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The Environmental Impact of Capacity Utilisation on RoRo Shipping

A Life Cycle Assessment

Ada Hovind

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Supervisor: Bjørn Egil Asbjørnslett, IMT

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The environmental impact of capacity utilisation in RoRo shipping

A life cycle assessment

Miljøpåvirkningen av utnyttelsesgrad innen RoRo shipping

En livssyklusanalyse

Background:

Seaborne transport meets approximately 85% of the global transport demand, and it is expected that the total world fleet increase up to 50% (measured in million dwt) in the following years. The general environmental awareness becomes stronger, making it important to understand the environmental impacts of the shipping industry.

Several mitigation measures are implemented on existing vessels, and new vessels are being outfitted with modern, green technology. Alternative fuels, scrubbers and ballast water treatment are examples of measures used to reduce the environmental footprint of ships. The design of the hull is also changing. The development of ship design leans toward larger vessels. Some benefits are cost related, building and operational cost, but they also obtain environmental advantages. The larger vessels have lower emissions per unit cargo than the smaller vessels.

However, there are questions related to the utilisation factor of the large vessels. How high does the utilisation factor has to be to make the large vessels better than the smaller ones not only in theory, but also in practice?

Objective:

The overall objective of this thesis is to find the utilisation needed for a large vessel to be more sustainable than a smaller vessel. Life Cycle Assessment methodology is used to evaluate the environmental impact of the vessels at 100% utilisation. The results of the LCA is further used to determine the needed utilisation factor.

Tasks:

1. Provide a description of the background to the problem at hand. Research relevant regulations.
2. Do a literature study on the development of RoRo design throughout time.
3. Study the capacity developments in the RoRo segment.
4. Describe the designs and their theoretical strengths and weaknesses with regards to fleet deployment.
5. Describe LCA methodology and define the goal and scope of the study.
6. Collect data on each step of the value chain for all designs, and calculate the total GHG emissions/environmental impact. The results should be presented in a way that allows for comparison with other studies.
7. Understand the impact of cargo utilisation on good ship design by comparing the utilisation for larger and smaller vessels.
8. Discuss the results critically and compare the results with other studies. Discuss strengths and weaknesses of the study.

General

In the thesis the candidate shall present his personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature. The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: a text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The work shall follow the guidelines given by NTNU for the MSc Thesis work. The work load shall be in accordance with 30 ECTS, corresponding to 100% of one semester.

The report shall be submitted electronically on DAIM:

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Supervision

Supervisor: Professor Bjørn Egil Asbjørnslett, NTNU

Company contact: Gunnar Malm Gamlem, Wilh. Wilhelmsen ASA

Deadline 10.06.2016

Preface

This master thesis represents the final part of the study program Marine Technology, at the Norwegian University of Technology and Science (NTNU). It corresponds to 30 credits. The thesis was written during the spring 2016, by Ada Næsset Hovind.

The theme of the thesis is a continued work of the project thesis written the fall of 2015. However, a topic was initiated from Wilh. Wilhelmsen ASA, changing the main objective of the project thesis. The objective of this thesis is to investigate the environmental impacts of building larger vessels, and to see which impact utilisation has on the matter. In theory, the larger vessels emit less per unit cargo, and the purpose of this thesis is to see whether this applies to the real world.

The motivation for this study is the increasing focus on sustainable shipping. There are few existing studies on the environmental impact of a vessel's life cycle, and no studies relating emissions and utilisation have been found. This has also made it challenging to conduct an accurate analysis. It has been demanding to calculate accurate data for all phases of the life cycle, and several assumptions have had to be made. However, the objective was to compare the environmental impact of several vessel sizes, and the assumptions made do not affect the comparison of these.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett at the Institute for Marine Technology, for guidance throughout the master thesis work. Additionally, I would like to thank Gunnar Malm Gamlem from Wilh. Wilhelmsen ASA with guidance and help with making an as accurate analysis as possible. I would also like to thank Jon Helge Ulstein at Wilh. Wilhelmsen Ship Management and Chief Officer at M.V Thalatta for helping with data collection for the operational phase.

Trondheim, June 2016

Ada Næsset Hovind

Ada Næsset Hovind

Abstract

The focus on reducing global emissions has increased over the last decades, and has resulted in stricter environmental requirements for the shipping industry. New regulations focus on reducing the pollution of ships to sea and air. This is done through limiting CO_2, NO_x, and SO_x emissions, and reducing the transfer of ballast water from one part of the world to another, to mention a few. However, the environmental impact of a vessel does not only include the operational phase. The emissions begin with the materials production, fuel refinement and energy production before the vessel is even built, and continues throughout its entire life cycle. Many ship owners have taken action to reduce pollution by changing fuel in emission control areas (ECAs), using emission reduction technology or build larger vessels. In theory, a larger vessel is more energy effective, and cost effective, per unit of cargo transported.

The main object of this thesis was to investigate the impact of utilisation on the environmental performance of RoRo vessels. This was done to determine if using larger vessels is the most energy effective overall, or if smaller vessels are a better choice when the utilisation decreases. A life cycle assessment (LCA) was performed to map the environmental impact of five RoRo vessels, with varying cargo capacity. The environmental impact categories selected for the LCA were climate change, human toxicity and terrestrial acidification. These were chosen due to a concern for global warming, and the local impact of shipping on human health and acidification.

The case study included five RoRo vessels, with a capacity of 2,000, 4,000, 6,000, 8,000 and 10,000 RT. A cradle-to-gate assessment was used for the LCA, including the building phase, operational phase, dry-docking and scrapping phase of the vessels, as well as the process of material production, fuel refining and more. The operational pattern was assumed equal for all vessels, with 75% sailing time and 25% port-stay. The results from the assessment were given as emissions per vessel per year, in order to compare the performance of the different vessels.

To calculate the relationship between emissions and utilisation, the results from the LCA were used. The calculations were performed to represent emissions per RT, a standard car unit, nautical mile for different utilisation factors. Three different results were presented; the comparison of the five vessel sizes, the comparison of five fleets, and the comparison of emissions when transporting a specific amount of cargo. For the fleet perspective, homogenous fleets were used, and it was assumed that all fleets should transport 200,000 cars per year. As a

result of this, the amount of vessels varied from 20 for the fleet of 10,000 RT vessels, to 100 for the fleet of 2,000 RT vessels. In addition to the emission-utilisation calculations, a cost-utilisation analysis was performed. This was included because cost is the most important decision making criteria in shipping, and it was interesting to see how the cost reacted to variations in utilisation.

The results from the LCA showed that the operational phase had the largest impact on climate change and terrestrial acidification, while the building phase had the largest impact on human toxicity. At the 100% emissions baseline (6,000 RT, 95% utilisation), the 10,000 RT vessel obtained the lowest emissions per RT nm. The 6,000, 8,000 and 10,000 RT vessels need a utilisation rate of 95%, 93% and 81% respectively, to achieve the same emissions per RT nm for climate change. The results varied a few percent for the human toxicity and terrestrial acidification, but the trends were the same. The cost-utilisation analysis showed that the largest vessel would give the lowest required freight rate with a utilisation of 80% or higher.

For the fleet perspective, the fleet with 2,000 RT vessels obtained the lowest emissions, while the fleet with 10,000 RT vessels gave the highest emissions per RT nm. The reason for the opposite results is the sailing distance. The sailing distance for the fleets with small vessels is much larger because there are many more vessels. If the results were presented as emission per RT, the 10,000 RT fleet would again be the most sustainable, down to 85% utilisation. The results giving emissions for a specific amount of cargo showed that when a vessel is fully loaded, it is the best choice, however, when additional cargo is added, the emissions increase drastically because another vessel has to be used.

Based on the results from the LCA and the utilisation calculations, it is concluded that utilisation has an impact on the environmental performance of a vessel, and that the largest vessels are not the most sustainable for all utilisation factors. The largest vessels, when looking at emissions per RT nm for a one vessel perspective and emission per RT for the fleet perspective, can sail with lower utilisation, and still achieve the same emission levels per transport work, or per car, as the smaller vessels. However, it is important to notice that the large vessels have to transport more cargo at lower utilisation rate, and they are therefore dependent on large enough cargo base. This means that the advantage only can be realized in major shipping trade lanes, e.g. Asia to Europe, but not North America to the West Coast of South America.

Sammendrag

Fokuset på å redusere globale utslipp har økt de siste tiårene, og det har resultert i strengere miljøkrav for shippingbransjen. Nye reguleringer fokuserer på å redusere utslipp til både sjø og luft, gjennom å minimere mengden CO_2, NO_x, SO_x og forflytting av ballastvann, for å nevne noen. Likevel er ikke miljøpåvirkningen til et skip kun avhengig av operasjonsfasen. Utslippene begynner allerede lenge før skipet er bygget, gjennom produksjon av materialer, drivstoff og energi for bygging og drift. Videre påvirkes miljøet gjennom hele skipets levetid. Mange skipseiere har gjort reduserende tiltak gjennom drivstoffskifte i kontrollområder (ECAs), installering av utslippsreduserende teknologi eller ved å bygge større skip. I teorien er et stort skip mer energieffektivt og kostnadseffektivt per enhet last transportert, enn et lite skip.

Hovedformålet med denne oppgaven var å undersøke effekten lastutnyttelse har på miljøpåvirkningen til RoRo skip. Dette var gjort for å bestemme om store skip er mest energieffektive uansett, eller om små skip er mer lønnsomme ved lavere utnyttelsesgrad. En livssyklusanalyse ble utført for å kartlegge miljøpåvirkningen til fem RoRo skip med varierende lastekapasitet. Miljøkategoriene som ble undersøkt var global oppvarming, forsuring og menneskelig forgiftning.

Casestudiet inneholdt fem skip med en kapasitet på 2,000, 4,000, 6,000, 8,000 og 10 000 RT. En krybbe-til-grav tilnærming ble valgt for livssyklusanalysen og inkluderte byggefasen, operasjonsfasen, tørrdokk og skrotingsfasen. I tillegg ble materialproduksjon, drivstoffproduksjon og deler av energiproduksjonen tatt med. Operasjonsprofilen ble antatt lik for alle skipene, med 75% seilingstid og 25% havneligge. Resultatene fra analysen ble gitt som utslipp per skip per år. Dette var for å gjøre det enklere å sammenligne ytelsen til de forskjellige skipene.

Resultatene fra livssyklusanalysen ble brukt til å beregne forholdet mellom utslipp og utnyttelsesgrad. Beregningene ble gjort for å representere utslipp per RT nautisk mil for varierende utnyttelsesgrad. Tre forskjellige sammenligninger ble gjort; sammenligning av et skip av hver type, sammenligning av en flåte av hver skipsstørrelse og sammenligning av utslipp ved å transportere enn gitt mengde last. For flåteperspektivet var det antatt at flåtene kun bestod av samme skipsstørrelse, og at de kunne transportere 200 000 biler hver. Dette

resulterte i varierende flåtestørrelser, fra 20 båter i 10 000 RT flåten, til 100 båter i 2,000 RT flåten. I tillegg ble en kostnad-utnyttelsesanalyse utført. Dette ble gjort fordi kostnader er det viktigste beslutningskriteriet innen shipping, og det er derfor interessant å se om kostnadene oppfører seg likt som utslippene ved varierende utnyttelsesgrad.

Resultatene fra livssyklusanalysen viste at operasjonsfasen hadde størst påvirkning på global oppvarming og forsuring, mens byggefasen hadde størst påvirkning på menneskelig forgiftning. For sammenligningen av ett og ett skip oppnådde 10 000 RT båten det laveste utslippet per RT nm, mens 2,000 RT båten hadde den dårligste miljømessige ytelsen. 6,000, 8,000 og 10 000 RT båtene trengte en utnyttelsesgrad på henholdsvis 95%, 93% og 81% for å oppnå samme utslipp per RT nm for global oppvarming. Prosentvis var det noen små forandringer for de andre kategoriene, men trenden var den samme. Kostnadsanalysen viste at det største skipet også oppnådde den laveste nødvendige fraktraten, ved en utnyttelsesgrad på 80% eller høyere.

Det var de minste skipene som oppnådde best resultater for flåteperspektivet, mens de største båtene hadde dårligst ytelse. Grunnen til dette er forskjellen i seilingsdistansen for flåtene. Flåtene med de minste skipene har mange flere skip, og ender derfor opp med en større seilingsdistanse totalt sett. Hvis resultatene hadde blitt gitt som utslipp per RT ville det største skipet oppnådd de laveste utslippene, ned til 85% utnyttelsesgrad. Resultatene som gir utslipp ved å transportere enn gitt mengde last viser at alle skipene yter best når de er fullastet, men at utslippene øker drastisk når ekstra last er lagt til, fordi et nytt skip må tas i bruk.

Basert på resultatene fra livssyklusanalysen og beregningene av utnyttelsesgrad, er det konkludert at utnyttelsesgrad påvirker miljøpåvirkningen til et skip. De største skipene kan seile med lavere utnyttelsesgrad, og oppnå samme utslipp som de mindre skipene med høyere utnyttelsesgrad. Samtidig er det viktig å legge merke til at de største skipene må frakte mer last, selv om utnyttelsesgraden er lavere. For å oppnå miljøgevinsten er de derfor avhengige av store nok lastebaser. Dette betyr at storskalafordelen kun kan oppnås i store transportruter som Asia til Europa, men ikke Nord-Amerika til vestkysten av Sør-Amerika.

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Abbreviations

AFS Anti-fouling systems

BC Black carbon

CATCH Cost-effectiveness criterion

C_b Block coefficient

CEU Car equivalent unit

CF Carbon factor

CH_4 Methane

CO Carbon monoxide

CO_2 Carbon dioxide

ConRo Container RoRo vessel

DB Dichlorobenzene

ECA Emission control area

EEDI Energy efficiency design index

EOS Economies of scale

FOC Fuel oil consumption

GenRo General Ro-Ro vessel

GHG Greenhouse gas

GRP Glass-reinforced plastic

HFO Heavy fuel oil

IMO International Maritime Organization

IPPC Intergovernmental Panel on Climate Change

ISO International Organization for Standardization

LCA Life cycle assessment

LCC Life cycle cost

LCI Life cycle inventory

LCIA Life cycle impact assessment

LCTC Large car truck carrier

LNG Liquefied natural gas

MARPOL International Convention for the Prevention of Pollution from Ships

MCR Max continuous rating

NECA NO$_x$ emission control areas

NO$_X$ Mono-nitrogen oxides

PCB Polychlorinated biphenyl

PCC Pure car carrier

PCTC Pure car truck carrier

PM Particulate matter

R134 Refrigerant

RFR Required freight rate

Ropax RoRo passenger vessel

RoRo Roll-on Roll-off

RT Car equivalent unit (equal to CEU)

SECA Sulphur emissions control area

SEEMP Ship energy efficiency management plan

SFC Specific fuel consumption

SO$_x$ Sulphur dioxide

SPC Self-polishing copolymer

TBT Tribultin

TEU Twenty foot equivalent unit

USD United states dollar

VOC Volatile organic compounds

Chapter 1

Introduction

1.1 Background

Sea transport covers about 90% of the world's trade, and is considered the most cost-efficient way to transport raw materials and goods (IMO, 2016b). The economic growth and global economy have pushed an increase in international trade to and from countries from east and southeast. There is a growing amount of cargo being produced and transported between the Eastern and Western part of the world.

In the period from 2007 to 2012, the total shipping industry emitted 3.1% of the annual global CO_2 emissions and 2.8% of the annual greenhouse gas (GHG) emissions, given in CO_2-equivalents (IMO, 2014). International shipping was responsible for 2.6% of these CO_2 emissions and 2.4% of these GHG emissions. According to the European Commission, the pollution from shipping is expected to increase between 150-250% by 2050, depending on the future economic situation and developments within the energy sector (EC, 2016).

1.1.1 Larger vessels

The trend over the last years has been to build larger vessels. Examples of this are the oil carriers Jahre Viking and Hellespont Alhambra, and the container vessels Emma Maersk and MSC Oscar (Gamlem, 2016a). From an economical point of view, larger vessels are more cost-effective per unit of cargo, to build and operate. Additionally, they are more energy effective per cargo unit, which results in lower energy consumption and reduced emissions. These benefits are defined as economies of scale.

There have been studies on the importance of economies of scale (Cullinane & Khanna, 2000; Lindstad, Asbjørnslett, & Strømman, 2012), showing the effects on both cost and emissions.

Cullinane et al. (2000) presented a model that quantified the effect of economies of scale for container vessels, while Lindstad et al. (2012) investigated the effect for several different vessel types.

DNV GL did a study on the relationship between cost and utilisation for container vessels (Grimstad & Neumann-Larsen, 2013) to see whether the economies of scale could be quantified. One of the findings was that the cost advantage of a vessel one size larger (an increase of 2,000 TEU) was cancelled if the utilisation was reduced between 3-5%. Additionally, the possible maximum utilisation difference between a 14,000 and 21,000 TEU vessel was only 12%, meaning that there is a need for 5,000 additional TEU's per voyage of the larger vessel, to gain equal slot cost for the vessels.

Nevertheless, it has been little focus on the impact of capacity utilisation on the emissions of the larger ships. When a large vessel utilises its entire capacity, it is more cost-effective and energy effective per unit of cargo. However, there are not any studies showing for which utilisation factors this is valid. If a large RoRo vessel only uses 50% of its capacity, is the emissions per unit cargo still lower than a smaller vessel with 100% utilisation?

1.2 Objective and outline of thesis

The main objective of this thesis is to determine the effect capacity utilisation has on emissions, for RoRo vessels. A Life Cycle Assessment (LCA) is used to calculate the environmental impact of five vessels with different capacity. These results are further used to determine the lowest utilisation the largest vessel can have, to remain more environmentally friendly than the smaller vessels. In addition, a life cycle cost (LCC) analysis was done to establish a relationship between cost and utilisation, and to investigate this behaviour compared to the behaviour of the emissions at varying utilisation.

The thesis is structured in a way that first presents the theory needed to understand the analysis, and the reason and logic behind it. Design developments of RoRo vessels, and the problem of fleet deployment and capacity utilisation are described in the second chapter of the thesis, while the principle of economies of scale is presented in Chapter 3. Chapter 4 and 5 builds up to the LCA modelling by explaining the environmental concerns of a vessel life cycle, and the theory of life cycle assessment. In Chapter 6, the modelling with assumptions, calculations and limitations are shown, while Chapter 7 presents the results of the emission-utilisation analysis and the cost-utilisation analysis. These results, and the results of the LCA, are further discussed in Chapter 8, while concluding remarks and proposed further work are given in Chapter 9 and 10.

1.3 Limitations

The LCA model presented in Chapter 6 is a simplified version of a vessel life cycle. The model is limited by the assessment tool, and by available data on the different life cycle phases. Another drawback of this study is that there are not found any studies analysing the relationship between total life cycle emissions and utilisation. This makes it challenging to make a good discussion of the results, and evaluate their credibility.

Chapter 2

RoRo Shipping

2.1 Introduction to RoRo Shipping

RoRo is an acronym for Roll-on Roll-off, and is referring to the cargo handling on the vessels. A RoRo vessel is designed to carry wheeled cargo, and uses straight or angled stern and, on some vessels, side ramps to load and unload (Gamlem, 2016a). The first RoRo vessels were designed to transport trains that were too wide for the bridges, across rivers (Raunek, 2010). Now, the vessels can carry everything that can be rolled on and off. Typical cargo is vehicles, but many vessels also have the capacity to transport high and heavy, and non-containerized cargo. High and heavy is a term used for large vehicles like tractors, bulldozers, trucks and trailers (WW, 2016) while non-containerized cargo, or breakbulk, is static, voluminous and/or heavy cargo like windmill parts, machine parts or paper rolls. This type of cargo is placed on roll trailers pulled by trucks before they are loaded on board the ships (Gamlem, 2016a).

There are several types of RoRo vessels. The classical RoRo vessel can transport all of the cargo types mentioned above. Pure Car Carriers (PCC) only transport vehicles, while Pure Car and Truck Carriers (PCTC) also include heavier cargo units, as described above, on some decks. Other variations are ConRo, which is a hybrid of a container vessel and a RoRo vessel, GenRo (general cargo and RoRo) and RoPax (RoRo and passenger carrier). Typical for a RoRo fleet is the wide variety of amount and type of cargo the ships can take (Chandra, Fagerholt, & Christiansen, 2015).

The capacity of a RoRo vessel is given in lane meters, Car Equivalent Unit (CEU) or RT43. A lane is a 2 m wide strip of deck, while a lane meter is a deck area one lane wide and one meter long (Rowlett, 2008). RT43 measures 7.38975 m^2, and is defined from the measurement of a 1967 Toyota Corona, including required stowage space around the car (WWL, 2016). For a vessel that only transport cars, CEU is equal to RT43, if however the vessel transport high cargo, the CEU is higher than RT43 (Gamlem, 2016a). There is a wide range of vessel sizes in the RoRo segment, and the largest vessels can take up to 8,500 RT.

2.2 Developments in RoRo design

The first vessel using the RoRo principle was the Firth of Forth ferry. The vessel started operating in 1851 in Scotland. However, it was not until the 1940s and 1950s that the principle was transferred to merchant ships (Raunek, 2010). Before this, cars were shipped in ordinary cargo liners and were lifted on and off the vessels (Small, 2015).

2.2.1 Increase in size and capacity

Building larger vessels has several benefits that are described in more detail in Chapter 3. The profits of big vessels have pushed ship owners to design higher, longer and most recently, with the new Panama Canal, wider vessels, to lower the freight rate and emissions per unit of cargo. A vessel with lower freight rate is more attractive to clients, and a sustainable vessel meets the stricter regulations on pollution. There are however some negative sides of building larger vessels. Even though the transport cost decreases, other costs may increase. One example is port costs, which are dependent on the amount of cargo handling available in port, and the size of the vessel.

The container shipping industry has exploited economies of scale. The MSC Oscar is one of the world’s largest container vessel, with a length of 396 m and a capacity of approximately 20,000 TEU (Technology, 2015). In comparison, the RoRo segment has not followed the trend to the same extent, but there is evidence of growth in size and capacity for the RoRo fleet the last decades. Before the 1990s, the largest vessels had a capacity of 6400 RT, while the largest vessels today have a capacity of up to 8,500 RT (Clarkson, 2016). About 70% of new vessels under construction will be larger than 7,000 RT (Gamlem, 2016a). According to WWL (WWL, 2015), client expectations on accommodation of various cargo types and increased focus on sustainability, and a market ruled by costs and profits are the main reasons for the growing cargo capacity.

In addition to increasing the capacity, the RoRo vessels are designed to be more flexible, by including more transport of high and heavy cargo. By allowing for more covered capacity, and using hoistable decks, several types of cargo can be fitted in one vessel. When Wallenius

Wilhelmsen designed the Mark IV vessels in 2000, the vessels had 35% more covered capacity for specialised RoRo cargo than the previous design, Mark III (ASA, 2000). The next design, Mark V, was designed to support even larger and heavier cargo than before (WWL, 2012), and incorporates the highest main deck built. Höegh Target is the world's largest PCTC, with a capacity of 8,500 RT. According to Höegh Autoliners, the new vessel is more flexible with regards to cargo types, and it is built in a way that makes it more efficient and increases the cargo space utilisation (Anon, 2016).

2.2.2 Focus on sustainability

With increased global warming, the environment is more in focus than before. This is reflected in new regulations, improved hull design, equipment and vessel operation. The goal is to reduce the environmental impact of shipping, by reducing the environmental footprint of the world fleet. Some ship owners have taken voluntary action, like WWLs policy on low sulphur fuels before the IMO requirements were implemented (Gamlem, 2016a). Yet, the introduction of new regulations is also enforcing a sustainable development. Regulations on NO_x and SO_x emissions entered into force in 2000 and 2005, and amendments tightening the rules are constantly implemented (IMO, 2016c, 2016d). The Energy Efficiency Design index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) were introduced to reduce the CO_2 emissions from international shipping. These regulations were adopted by IMO in 2011, and they entered into force 1 January 2013 (IMO, 2016a).

Energy efficiency

CE Delft (DELFT, 2016) did a study analysing which factor or factors contributes to changes in design efficiency, and what importance the different factors have had. They investigated the change in design efficiency from the 1960s until today, for container vessels, tankers and bulk carriers. Figure 2.1 shows an indicative development of design efficiency during the last century, expressed in g CO_2 / tonne-nautical mile (nm). The figure is from the *Second IMO GHG study in 2009*.

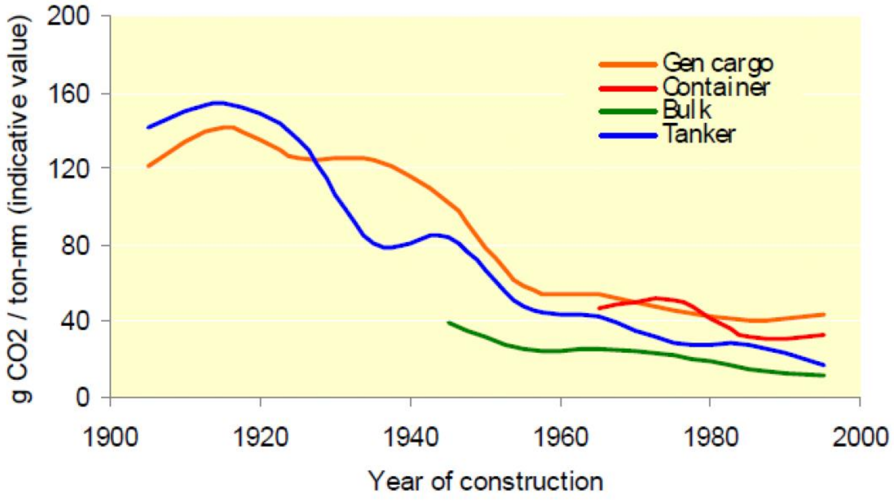

Figure 2.1: Indicative development in average ship design transport efficiency (Buhaug et al., 2009)

The figure shows that the design efficiency generally has improved over the last century, but there have been periods where it has deteriorated. A good design efficiency is high, and implies low emissions per ton-nm. According to CE Delft, the design efficiency for all three vessel types improved in the mid-1980s, then had a gradual deterioration in the 1990s and 2000s, before it began improving again in the recent years. A lower design efficiency could be the result of lower fuel prices. When the fuel price is less important, it is profitable to build fuller vessels to increase capacity. However, the introduction of the EEDI and SEEMP have likely contributed to the improvement in the design efficiency over the last years, regardless of fuel prices and focus on profit.

The analysis done by CE Delft identified several factors affecting the design efficiency; changes in design speed, changes in capacity and the average size of ships, changes in the required main engine power, and changes in the difference between actual main engine power and expected power. A vessel with lower actual power than expected power implies a rather efficient design (DELFT, 2016). Ship design was in the study identified as the most significant contributor to changes in the design efficiency by contributing to reduced engine power.

By improving the hull shape, less engine power is needed to overcome total resistance. Slender vessel designs, like reefer vessels and frigates, have low resistance, yielding less need for power. A parameter that greatly affect the ship resistance is the block coefficient (C_b). C_b says something about the fullness of the hull shape, at a certain draught. Figure 2.2 shows how the total resistance, R_T, increases exponentially with a higher block coefficient.

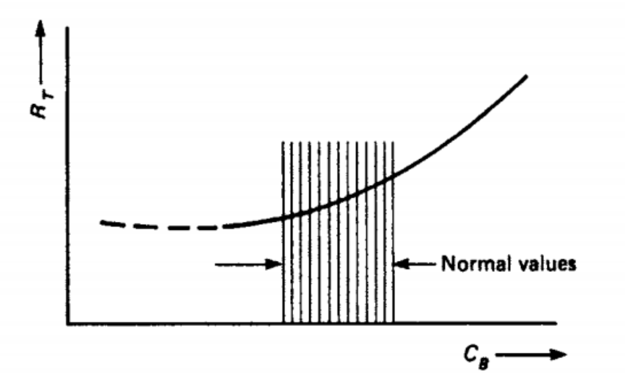

Figure 2.2: Ship resistance as a function of block coefficient (Schneekluth & Bertram, 1998)

Low block coefficient implies a slender hull. RoRo vessels also have a slender design with block coefficients between 0.55 and 0.75, even though it looks like a shoebox above the waterline (see top of Figure 2.3). If only the underwater hull is considered, the shape of the hull is quite slender (see bottom of Figure 2.3). The vessels are designed this way to optimise both the cargo capacity and the energy efficiency. In comparison, an oil tanker has a block coefficient between 0.70 and 0.85 (Gamlem, 2016a).

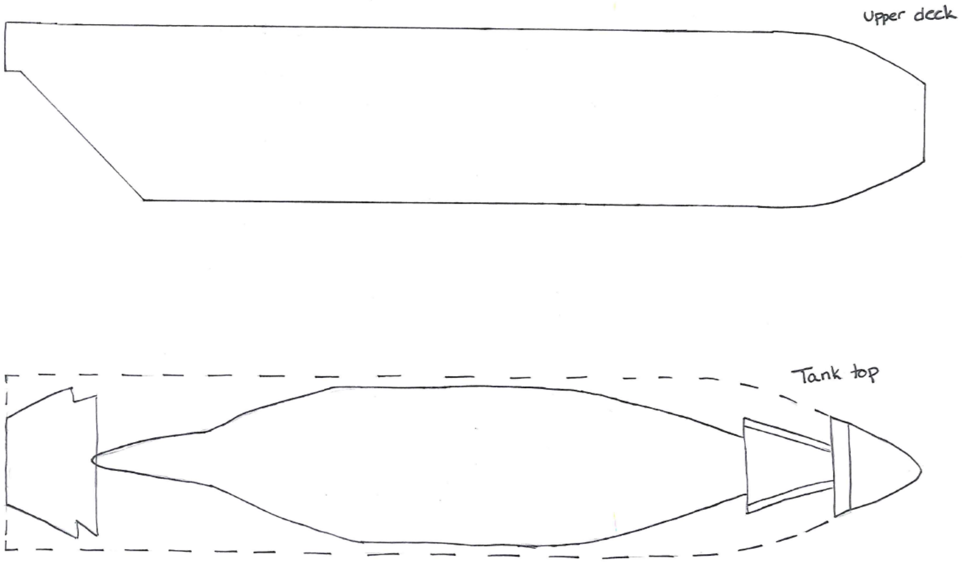

Figure 2.3: Hull design, RoRo

Machinery

In addition to optimise the hull shape, a vessel can reduce its emissions by improving its machinery, change to cleaner fuel alternatives than heavy fuel oil (HFO) or employ exhaust gas cleaning systems. IMO has introduced several Emission Control Areas (ECA) to limit the pollution of SO_x and NO_x close to shore (IMO, 2016a). In these areas, vessels must use exhaust gas cleaning, modern machinery or switch to low sulphur fuels. Many vessels have installed scrubbers in combination with using HFO, to limit the pollution. Low emission engines can also be used. Both scrubbers and low emission engines are used in the RoRo fleet today (Anon, 2015; WWL, 2015).

Other alternatives, that are not widely used in the RoRo segment, are LNG and battery driven engines. LNG contains very little sulphur, so SO_x emissions are almost zero (Gamlem, 2016a). Low pressure gas and dual fuel engines reduce NO_x emissions by 85-90% and lower GHG emissions by up to 20% (WPCI, 2015). The negative side of using LNG, depending on the engine type, is the high methane emissions and that it currently is not as available to the vessels as HFO and MDO. This is especially a problem to deep-sea RoRo vessels, with global operation and long sailing distances.

2.3 Operational pattern and fleet deployment

Operational pattern, and how the fleet deployment problem is solved, can affect the total environmental impact of a vessel. If the route is planned well with regards to cargo flows, cost and emission savings can be achieved. It is therefore important to understand the basics of this subject before the assessment is carried out, to better interpret the results.

Sea transportation can be divided into three types of operation: tramp, industrial and liner (Chandra et al., 2015). Tramp shipping is similar to taxi services. The vessels have cargo they are committed to carry and spot cargo is loaded to maximize profit. Industrial shipping is a segment defined by large customers and long term relationships between shipping companies and cargo owners (Gamlem, 2016a). The goal is minimizing the transport costs. In liner shipping, the vessels operate on predefined schedules and routes, similar to a bus line. The majority of RoRo vessels operate in the liner segment, with some tramp sailings for major customers on major trade lanes (Gamlem, 2016a).

The demand for maritime transport is dependent on the global economic activity, and the need for carrying merchandise trade (UNCTAD, 2015). Economies are often characterised by good and bad times that influence the maritime transport market. The demand reacts quickly to changes in freight rate, whereas the supply adopts slowly to changes in the demand (Christiansen, Fagerholt, & Nygreen, 2007; Pantuso, Fagerholt, & Hvattum, 2014). This means that imbalances between supply and demand occur, affecting the utilisation levels, operational pattern and fleet deployment problem for the ship owners. The next section will describe the three different levels of planning maritime transport, before a deeper understanding of RoRo logistics is provided.

2.3.1 Three levels of planning

According to Christiansen et al. (2007), there are three levels of planning maritime transport; strategic, tactical and operational planning. The strategic planning has a long-term perspective, and begins already in the process of designing new vessels. When a new vessel is designed, it is important to evaluate the expectations to the future market conditions. The ship has to be commercially viable over its entire lifespan of typically 30 years, and there are several factors affecting the design decisions. One important decision is the size of the vessel. The cost per cargo ton-mile generally decreases with increasing capacity, but if the market is experiencing a down period it may be difficult to utilize a larger vessel.

Fleet size and mix is a strategic and tactical planning problem. Strategically, the objective is to plan the fleet size and mix in a way that minimizes capital cost and operational cost (Christiansen et al., 2007). Determining the type of ships, their sizes and the number of vessels of each size to include in the fleet, is the strategical part of the planning.

Tactical planning only focuses on the operating costs, since the fleet is already existing. It has a shorter time-perspective, and consider issues like the maritime supply chain, fleet deployment and ship management (Christiansen et al., 2007).The sea transportation is only one part of the total maritime supply chain, and the shipping companies have to plan, or fit into, the logistics for the entire transport chain. The cargo owner decides cargo deliveries to the vessels, and the fleet has to adopt to cargo quantities and tight schedules from the clients.

Ship management includes crew scheduling, maintenance scheduling, positioning of spare parts and bunkering (Christiansen et al., 2007). This is an importation part of the logistics, in addition to assigning vessels to routes and cargo. The crew scheduling is not as important for deep-sea vessels, since the crew spend long periods on board the vessel at a time. Maintenance can be done on board if spare parts and crew are available. Additionally, the ship has to undergo annual, intermediate and special surveys by the class society. The amount of spare parts available on the ship is dependent on port calls and the availability of spare parts in these ports. Bunker fuel prices affects the operating costs, and in periods of high fuel prices, the bunker fuel cost is much larger than the other operating costs. In these periods, it may be advantageous to bunker up in a port outside the route, if the price savings are larger than the costs of a possible delay.

Operational planning is short-term and solves the problem of the dynamic and uncertain environment that is maritime transportation (Christiansen et al., 2007). Operational scheduling is the assignment of single voyages to vessels. This gives advantages when the supply of cargo is uncertain, but one has to find the trade-off between cargo and repositioning voyages, also known as ballast voyages, with respect to profit and costs. Handling trade imbalances is part of the operational scheduling (see section 2.3.2)

According to Christiansen et al. (2007), weather routing is another operational planning problem. Vessels face currents, tides, waves and winds that will increase fuel consumption and may cause delays. To reduce the risk of delays, the route has to be selected to circumnavigate the environmental effects, or the ship owners can choose routes that take advantage of them.

The last part of operational planning is speed selection. If the speed is lowered, the fuel consumption is greatly reduced, minimizing the operating costs (Lindstad, Asbjørnslett, & Strømman, 2011). In periods of high fuel prices, this can be a good way to minimize costs. Slow steaming also reduces the transport work of the vessel (Christiansen et al., 2007). This is advantageous in periods with low activity. However, the time schedules are often tight to minimize cost, making it more difficult to reduce the speed if not planned. Finally, the possibilities of reducing speed are greatly limited in liner trades, and customers expect a certain minimum frequency, as well as maximum transit time (Gamlem, 2016a).

2.3.2 RoRo logistics

RoRo vessels operate in the liner segment, but their operational pattern differs from regular liners. Container vessels are for instance locked to regular routes/operations and are not flexible. RoRo vessels on the other hand, operate in a flexible way where the vessels and their capacity are allocated at a global level to where they are needed (Fagerheim, 2016). This is done to optimise the capacity utilisation of the fleet. The goal of the fleet deployment is to maximize utilisation and profit, and minimize cost (Chandra et al., 2015; Fagerholt, Johnsen, & Lindstad, 2009), by selecting the optimal number of vessels and the optimal ship sizes for each voyage (Mulder & Dekker, 2014). Good planning can also reduce the emissions per unit cargo.

The operational pattern of RoRo vessels is dependent on the cargo owners. They want frequent, and smaller deliveries of cargo (Fagerheim, 2016). This implies that to fill up a vessel, it has to sail to several ports in order to load enough cargo, yielding more time spent on each journey. The customers give strict time constraints, and the vessel owners have to find the balance between high utilisation and maintaining scheduled deliveries.

Another challenge for liner vessels, especially container vessels, is trade imbalances. The shipping lines calculate the slot costs for the cargo on a return-trip basis, to compensate for the chances of returning with little or no cargo (UNCTAD, 2015). When the imbalances are high, the cost of transporting cargo on the leg with most traffic increases, to compensate for the loss of income on the return trip. Simultaneously, the freight rates for the less trafficked route decreases, to attract as many customers as possible. Allowing a more flexible fleet deployment helps reducing the impact of trade imbalances, since vessels are allocated based on cargo supply and not on regular routes.

Port limitations and other factors influencing fleet deployment

Several external factors influence the fleet deployment and decisions made by the ship owners. Fleet deployment is relevant from the design process and throughout a vessel’s lifetime. The expansion of the Panama Canal is an example of this. The new canal allows for larger ships with increased cargo capacity (APC, 2010). It gives the opportunity of length, beam and draught increases for the vessels. The construction of a second Suez Canal yields an increase in traffic, from 47 to an estimate of 97 ships per day (UNCTAD, 2015). This affects the transit and waiting time for vessels using the Suez Canal, which again affects the total sailing time. Reduced sailing time gives the opportunity of additional port calls, or shorter transit times and higher annual production.

Ports can restrict the use of large vessels. A few ports still have strict limitations on length and draught, limiting the use of large vessels on certain routes. Japan is an example of this, where some ports only allows for vessels with a maximum length of 200 m (Fagerheim, 2016; Means, 2012). Another limiting factor in port is the amount of cargo handling equipment present. A large vessel, with high cargo capacity, will use a considerable amount of time loading and unloading in a port with limited cargo handling equipment.

2.4 Capacity utilisation for RoRo

The technical definition of capacity utilisation is a ratio, usually in percentage, between the actual input and the actual output (Styhre, 2010). In the shipping industry, capacity utilisation refers to the ratio between used capacity and potential capacity. A ship with low utilisation has unused capacity.

Styhre wrote a PhD on capacity utilization in short sea shipping, including a case study on the RoRo segment (Styhre, 2010). This study identified several factors, both external and internal, that influences the capacity utilisation. According to Styhre, the likelihood of unused capacity increases with more trade imbalances and daily/seasonal demand variations. This implies that there is a need for a flexible fleet to adjust for fluctuations in the demand.

The study identified four external factors; market, customer, port and surroundings, and two internal factors; management and vessel. Even though these factors were found for short sea shipping, many of them are relevant for deep-sea shipping as well. The state of the market, and the available cargo and cargo mixes affect the utilisation. In a market where supply of tonnage exceeds the demand for transportation, the vessel owners have to choose which loads to include, whereas in markets with lacking tonnage, it is difficult to avoid unused capacity. The type of cargo can also affect the utilisation, if the shapes or properties of the cargo does not allow for tight stacking.

Fleet deployment and planning impacts the capacity utilisation. Since RoRo vessels use a flexible approach to the deployment problem, the ship owners can avoid unused capacity by allocating the right vessels to routes, dependent on cargo availability and market state. If the market is good and the ports have high capacities, a large vessel is profitable from both an economic and an environmental perspective, because it benefits from its size. However, if the cargo availability is low, or the cargo deliveries are small, the benefits may be larger with a smaller ship with high utilisation and the need for fewer port calls. Cancellations and double booking from customers will also lead to last minute empty cargo space that is difficult to fill up before departure (Styhre, 2010).

As mentioned in Section 2.1, there are several different design solutions for RoRo vessels. This can also affect the capacity utilisation. If a vessel primarily is designed to carry vehicles, and the demand for vehicles are low, the vessel will struggle to fill up. However, if the vessel is designed to carry a variety of goods, it is easier to adjust to other types of cargo, if one segment is struggling. A flexible design can increase the capacity utilisation in tougher times, but it comes at a cost, generally increasing both the building cost and the operating costs (Gamlem, 2016a).

According to WWL Global Market Intelligence, the RoRo segment usually has high utilisation and is not as exposed to large fluctuations in supply and demand as other vessel types. The global fleet utilisation was just below 90% in 2000, while it rose to 100% just before the market collapse in 2008 (Ward, 2013). However, the industry recovered, and the fleet utilisation was approximately 94% in 2012, according to WWL Global Market Intelligence. Since the collapse of the oil price, it is expected that the RoRo fleet is affected by the economic decline, and that the utilisation has not recovered to the levels prior to 2008. However, the numbers from WWL Global Market Intelligence shows that even though there are collapses in economy or oil prices, the implications on the RoRo segment are not as high as for other segments.

Chapter 3

Economies of scale

Historically, emission and cost reductions have been achieved by building larger vessels (Lindstad et al., 2012). This is known as economies of scale (EOS). According to The Geography of Transport Systems, economies of scale is the cost reduction resulting from larger transport modes, terminals and distribution centres (Rodrigue, 2013). In shipping, EOS refers to the gain from replacing many small vessels with fewer, larger ones. This leads to reduction in cost and emissions, which benefits ship owners, cargo owners and the environment.

3.1 Cost reduction

Cost is the most important factor in the decision making progress for ship owners. When there are uncertainties in the maritime transport market, or signs of decreasing global trade, ship owners rush to reduce expenses through economies of scale ("Business: Economies of scale made steel; Shipping," 2011). Building larger vessels reduce the cost per unit of cargo transported (unit cost), by reducing fuel costs and shipping costs per unit (MarineLink.com, 2013).

According to Geir Fagerheim from WWL, small vessels do not survive in the market today, due to too high unit costs ($/RT) as a result of operational costs, capital costs and port/channel fees (Fagerheim, 2016). For larger vessels, the unit costs are greatly reduced, while the freight potential is increased. Lindstad et al. (2012) did a study on the effects of economies of scale on GHG emission reduction, where a study on cost reductions was included. The study showed that the cost in USD per million tonne nm could be reduced with approximately 60%, if the existing RoRo fleet in 2007 was replaced by an EOS fleet at the end of the vessel lifetime. It was assumed that the EOS fleet would consist of the largest vessels from the 2007 fleet, which was 45,000 dwt, while the average vessel size of the 2007 fleet was 7,200 dwt.

The maximum benefit from EOS is dependent on external factors as well. Lindstad et al. (2012) identified some of these in their study. Most ports today have the ability to accommodate a certain rise in vessel size without expanding. However, the amount of transhipment and feedering used will increase, since the largest vessels will be too big for some ports. Moreover, an increase in size may lead to a reduction in sailing frequencies, due to the additional capacity of each vessel. This results in an increase in time from factory gate to customer (Lindstad et al., 2012). Port and canal fees result in cost increases, reducing the benefit of building vessels larger than a certain size. For RoRo vessels, the largest vessels currently have a capacity of between 8,000 – 8,500 RT. This is estimated to be the largest reasonable capacity, due to practical and economic considerations (Fagerheim, 2016). According to Gamlem (2016a), only 10% of the current fleet is larger than 7,000 RT, and only 3% is larger than 8,000 RT.

3.2 Emission reduction

The principle of economies of scale is similar for emissions as it is for costs. When vessels grow in size, the emissions per transport work are reduced. As long as the capacity increases more than the power and fuel consumption of the vessel, environmental benefits are obtained. The fuel consumption per unit cargo is reduced, hence reducing exhaust gas emissions per unit.

As mentioned for cost reductions, larger vessels will increase the use of feeder vessels. Yet, the additional emissions associated with feeder vessels are smaller than the emission reduction obtained by using larger vessels for deep-sea transportation (Lindstad et al., 2012). The explanation to this is the much shorter sailing distances for the feeder, than the main vessel.

The study done by Lindstad et.al (2012) illustrated the benefits of using EOS to reduce GHG emissions. It identified the potential savings in emissions per transport work, and annual emissions. For RoRo vessels, the CO_2 emitted per freight unit (gram per ton nm) was reduced from 75.8 to 25.7 gram per ton nm. This is a 66% reduction by changing from a fleet with average vessel size of 7,200 dwt to 45,000 dwt. The annual emissions were reduced from 68 million tonnes with the 2007 fleet, to 23 million tonnes with the EOS fleet, which is a 66% reduction. This shows that it is a large emission reduction potential when utilising economies of scale.

3.3 Abatement cost

Abatement cost is calculated to evaluate and identify cost-efficient emission reduction options. Most abatement options are more expensive than the economic benefit of for instance lower fuel consumption, meaning that the implementation of a reduction measure is more expensive than the economic gain from reduced consumption. Yet, in the shipping industry, emission reduction options can be adopted at a negative abatement cost, which is economically beneficial and sustainable (Alvik, Eide, Endresen, Hoffmann, & Longva, 2009; Faber et al., 2009; IMO, 2009).

The findings of these studies do not include the focus on profit and opportunity assessment obtained by selling and buying vessels during their lifetime. The results are obtained by assuming long-term vessel ownerships with ongoing operation (Lindstad et al., 2012). According to Lindstad et al. (2012), it is possible to obtain a negative abatement cost of -739 USD per ton CO_2 for RoRo vessels, assuming that old vessels are replaced by larger vessels when scrapped. In comparison to other vessel types, RoRo vessels have the largest negative abatement cost.

According to Lindstad et al. (2012), several studies have shown that the effect of economies of scale has been underestimated in previous studies investigating abatement potential and emission reduction. The studies of DNV (DNV, 2010), and the Second IMO GHG Study 2009 (Buhaug et al., 2009) identified a potential of approximately 30% emission reduction at a negative abatement cost, excluding the effect of economies of scale. Lindstad et al. (2012) identified a reduction potential of 30% for the world fleet by economies of scale alone. This shows that the effect of building larger vessels is bigger than some studies have assumed.

3.3.1 EEDI

Abatement cost has also been discussed in relation to the EEDI requirements. All vessels must have an EEDI value below a given baseline to comply with the regulations. RoRo vessels were included in the EEDI regulations on the 17th of May 2013. The baseline, or the estimated index value, is calculated using Equation (3.1) and (3.2) (MEPC, 2013).

$$Estimated\ index\ value = f_{roroV} * 3.1144 * \frac{190 * \sum_{i=1}^{nME} P_{MEi} + 215 * P_{AE}}{Capacity * V_{ref}} \qquad (3.1)$$

$$f_{roroV} = \frac{-15571 * F_n^2 + 5538.4 * F_n - 132.67}{287} \tag{3.2}$$

According to Lindstad et al. (2012), most new RoRo vessels are above the baseline. This suggest that when the requirements become 30-35% stricter than today, it will become difficult for RoRo vessels to satisfy the regulations, using only technical improvements.

Previous studies have investigated how the EEDI baseline and the emission reduction measures could be related to the issue of cost-effectiveness (Eide, Endresen, Skjong, Longva, & Alvik, 2009; Eide, Longva, Hoffmann, Endresen, & Dalsøren, 2011; Hoffmann, Eide, & Endresen, 2012; Longva, Eide, & Skjong, 2010). These studies looked at several emission reduction measures, and evaluated their economic benefit.

A cost-effectiveness criterion, CATCH, was calculated for each measure (see Equation (3.3)), giving the cost of averting one tonne of CO_2-equivalence of heating (Longva et al., 2010). A negative CATCH implies that the measure is economically beneficial, due to reduction in fuel consumption being higher than the cost of implementing the measure.

$$CATCH = \frac{\Delta Cost - \Delta Benefit}{\Delta Emissions} \tag{3.3}$$

In addition to the cost-effectiveness criterion, an index (gram CO_2/tonne nm) for the ship was calculated using Equation (3.4) and (3.5). This index is used as a reference point for the existing vessels.

$$Index = \frac{Emission}{Transport\ Utility} \tag{3.4}$$

$$I = \frac{P * l * SFC * CF}{C * v} \tag{3.5}$$

where P is installed main engine power (kW); l is the main engine load as a fraction of MCR (%); SFC is the specific fuel consumption at the given main engine load (g fuel/kWh); CF is the carbon factor for the specific fuel (g CO_2/g fuel); C is the maximum load carrying capacity (tonnes) and v is the speed of the vessel at the given load (knots).

Each measure has an individual reduction effect (%) that is valid when no other measures are applied. However, when several measures are applied at the same time, the total emission reduction is lower than if each measure is implemented separately. This is called cumulative emission reduction. The cumulative emission reduction is used to calculate a new CATCH, called marginal CATCH. This signifies the cost of reducing the next percentage of emissions (Longva et al., 2010). The marginal CATCH is higher than the individual CATCH because the individual CATCH is based on a ship where no measures are implemented.

Eide et al. (2009) proposed a maximum limit of CATCH = 50 USD/tonne for the measures to be economically viable, based on values for reaching the 2°C set by the IPPC. This means that no emission reduction measures with a marginal CATCH > 50 USD/tonne should be included in the design, from an economic perspective. The EEDI baseline (I_R) is determined by reducing the index, I, with the percentage given by all measures with a CATCH < 50 USD/tonne. By using a cost-effectiveness criterion, the shipbuilders and designers would be free to choose the most cost-efficient technology to comply with the regulations. However, this decision criterion can result in lower emission reduction than possible, because measures that are not economically viable will be discarded.

Chapter 4

Environmental concerns of a RoRo vessel

The life cycle of a ship can be divided into three main phases; building, operation and scrapping. Figure 4.1 shows a simplified life cycle of a vessel, where dry-docking is included, in addition to the mentioned phases. The operation of the ship contributes most to its environmental impact (Fet & Hayman, 2000), and in a global scale, the building and dismantling phases are negligible. However, they have local impacts that should be included in an extensive analysis of the environmental impact of a ship (see Section 6.3 and 6.4 for results and discussion on this). Figure 4.1 illustrate the life cycle of a vessel.

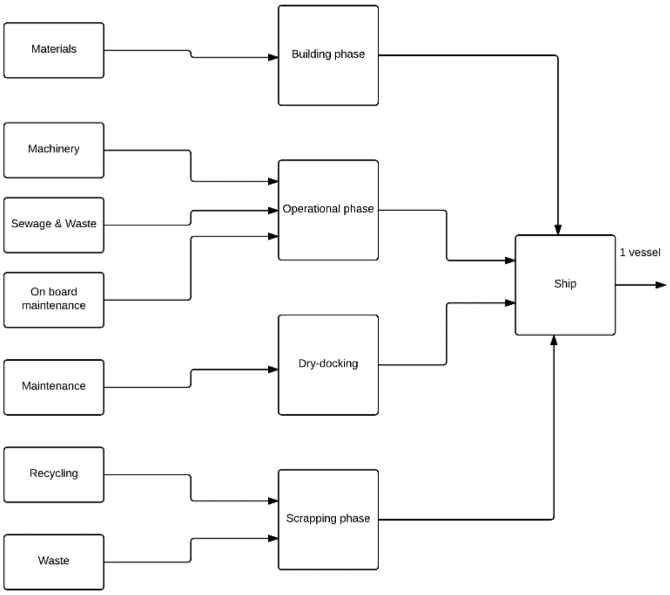

Figure 4.1: Life cycle of a vessel

4.1 Building phase

During the building of a vessel, there are several emissions related to water, air and waste (Fet & Hayman, 2000). The environmental impact depends on the technology used, but important processes are nevertheless; cutting, forming, joining, grinding, sandblasting, painting and outfitting. Substances from grinding and blasting, anti-fouling and coatings may transfer to the water, affecting the water quality and the organism habitat, while dust, particles and gases cause emissions to air.

Waste builds up during a building phase. Metal pieces, paint, cables and oil-contaminated waste are examples of waste that needs proper treatment to reduce environmental impact. Energy and material use are other processes that influence the environment because of the way they are produced (Hovind, 2015). Electricity produced by hydropower in Norway has approximately zero impact, while electricity mixes from China, usually made from hard coal, leave a large environmental footprint.

Energy production has a global impact if it is produced from coal, gas or oil, and material production has a global impact due to the power needed to make the materials. However, the main emissions related to ship building are only significant from a local perspective and the environmental impact of the building phase is almost negligible in a ship lifecycle.

4.2 Operational phase

The operational phase has the largest impact on the environment, and cause emissions to both air and sea (see Figure 4.2). The most acknowledged emissions by the public are oil spills as a result of collision or running aground, and the exhaust gases Carbon dioxide (CO_2), Nitrogen Oxides (NO_x) and Sulphur Oxides (SO_x).

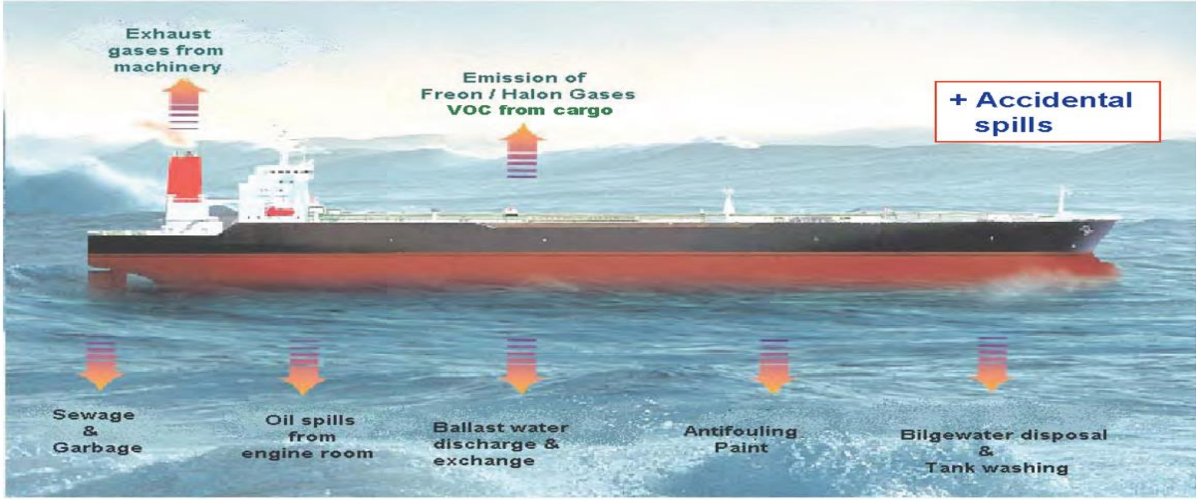

Figure 4.2: Emission from ships (Lindstad, 2015)

4.2.1 Exhaust gases from machinery

Exhaust gases from the machinery are both greenhouse gases (GHG) and conventional air pollutants. GHGs are defined as any gases that absorb infrared radiation in the atmosphere (EPA, 2015b). The primary GHG is CO_2, which is naturally present in the atmosphere and work as a heat-trapping gas, slowing the loss of heat to space (EPA, 2015b). Methane (CH_4), Nitrous Oxide (N_2O) and Fluorinated gases are other GHGs.

NO_x and SO_x are typical air pollutants resulting from anthropogenic activities. They are harmful to human health and the environment, in addition to causing property damage (EPA, 2015a). Other air pollutants are Carbon Monoxide (CO), Ozone (O_3) and Particulate Matter (PM). Black Carbon (BC) is the form of PM that is most effective at absorbing solar energy (EPA).

Some of the exhaust gases contribute to global warming, while others mitigate it. Both NO_x and SO_x have a cooling effect on global warming, due to alteration of clouds (Eyring et al., 2010). CO_2, CH_4 and BC on the other hand, contribute to a temperature increase (Parry & Intergovernmental Panel on Climate Change Working, 2007). BC reduces the albedo effect[1] of the surface it covers, by absorbing the energy from the sunlight (Dalsøren et al., 2013). This is especially critical for Arctic areas, because it speeds up the melting process.

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[1] Albedo effect is how much of the sun energy is reflected back to the atmosphere.

4.2.2 Sewage and garbage

Sewage and garbage come from toilets, galley drains and other parts of the crew and passenger accommodation. The pollution of sewage and garbage from ships impose several health and environmental impacts. Discharging raw sewage into the sea can force health hazards, oxygen depletion and visual pollution in coastal areas (IMO, 2013). The latter is of special concern for areas depending on tourism.

Throwing garbage overboard can be as deadly to marine life as oil or chemical spills (IMO, 2012). Garbage includes; food, domestic and operational waste, all types of plastic, cargo residues, incinerator ashes, cooking oil, fishing gear and animal carcasses. Plastic is one of the most critical types of garbage for marine life. It can float for years and is often mistaken for food by fish and other marine species. Additionally, it may trap the animals, causing stress and possible breathing problems. By having good reception facilities for garbage in ports, disposing at sea can be avoided.

4.2.3 Ballast water discharge and exchange

Shipping is considered the main cause of the high number of “invasive species” found in the oceans (Anon, 2009). This is due to the discharge and exchange of ballast water. A ship needs ballast water for stability when it has little cargo, and the water is discharged when new cargo is picked up. The sailing areas for a cargo ship are large, and a ship sails in waters containing thousands of different organisms. When ballast water is filled in one area and pumped into another, marine species are brought with it, infiltrating the habitat of other species.

According to World Wildlife Foundation (WWF, 2009a), about 7,000 marine and coastal species are transported across the world in ballast tanks every day. Examples of invasive species are microorganisms, algae, crab, mussels, fish and seaweed (DNVGL, 2014). The species bring with them diseases and cause changes in the food chains, which may result in extinction of local species. One example of this is the North American comb jellyfish. An invasion of this specie helped wipe out anchovy and sprat stocks in the Black Sea in the late 1980s, and has been reported spreading to the Caspian Sea, the North Sea and the Baltic Sea (WWF, 2009b).

4.2.4 Antifouling paint

A definition of antifouling is “a coating, paint, surface treatment, surface or device that is used on a ship to control or prevent attachment of unwanted organisms” (DNVGL, 2014). Antifouling paint limits the increase in ship resistance by avoiding organisms to attach to the hull, using biocides.

Throughout history, several compounds have been used in antifouling paint. Lime, arsenic and mercury were historically used in antifouling paint (Amdahl et al., 2011; DNVGL, 2014), but they were changed to the more traditional biocides, copper compounds and Tribultin (TBT). TBT was however banned following the AFS (Anti-Fouling System) Convention entering into force 17th of September 2008, due to large negative consequences to the environment (DNVGL, 2014). Debates on the environmental impact of biocides have taken place, and some of the biocides used have proven to be toxic to the marine environment (Guardiola, Cuesta, Meseguer, & Esteban, 2012).

Today, there are several types of antifouling paints (DNVGL, 2014), with and without biocides. One example is the Soluble Matrix Technology that releases biocides by physical partitioning of the paint. Another type of paint is the Contact Leaching Antifouling. This is hard and does not erode over time. A third type of paint is the Self-Polishing copolymer antifouling (SPC). There are two alternatives for SPC, either a silicon based coating that excludes the use of biocides, or a toxin antifouling that has active ingredients in the paint, providing a controlled release of biocides.

4.2.5 Maintenance

Maintenance can be divided into two main categories; preventive and corrective maintenance. Preventive maintenance is maintenance performed to avoid future component failure (Utne, Rasmussen, & NTNU, 2012). This type of maintenance is usually done at fixed intervals, for instance during docking or port stays. Corrective maintenance is performed on a component after it has failed, in order to get it to function again. Time intervals for corrective maintenance cannot be planned, as it is dependent on component failure. Corrective maintenance therefore has a bigger impact on cost and safety, than preventive maintenance.

There are several environmental impacts related to ship maintenance. As for the building phase, pollution to water due to hull surface cleaning, paint removal, changes of zinc anodes and paint applications may take place (Fet & Hayman, 2000). Emissions of solvents and dust can occur from sandblasting or similar operations, polluting the air.

Waste is also an important issue related to maintenance (Fet & Hayman, 2000). Machinery and auxiliary systems generate electronic waste and scrap-metals that need to be treated in the right manner to prevent pollution. This type of waste is produced when a component is broken or worn-out. To maintain the systems, new parts have to be produced and installed, causing emissions further up in the value chain.

4.2.6 Others

Emission of Freon/halon gases (VOC from cargo)

Freon and halon gases contribute to rapid decomposition of the ozone layer. However, both gases are prohibited today, and are not relevant for an LCA. Volatile organic compounds (VOC) are organic chemicals that have a high vapour pressure at ordinary, room-temperature conditions (Lindstad, 2015). They contribute to global warming, and to the decomposition of the ozone layer, in addition to causing respiratory disorders. VOC emissions are mainly related to loading and unloading of crude oil from tankers, and are not considered relevant for RoRo vessels.

Bilge water disposal and tank washing

Bilge water disposal and tank washing are not considered relevant issues for RoRo. The cargo space of these vessels does not contain cargo with danger of spilling oil or toxic components.

Oil spills from engine room

Oil spills are easy to spot, since oil has a lower density than water, and will float. The spills are bad for the biological environment, and affect both animals living in the water and the ones living on land. Approximately two thirds of the oil spills from shipping are mainly due to spills of oil-containing water and grease from the machinery systems (Amdahl et al., 2011). Separation, filtering and storage of the oily water and grease can greatly reduce the environmental impact.

4.3 Scrapping

Ship recycling and scrapping impose health, safety and environmental issues (Chang, Wang, & Durak, 2010; DNVGL, 2014). Prior to 2009, most vessels were scrapped and recycled on beaches in Asia due to high costs of using recycling facilities (Chang et al., 2010). The Convention on Ship Recycling was adopted in May 2009 (also known as the Hong Kong convention) to provide regulations for safe and environmentally friendly ship recycling (DNVGL, 2014).

A vessel mainly consists of recyclable materials, such as steel, but it also contains hazardous and toxic substances. Following the Convention on Ship Recycling, all vessels must have a list of hazardous materials on board, if they are to be delivered to a ship recycling facility. This helps enforce safe handling of dangerous compounds. Important environmental concerns related to ship scrapping are listed below (Fet & Hayman, 2000).

- Cathodic protection (Al, Zn)
- Batteries (Pb, Cd, Ni and sulphuric acid)
- Coatings and paint (PCB, Cu, Zn, Cl and TBT)
- Firefighting agents
- Thermal insulation (asbestos, PCB)
- The hull and large steel structures (Fe)
- Electric cables (Cu)
- Electrical systems (Cu, PVC, PCB, Pb, Hg)
- Hydrocarbons and cargo residues

Chapter 5

LCA Methodology

5.1 Introduction

Given the environmental concerns the world is facing today, the need for tools to guide technology in a sustainable direction increases. LCA is such a tool. It is a holistic approach, able to analyse the environmental impact of a product from cradle to grave. The LCA methodology is described through its four phases in this chapter, and an overview of the method is shown in Figure 5.1.

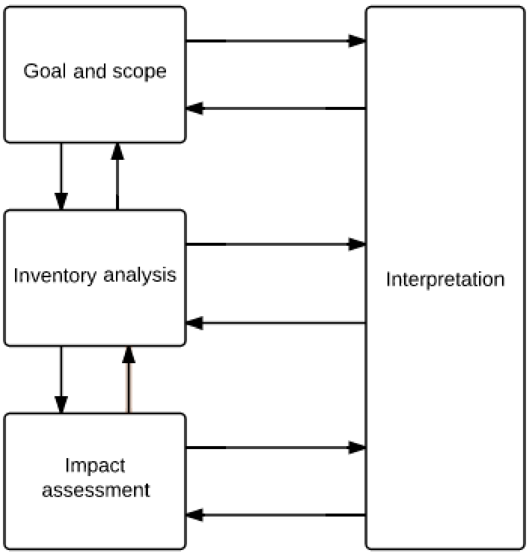


Figure 5.1: Overview LCA methodology

5.2 Goal and scope definition

An LCA begins with the goal and scope definition. The goal identifies the intended application of the assessment, why the study is done, whom the results of the study are intended for and whether the results are intended to be used in work disclosed to the public (ISO14040, 2006).

The scope definition includes making methodological choices. For an LCA, this includes determining the functional unit, the system boundaries and the allocation method intended for the study. In addition, the assumptions and limitations of the study, data type and choice of impact categories should be presented.

5.2.1 Functional unit

The functional unit is a measure of the function of the system that is studied, and it is used as a reference for the inputs and outputs (ISO14040, 2006). The choice of a functional unit is important for a good result, but it can also be difficult to find a unit that is a good representation of the problem at hand.

The functional unit has to make it possible to compare the solutions of the assessment. If it only represents a part of the problem, it can be hard to make an interpretation of the results. An example of a functional unit for material selection can be the production of one bike. For a comparison of two modes of transportation, a functional unit can be 1 km of transportation. The functional unit should be chosen through elaboration of the collected data and the study (Life, 2006).

5.2.2 System boundaries

The system boundaries are used to determine which processes that should be included in the assessment. An LCA is defined as a holistic approach, but a definition of the system boundaries is important to limit the problem. Selecting the system boundaries is a subjective choice, made during the scope definition (Life, 2006).

The issue of a life cycle is extensive, and the activities are often interrelated. There is no clear beginning or end. A system boundary helps determining the beginning and the end of the analysis. An example of a system boundary is a cradle-to-grave analysis. This includes everything from raw material extraction, production and waste treatment. It is also possible to narrow the problem by excluding one or several of the life cycle phases.

5.2.3 Allocation methods

When two or more products share a process, several outputs are generated. This addresses the issue of allocation. How should the emissions from the upstream operation and upstream environmental loads be allocated to the different products (Curran, 2012)?

There are several methods for handling allocations. Subdivision of the processes, aggregation of the functional unit or manipulation of the functional unit can be used to avoid allocation (Cherubini, 2015). Nevertheless, it is not always possible to avoid, and two methods for handling allocation are described in the next paragraph.

The two most common methods are the substitution approach (system expansion method) and the partitioning approach. The substitution method, also known as system boundary expansions, defines a main product of the production of co-products. When identifying the impact related to the main product, the impact of producing a co-product, as a bi-product, is found (for instance using a new technology), and it is subtracted from the total impact of the process. The system boundary is therefore expanded to include other ways of producing the co-product (Cherubini, 2015). The partitioning method resolve the problem of allocation by dividing the resource consumptions and emissions between the multiple products (Baumann & Tillman, 2004), using partitioning coefficients. Mass, volume, energy or economic measures are examples of such coefficients.

5.3 Life cycle inventory

Life cycle inventory constitutes the foundation of the life cycle assessment, by defining inventory for the system (Curran, 2012). The inventory quantifies the inputs and outputs of the problem, and is the most resource consuming part of an LCA. A general inventory process is shown in Figure 5.2.

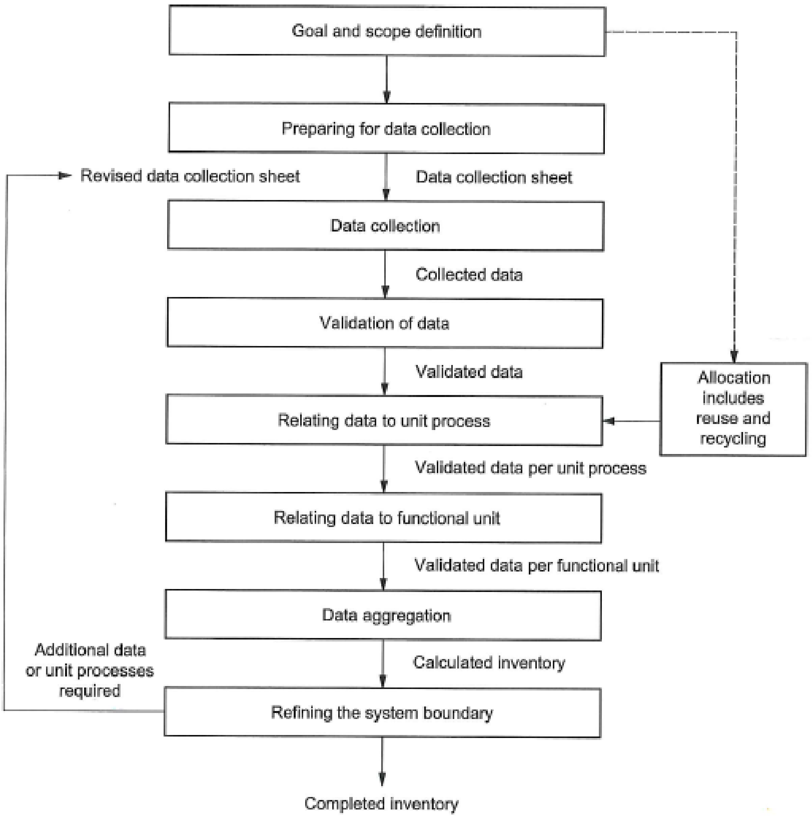


Figure 5.2: Life cycle inventory process

An inventory consists of the following steps; drawing of a flow chart based on the system boundaries defined in the scope, data collection and calculations of environmental loads. The flow chart is an illustration of the problem, based on the system boundaries defined in the scope. Flow charts are important when the LCA problem is communicated to others. It should describe the entire problem, including all relevant processes, flows and emissions.

Validation of data should be done throughout the analysis (ISO14044, 2006), to ensure that the data is understood and the system boundaries are valid for the problem at hand (Baumann & Tillman, 2004). It may be difficult to find good data, but choosing the most accurate sources will increase the end quality of the assessment.

The calculation of environmental loads includes solving allocation issues. According to ISO 14044, allocation should be avoided whenever it is possible, by using system boundary expansion. When allocation cannot be avoided, partitioning reflecting the physical relationship between different products should be tried first, before partitioning reflecting other types of relationships between products are used.

5.4 Life cycle impact assessment

During the impact assessment, the environmental loads from the inventory are translated to environmental impacts (Baumann & Tillman, 2004). The phase includes the selection of impact categories, category indicators and characterisation models (ISO14044, 2006). A definition of each impact category is given in Appendix A.

The first step of the LCIA is the classification, which is the assignment of environmental loads to the selected impact categories. The next step is the characterisation, which is the calculation of category indicator results. The LCI results are here converted to common units, making it possible to accumulate the converted environmental loads within the same impact category (ISO14044, 2006). The conversion is done using characterisation factors. An example of characterisation is how methane emissions are converted to kg of CO_2 equivalents, to make it possible to aggregate the results with other emissions affecting climate change. The characterisation factor for methane is 23 kg of CO_2 equivalents per kg CH (Strømman, 2010).

Figure 5.3 shows how the results from the inventory are used in the impact assessment. The figure also divides between midpoints (impact categories) and endpoints (areas of protection).

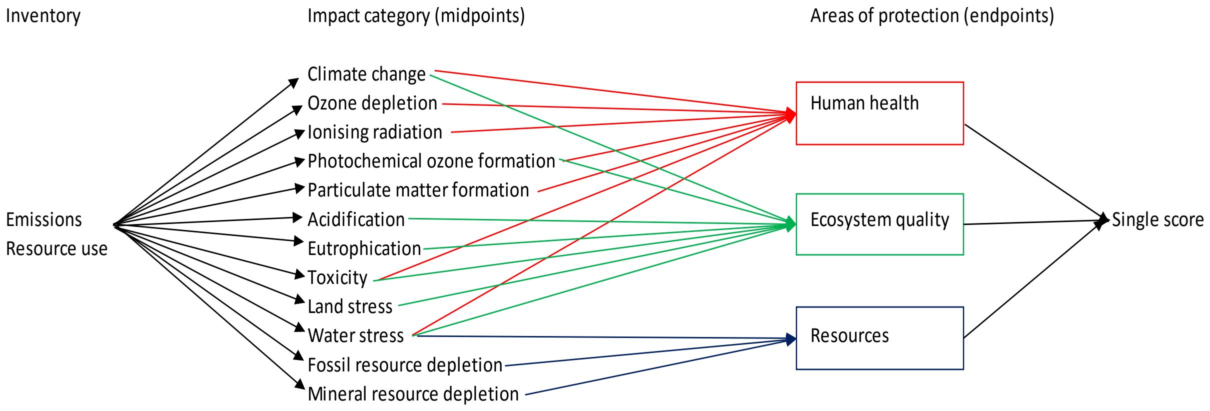


Figure 5.3: Overview of the elements of a life cycle impact assessment (Verones, 2015)

There are three ways to present the results from an LCA; midpoint approach, endpoint approach and as a single score (as shown in Figure 5.3). The midpoint approach is the presentation of the total environmental impact for the chosen impact categories. However, it is possible to accumulate the results into three areas of protection. These are Human health, Ecosystem quality and Resource scarcity. Figure 5.3 shows which impact categories affect which areas of protection. It is most common to present the midpoint results, because the endpoint results are more uncertain, due to the factors used to convert from midpoint to endpoint (Curran, 2012).

5.5 Life cycle interpretation

The last phase of the LCA is the interpretation. The aim of this phase is to deliver results that are consistent with the goal and scope of the study, clarify the limitations and give recommendations for the decision-makers (ISO14040, 2006). The results of the LCI and the LCIA are interpreted together in this phase, and significant issues should be identified from the findings. Caution should be taken when interpreting the results from the inventory, since the results refer to input and output data, and not to environmental impact (ISO14044, 2006).

Chapter 6

LCA modelling

6.1 Goal, scope and boundaries

The main intention of this chapter is to perform an LCA study, to compare the environmental impact of vessels with different cargo capacity and size. It is assumed that the vessels have the same operational pattern through their lifecycles, sailing 75% of the time with 100% utilisation and spending 25% of the time in port.

6.1.1 System boundaries and functional unit

The building phase, operational phase and scrapping phase were all included in the life cycle assessment, to determine the impact of the total life cycle from cradle to grave. The emissions related to building and scrapping occur once throughout the life cycle, while the emissions from the operational phase recur every year. To adjust for the differences, the operational processes are given yearly, while the input to the end process is 30 years. Dry-docking is also included, and is assumed every five years for the first 15 years, and every 2.5 years the rest of the lifetime.

The functional unit is given in emissions per year. This is obtained by dividing the demand of one vessel by 30. The choice of functional unit is made because the results from one analysis can be used for different capacities, by changing the transport work. When calculating emissions depending on utilisation, the results used have to be flexible with regards to transport work.

The amount of data included in the assessment is limited by the lack of available data and calculation methods. In addition, some of the emissions described in Section 4.2.1 have not been included due to little relevance, or due to lack of appropriate processes in the Ecoinvent database.

6.1.2 Allocation issues

Allocation has been avoided as much as possible in this problem. The functional unit is given per year. This type of functional unit does not require any allocation (Cherubini, 2015). The recycling part of the inventory could have caused allocation issues. However, the recycling was only inserted in one phase, avoiding potential problems. This is described in section 6.2.9.

6.1.3 Database and analysis tool

The life cycle impact assessment is calculated using Arda. This is a tool that was developed at NTNU, to meet the needs of the studies done at the University. Arda uses the ReCiPe method to calculate the impacts, and the Ecoinvent database to accumulate process data. Arda runs through Matlab, and a template is uploaded containing the life cycle inventory.

The Ecoinvent database is a commercial database containing process data for thousands of products (Ecoinvent, 2016). The database is known as the best and most complete database, focusing on European purposes (Strømman, 2010). It is a collaboration of several institutions, and it is a continuation of the ETH-ESU 96 database.

6.1.4 Choice of vessels and impact categories

Five different designs were included in the LCA. The smallest vessel has a capacity of 2,000 RT, while the largest design can take up to 10,000 vehicles. The main dimensions and some key parameters of the vessels are shown in Table 6.1.

Table 6.1: Overview of design parameters for Case 1-5

		Case 1	Case 2	Case 3	Case 4	Case 5
Car capacity	RT	2,000	4,000	6,000	8,000	10,000
Deck Area	m^2	16,500	33,000	49,800	66,400	83,000
LOA	m	156	189	211	228	243
B	m	21.9	26.4	29.6	32.0	34.1
T	m	7.0	8.4	9.4	10.2	10.8
Lightship weight	t	7,700	12,700	17,000	21,000	24,600
Service speed	kn	17.0	18.0	19.0	20.0	20.0
Main engine MCR	kW	5,600	8,600	12,600	17,900	18,400
Propulsion power	kW	3,100	4,800	7,000	10,000	10,200
M/E FOC	t/d	13.4	20.7	30.2	42.8	44.0
Sailing distance per year	nm/y	93,600	99,100	104,700	110,200	110,200

The analysis focuses on environmental impact on climate change, human toxicity and terrestrial acidification. Climate change is a logical choice of impact category, due to the increased focus on global warming in relation to shipping. Human toxicity was selected because it is interesting to investigate the effect of shipping on human health. According to Gamlem (2016a), a large part of deep-sea RoRo routes is close to shore, and can effect humans. The focus on reducing SO_x and NO_x emissions is high in the shipping industry. The gasses can travel a great distance before causing acid rain in other parts of the world. Due to this, terrestrial acidification was selected as the last impact category.

6.2 Life cycle inventory

The data used in the inventory is based on information from Wilh. Wilhelmsen ASA (Gamlem, 2016b). Some of the data is based on assumptions and relationships between parameters, since less detailed information is provided on the subject. Other data is calculated, and is hopefully a good representation of the reality. The problem is modelled as showed in Figure 6.1, and the full inventories are found in Appendix B.

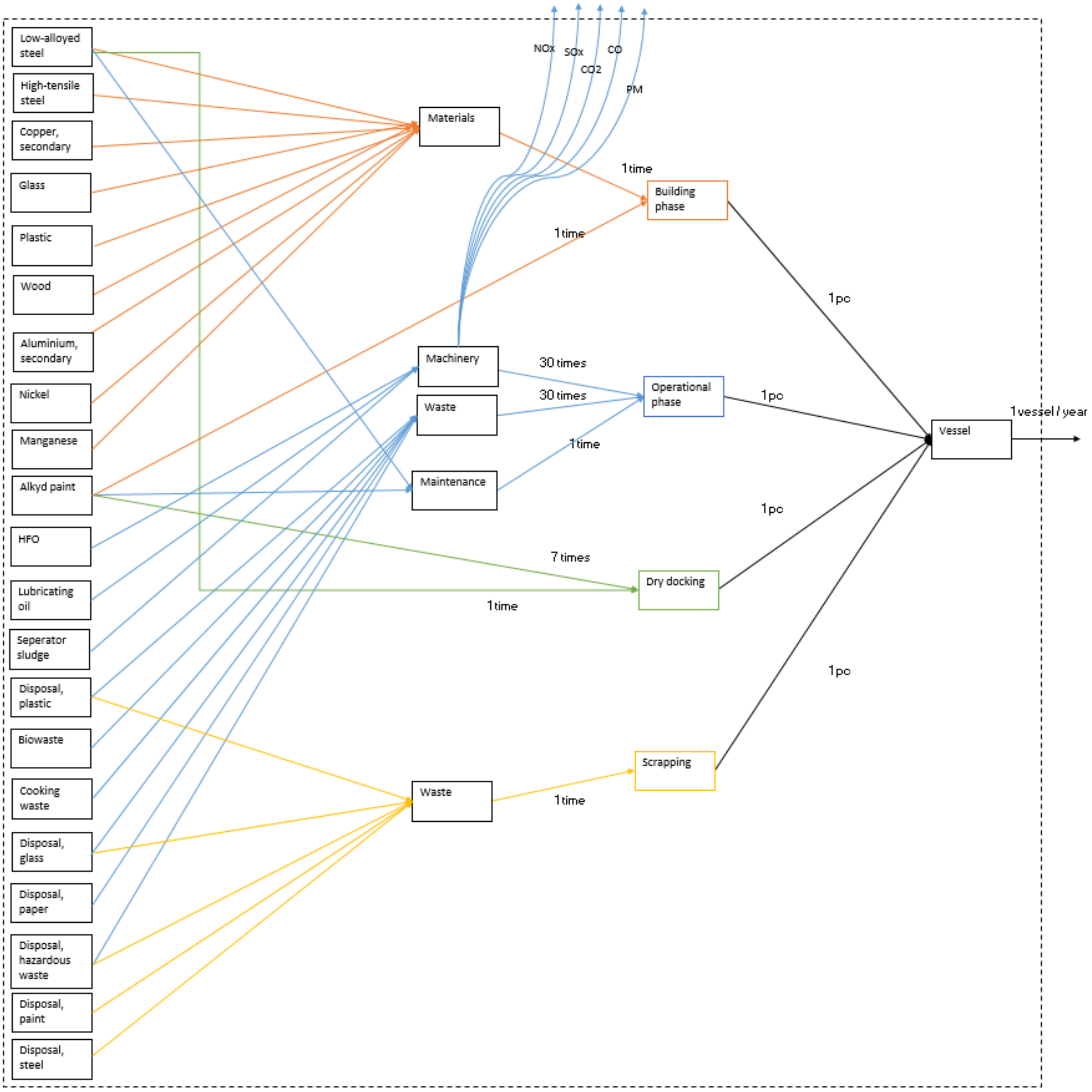


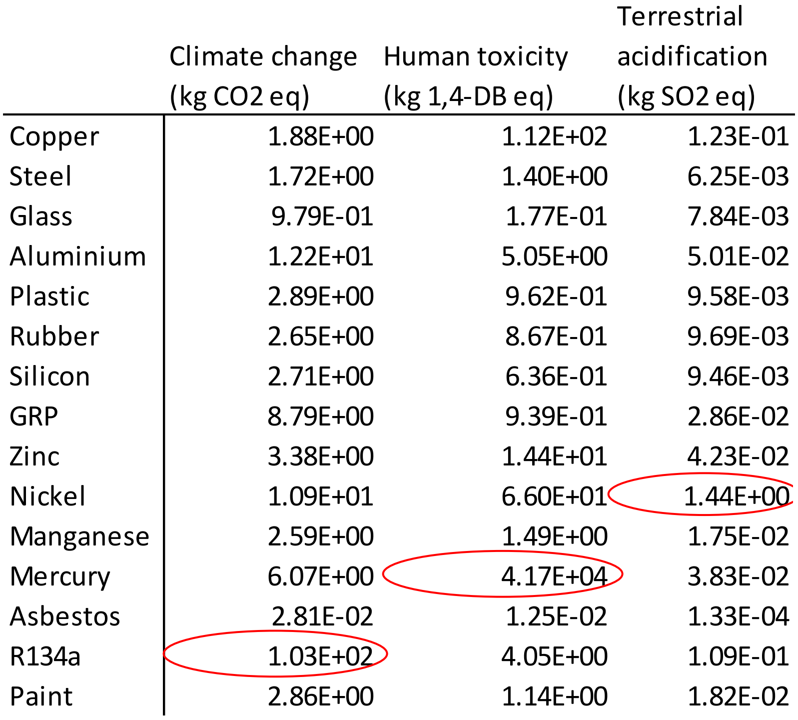
Figure 6.1: Flow chart of LCI

As seen from the figure, the problem can be divided into the three above-mentioned phases, plus dry-docking. These foreground processes are then divided into smaller processes again, to illustrate the various elements of each phase.

6.2.1 Comparison of the environmental impact of different materials

A study was executed to determine the environmental impact of different materials. The intention of the study was to better understand the importance of the materials, and their footprint. Three impact categories were investigated, as shown in Table 6.2.

Table 6.2: Environmental impact of different materials



	Climate change (kg CO2 eq)	Human toxicity (kg 1,4-DB eq)	Terrestrial acidification (kg SO2 eq)
Copper	1.88E+00	1.12E+02	1.23E-01
Steel	1.72E+00	1.40E+00	6.25E-03
Glass	9.79E-01	1.77E-01	7.84E-03
Aluminium	1.22E+01	5.05E+00	5.01E-02
Plastic	2.89E+00	9.62E-01	9.58E-03
Rubber	2.65E+00	8.67E-01	9.69E-03
Silicon	2.71E+00	6.36E-01	9.46E-03
GRP	8.79E+00	9.39E-01	2.86E-02
Zinc	3.38E+00	1.44E+01	4.23E-02
Nickel	1.09E+01	6.60E+01	1.44E+00
Manganese	2.59E+00	1.49E+00	1.75E-02
Mercury	6.07E+00	4.17E+04	3.83E-02
Asbestos	2.81E-02	1.25E-02	1.33E-04
R134a	1.03E+02	4.05E+00	1.09E-01
Paint	2.86E+00	1.14E+00	1.82E-02

The red marks show the materials with the highest impact for climate change, human toxicity and terrestrial acidification.

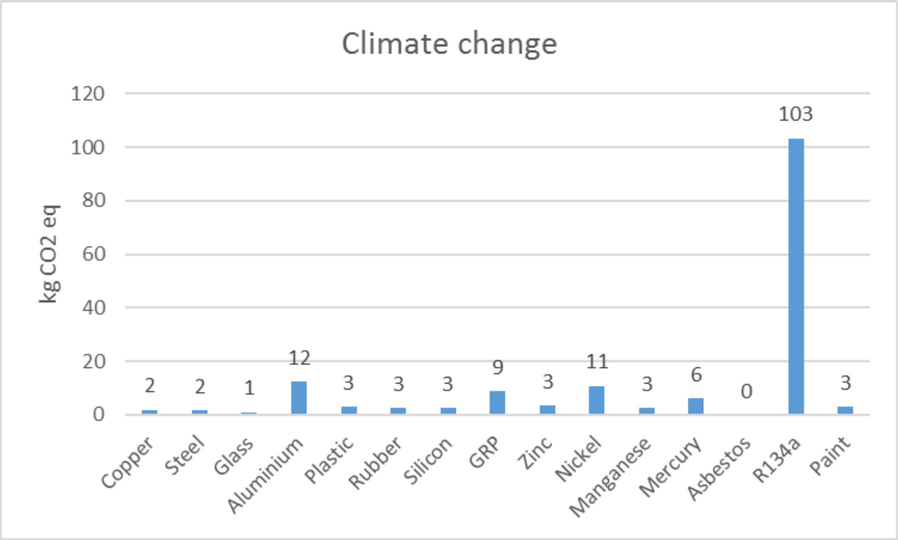


Figure 6.2: Material's impact on Climate change

From Figure 6.2, it is seen that R134a is the material with the highest impact on climate change. Per kilogram of R134a used, 103 kg CO_2-equivalents are produced. R134a is a hydrofluorocarbon refrigerant, used in fridges and icemakers. In comparison, aluminium creates 12 kg of CO_2-equivalents per kg, mainly due to the extensive process of extracting and producing pure aluminium. Furthermore, aluminium has an impact on climate change that is six times the impact of steel. In theory, an aluminium structure has to be six times lighter than an equivalent steel structure, to have the same environmental impact.

However, the analysis does not include recycling of materials. When recycling materials, some of the emissions from the production process are retrieved, making the overall impact lower. Due to the extensive process of making aluminium, it is more common to use secondary aluminium than primary, and some of the emissions related to the material are saved. Nickel, glass-reinforced plastic (GRP) and mercury also have a substantial impact on climate change.

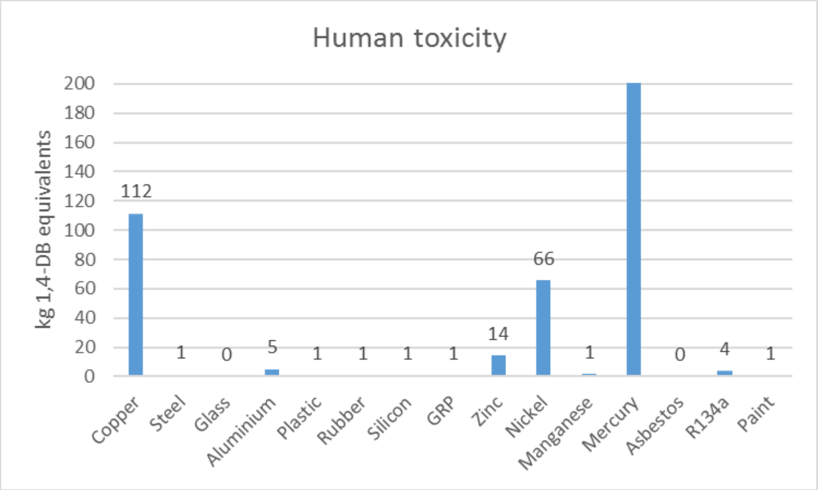


Figure 6.3: Material’s impact on Human toxicity

When looking at human toxicity, one material has a much higher impact than the others, as seen from Figure 6.3. Mercury creates approximately 41,700 kg 1,4 dichlorobenzene (DB) equivalents per kg material used. In comparison, copper has an impact of 112 kg 1,4 DB equivalents per kg material. It was expected that asbestos would have a high impact on human toxicity. However, the analysis gave low impact of asbestos for all impact categories, implying that the emissions related to the asbestos process chosen from the Ecoinvent database are low, and not representative of the type of asbestos associated with ship scrapping.

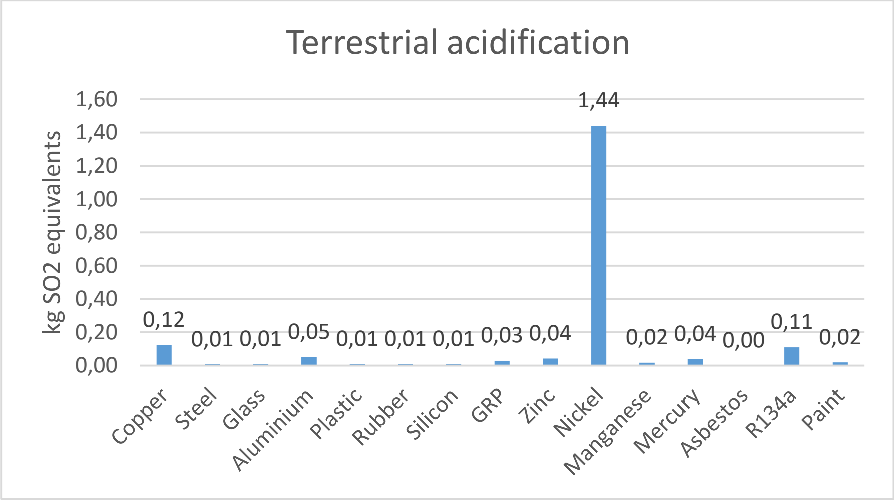


Figure 6.4: Material’s impact on Terrestrial acidification

Terrestrial acidification was the last impact category that was analysed. Nickel is the material with highest impact, with 1.44 kg SO_2 equivalents per kg used. From Figure 6.4, it is seen that the impact of the other materials are almost negligible in comparison to nickel. However, copper and R134a have a higher impact than the rest, with 0.12 kg SO_2 equivalents and 0.11 kg SO_2 equivalents per kg, respectively.

The study shows that there are differences in the impact of materials. Even though some materials are in small amounts, the impact on climate change, human toxicity or terrestrial acidification can be large. Materials that are worth noticing when doing an LCA are mercury, copper, R134a and aluminium.

6.2.2 Materials

A ship consists mainly of steel, but other materials such as copper, plastic and glass are present as well. The material breakdown for the cases is based on the lightweight breakdown of a LCTC (Large car truck carrier) from WW ASA (Gamlem, 2016b).

Every vessel is different, and one lightweight breakdown may not be representative of another vessel. For the inventory of this problem, it was assumed that the five cases were identical types of vessels, only with different capacity and sizes. This avoids the problem of fitting different lightweight breakdowns to each case. The assumptions made for the lightweight were similar for all the vessels, and are presented below.

- 35% of the steel is high-tensile steel
- 20% of the piping system is copper pipes
- The accommodation consists of 20% steel, 20% glass, 20% plastic and 40% wood
- Materials for machinery and mooring are more similar for the different sizes, while the amount of steel increases faster with larger capacity and size.

Even though steel is the most used material in ships, it is important to identify other, potentially more harming materials. One example of this is copper. Copper is one of the main materials used in electric components, and it is also used in pipes for compressed air. 1 kg of copper has a larger environmental impact than steel in each of the three impact categories. It has 9% higher impact on climate change and 99% higher impact on human toxicity than steel, meaning that 9% more steel could be used without having larger impact on climate change than copper (see Table 6.2).

6.2.3 Energy

Energy consumption during the building phase is not included in the inventory, due to lack of information on energy consumption at the yards. The yards are taking measures to reduce their environmental footprint, by looking to other energy sources (HHI, 2013). However, they do not say anything about how much, and what type of energy is used to build a vessel. It is therefore better to exclude the process, instead of using a wrong estimate that can give incorrect results. The energy used to produce steel, aluminium, plastic and copper are however included in the assessment, since processes for this were available in the Ecoinvent database.

6.2.4 Machinery

Fuel oil consumption

The fuel consumption (FOC) was assumed constant throughout the lifetime, and was therefore only calculated for one year and multiplied by a lifetime of 30 years. The daily fuel consumption for main and auxiliary engines were given from Gamlem (2016). It was assumed 75% sailing time and 25% port-stay for all vessels, based on operational patterns from Wilh. Wilhelmsen vessels (Gamlem, 2016b).

First, the amount of days sailed per year was calculated from the sailing distance per year and the eco speed (propulsion power is based on V_{eco}). Then total FOC per year was calculated, using Equation (6.1).

$$\begin{aligned}(Main\ engine\ FOC +\ Aux.engine\ FOC\ at\ sea) * Days\ sailed\ per\ year \\ +\ Aux.enigne\ FOC\ in\ port * (365 - Days\ sailed\ per\ year)\end{aligned} \tag{6.1}$$

Lubrication oil

Lubrication oil can be divided into two types; cylinder oil and system oil. The cylinder oil is used for the engine cylinders, while the system oil lubricates the rest of the engine (Rajeevan, 2016). The cylinder oil consumption was set to 0.6 g/kWh, based on engine data from MAN Diesel & Turbo (MAN, 2016). For the main engine, it was assumed that the system oil consumption was 25% of the cylinder oil consumption. The auxiliary engine was assumed to use 50% of the system oil consumption of the main engine. These estimates were made based on purchase data for system oil and cylinder oil, for several WWL vessels (Rajeevan, 2016).

To obtain the total lubrication oil consumption, the propulsion power and amount of hours sailed, or in port, were multiplied by the consumption in g/kWh. For the assessment, the type of oil was assumed equal, because the Ecoinvent database only contain one process for lubrication oil.

Sludge

The sludge is calculated from the amount of HFO used. The amount of sludge was assumed to be 1% of the total HFO consumption. This was based on experience from vessel managers at Wilhelmsen Ship Management (Ulstein, 2016).

Emissions from combustion of fuel

The emissions related to the combustion of the heavy fuel oil (stressors) were calculated based on ISO 8178-1:2006 and Regulation 13 and 14 of MARPOL (International Maritime, 2011; ISO8178-1, 2006). It was assumed that the vessels sail 20% in SECA areas and 17% of the time in NECA areas (Gamlem, 2016b). The limits for NO_x emissions are shown in Table 6.3.

Table 6.3: NOx emission limits (IMO, 2016c)

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 – 1999	n ≥ 2,000
I	1 January 2,000	17.0	$45 \cdot n^{-0.2}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{-0.23}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{-0.2}$ e.g., 720 rpm – 2.4	2.0

The engines of the investigated designs are slow, and have a n = 105 rpm. This gives a limit of 3.4 g/kWh in NECA, where Tier III is applicable, and 14.4 g/kWh outside NECA, where Tier II is applicable. The tier limits are the maximum allowed emissions. NO_x emissions are engine specific, and the most accurate results are obtained through measurements. Since the engines used for the five cases are similar, the tier limits have been used to illustrate the emissions, even though it is not as exact as measurements.

The NO_x emissions were calculated using Equation (6.2) (BW, 2014).

$$NO_x\ emissions\ [kg] = \frac{Engine\ load\ [kW] \times NO_x\ limit\ \left[\frac{g}{kWh}\right] \times Time\ sailed\ in\ area\ [h]}{1000\ \left[\frac{g}{kg}\right]} \tag{6.2}$$

Sulphur emissions are regulated by the amount of sulphur allowed in the fuel. The limit is 0.1 % m/m inside SECA and 3.5 % m/m outside SECA (International Maritime, 2011). However, WWL has a policy on Sulphur emissions, only allowing 1 % m/m sulphur outside of SECA. This limit was used for calculating SO_x emissions.

The SO_x emissions were calculated using Equation (6.3) (ISO8178-1, 2006).

$$SO_x\ emissions\ [kg] = FOC\ [kg] \times Sulphur\ content\ [\%] \times 0.02 \tag{6.3}$$

CO_2 emissions depend on the carbon content of the fuel. Heavy fuel oil has a CO_2/fuel-carbon ratio (C_{carbon}) of 3.114, meaning that there are 3.114 tons of CO_2 per ton HFO. The CO_2 emissions were calculated using Equation (6.4) (BW, 2014).

$$CO_2\ emissions\ [kg] = FOC\ [t] \times C_{carbon} \left[\frac{t\ CO_2}{t\ fuel}\right] \tag{6.4}$$

As mentioned in Section 4.2.1, there are several other emissions related to the combustion of fuel. Many of these emissions are difficult to calculate, and are based on engine measurements. To include as much as possible in this assessment, estimates from BW (2014) were used to calculate CO and PM emissions (BW, 2014). The amendment gives approximate specific emission levels for operation on diesel for 100% load, 75% load and 50% load. These emission levels do not give correct values for 90% MCR for HFO, but they give approximate values that are better than excluding the emissions. The specific emission levels are given in Table 6.4.

Table 6.4: Approximate specific emission levels for operation on diesel (BW, 2014)

Spesific emission [g/kWh]	100 % load	75% load	50% load
CO	0.2	0.2	0.3
PM	0.5	0.3	0.5

The emissions were calculated using Equation (6.5).

$$Emission\ [kg] = \frac{Specific\ emission\ level\ \left[\frac{g}{kWh}\right] \times Engine\ load\ [kW] \times Time\ sailed\ [h]}{1000\ \left[\frac{g}{kg}\right]} \tag{6.5}$$

6.2.5 Sewage & garbage

Data on garbage was received from a chief officer on one of WWLs vessels (Gosain, 2016). Five types of garbage were reported; plastics, food waste, domestic waste, cooking oil and operational waste. Domestic waste is defined as all waste, not covered by other regulations, that are generated in the accommodation spaces on board the ship. Examples of domestic waste are paper, glass bottles and rags. Operational waste is defined as all solid wastes, not covered by other regulations, that are collected on board during normal maintenance or operations of a ship, or used for cargo stowage and handling (Gosain, 2016). An example of operational waste is oily rags. The operational waste was assumed to be hazardous because no other appropriate processes could be found in the Ecoinvent database.

The garbage amounts were given in cubic metres, and had to be converted to kg for the assessment. Below are the densities used for the conversions listed.

- Plastic: 75 kg/m^3
- Food wastes: 514 kg/m^3
- Domestic waste
    - Paper: 152 kg/m^3

    - Glass bottles: 250 kg/m^3
- Cooking oil: 920 kg/m^3
- Operational waste
    - Oily rags: 100 kg/m^3 (based on the density of textiles)

6.2.6 Ballast water

Ballast water was not included in the LCA. The Ecoinvent database does not contain processes specific for the maritime industry, and processes that can represent the environmental impact of ballast water does not exist.

6.2.7 Painting

The first time the vessel is painted, is when it is built. To protect the hull and to keep it from fouling, the hull is frequently painted. There are two ways the hull can be painted, either during dry-dock every 2.5 to 5th year, or by the crew during voyage (using sea-stock paint). In the LCA, the paint was divided between the different foreground processes. In the Ecoinvent database, the paint is given in kilograms, while the amounts from the manufacturers were given in litres. A density of 1.313 kg/l was used to convert to the correct unit.

Data from paint producers was utilised to calculate the total amount of paint used throughout the vessel lifetime (Brynjulfsen, 2016). Several types of paint are used, but the Ecoinvent only contains Alkyd paint. In this inventory, all the paint was therefore assumed to be this type. This makes the analysis less realistic, but it will not affect the comparison of the vessels, since the assumption is valid for all the designs.

6.2.8 Dry-docking

The work done during dry-docking consisted of paint and steel. The assumptions for paint are described above. Additionally, it was assumed that 100 tonnes of steel were used during dry-docking.

6.2.9 Scrapping

Data for the scrapping phase was based on the Inventory of Hazardous Materials. Important materials were identified using the results presented in Section 6.2.2, as a reference.

Recycling

Between 85-90% of all materials used in a vessel are recycled (Carvalho, Antão, & Soares, 2011). Recycling a material compensates for some of the emissions from the production phase, and the total environmental impact is reduced. A few materials have processes related to recycling in the Ecoinvent database, while for other materials, the recycling has to be modelled separately.

Due to limited time and knowledge on recycling modelling, the materials that did not have a process related to recycling were assumed to be disposed. Copper and aluminium were modelled to include recycling. In Ecoinvent, both materials have processes where the material used for building is secondary, meaning that the material is recycled. To include recycling for copper and aluminium, the input material to the building phase was secondary material, not primary. This is not a correct presentation, since shipbuilding is mostly done with primary materials, but it was done to avoid excluding all types of recycling. The result of this is that the emissions related to the recycling process and the material conversion is added to the building phase and the scrapping phase emissions are lower than in reality. However, when the analysis was run with and without recycling, the increase and decrease in environmental impact for the building and scrapping phase were so small that the total impact on the results are almost negligible.

Waste treatment

Not all materials can be recycled, and the ones that cannot have to go through waste treatment, before final disposal. There are several types of waste treatment. Incineration, landfill and deposits are a few examples. According to Gamlem (2016), WWL stopped using incineration as a waste treatment method. Therefore, all materials are transported to landfill or deposits in this thesis.

6.3 Life cycle impact assessment

The results from the impact assessment make it possible to compare the environmental impact of the different life cycle phases of a vessel. The total impact is given for the impact categories, in addition to a breakdown of the total impact for the foreground processes. Table 6**.5** shows the distribution of the impact from the building phase, operational phase, dry-docking and the scrapping phase for climate change, human toxicity and terrestrial acidification, for the 6,000 RT vessel.

Table 6.5: Results from LCIA

Impact category	Building phase [%]	Operational phase [%]	Dry-docking [%]	Scrapping phase [%]
Climate change	7	93	0	0
Human toxicity (landfill)	63	36	1	0
Human toxicity (incineration)	49	28	0	23
Terrestrial acidification	2	98	0	0

It is seen from the table that the contributions from dry-docking and the scrapping phase, on climate change, are so small that they are negligible. As expected, the operational phase has the highest impact on climate change, with 93% of the emissions. The building phase has an impact of 7% on climate change. The smaller and larger vessels have approximately the same distribution, and are therefore not shown. The trend is that the operational phase is 1% more important for the smaller vessels (94%), than for the largest ones.

For human toxicity, the distribution is different. The contribution from the dry-docking and scrapping phase is still negligible, but the building phase contributes more than the operational phase. There is no clear trend for the different vessel sizes, but the impact of the building phase varies from 61% to 65%, where the 4,000 RT vessel has 65% and the 8,000 RT vessel has 61% impact from the building phase.

To illustrate the impact of waste treatment method, an analysis using incineration as waste treatment was used for steel and plastic. The results gave the distribution described as human toxicity (incineration), in Table 6.**5**. When using incineration, the impact of the scrapping phase on human toxicity increases from almost negligible, to approximately 23%. The impact on climate change and terrestrial acidification did not change noticeably. However, these findings show how changes in technology can have a small influence on one impact category, while completely changing the outcome of another.

The emission distribution for terrestrial acidification is similar to the one for climate change. The operational phase is the largest contributor, due to exhaust gas emissions from combustion of heavy fuel oil. The building phase contribute to 2% of the emissions, while the dry-docking and the scrapping phases are negligible. The distribution for terrestrial acidification is similar for all five vessel sizes.

6.4 Life cycle interpretation

From the impact assessment, it is observed that the building and operational phase contributes most to the environmental impact of a vessel. Overall, the operational phase has the highest environmental impact of the phases of a vessel’s life cycle. For climate change and terrestrial acidification, the operational phase was the phase with the highest impact, as well as it having a substantial impact on human toxicity. This supports the argument made in Chapter 4, about the operational phase contributing most to the total emissions.

It is interesting to investigate the underlying causes of the contribution to the impact categories, to better understand which processes cause most emissions, and to take action in the right areas. A structural path analysis is a part of the impact assessment. The analysis maps the emissions from cradle-to-grave, making it easier to see what is causing the impact on the various impact categories. A structural path analysis was done for each of the three impact categories.

The results showed that the most contributing processes were similar for all vessel sizes. For climate change, the consumption of heavy fuel oil was the largest contributor. In addition, the production of HFO contributed to climate change, though not nearly as much as the combustion. The steel production at the steel mill did also have a high impact on climate change. The main reason for this, bearing in mind that several materials have worse environmental performance than steel, is the amount of steel used on the vessels. The analysis also showed that the disposal of steel and steel production were the largest contributors to human toxicity. Again, this is most likely due to the extensive amount of material consumed. Copper was also represented in the results, though with a lower impact than steel, due to the small amounts of copper, compared to steel. The results for terrestrial acidification showed that the contributing element was mainly fuel consumption during operation, but crude oil and natural gas used for burning and transportation during fuel production were also represented.

The small variations in the distribution of impact from one vessel size to another are because the consumption is not increasing linearly. The assumptions made in the building phase on steel weight, machinery and mooring, and the differences in sailing speed affecting sailing distance and fuel consumption, contribute to small variations in the impact from the different life cycle phases.

The results from the impact assessment show that measures have to be taken in several parts of the value chain, to reduce the total environmental impact of a vessel. Reductions of the emissions from the operational phase itself, by implementing sustainable solutions, are effective. Yet, it is possible to look for more sustainable solutions in the production processes as well. The results also present an interesting view on how shipping affects other aspects of the planet, other than climate change. This implies that the focus should not only be on global warming, but include impact on a local level as well. Material productions and dismantling, and emissions causing respiratory diseases and acidification should be taken seriously.

Chapter 7

Results

A final evaluation of the environmental impact, in addition to a LCC analysis, is presented in this chapter, with the goal of recommending whether or not it is sustainable to build even larger vessels than those existing today. The results from the LCA are used to find the relationship between environmental impact and utilisation to determine if building and using larger vessels are less pollutive than smaller vessels, despite the unused cargo space.

7.1 Brief summary of results from LCA

The life cycle assessment showed that the operational phase has the highest impact on climate change and terrestrial acidification, while the building phase has the largest impact on human toxicity. The processes causing the largest impacts are the heavy fuel oil consumption, heavy fuel oil production, steel production and disposal of steel (see section 6.3).

7.2 Capacity utilisation

7.2.1 Method for post-processing LCIA results

Emissions

There are different ways of illustrating the relationship between capacity utilisation and environmental impact. For this thesis, a comparison given in percentage has been used to illustrate the trends, without focusing too much on specific values (see Appendix C for utilisation calculations). Three different graphs are given for each impact category, illustrating the relationship between emissions of one vessel and utilisation, fleet emissions and utilisation and emissions of one vessel when transporting a specific amount of cargo. For all graphs, the

6,000 RT vessel at 95% utilisation is used as the reference point, equal to an emission level of 100%.

The method used to calculate the emission-utilisation relationship for a one vessel and a fleet perspective, is similar. From the LCIA, the total yearly emissions for one vessel are given. These results were used to calculate the emissions per RT nm for a given utilisation, by dividing the annual emissions on the transport work. The transport work was defined as the sailing distance, multiplied by the vessel capacity and the utilisation.

When calculating emissions per RT nm for a fleet, some assumptions had to be made. It was assumed that each fleet had to be able to carry 200,000 cars, and the number of vessels needed for each vessel size was calculated based on this. Then, the results from the LCIA were multiplied with the amount of vessels, to give yearly emissions for the fleet. This was further divided by the transport work. For the fleet, the transport work was defined as the total sailing distance for the fleet, multiplied with the fleet capacity and the fleet utilisation. In this chapter, the term emissions is used to describe relative emissions per RT nm.

When calculating the emissions for a specific amount of cargo transported, it was assumed that whenever the vessel was fully loaded, another vessel of the same size was added. To calculate the emissions, the yearly emissions from the LCIA were multiplied with the number of vessels needed to transport the cargo. Then, this value was divided by the transport work. The transport work was defined as the sailing distance multiplied by the amount of cargo transported.

Cost

A LCC analysis was calculated to illustrate the relationship between cost and utilisation. Due to limited cost data, most costs were based on the “Ship Operating Costs – Annual Review and Forecast” for 2014/2015 (Drewry Shipping), and a design case from the Marin intro/Marin Teknikk 1 compendium (Amdahl et al., 2011). The formulas and assumptions used are shown in Appendix D.

7.2.2 Climate change

Below are the emissions for varying utilisation shown for the impact category climate change (see Figure 7.1). The graph on the left hand side shows the emissions for one vessel, while the graph on the right shows the fleet emissions.

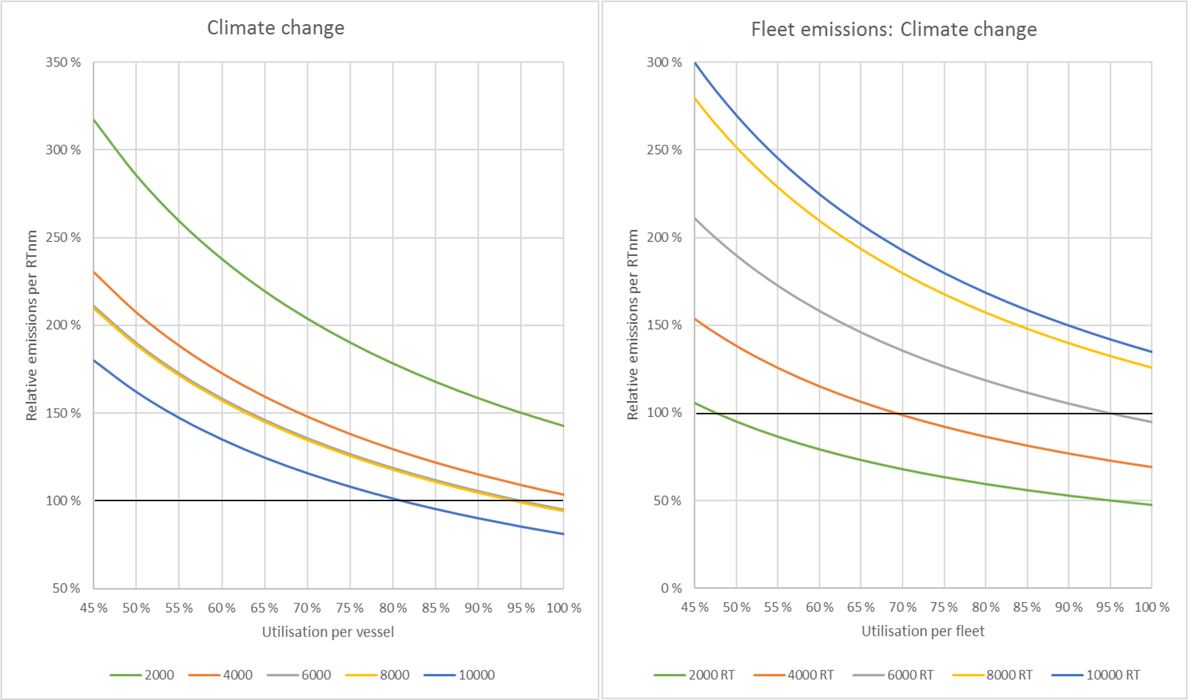


Figure 7.1: Relative emissions per RT nm for a given utilisation for one vessel and a fleet (Climate change)

When analysing one vessel of each size, it is seen that the largest vessel obtains the lowest emissions, if all vessels should sail with equal utilisation. The two smallest vessels, with a capacity of 2,000 and 4,000 RT, never reach an emission level below the 100% baseline.

At the baseline, the 6,000 RT vessel has a utilisation of 95%. The 8,000 RT vessel must then have a utilisation of 93% and the 10,000 RT vessel must have a utilisation of 81% to achieve the same emissions. This means that the larger vessels can sail with lower utilisation, and still be more environmentally friendly than the 6,000 RT vessel. However, the 10,000 RT vessel is dependent on getting more cargo transported than the 6,000 RT vessel, even though its utilisation is lower. The 6,000 RT vessel needs to transport 5,700 cars, while the 8,000 RT vessel needs to transport 7,440 cars and the 10,000 RT vessel needs to transport 8,100 cars, to emit the same amount per RT nm.

The graph showing fleet emissions gives opposite results than the emissions for one vessel (see Chapter 8 for a further discussion of this). The two fleets with the largest vessels are now the ones never reaching below the emission baseline, while the 2,000 RT fleet is the one that obtain the lowest emissions. At the emission baseline, the 2,000 RT fleet needs a utilisation of 50%, meaning the fleet has to transport at least 100,000 cars. The 4,000 RT fleet must have a utilisation of 71% and needs to transport 142,000 cars, while the 6,000 RT fleet must have a utilisation of 95%, making it necessary to transport 190,000 cars to reach the same emissions.

Figure 7.2 shows the emissions for a specific amount of transported cargo for climate change.

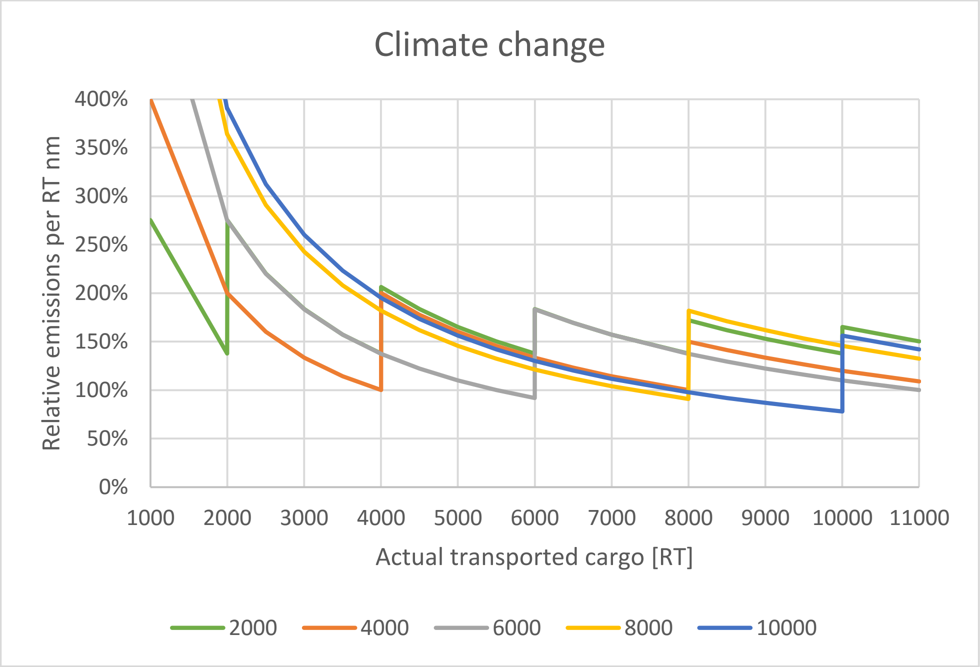


Figure 7.2: Relative emissions per RT nm for the actual transported cargo (Climate change)

The graph shows the impact of adding another vessel to be able to transport the cargo. All the vessels are most sustainable when they are full, but when 1 car is added, the emissions increase substantially. This is because the vessel utilisation is reduced from 100% to 50%, due to the additional vessel that is needed. It is worth noticing that with 8,000 cars on board, the 10,000 RT vessel is almost as good as the 8,000 RT vessel. Additionally, the 4,000 RT vessel performs well, mainly because it requires two fully loaded 4,000 RT vessels, which have relatively low emissions per RT nm.

7.2.3 Human toxicity

This subsection shows the results from the impact category human toxicity. Figure 7.3 gives the emissions for varying utilisation, for one vessel and a fleet perspective. The graph on the left illustrates the one vessel perspective, while the graph on the right shows the results from a fleet perspective.

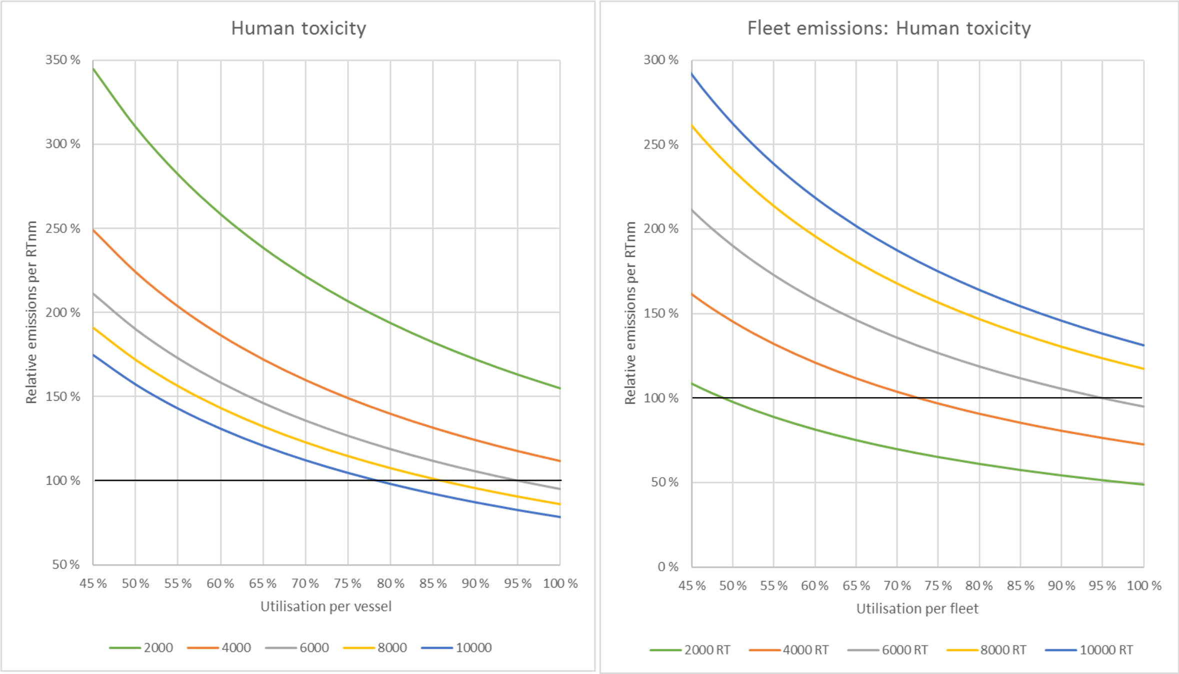


Figure 7.3: Relative emissions per RT nm for a given utilisation for one vessel and a fleet (Human toxicity)

The results for human toxicity look similar to the results for climate change. However, the difference in utilisation is larger for the one vessel perspective. The 2,000 RT vessel and the 4,000 RT vessel are still the least sustainable vessels, and never reach emissions below the baseline. When the 6,000 RT vessel has a utilisation of 95%, the 8,000 RT vessel needs a utilisation of 87%, while the 10,000 RT vessel needs a utilisation of 79% to achieve the same specific emission levels. If only human toxicity is considered, this means that the two largest vessels need to transport fewer cars than for climate change, to achieve equal emissions.

For the fleet results, the difference in utilisation is smaller than for climate change. The two fleets containing the largest vessels never reach the emission baseline, and the 2,000 RT fleet is still the most sustainable per RT nm. When the 6,000 RT fleet has a utilisation of 95%, the 4,000 RT fleet must have a utilisation of 75%, needing to transport 150,000 vessels. The 2,000 RT fleet must have a utilisation of 52% to achieve the same emissions, and is dependent on transporting 104,000 cars.

Figure 7.4 shows the emissions for a specific amount of transported cargo for human toxicity.

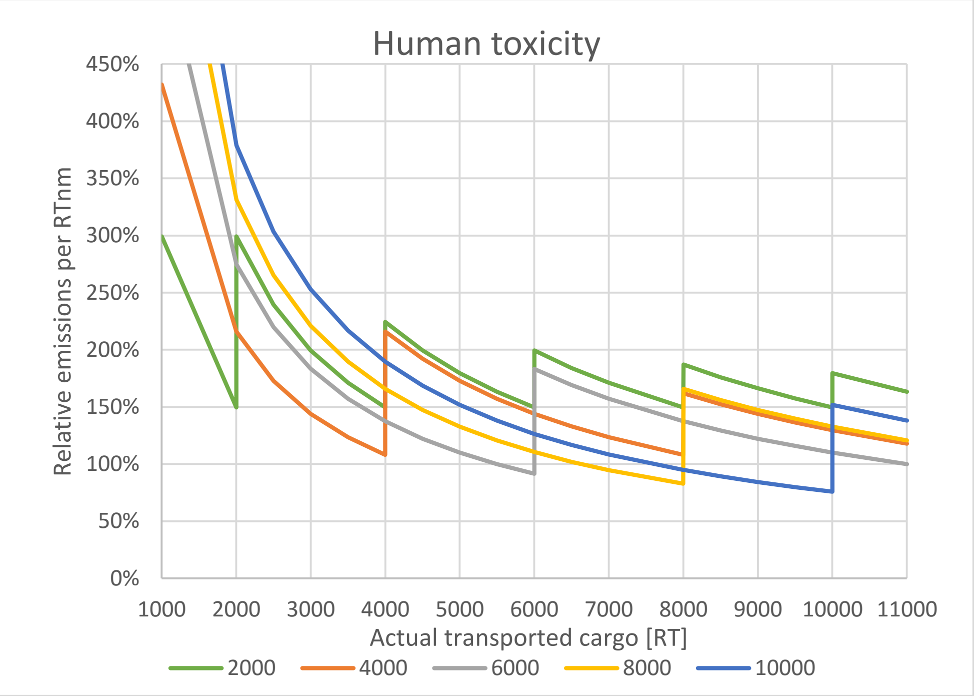


Figure 7.4: Relative emissions per RT nm for the actual transported cargo (Human toxicity)

As for climate change, the impacts of adding another vessel are substantial. One difference though, is that for human toxicity, the 8,000 RT vessel seems to give better results compared to the other vessels. As mentioned in Section 6.4, the scrapping and production of steel were the most important processes for human toxicity, implying that the 8,000 RT vessel performs better, from an environmental perspective, for this category. This is further discussed in Chapter 8.

7.2.4 Terrestrial acidification

In this subsection, the results for terrestrial acidification are shown. Figure 7.5 shows the emissions for different utilisation factors. The graph on the left shows the results when comparing a single vessel of each size, while the graph on the right shows the results when comparing the different fleets.

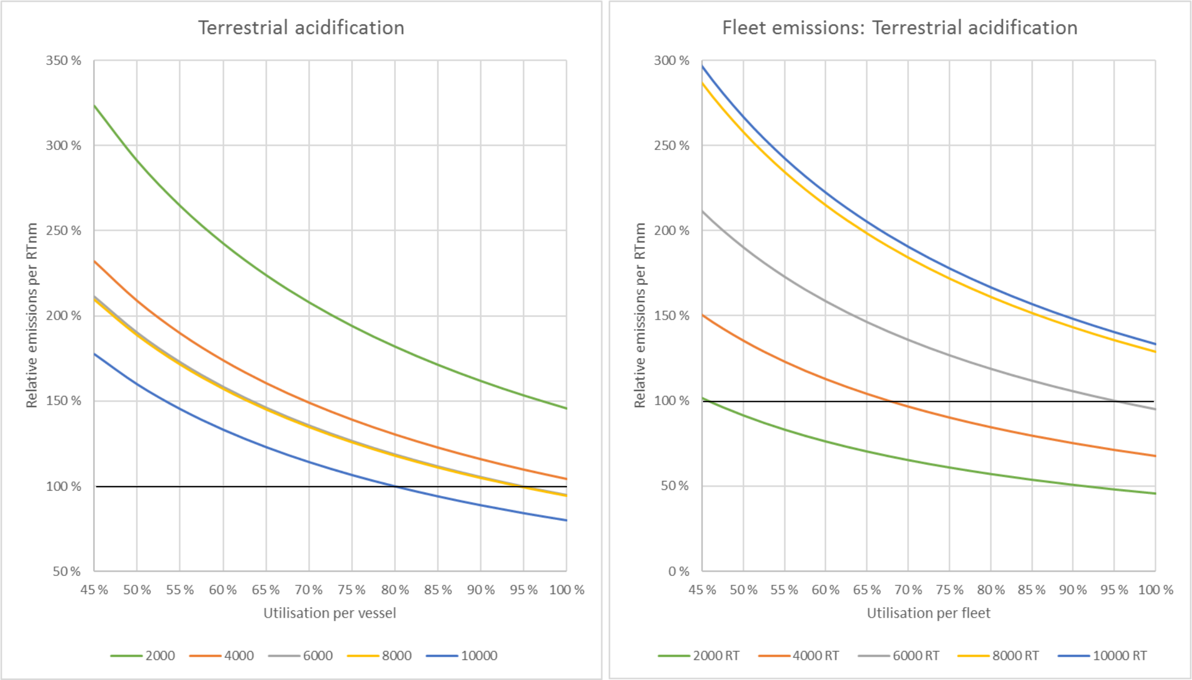


Figure 7.5: Relative emissions per RT nm for a given utilisation for one vessel and a fleet (Terrestrial acidification)

As expected, based on the results from the impact assessment, the results for terrestrial acidification are more similar to the results for climate change, than for human toxicity. The 4,000 and 2,000 RT vessels lie above the emission baseline for all utilisation factors, while the 10,000 RT vessel obtain the lowest emissions. At the emission baseline, the 6,000 RT vessel has a utilisation of 95%, while the 8,000 and 10,000 RT vessels need a utilisation of 95% and 80% respectively. This means that the 6,000 RT vessel needs to transport 5,700 cars, while the 8,000 RT vessel has to transport 7,600 cars, and the 10,000 RT vessel needs to transport 8,000 cars. The 8,000 RT vessel has a bad environmental performance for this impact category.

The fleet perspective shows that the 2,000 RT fleet only need a utilisation of 48% to obtain the emission baseline. This translates into transporting 96,000 cars. The 4,000 RT fleet needs a utilisation of 70%, transporting 140,000 cars, while the 6,000 RT fleet needs to transport 190,000 cars to achieve the same emissions.

Figure 7.6 shows the emissions for a specific amount of transported cargo.

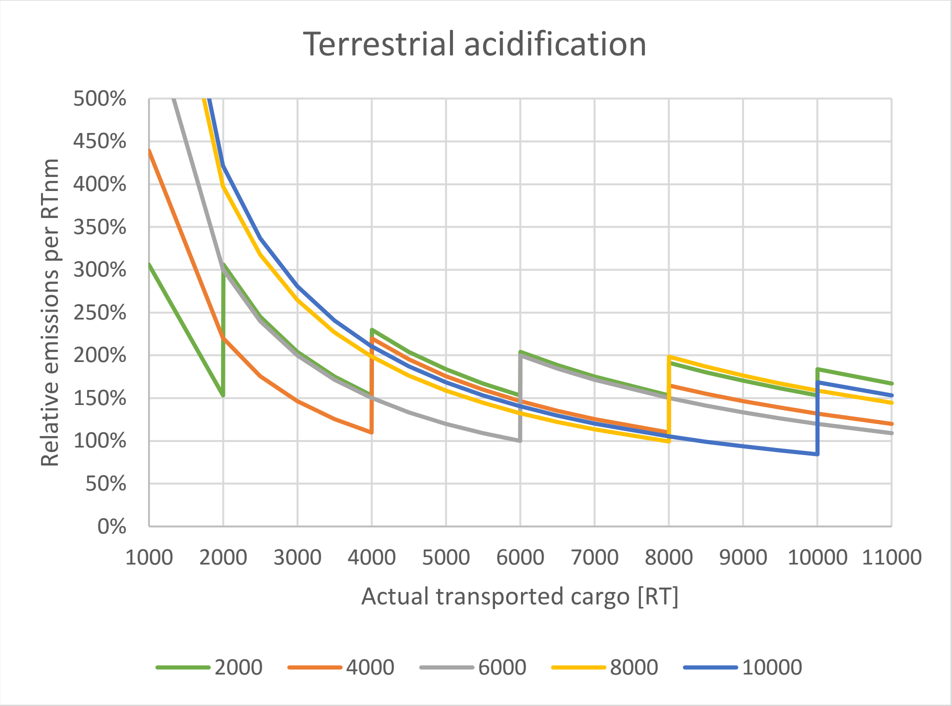


Figure 7.6: Relative emissions per RT nm for the actual transported cargo (Terrestrial acidification)

The graph shows that the 10,000 RT vessel is almost as good as the 8,000 RT vessel when transporting 8,000 cars, as was the case for climate change. The emissions are lowest when the largest vessel transport 10,000 cars. This clearly shows the benefit of building larger vessels, if only looking at emissions per RT nm, excluding utilisation.

7.2.5 Life cycle cost

Shipping and costs are closely linked together, and economy is crucial in every decision making process. It is therefore interesting to look at the impact of utilisation on freight rates, because this influences the choice of vessel size, which again affects the environmental impact. Figure 7.7 shows the relative required freight rate (RFR) for the five vessel sizes, when the utilisation varies. The calculations were only done for one vessel, not for a fleet.

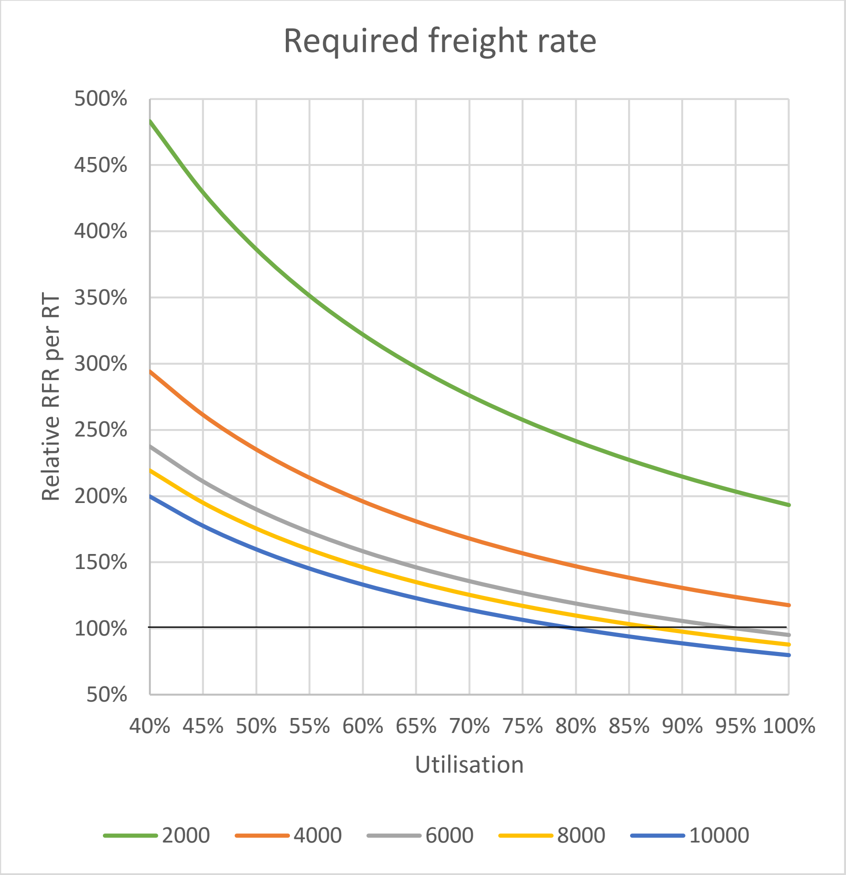


Figure 7.7: Relative required freight rate

The graph shows that the largest vessels are the most economically beneficial per RT. The lowest RFR for the 2,000 RT vessel is equal to the RFR for the 10,000 RT vessel, at 42% utilisation. The 4,000 RT vessel at 100% utilisation can compete with the freight rate of the 10,000 RT vessel with a utilisation of less than 67%. This means that the largest vessel needs to transport approximately twice the amount of cars as the 2,000 RT vessel, and almost 60% more cars than the 4,000 RT vessel to obtain the same freight rate.

The lowest freight rate is achieved for the 10,000 RT vessel at 100% utilisation. At a freight rate level of 100%, the 6,000 RT vessel needs a utilisation of 95%, the 8,000 RT vessel needs a utilisation of 89% and the 10,000 RT vessel can have a utilisation of only 80%, to achieve the same required freight rate. This means that to obtain an equal freight rate, the 10,000 RT vessel needs to transport 8,000 cars, while the 6,000 RT vessel only needs to transport 5,700 cars.

The results show that the required cargo needed for the larger vessels to be equal to the 6,000 RT vessel at 95% utilisation, is equal for both emissions and cost. This is interesting because it implies that economic benefit also benefits the environment, and that decisions can be made based on both criteria, not only on cost. The reason for the results is most likely the fuel consumption, because it is the key factor for both emissions and cost.

Chapter 8

Discussion

The execution of the LCA is discussed in the following sections, together with the results. No previous studies on the impact of utilisation on emissions and cost have been found for RoRo vessels. Bearing this in mind, it is challenging to conclude on the robustness of the results. However, the chapter is used to discuss the findings, and prove their credibility based on theory and shipping practice.

8.1 Execution of LCA

The Ecoinvent database used in the LCA, is made for the building industry. This sets some limitations for the assessment of a vessel, as vessel specific processes, like ballast water, are not included. With this in mind, it is clear that assumptions and simplifications had to be made during the modelling phase. Lack of knowledge on the Ecoinvent processes can also have affected the result, due to the use of wrong or unsuitable processes in the model. Little data was available on the subject, and most processes were chosen based on experience from an LCA class attended last semester.

The parameters of the five vessels used in this thesis, were inter- and extrapolated from several existing RoRo vessels. Consequently, uncertainty around the correctness of the data exists. From Section 6.3 and Chapter 7, it is seen that the 8,000 RT vessel has varying performance from one impact category to another. The vessel performs best for human toxicity, and worst for terrestrial acidification. Both terrestrial acidification and climate change are impacted mostly by the fuel consumption, whereas the impact on human toxicity is mostly dependent on steel production and disposal. The results imply that the initial fuel oil data for the 8,000 RT is higher, relative to the other vessels, causing the weak environmental performance.

Several assumptions have been made in the modelling phase. First, the problem was simplified and adjusted to the available data and processes. The material phase was calculated based on the lightweight breakdown of an LCTC, and on expert judgment of the author. It was assumed that the breakdown was similar for the vessels, except from for the steel, machinery and mooring. However, every vessel is different, and it is not certain that the calculations done in this thesis represent the reality. Nevertheless, it is assumed adequate for the purpose of this study, because of the low impact of the building phase, compared to the operational phase, as shown in Section 6.3.

Many of the calculations for the operational phase were performed according to given formulas. The fuel oil consumption was calculated based on given ship data, and wrong results here are most likely due to errors in the inter- and extrapolation. Yet, several assumptions had to be made. Both the lubrication oil and sludge calculations were based on approximations. In addition, it was assumed that all the paint used on the vessels was alkyd paint, due to limited processes in Ecoinvent. Dividing the paint into different types may have influenced the results, due to different properties and environmental impact from one product to another. The sewage and waste calculations were based on reported data from one vessel. It is important to bear in mind that the waste accumulation is different from one vessel to another, based on operational areas and the crew on board. However, due to lack of more data, the waste data was assumed adequate for the assessment.

Calculations of the emissions from the combustion of HFO were done according to regulations (see Section 6.2.4). The exhaust gas emissions are however not as straight forward to determine, because some emissions are engine specific and some are fuel specific. NO_x emissions are engine specific, and the amount emitted depends on the time available for the formation of nitric oxides (Springer & Patterson, 1973). For the LCA, the NO_x and SO_x emissions were calculated based on the maximum allowed emissions, not on exact measurements. Since both of these gasses have a cooling effect on the environment, the impact of the approximations may lead to a too high impact on climate change and terrestrial acidification. However, the differences would be small, and not considered very important for the end result. The same applies for the emissions of CO and PM. The specific emissions of these gasses were based on Marine Diesel Oil, not HFO, which could result in small deviations from real emission values.

Several assumptions were made for the scrapping phase, the most prominent being that only aluminium and copper were assumed recycled. This decision was made by the author, due to lack of time and lack of knowledge on how to model recycling. To avoid complications with the modelling and possible allocation problems, using waste treatment was a better choice. The only information on the waste treatment was that incineration was no longer used. Different types of landfill were therefore assumed for the materials. As shown in Section 5.4, waste treatment methods have a large impact on the results, and more secure information on the exact type of waste treatment would be beneficial to make sure all emissions are accounted for. It is important to bear in mind that the impact of the scrapping phase on human toxicity is much larger if other types of treatments are chosen, and that the results of the assessment only is valid if landfill is used for all waste types.

It is difficult to estimate how much the assumptions impact the results. However, it is fair to assume that mistakes in the calculations for the processes with the highest impact can contribute more to changes in the results, than small changes in processes that have little impact. In Section 6.4 it was concluded that the operational phase was the phase with the largest impact overall. Additionally, the heavy fuel oil production was identified as the most important background process. Therefore, one can assume that incorrect fuel calculations would affect the end result more than assumed paint consumption or material consumption. Yet, when doing a LCA it is challenging to conclude what processes would change the results the most. Arda is a black box tool, where data is inserted, and output is delivered, without the analyst being able to see how the data is manipulated during the assessment.

8.2 Results

The results presented in Chapter 8, showed small variations of utilisation for the different impact categories. The utilisation rate required to perform on par with the base case for the 10,000 RT vessel, varied from 79% for human toxicity to 81% for climate change. This means that the vessel can transport 200 cars less, and still be as efficient as the reference vessel, if human toxicity is used as the deciding criterion. The reason is that the correlation between increased vessel size and increased consumption is non-linear. The steel consumption increase more per vessel size, than for instance copper consumption.

Results for the fleet perspective showed a completely different trend than the one vessel perspective. It is interesting to discuss the reasons why the smallest vessels seem to be the most beneficial. The results presented in Chapter 8 are given as emissions per RT nm. For this thesis it was assumed that every vessel spent 75% of the time sailing, and 25% of the time in port, regardless of size and sailing speed. This resulted in a shorter sailing distance for the smaller vessels, and a lower transport work. For the fleet perspective, the transport work was given as fleet capacity multiplied by the total sailing distance of the fleet. It was assumed that every fleet should transport 200,000 cars, resulting in fleets varying from one hundred 2,000 RT vessels, to twenty 10,000 RT vessels. When the transport work was calculated, the sailing distance per vessel was multiplied with the number of vessels in the fleet, and even though the smallest vessels had the shortest individual sailing distance, the total sailing distance of the fleet was much larger due to the additional amount of vessels. This resulted in a much larger transport work for the smaller vessels. Since the capacity was similar for every fleet, the sailing distance resulted in lower emissions per RT nm for the smallest vessels.

If the results were presented as emissions per RT, excluding the sailing distance, the results for the fleet perspective would be similar to the one vessel perspective. This is shown in Figure 8.1, where an example is given for climate change. The only difference from the results in Chapter 8, is that the fleet emissions are divided by the fleet capacity only, not the transport work. If it was assumed that the transport work, not only the capacity, was equal for each fleet, the results would also show the benefits of larger vessels.

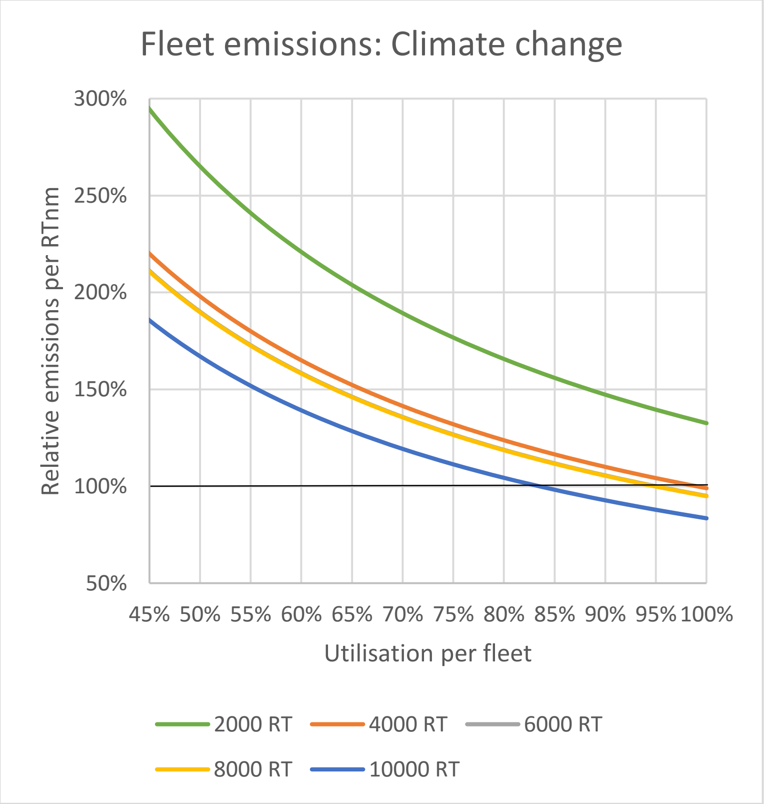


Figure 8.1: Relative fleet emissions per RT for a given utilisation (climate change)

It is worth noticing that when assuming a similar operational pattern for small and large vessels and dividing the emissions per transport work, this will have great impact on the results and the decision making process for the ship owners. An interesting observation from Figure 8.1, is that the benefits of building larger vessels are smaller than for the results presented in the previous chapter, looking more similar to the utilisation levels obtain from the one vessel perspective. This also indicates how much impact the sailing distance had on the calculations of fleet emissions. It is also worth mentioning that the fleets in this thesis are assumed homogenous. This is not very realistic since most ship owners have a heterogeneous fleet that easier can adapt to variations in the demand and supply, optimising both cost and emissions.

Results for the specific amount of cargo transported show the disadvantage of adding another vessel. Even though the graphs presented in the result chapter give interesting results, the handling of additional cargo is different in reality. When a ship owner receives an order that exceeds the vessel capacity, it is more likely that they “give away” the cargo to another company, instead of adding another vessel to the route. The earnings lost by giving the cargo to someone else are much smaller than the cost of another vessel. In addition, the emissions are kept low when the cargo is outsourced. Nevertheless, the results can for instance be used when determining which vessel, or vessels, to use when transporting cargo that does not 100% utilise the cargo capacity of any of the vessels.

Several assumptions were made during the LCC analysis, due to limited data. LCC was not a part of the research question for this thesis, but since shipping and cost are closely linked together, a simplified analysis was done. The result of the cost-utilisation analysis presented in Section 7.2.5 shows similar results as the emission-utilisation analysis. This shows that larger vessels, at least when comparing one vessel of each size, are more beneficial with regards to emissions and cost. A large vessel is still the most cost- and energy efficient down to a utilisation of approximately 80%, when compared to a 6,000 RT vessel with 95% utilisation, but it is dependent on transporting more cargo. If for instance only 5,000 cars were available for transport, the 10,000 RT vessel is not the best alternative when looking at emissions and cost, and a smaller vessel should be utilised.

Chapter 9

Conclusion

The main objective of this thesis was to create a relationship between capacity utilisation and emissions for RoRo vessels, to determine whether large vessels are more sustainable than small vessels at varying utilisation factors. A LCA was used to determine the environmental impact of five vessel sizes, and these results were used to illustrate the relationship between emissions and utilisation. In addition, an LCC analysis was performed, to illustrate the relationship between freight rate and utilisation.

The results from the life cycle assessment give a perspective on the environmental debate. It illustrates that there are other aspects than climate change to worry about, and that shipping has a significant impact on both acidification and human health. With a better database, or an assessment tool fitted for the shipping industry, LCA is a good way of highlighting areas where the industry can improve and implement more sustainable solutions. The results also show the benefits of building larger vessels, both from an environmental and an economic perspective. However, it is worth noticing that how the results are presented, and the assumptions used during the calculations, influence the results. It is crucial to be aware of the limitations and assumptions in both the LCA modelling, and the calculations done with the results from the impact assessment.

Based on the results from the LCA and the utilisation calculations, it is concluded that utilisation has an impact on the environmental performance of a vessel, and that the largest vessels are not the most sustainable for all utilisation factors. The largest vessels, when looking at emissions per RT nm for a one vessel perspective and emissions per RT for the fleet perspective, can sail with lower utilisation, and achieve the same emission levels per transport work, or per car, as the smaller vessels. However, it is important to notice that the large vessels have to transport more cargo at lower utilisation rate, and they are therefore dependent on large enough cargo base. This means that the advantage only can be realized in major shipping trade lanes, e.g. Asia to Europe, but not North America to the West Coast of South America.

Chapter 10

Further work

To produce a better and more reliable result, there are several issues that should be further addressed. The first challenge is the Ecoinvent database. To achieve realistic LCA results, it is necessary to use a tool or a database that contains vessel specific processes. In this thesis, several processes were simplified or excluded due to limitations of the database.

Secondly, the modelling should be done with more accurate data than in this thesis. Many assumptions were made along the way, due to limited data and knowledge on the consumption of the various life cycle phases of a vessel. It is an idea to more accurately map the consumption through all life cycle phases to ease the workload, and receive a better result.

Lastly, the utilisation calculations should be done for a heterogeneous fleet. In this thesis, the fleet perspective was done with a homogenous fleet, which is an unrealistic scenario. This was done to illustrate the effects of building larger vessels. Nevertheless, calculations should be done with a realistic fleet with several vessel sizes, to get a better understanding on how fleet emissions and utilisation are connected in practice. In addition, a realistic operational pattern should be used for the operational phase, not the simple assumption 75% sailing time and 25% port-stay used in this thesis. Different vessel sizes result in different operational patterns, which should be included to increase the credibility of the life cycle assessment.

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APPENDIX

Impact categories

The table below gives a definition of the impact categories represented in Arda. The definitions are taken from the tables presented in Chapter 3 in Acero, et. al (2014).

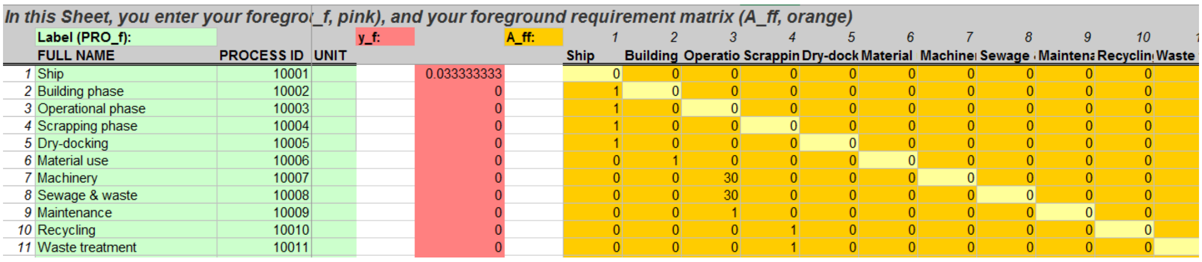
Table A.1: Impact categories (Acero, Rodríguez, & Ciroth, 2014)

Impact category	**Unit**	**Definition/description**
Climate change	Kg CO_2 eq	"Alteration of global temperature caused by greenhouse gases "
Ozone depletion	Kg CFC-11 eq	"Diminution of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances"
Ionising radiation	Kg 1,4-DB eq	"Type of radiation composed of particles with enough energy to liberate an electron from an atom or molecule"
Photochemical ozone formation	Kg NMVOC eq	"Type of smog created from the effect of sunlight, heat and NMVOC and NO_x"
Particulate matter formation	Kg PM10 eq	"Suspended extremely small particles originated from anthropogenic processes such as combustion, resource extraction etc."
Acidification	Kg SO_2 eq	"Reduction of the pH due to the acidifying effects of anthropogenic emissions"
Freshwater and marine eutrophication	Kg N eq, kg P eq	"Accumulation of nutrients in aquatic systems"
Freshwater, marine and	Kg 1,4-DB eq	"Toxic effects of chemicals on an ecosystem"

terrestrial ecotoxicity		
Metal, fossil and water depletion	Kg of minerals, MJ of fossil fuels, m^3 water consumption	“Decrease of the availability of non-biological resources as a result of their unsustainable use”
Human toxicity	Kg 1,4-DB eq	“Toxic effects of chemicals on humans”
Land use	m^2, m^2a	“Impact on the land due to agriculture, anthropogenic settlement and resource extraction”

Inventory

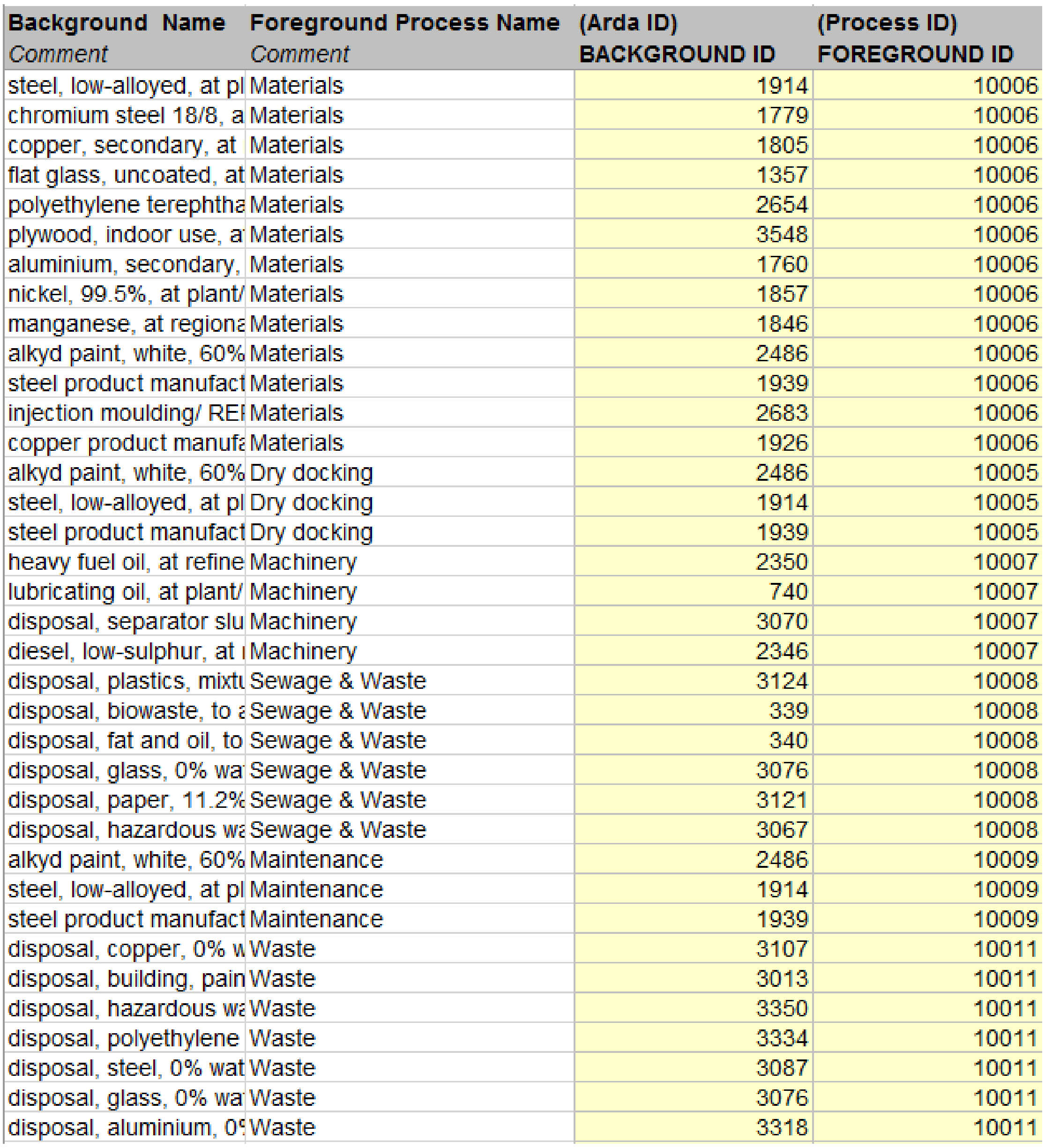
Note that the inventory values have been removed from the appendix, due to confidential data. Only the chosen processes, and the relationship between foreground and background processes are shown, in addition to the relationship between the foreground data (Figure B.1). The Inventory data itself is included in a separate, confidential appendix.



In this Sheet, you enter your foregro_f, pink), and your foreground requirement matrix (A_ff, orange)

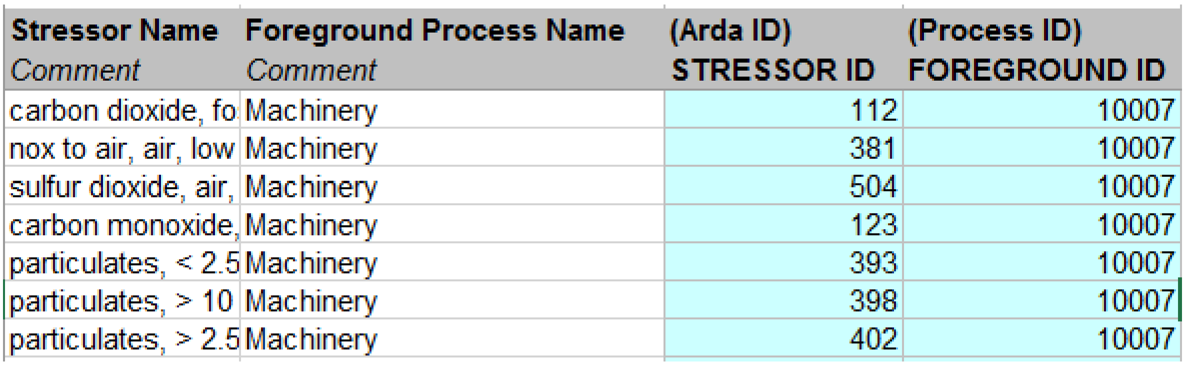
	Label (PRO_f):			y_f:	A_ff:	1	2	3	4	5	6	7	8	9	10	
	FULL NAME	**PROCESS ID**	**UNIT**			**Ship**	**Building**	**Operatio**	**Scrappin**	**Dry-dock**	**Material**	**Machine**	**Sewage**	**Maintena**	**Recyclin**	**Waste**
1	Ship	10001		0.033333333		0	0	0	0	0	0	0	0	0	0	
2	Building phase	10002		0		1	0	0	0	0	0	0	0	0	0	
3	Operational phase	10003		0		1	0	0	0	0	0	0	0	0	0	
4	Scrapping phase	10004		0		1	0	0	0	0	0	0	0	0	0	
5	Dry-docking	10005		0		1	0	0	0	0	0	0	0	0	0	
6	Material use	10006		0		0	1	0	0	0	0	0	0	0	0	
7	Machinery	10007		0		0	0	30	0	0	0	0	0	0	0	
8	Sewage & waste	10008		0		0	0	30	0	0	0	0	0	0	0	
9	Maintenance	10009		0		0	0	1	0	0	0	0	0	0	0	
10	Recycling	10010		0		0	0	0	1	0	0	0	0	0	0	
11	Waste treatment	10011		0		0	0	0	1	0	0	0	0	0	0	

Figure B.1: Foreground matrix



Background Name *Comment*	Foreground Process Name *Comment*	(Arda ID) BACKGROUND ID	(Process ID) FOREGROUND ID
steel, low-alloyed, at pl	Materials	1914	10006
chromium steel 18/8, a	Materials	1779	10006
copper, secondary, at	Materials	1805	10006
flat glass, uncoated, at	Materials	1357	10006
polyethylene terephtha	Materials	2654	10006
plywood, indoor use, a	Materials	3548	10006
aluminium, secondary,	Materials	1760	10006
nickel, 99.5%, at plant/	Materials	1857	10006
manganese, at regiona	Materials	1846	10006
alkyd paint, white, 60%	Materials	2486	10006
steel product manufact	Materials	1939	10006
injection moulding/ RE	Materials	2683	10006
copper product manufa	Materials	1926	10006
alkyd paint, white, 60%	Dry docking	2486	10005
steel, low-alloyed, at pl	Dry docking	1914	10005
steel product manufact	Dry docking	1939	10005
heavy fuel oil, at refine	Machinery	2350	10007
lubricating oil, at plant/	Machinery	740	10007
disposal, separator slu	Machinery	3070	10007
diesel, low-sulphur, at	Machinery	2346	10007
disposal, plastics, mixtu	Sewage & Waste	3124	10008
disposal, biowaste, to	Sewage & Waste	339	10008
disposal, fat and oil, to	Sewage & Waste	340	10008
disposal, glass, 0% wa	Sewage & Waste	3076	10008
disposal, paper, 11.2%	Sewage & Waste	3121	10008
disposal, hazardous wa	Sewage & Waste	3067	10008
alkyd paint, white, 60%	Maintenance	2486	10009
steel, low-alloyed, at pl	Maintenance	1914	10009
steel product manufact	Maintenance	1939	10009
disposal, copper, 0% w	Waste	3107	10011
disposal, building, pain	Waste	3013	10011
disposal, hazardous wa	Waste	3350	10011
disposal, polyethylene	Waste	3334	10011
disposal, steel, 0% wat	Waste	3087	10011
disposal, glass, 0% wa	Waste	3076	10011
disposal, aluminium, 0	Waste	3318	10011

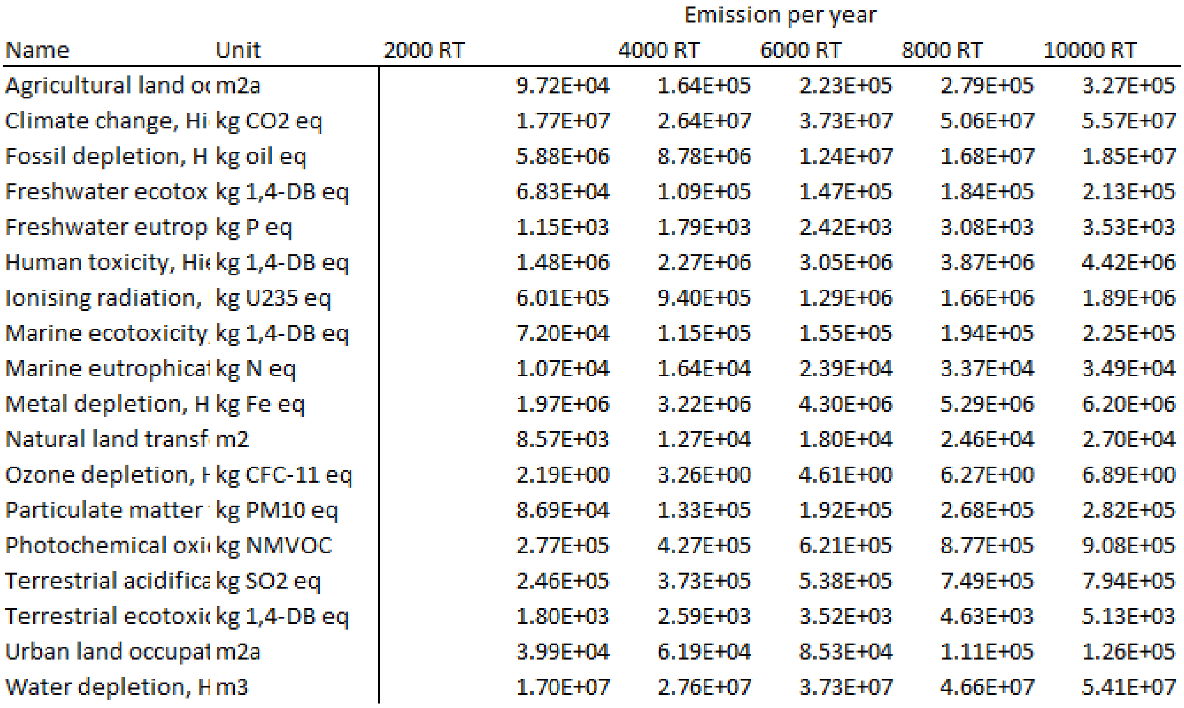
Figure B.2: Background matrix



Stressor Name *Comment*	Foreground Process Name *Comment*	(Arda ID) STRESSOR ID	(Process ID) FOREGROUND ID
carbon dioxide, fo	Machinery	112	10007
nox to air, air, low	Machinery	381	10007
sulfur dioxide, air,	Machinery	504	10007
carbon monoxide,	Machinery	123	10007
particulates, < 2.5	Machinery	393	10007
particulates, > 10	Machinery	398	10007
particulates, > 2.5	Machinery	402	10007

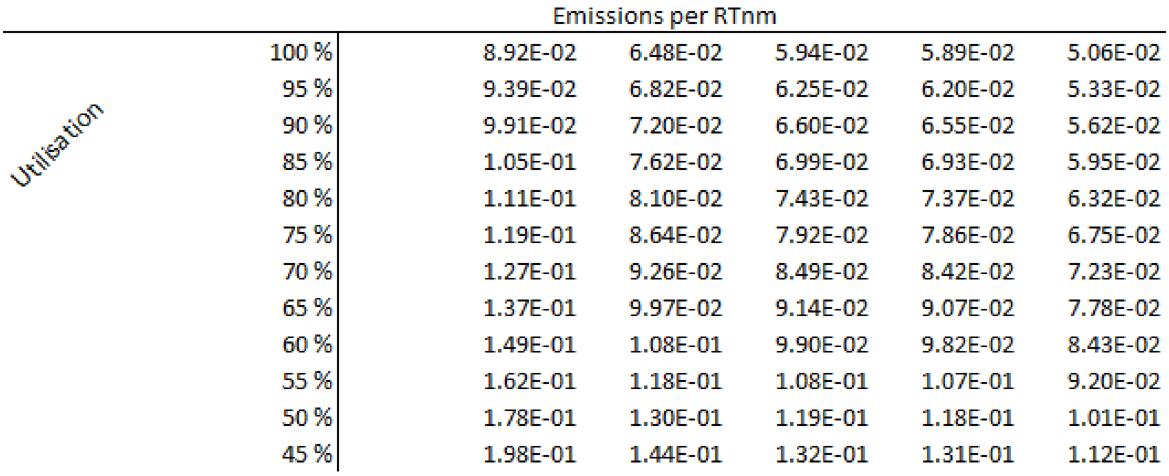
Figure B.3: Stressors matrix (direct emissions)

Utilisation calculations



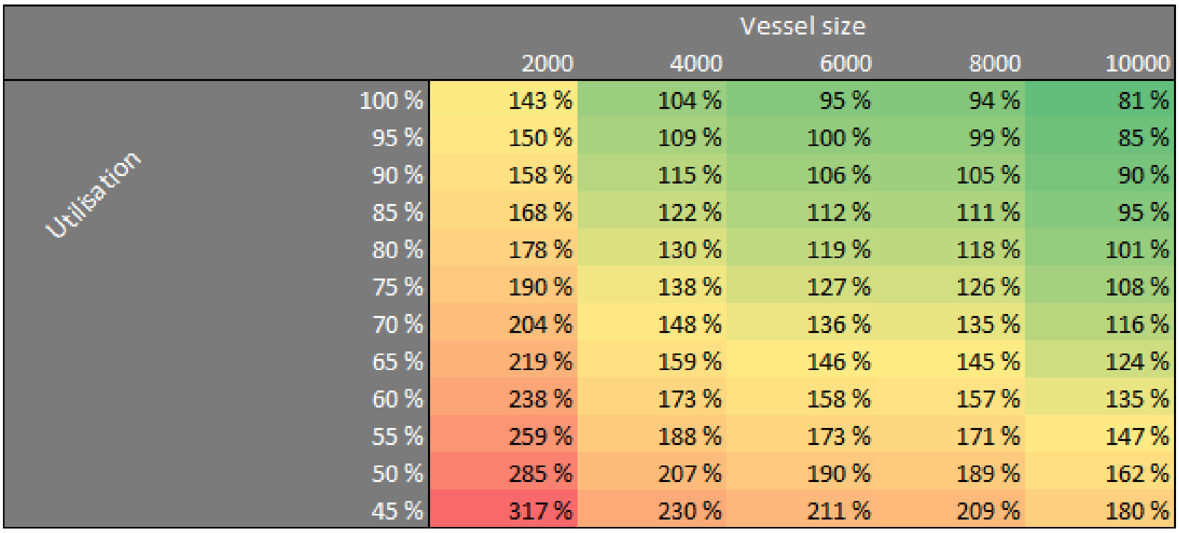
Name	Unit	Emission per year 2000 RT	4000 RT	6000 RT	8000 RT	10000 RT
Agricultural land o	m2a	9.72E+04	1.64E+05	2.23E+05	2.79E+05	3.27E+05
Climate change, Hi	kg CO2 eq	1.77E+07	2.64E+07	3.73E+07	5.06E+07	5.57E+07
Fossil depletion, H	kg oil eq	5.88E+06	8.78E+06	1.24E+07	1.68E+07	1.85E+07
Freshwater ecotox	kg 1,4-DB eq	6.83E+04	1.09E+05	1.47E+05	1.84E+05	2.13E+05
Freshwater eutrop	kg P eq	1.15E+03	1.79E+03	2.42E+03	3.08E+03	3.53E+03
Human toxicity, Hi	kg 1,4-DB eq	1.48E+06	2.27E+06	3.05E+06	3.87E+06	4.42E+06
Ionising radiation,	kg U235 eq	6.01E+05	9.40E+05	1.29E+06	1.66E+06	1.89E+06
Marine ecotoxicity	kg 1,4-DB eq	7.20E+04	1.15E+05	1.55E+05	1.94E+05	2.25E+05
Marine eutrophica	kg N eq	1.07E+04	1.64E+04	2.39E+04	3.37E+04	3.49E+04
Metal depletion, H	kg Fe eq	1.97E+06	3.22E+06	4.30E+06	5.29E+06	6.20E+06
Natural land transf	m2	8.57E+03	1.27E+04	1.80E+04	2.46E+04	2.70E+04
Ozone depletion,	kg CFC-11 eq	2.19E+00	3.26E+00	4.61E+00	6.27E+00	6.89E+00
Particulate matter	kg PM10 eq	8.69E+04	1.33E+05	1.92E+05	2.68E+05	2.82E+05
Photochemical oxi	kg NMVOC	2.77E+05	4.27E+05	6.21E+05	8.77E+05	9.08E+05
Terrestrial acidifica	kg SO2 eq	2.46E+05	3.73E+05	5.38E+05	7.49E+05	7.94E+05
Terrestrial ecotoxi	kg 1,4-DB eq	1.80E+03	2.59E+03	3.52E+03	4.63E+03	5.13E+03
Urban land occupat	m2a	3.99E+04	6.19E+04	8.53E+04	1.11E+05	1.26E+05
Water depletion, H	m3	1.70E+07	2.76E+07	3.73E+07	4.66E+07	5.41E+07

Figure C.1: Total impact matrix, all vessels and impact categories



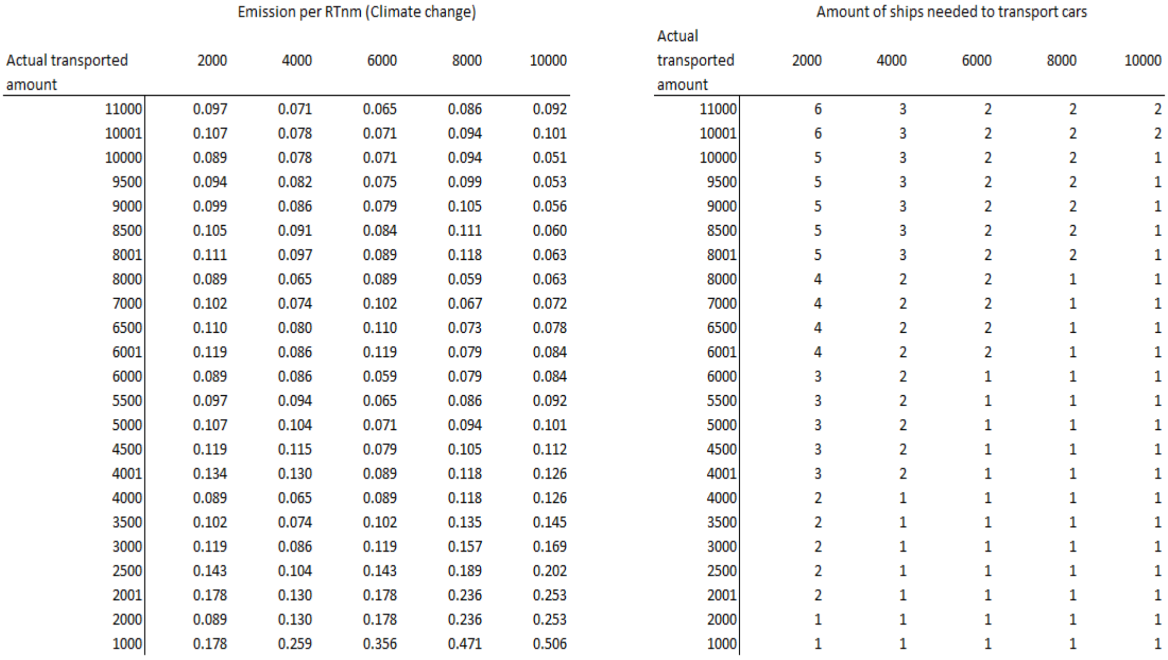
		Emissions per RTnm				
Utilisation	100 %	8.92E-02	6.48E-02	5.94E-02	5.89E-02	5.06E-02
	95 %	9.39E-02	6.82E-02	6.25E-02	6.20E-02	5.33E-02
	90 %	9.91E-02	7.20E-02	6.60E-02	6.55E-02	5.62E-02
	85 %	1.05E-01	7.62E-02	6.99E-02	6.93E-02	5.95E-02
	80 %	1.11E-01	8.10E-02	7.43E-02	7.37E-02	6.32E-02
	75 %	1.19E-01	8.64E-02	7.92E-02	7.86E-02	6.75E-02
	70 %	1.27E-01	9.26E-02	8.49E-02	8.42E-02	7.23E-02
	65 %	1.37E-01	9.97E-02	9.14E-02	9.07E-02	7.78E-02
	60 %	1.49E-01	1.08E-01	9.90E-02	9.82E-02	8.43E-02
	55 %	1.62E-01	1.18E-01	1.08E-01	1.07E-01	9.20E-02
	50 %	1.78E-01	1.30E-01	1.19E-01	1.18E-01	1.01E-01
	45 %	1.98E-01	1.44E-01	1.32E-01	1.31E-01	1.12E-01

Figure C.2: Emissions per RT nm for one vessel and varying utilisation (climate change)



Utilisation	Vessel size 2000	4000	6000	8000	10000
100 %	143 %	104 %	95 %	94 %	81 %
95 %	150 %	109 %	100 %	99 %	85 %
90 %	158 %	115 %	106 %	105 %	90 %
85 %	168 %	122 %	112 %	111 %	95 %
80 %	178 %	130 %	119 %	118 %	101 %
75 %	190 %	138 %	127 %	126 %	108 %
70 %	204 %	148 %	136 %	135 %	116 %
65 %	219 %	159 %	146 %	145 %	124 %
60 %	238 %	173 %	158 %	157 %	135 %
55 %	259 %	188 %	173 %	171 %	147 %
50 %	285 %	207 %	190 %	189 %	162 %
45 %	317 %	230 %	211 %	209 %	180 %

Figure C.3: Relative emissions per RT nm for one vessel and varying utilisation (climate change)



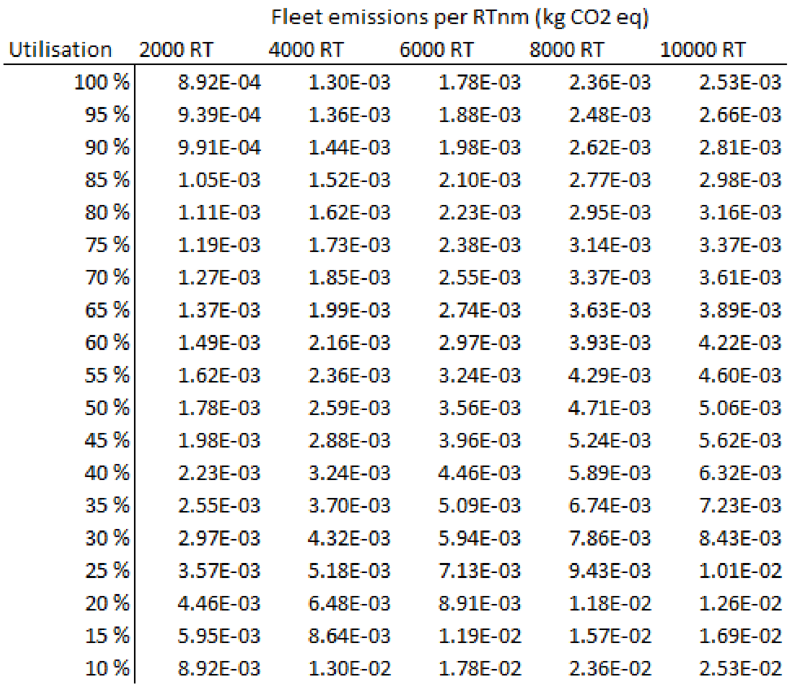
Emission per RTnm (Climate change)

Actual transported amount	2000	4000	6000	8000	10000
11000	0.097	0.071	0.065	0.086	0.092
10001	0.107	0.078	0.071	0.094	0.101
10000	0.089	0.078	0.071	0.094	0.051
9500	0.094	0.082	0.075	0.099	0.053
9000	0.099	0.086	0.079	0.105	0.056
8500	0.105	0.091	0.084	0.111	0.060
8001	0.111	0.097	0.089	0.118	0.063
8000	0.089	0.065	0.089	0.059	0.063
7000	0.102	0.074	0.102	0.067	0.072
6500	0.110	0.080	0.110	0.073	0.078
6001	0.119	0.086	0.119	0.079	0.084
6000	0.089	0.086	0.059	0.079	0.084
5500	0.097	0.094	0.065	0.086	0.092
5000	0.107	0.104	0.071	0.094	0.101
4500	0.119	0.115	0.079	0.105	0.112
4001	0.134	0.130	0.089	0.118	0.126
4000	0.089	0.065	0.089	0.118	0.126
3500	0.102	0.074	0.102	0.135	0.145
3000	0.119	0.086	0.119	0.157	0.169
2500	0.143	0.104	0.143	0.189	0.202
2001	0.178	0.130	0.178	0.236	0.253
2000	0.089	0.130	0.178	0.236	0.253
1000	0.178	0.259	0.356	0.471	0.506

Amount of ships needed to transport cars

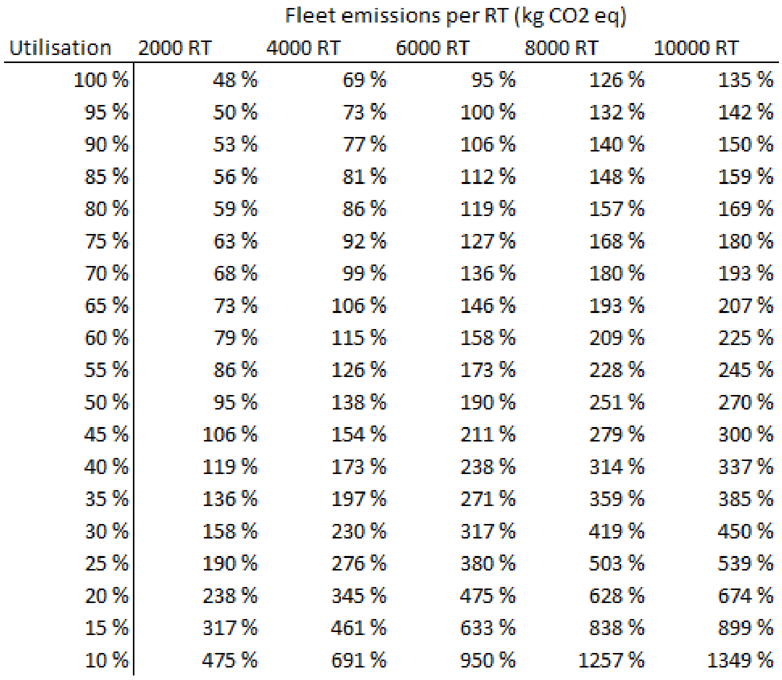
Actual transported amount	2000	4000	6000	8000	10000
11000	6	3	2	2	2
10001	6	3	2	2	2
10000	5	3	2	2	1
9500	5	3	2	2	1
9000	5	3	2	2	1
8500	5	3	2	2	1
8001	5	3	2	2	1
8000	4	2	2	1	1
7000	4	2	2	1	1
6500	4	2	2	1	1
6001	4	2	2	1	1
6000	3	2	1	1	1
5500	3	2	1	1	1
5000	3	2	1	1	1
4500	3	2	1	1	1
4001	3	2	1	1	1
4000	2	1	1	1	1
3500	2	1	1	1	1
3000	2	1	1	1	1
2500	2	1	1	1	1
2001	2	1	1	1	1
2000	1	1	1	1	1
1000	1	1	1	1	1

Figure C.4: Emissions per RT nm for actual transported cargo and amount of ships needed to transport cargo (climate change)



Utilisation	Fleet emissions per RTnm (kg CO2 eq) 2000 RT	4000 RT	6000 RT	8000 RT	10000 RT
100 %	8.92E-04	1.30E-03	1.78E-03	2.36E-03	2.53E-03
95 %	9.39E-04	1.36E-03	1.88E-03	2.48E-03	2.66E-03
90 %	9.91E-04	1.44E-03	1.98E-03	2.62E-03	2.81E-03
85 %	1.05E-03	1.52E-03	2.10E-03	2.77E-03	2.98E-03
80 %	1.11E-03	1.62E-03	2.23E-03	2.95E-03	3.16E-03
75 %	1.19E-03	1.73E-03	2.38E-03	3.14E-03	3.37E-03
70 %	1.27E-03	1.85E-03	2.55E-03	3.37E-03	3.61E-03
65 %	1.37E-03	1.99E-03	2.74E-03	3.63E-03	3.89E-03
60 %	1.49E-03	2.16E-03	2.97E-03	3.93E-03	4.22E-03
55 %	1.62E-03	2.36E-03	3.24E-03	4.29E-03	4.60E-03
50 %	1.78E-03	2.59E-03	3.56E-03	4.71E-03	5.06E-03
45 %	1.98E-03	2.88E-03	3.96E-03	5.24E-03	5.62E-03
40 %	2.23E-03	3.24E-03	4.46E-03	5.89E-03	6.32E-03
35 %	2.55E-03	3.70E-03	5.09E-03	6.74E-03	7.23E-03
30 %	2.97E-03	4.32E-03	5.94E-03	7.86E-03	8.43E-03
25 %	3.57E-03	5.18E-03	7.13E-03	9.43E-03	1.01E-02
20 %	4.46E-03	6.48E-03	8.91E-03	1.18E-02	1.26E-02
15 %	5.95E-03	8.64E-03	1.19E-02	1.57E-02	1.69E-02
10 %	8.92E-03	1.30E-02	1.78E-02	2.36E-02	2.53E-02

Figure C.5: Fleet emissions per RT nm for varying utilisation (climate change)



Utilisation	Fleet emissions per RT (kg CO2 eq) 2000 RT	4000 RT	6000 RT	8000 RT	10000 RT
100 %	48 %	69 %	95 %	126 %	135 %
95 %	50 %	73 %	100 %	132 %	142 %
90 %	53 %	77 %	106 %	140 %	150 %
85 %	56 %	81 %	112 %	148 %	159 %
80 %	59 %	86 %	119 %	157 %	169 %
75 %	63 %	92 %	127 %	168 %	180 %
70 %	68 %	99 %	136 %	180 %	193 %
65 %	73 %	106 %	146 %	193 %	207 %
60 %	79 %	115 %	158 %	209 %	225 %
55 %	86 %	126 %	173 %	228 %	245 %
50 %	95 %	138 %	190 %	251 %	270 %
45 %	106 %	154 %	211 %	279 %	300 %
40 %	119 %	173 %	238 %	314 %	337 %
35 %	136 %	197 %	271 %	359 %	385 %
30 %	158 %	230 %	317 %	419 %	450 %
25 %	190 %	276 %	380 %	503 %	539 %
20 %	238 %	345 %	475 %	628 %	674 %
15 %	317 %	461 %	633 %	838 %	899 %
10 %	475 %	691 %	950 %	1257 %	1349 %

Figure C.6: Relative fleet emissions per RT nm for varying utilisation (climate change)

LCC calculations

The relationship between cost and utilisation is illustrated by the required freight rate (RFR) needed at a certain utilisation, to break even. The first step of the LCC calculations is to find the building costs, operational costs and the expected sales value of the vessel after its lifetime. One important thing to remember, is to adjust the operational costs and the sales value, to present value.

When the life cycle cost has been calculated, the required freight rate can be found. First, the yearly income, in present value, needed to break even over the vessel lifetime is found, using Equation (D.1).

$$F * \left[\frac{(1+p)^n - 1}{p * (1+p)^n}\right] - LCC = 0 \tag{D.1}$$

where p is the market rate and n is the lifetime of the vessel. The market rate was set to 10%, based on the market rate used in the Marin Teknikk intro/Marin Teknikk 1 compendium (Amdahl et al., 2011). After the yearly income was calculated, the required freight rate was found, using Equation (D.2).

$$RFR = \frac{Required\ yearly\ income\ F\ [\$]}{Freight\ rate\ per\ year\ [RT]} \tag{D.21}$$

It was assumed that the vessels sail three trips per year, and the freight rate was found by multiplying the vessel capacity by three.