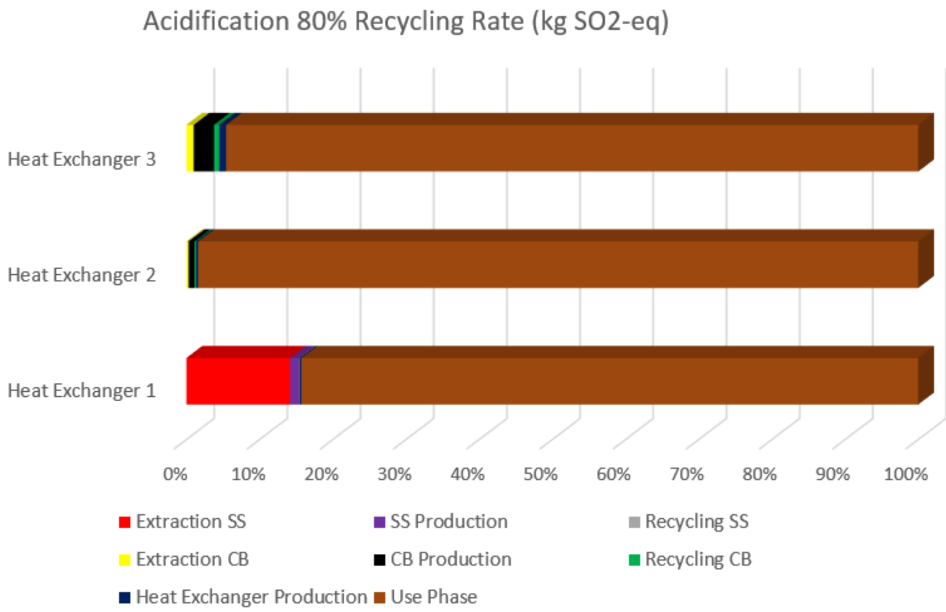

Figure 21. The acidification distribution for the process steps of the heat exchangers life cycle with 80% recycling. SS stands for stainless steel and CB for carbon steel.

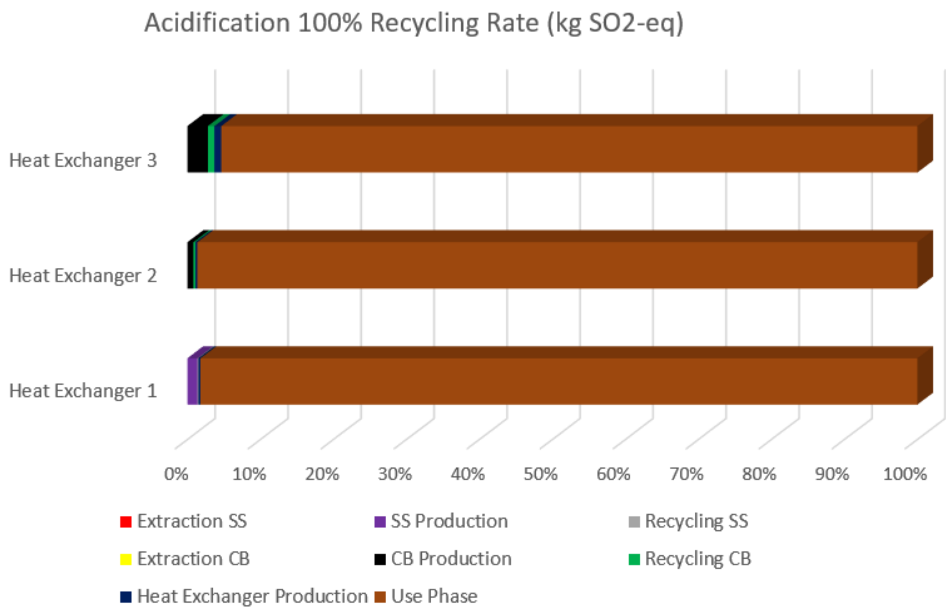

Figure 22. The acidification distribution for the process steps of the heat exchangers life cycle with 100% recycling. SS stands for stainless steel and CB for carbon steel.

The figures above which shows the different impact categories, a trend can be seen. The material that the heat exchangers are made of is crucial for all the impact categories except for a 100% recycling rate. In that case, the weight of the heat exchangers is the main factor. Therefore, heat exchanger 3 has the biggest impact for all of the categories. With a 100% recycling rate, there is no extraction phase which eliminates the consideration of virgin metals that needs to be extracted. Chromium and nickel are the main contributors for the impact categories, since rest of the world and global energy mix were used during the extraction phase. The high amount of chromium and nickel in stainless steel also have a big impact on the result regarding the impact categories.

As seen in the previous figures, the use phase is the dominating process for the contribution of the impact categories. A sensitivity analysis was conducted to see how a percentage change for the different energy sources would affect the impact categories for its lifetime which is 30 years. Table 19 shows an increase of 20% and 40% for each energy source compared to the base values (figure 7, 11, 15 and 19) with a recycling rate of 60%, since it's the basic case in reality. By increasing one energy source, the other two will decrease since the energy use is the same. Only the percentages changes for the energy sources. Calculations for this sensitivity analysis is shown in Appendix A.

For global warming potential, the impact slightly decreases for an increased amount of pellets and natural gas. However, by increasing the heating fuel the global warming potential increases slightly. This is due to, heating fuel has a higher carbon content compared to pellets and natural gas. By increasing pellets, depletion of abiotic resources decreases since it is not considered to be a scarce material. However, for natural gas and heating fuel depletion of abiotic resources increases. This is due to natural gas and heating fuel are considered to be more scarce than pellets. For natural gas and heating fuel the increase is relatively small, while the decrease of pellets is higher. Basically, it's more environmental friendly to use pellets instead of natural gas and heating fuel. For human toxicity, an increase in pellets contributes to a much higher human toxicity level compared to natural gas and heating fuel. The reasons for this is, in this case, the amount of pellets are much higher than natural gas and heating fuel from the initial system and by increasing it further more leads to a higher human toxicity level. Compared to natural gas, which is decreasing with an increased amount, it releases much more NO_x and SO_x emissions from the combustion which is toxic for human beings. The reason for a small increase with an increased percentage of heating oil is due to, the initial amount of heating fuel is very small in the system. For acidification, it similar to human toxicity due to the same emissions that are released from the combustion of pellets and heating fuel. Meaning that acidification levels increases with an increased percentage of pellets and heating fuel, pellets being more crucial than heating fuel due to the total amounts in the system.

The sensitivity analysis during the use phase shows a trade-off regarding the energy sources (table 20). For global warming potential and depletion of abiotic resources, it is better to have an increased amount of pellets. However, for human toxicity and acidification it shows a higher impact for these two categories with an increased amount of pellets. It is actually better with a higher amount of natural gas regarding human toxicity and acidification. According to the calculations in this assessment, natural gas has lower NO_x and SO_x emission compared to pellets. Heating fuel is the worst energy source and all the impact categories increases with a higher amount of heating fuel.

Table 20. Change of the impact categories for the heat exchangers (60% recycling rate) lifetime by increasing each of the energy sources during the use phase by 20% and 40% compared to the base values. The values are in percentage and those with a minus means a decrease.

Global Warming						
	Pellets		**Natural Gas**		**Heating Fuel**	
	20%	*40%*	*20%*	*40%*	*20%*	*40%*
Heat Exchanger 1	-1,22	-2,42	-1,07	-2,13	1,14	2,28
Heat Exchanger 2	-1,33	-2,63	-1,16	-2,3	1,24	2,48
Heat Exchanger 3	-1,25	-2,48	-1,09	-2,18	1,17	2,34
Depletion of Abiotic Resources						
	Pellets		**Natural Gas**		**Heating Fuel**	
	20%	*40%*	*20%*	*40%*	*20%*	*40%*
Heat Exchanger 1	-3,6	-7,15	0,67	1,38	0,71	1,42
Heat Exchanger 2	-3,88	-7,72	0,72	1,44	0,77	1,49
Heat Exchanger 3	-3,7	-7,35	0,68	1,41	0,73	1,4
Human Toxicity						
	Pellets		**Natural Gas**		**Heating Fuel**	
	20%	*40%*	*20%*	*40%*	*20%*	*40%*
Heat Exchanger 1	9,58	37,17	-5,37	-10,73	0,57	1,16
Heat Exchanger 2	12,89	25,8	-7,22	-14,44	0,77	1,57
Heat Exchanger 3	11,64	23,3	-6,52	-13,03	0,69	1,41
Acidification						
	Pellets		**Natural Gas**		**Heating Fuel**	
	20%	*40%*	*20%*	*40%*	*20%*	*40%*
Heat Exchanger 1	7,88	15,77	-0,95	-8,23	0,28	0,54
Heat Exchanger 2	10,44	21	-5,49	-10,94	0,34	0,71
Heat Exchanger 3	10,2	20,03	-5,21	-10,46	0,36	0,72

5.2 Life Cycle Cost

The payback time for the heat exchanger alternatives are displayed below in table 21. The payback time considers all costs during the heat exchangers life cycle and the operating cost savings. ViFlow´s heat exchangers have the shortest payback time of the three alternatives, with a payback time of 2,6 years.

Table 21. Payback time for the three heat exchangers.

Payback time (years)		
Alfa Laval	**ViFlow**	**GB Tank**
5,5	2,6	2,8

Table 22, shows the sensitivity analysis for the payback time regarding the three heat exchangers due to a change in energy price. The payback time for the heat exchangers does not change significantly with different energy prices. This is due to the current heat exchangers have a high operating costs. Even with an increased energy price by 50% for the new heat exchangers, Inter Terminals would still benefit by investing into new heat exchangers from an economic point of view. ViFlow´s heat exchanger (heat exchanger 2) has the shortest payback time compared to the others. This sensitivity analysis indicates that these heat exchangers are solid option for investing into, especially ViFlow´s and GB Tank´s from an economic point of view.

Table 22. Payback time for the three heat exchangers with change in energy price.

Payback time (years)			
Change in energy price	**Alfa Laval**	**ViFlow**	**GB Tank**
10%	5,6	2,6	2,9
25%	5,8	2,7	3,0
50%	6,2	2,9	3,2
-10%	5,4	2,5	2,7
-25%	5,2	2,4	2,6
-50%	4,9	2,3	2,5

Investing in new heat exchangers for the three caverns would be very cost saving for Inter Terminals when it comes to the operating cost. Over one year Inter Terminals would save 1.3 MSEK when it comes to the operating cost, by replacing the three existing heat exchangers with new ones. Furthermore, the new heat exchangers are assumed to have a lifetime of 30 years and the cost savings for the operation cost will accumulate over that time. This results in a cost saving of close to 40 MSEK over 30 years and with proper maintenance they would probably function longer than that.

6. Discussion

In this chapter, thoughts will be shared regarding the results and how decisions could have affected the result. The research questions for this assessment were the following:

- Using LCA and LCC, which heat exchanger is best suited for Inter Terminals concerning the environmental and economic aspects?

  As presented in the result and analysis chapter, the best alternative from an environmental and economic point of view is heat exchanger 2 which is ViFlow´s suggestion. It has the shortest payback time and lowest total cost as well as the lowest environmental impacts throughout its lifetime.

- Is there a trade-off between the environmental and economic aspects?

  There is no trade-off for heat exchanger 2, it is the most environmental friendly option for each impact category and has the shortest payback time.

Heat exchanger 1 is actually over-dimensioned. It is bigger than necessary due to wrong data were obtained from Inter Terminals at the beginning regarding the flows through the heat exchangers and other relevant parameters related to the products. Alfa Laval did not have the time to change their calculations regarding their alternative. Therefore, this will affect the results, hence heat exchanger 1 probably would be smaller when designing it with the right properties, thus lighter. This would impact both the environmental and economic aspects. From an economic point of view, it would have a cheaper capital cost leading to a different payback time. The environmental impacts would be slightly different, but not in a crucial way since it is still made of a less environmentally friendly material, stainless steel.

The use of chemicals, gases and other substances during the processes were neglected due to lack of data, if not included in the processes of ecoinvent. Neglecting these substances affects the results, if they were included it would probably lead to a higher impact for all the impact categories. If Environmental Product Declaration (EPD) documents were available, these parameters would have been taken into account. For a more specific LCA, these type of data are necessary. Also the assumption that the whole heat exchangers were made of either stainless steel or carbon steel changes the outcome of the result from an environmental point of view. The amount of each element in carbon steel and stainless steel can vary in many ways, the “recipe” depends on the desired properties of the steel. Use of other ratio between the elements for the steel will have an effect on the results for the impact categories.

There are other factors that can have an impact on the result when conducting an LCA. The electricity mix is a major factor; in this assessment the Swedish electricity mix have been used as much as possible for the calculations. Many companies including Alfa Laval, Viflow and GB Tank sometimes buys complete components for the heat exchangers from other countries. The extraction phase is also different in reality when these companies buys their products from other countries, due to the difference in the processes in terms of energy, transport, emissions etc. However, this assessment has its boundaries within Sweden if data is available in ecoinvent. If not, then RoW and GLO processes and flows are used. Rest of the world and global energy mix were used during the extraction and use phase due to lack of data in ecoinvent. If Swedish energy mix was used, the environmental impact categories would be smaller. This is due to Swedish energy mix is more environmentally friendly than RoW and GLO energy mix.

For a more complete LCC, other parameters should be considered such as downtime cost for heat exchangers and net present value (NPV) which is how the value of a product changes over time. Most the data for the LCC used in this assessment are based on the companies approximations and can differ in reality.

7. Conclusion

The aim of this assessment was to conduct a life cycle assessment and life cycle costing for new heat exchangers to help Inter Terminals with their decision-making for future investment. The research questions were to determine which heat exchanger was the best alternative for Inter Terminals from an environmental and economic point of view and if there were any trade-offs between them.

By having three different heat exchangers to analyze and compare, the conclusion can be drawn that for heat exchangers made of stainless steel, the recycling rate is more important than for carbon steel. This is due to the amount of nickel and chromium extracted and used at a level which is as low as possible will have a positive impact on the impact categories. The higher recycling rate for stainless steel the better. For carbon steel, the change in the impact categories is very low even with a very high recycling rate. When it comes to heat exchangers made of carbon steel it is more important to reduce the weight of the heat exchanger rather than increasing the recycling rate. This is due to the amount of energy required in the steel production and manufacturing process. The more the heat exchanger weighs, the more energy is needed in these two processes.

Heat exchanger 1 (Alfa Laval) has the longest payback time and also the most impact on the environment regarding the impact categoreis for 60% and 80% recycling rate. With a recycling rate of 100%, heat exchanger 1 has the second highest environmental impact for all of categories.

Heat exchanger 2 (ViFlow) has the shortest payback time and is also the most environmentally friendly regarding all of the impact categories for all three recycling rates.

Heat exchanger 3 (GB Tank) is the second best alternative regarding these aspects. However, with a 100% recycling rate, there is a trade-off between the environmental and economic aspects for all of the environmental impact categories. In this case heat exchanger 3 has the second shortest payback time but has the highest impact on the environment.

From the results a conclusion can be drawn that heat exchanger 2 (ViFlow) is the best choice regarding environmental and economic aspects and there is no trade-off between these aspects for this heat exchanger.

During the use phase, an increased amount of pellets will decrease global warming potential and depletion of abiotic resources. However, for human toxicity and acidification an increase of pellets would have a higher impact for these two categories since the NO_x and SO_x emissions are higher than for natural gas. Therefore, there is a trade-off between the pellets and natural gas when increasing the amounts of them with 20 and 40%. An increase amount of heating fuel will lead to a higher impact for all categories. Heat exchanger 2 (ViFlow) was the best alternative to invest into and there were no trade-offs regarding the environmental and economic aspects.

8. Recommendations

Based on the assessment and the conclusions from this study there are some recommendations that are of interest to Inter Terminals AB in their investment decision. Detailed data is required from Inter Terminals regarding the flows and capacity of their pumps before investing in new heat exchangers. The manufacturers will be able to provide customized heat exchangers with the exact requirements.

From an environmental perspective it can be interesting to include more impact categories, such as ecotoxicity. This can be one of the first steps that makes Inter Terminals a company that strives towards sustainability. The environmental considerations are getting more and more attention in Sweden but also globally, and this can make Inter Terminals to be a step ahead of their competitors. A more detailed and specific LCA is needed for the heat exchangers to get a higher quality of the results. This can be done by including chemicals and substances during the different processes, since this assessment has not included those due to lack of data. The environmental aspect of this and future assessments can be used as a marketing tool for Inter Terminal to attract more customers in the future.

To further improve the environmental assessment a sensitivity analysis on different types of energy mixes needs to be performed because many manufacturing company often buys complete component for heat exchanger from different countries and this will have an effect on the impact categories. Comparisons can also be made by looking at international companies to see their processes and how it differs from the Swedish manufacturing companies. Will there be a trade-off between the environmental and economic aspect in that case? Also, how would Inter Terminals consider the trade-off? Often companies often look for the cheapest alternatives, but in order to be considered a company that strives towards sustainability there should be a balance between the environmental and economic aspect. This will make Inter Terminals to stand out compared to their competitors and attract new customers.

The economical evaluation with LCC can be improved by conducting a complete LCC. The LCC in this assessment needs more parameters such as downtime cost and Net Present Value (NPV). The added parameters would affect the costs throughout the lifetime of the heat exchangers, especially the payback time. The aim from the start was to conduct a complete LCC but due to time limitation and lack of data, it was not possible.

The methods LCA and LCC can be used for every product and not only for heat exchangers. In the future, Inter Terminals should conduct these methods when investing in bigger equipment’s for their facility to achieve higher environmental and economic efficiency. This assessment provides a good base for Inter Terminals to invest in of the analyzed heat exchangers, especially heat exchanger 2 from ViFlow. It is proved in this study that it is the best choice for Inter Terminals from an environmental and economic point of view.

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Appendix A – Sensitivity analysis for energy sources
Appendix B – Calculations on the return temperature for the current heat exchangers
Appendix C – Operating costs

Appendix A

Calculation for increasing the different energy source during the use phase.

- Total energy needed during the use phase: 553 116 MJ/year
- Energy from pellets: 373 353 MJ/year (67,5% of the total energy needed)
- Energy from natural gas: 171 466 MJ/year (31% of the total energy needed)
- Energy from heating fuel: 8297 MJ/year (1,5% of the total energy needed)

With a 20% increase of pellets: *373 353 MJ/year * 1,2 = 448 023,6 MJ/year*

The remaining amount of energy left: *553 116 MJ/year – 448 023,6 MJ/year = 105 092,4 MJ/year*

The relation between heating fuel and natural gas in percentage:
8297 / (8297 + 171 466) = 0,046 = 4,6%

The amount of energy coming from heating fuel from the remaining energy:
*4,6% * 105 092,4 = 4834,2504 MJ/year*

The amount of energy coming from natural gas of the remaining energy:
105 092,4 – 4834,2504 = 100 258, 1496 MJ/year

For the whole lifetime of the heat exchangers, simply multiply by 30 years.
The new energy demand from these three sources will therefore be:

Pellets:	448 023,6 MJ/year
Natural Gas:	100 258,1496 MJ/year
Heating Fuel:	4834,2504 MJ/year
Total:	553 116 MJ/year

With a 20% increase of natural gas: *171 466 MJ/year * 1,2 = 205 759,2 MJ/year*

The remaining amount of energy left: *553 116 MJ/year – 205 759,2 MJ/year = 347 356,8 MJ/year*

The relation between heating fuel and pellets in percentage:
8297 / (8297 + 373 353) = 0,0217 = 2,17%

The amount of energy coming from heating fuel of the remaining energy:
*2,17% * 347 356,8 = 7537,64256 MJ/year*

The amount of energy coming from pellets of the remaining energy:
347 356,8 – 7537,64256 = 339 819,1574 MJ/year

For the whole lifetime of the heat exchangers, simply multiply by 30 years.
The new energy demand from these three sources will therefore be:

Pellets:	339 819,1574 MJ/year
Natural Gas:	205 759,2 MJ/year
Heating Fuel:	7537,6256 MJ/year
Total:	553 116 MJ/year

With a 20% increase of heating fuel: *8297 MJ/year * 1,2 = 9956,4 MJ/year*

The remaining amount of energy left: *553 116 MJ/year – 9956,4 MJ/year = 543 159,6 MJ/year*

The relation between natural gas and pellets in percentage:
171 466 / (171 466 + 373 353) = 0,315 = 31,5%

The amount of energy coming from natural gas of the remaining energy:
*31,5% * 543 159,6 = 171 095,274 MJ/year*

The amount of energy coming from pellets of the remaining energy:
543 159,6 – 171 095,274 = 372 064,326 MJ/year

For the whole lifetime of the heat exchangers, simply multiply by 30 years.
The new energy demand from these three sources will therefore be:

Pellets:	372 064,326 MJ/year
Natural Gas:	171 095,274 MJ/year
Heating Fuel:	9956,4 MJ/year
Total:	553 116 MJ/year

For the 40% increase, the calculations are the same except from the percentage increase.

Appendix B

Calculations on the return temperature of the hot water for the current heat exchangers. The current heat exchangers are running with an average flow rate of 10 m^3/h. The inlet and outlet temperature of the water for that flow rate are 94°C and 75 °C, resulting in a delta temperature of 19°C. A new delta temperature is calculated for a flow rate of 30 m^3/h in order to compare the current heat exchangers and the new ones.

Delta temperature for 30 m^3/h:

$$\frac{10m3/h}{30m3/h} = 0{,}33 = 33\%$$

$$\Delta T_{10m3/h} * 0{,}33 = 19°C * 0{,}33 = 6{,}33°\mathrm{C}$$

$$\Delta T_{30m3/h} = 6{,}33°\mathrm{C}$$

Return Temperature for 30 m^3/h:

$$T_{water,out} = T_{water,in} - \Delta T_{\frac{30m3}{h}} = 94°\mathrm{C} - 6{,}33°\mathrm{C} = 87{,}67°\mathrm{C}$$

The return temperature for the current heat exchangers, with a flow rate of 30 m^3/h, is 87,67°C.

Appendix C

Calculations regarding the operating costs are presented here. The operating cost for the new and current heat exchangers are calculated in the same way, but with different values regarding temperatures and operating time.

Calculation of the energy price for year 2016:

$$Energy\ price\ 2016 = EP2015\left(0{,}4 * \frac{FV_1}{FV_{bas}} + 0{,}4 * \frac{PI_1}{PI_{bas}} + 0{,}2 * \frac{KPI_1}{KPI_{bas}}\right)$$

- EP_{2015} = Energy Price (SEK/MWh) for 2015 = 900 SEK/MWh
- FV_1 = Price per MWh of district heating for the current year from Göteborg Energi for the reference house in the rapport Nils Holgersson investigation (Nilsholgersson.nu, 2016) = 782 SEK/MWh
- FV_{bas} = As above with 2014 as base year = 765 SEK/MWh
- PI_1 = Pellets price index bulk (min. 15-ton delivery), annual average calculated from monthly index according to Pelletsförbundet for the year before the current year = 102,0
- PI_{bas} = As above with base year 2013 = 102,0
- KPI_1 = Consumption price index according to Statistiska Centralbyrån (Statistiska Centralbyrån, 2016), the average value of the year before the current year = 313,49
- KPI_{bas} = As above with base year 2013 = 314,06
  Insertion of values in equation 2 gives an energy price of 907,7 SEK/MWh for 2016.

The energy price for 2016 (Göteborg Energi) is 907,7 SEK/MWh.

Calculations for the energy required for the new heat exchangers during the use phase:

- Göteborg Energi heat up Inter Terminals water from 75 to 90 degree Celsius.
- The water flow rate in the heat exchangers are 30 m^3/h.
- The new heat exchanger has a capacity to heat the oil in the tanks and caverns by 1 degree Celsius per day, while the old ones could only heat 0,1 degree Celsius per day. Therefore, the new heat exchangers require only 10% of the time to heat up the oil products compared to the old ones.
- The current heat exchangers are estimated to operate 30% of the year which is 2628 h/year.
- The energy loss has been estimated to be 16% from pump, valves, pipes etc, which is the same value for Götebrg Energi when they produce the energy.

Heating water from 75-90 degree requires *504 kWh/h = 1814,4 MJ/h*
This is calculated by a calculator on the website Lenntech (Lenntech, 2016).

Operating time for the new heat exchangers: *10% * 2628 h/year = 262,8 h/year*

Amount of energy required to maintain the oil products at the desired temperature without energy losses: 262,8 h/year * 1814,4 MJ/h = 476 824 MJ/year/HX

Taking the energy losses into account: *476 824 MJ/year * 1,16 = 553 116 MJ/year/HX*

The energy required for the current heat exchangers is calculated in the same way as for the new heat exchangers, but with other values for the temperatures and the operating time which are specified below.

- Heating water from 87,66-94°C (766,8 MJ/h)
- Operating time 2628h/year

The energy required for the new heat exchangers is 476 824 MJ/year/HX without energy losses and 553 116 MJ/year/HX with 16% energy losses. The energy required for the current heat exchangers is 2 015 150 MJ/year/HX without energy losses and 2 337 574 MJ/year/HX with 16% energy losses.

Convert the energy from MJ/year to MWh/year because the energy price is in SEK/MWh.

Required Energy/HX				
	New HX without energy losses	**New HX with 16% energy losses**	**Current HX without energy losses**	**Current HX with energy losses**
MJ/year	476 824	553 116	2 015 150	2 337 574
MWh/year	132,45	153,64	559,76	649,33

The energy price depends on the return temperature of the water to Göteborg Energi. The lower the return temperature is, the higher effectivity bonus. The effectivity bonus, return temperature and the resulting energy price are shown below. The energy price for the current heat exchanger is highlighted for 87°C and the new heat exchanger is highlighted for 75°C. The energy price is calculated by subtracting the effectivity bonus to the energy price (907,7 SEK/MWh) calculated in the beginning of Appendix C.

Energy price (SEK/MWh)	Return temp. (°C)	Effectivity bonus (SEK/MWh)
907,7	87	0
877,7	86-85	30
847,7	84-83	60
817,7	82-81	90
787,7	80-79	120
777,7	78	130
767,7	77	140
757,7	76	150
747,7	75	160
737,7	74	170
727,7	73	180
717,7	72	190
707,7	71	200
697,7	70	210
687,7	69	220
677,7	68	230
667,7	67	240

The energy price (SEK/MWh) for the new and current heat exchanger is multiplied with the required energy (MWh/year) both with and without energy losses in order to calculate the operating costs. Using these two equations, with values for the current heat exchanger and the new heat exchanger, the operating cost (SEK/HX/year) can be calculated for both with and without energy losses.

$$Operting\ Cost_{Without\ Energy\ Loss} = Energy\ Price * Energy\ Required_{without\ Energy\ Loss}$$

$$Operating\ Cost_{With\ Energy\ Loss} = Energy\ Price * Energy\ Required_{With\ Energy\ Loss}$$

A mean value operating cost (SEK/HX/year) is calculated for the new and the current heat exchanger.

$$Operating\ Cost = \frac{(Operating\ Cost_{Without\ Energy\ Loss} + Operating\ Cost_{With\ Energy\ Loss})}{2}$$

The operating cost for the new heat exchangers is 106 955 SEK/HX/year
The operating cost for the current heat exchangers is 548 745 SEK/HX/year