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# Prospective Life Cycle Assessment of Container Shipping

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Submission date: June 2017
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Department of Energy
and Process Engineering

EPT-M-2017-67

# MASTER THESIS

for

Anna Ringvold

Spring 2017

**Prospective life cycle assessment of container shipping.**

## Background and objective

International maritime transport is the backbone of international trade. Though emissions per unit of goods transported are low compared to other transport modes, absolute emissions from the sector contribute between 2-3% of annual anthropogenic greenhouse gas emissions. These emissions are expected to increase significantly with some scenarios indicating a 250% increase by 2050. Container ships contribute approximately a quarter of annual emissions of the maritime sector, which is more than any other ship type. Thus, reducing impacts of the container segment aids significantly the reduction efforts required by the sector.

The main objective of this work is to assess the environmental impacts associated with global container shipping. Impacts associated with the current container fleet are to be considered, as well as several prospective fleet development scenarios.

## The analysis should include the following elements:

1) A literature study on the approaches for generating fleet development scenarios
2) Development of a parameterized life cycle inventory based on a previous inventory of individual container ships.
3) Environmental impact assessment of the current container fleet based on size and age cohorts.
4) Develop simple scenario for fleet development, based on assumptions and approaches discussed under 1), while taking into account the timeframe set for this project.
5) Analysis and discussion of prospective fleet-wide results.

The project work comprises 30 ECTS credits.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 20. January 2017

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# Abstract

International shipping has lower direct $CO_2$ emissions per unit of mass transported than any other transportation mode. However, the sector's absolute direct emissions in 2012 totalled 815 million tonnes $CO_2$-equivalents, accounting for 2.1% of all greenhouse gas emissions, and with a continuation of currents trends, are expected to increase between 50 and 250% by 2050. Containerships contribute about one fourth of these emissions, more than any other ship type. (Smith et al., 2014)

Life cycle assessments model a product or service from raw material extraction through to waste handling, capturing both direct and indirect environmental impacts occurring throughout their lifetime. Here, a bottom-up life cycle analysis of the global containership fleet is performed, as well as predictions for the composition and attributes of the containership fleet from 2016 until 2050. Thus emerges a more complete picture of the environmental footprint of the containership fleet, and the outcomes of different scenario developments can be examined.

The results show that the propulsion of the ship is the most important contributor to impacts where fuel combustion plays a central role: Ship propulsion accounts for about 80% of the climate change impact of the containership fleet. However, in other impact categories, e.g. toxicity potential, other stages of the vessel's life cycle, such as ship construction and the fuel value chain, plays a greater role. Looking at the development of the global warming potential of the fleet towards 2050 reveals that with the assumed improvements in ship emission efficiency and higher proportion of very large ships, above 8500 TEU, the emissions from the fleet do not exceed the 2016-level in any of the five business-as-usual scenarios.

# Sammendrag

Internasjonal skipsfart har lavere direkte CO2 utslipp per enhet masse transportert enn noen annen transportform. Men sektorens absolutte klimautslipp i 2012 var 815 millioner tonn $CO_2$ ekvivalenter, som var 2,1% av totale utslipp i 2012. Dersom tendensene observert de senere årene fortsetter, forventes det at utslippene vil øke mellom 50% og 250% innen 2050. Containerskip står for en fjerdedel av disse utslippene, som er mer enn noen annen type skip. (Smith et al., 2014)

Livssyklusanalyser modellerer et produkt eller en tjeneste fra utvinning av råvarer til avhending, og fanger både direkte og indirekte miljøpåvirkninger som forekommer i dets livsløp. I denne oppgaven utføres en nedenfra-og-opp livssyklusanalyse av den globale containerskipflåten, samt modellering av den framtidige containerskipflåten fra 2016 til 2050. Dermed danner det seg et mer komplett bilde av flåten og resultatene fra ulike scenarier kan undersøkes.

Resultatene viser at skipets kjørefase er den viktigste bidragsyteren til klima- og miljøpåvirkninger hvor forbrenning av drivstoff spiller en sentral rolle: Den utgjør omtrent 80% av containerskip-flåtens klimapåvirkning. Mens for andre typer påvirkning, blant annet toksisitet, er andre livsstadier som er viktigere, slik som skipsbygging og drivstoffets verdikjede. Når man ser på utviklingen av flåtens klimapåvirkning mot 2050, er det vist at med de antatte forbedringene i utslippseffektivitet og en stadig høyere andel av veldig store skip i flåten vil utslipp av klimagasser ikke overstige nivået i 2016 i noen av de fem scenariene.

# Preface

This master thesis is the culmination of my two years at the Industrial Ecology master's programme at the Norwegian University of Science and Technology (NTNU). The report is the result of the work done in the course TEP4930 *Industrial Ecology, Master's Thesis*, spring semester 2017.

A massive thank you to my supervisor prof. Anders Strømman and co-supervisor Evert Bouman for their skilful guidance throughout the process and for regular and valuable feedback. I also want to thank my husband for patiently listening to my questions and then listen to me answer them myself. Finally, thanks to my sparring partners at the industrial ecology study hall. This thesis would not exist without you.

You can't tell what's aboard a container ship.
We carried every kind of cargo,
all of it on view:
a police car,
penicillin,
Johnnie Walker Red,
toilets,
handguns,
lumber,
Ping-Pong balls,
and IBM data cards.

~ Christopher Buckley

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# Abbreviations

| | |
|---|---|
| DWT | Deadweight tonnage: The maximum capacity of a ship in terms of mass, i.e. how heavy it can safely carry. It is calculated by computing the weight of the water the ship displaces when it is fully loaded, adjusting for saltwater density and subtracting the lightweight displacement tonnage. (Dinsmore, 2010) |
| GT | Gross tonnage: The volume of all enclosed space on a ship, where one ton is equal to 100 cubic feet. (Dinsmore, 2010) |
| HFO | Heavy fuel oil |
| IMO | International Maritime Organization |
| IIASA | International Institute for Applied Systems Analysis |
| IPCC | International Panel on Climate Change |
| LCA | Life cycle assessment |
| LDT | Lightweight displacement tonnage: The mass of the ship. It does not include any consumables, such as fuel, water or supplies. It is calculated by computing the weight of the water the ship displaces and adjusting for the higher density of saltwater. (Dinsmore, 2010) |
| MCR | Maximum continuous rating: The maximum amount of work, expressed in kW, an engine can continuously perform under normal operating conditions. |
| NMVOC | Non-methane volatile organic carbon |
| $NO_x$ | Nitrogen oxides: NO and $NO_2$ |
| OECD | Organisation for Economic Co-operation and Development |
| SFOC | Specific fuel oil consumption: Consumption of fuel oil mass per unit time per energy output produced, expressed in g/kWh |
| $SO_x$ | Sulphur oxides: $SO_2$ is the most common |
| TEU | Twenty-foot equivalent unit: A unit of volume equivalent to a twenty-foot ISO container (Eurostat, 2013). How many containers a containership can carry. |
| tkm | Tonne-kilometre: Transporting one metric tonne the distance of one kilometre. |
| tonnes | Metric tonnes |
| UNCTAD | United Nations Conference on Trade and Development |
| UN DESA | United Nations Department of Economic and Social Affairs |
| UNFCCC | United Nations Framework Convention on Climate Change |

# 1 Introduction

World trade and global gross domestic product (GDP) have steadily increased the past 40 years, where trade has grown at a higher rate since 1990 (UNCTAD, 2016). Seaborne transport has increased 250% since 1990 (UNCTAD, 2016) and is the workhorse of this new reality of worldwide trade: More than 80% of the world trade in mass is carried by ships (Lindstad et al., 2012). This is advantageous from an environmental perspective because ships have lower emission intensities per unit mass transported than any other mode of transport (Sims et al., 2014). Nonetheless, the direct absolute emissions from shipping in 2012 were estimated to be 816 $CO_2$ equivalents, 2.4% of total global greenhouse gas emissions (Smith et al., 2014).

World GDP is expected to continue to increase beyond the middle of the century (IIASA, 2016), which means that if the historic relationship with trade holds true in the future, there will also be a continued increase in international trade. This presents a challenge for the shipping industry, which is expected to provide more of its services, and at the same time significantly cut emissions to be able to meet the ambitious goals set out in the Paris agreement: To limit the rise in global temperatures to «well below 2 degrees Celsius above pre-industrial levels» (UNFCCC, 2016).

Containerisation, i.e. the gradual progress towards standardisation in general cargo shipping culminating in the invention of the intermodal container, has been a catalyst for global trade the last half of the twentieth century, greatly reducing the logistical challenges to moving general cargo (Levinson, 2006). Although seaborne transport has the lowest intensities of all transport modes, emission intensities for containerships are in the upper quartile of the segment (Psaraftis and Kontovas, 2009), and have larger emissions than any other ship type: In 2012, containerships were responsible for one quarter of total $CO_2$ emissions in international shipping (Smith et al., 2014).

Greenhouse gas emissions in 2050 must be reduced by 50% compared to the 2010 level for it to be more likely than not that the rise in global surface temperature fall between 1.5 and 2 degrees Celsius (IPCC, 2015). If all sectors were to contribute equally and counting container shipping as an individual sector, this means that the climate change impact of the containership fleet in 2050 should not exceed 1.01E+11 kg $CO_2$ eq.

This thesis investigates the life cycle impacts of the containership fleet in 2016 and towards 2050, and whether prospected improvements in efficiency will enable the containership industry to meet the low carbon future. The shipping community at large is taking measures to limit the climate impact of the industry (IMO, 2017a), but the long lifetimes of ships means that there is a measure of system inertia that is difficult to overcome by stricter requirements for newbuilds. Additionally, slim profit margins may deter investment in new technologies and implementation of existing ones.

This thesis consists of two main parts: (i) Developing a life cycle assessment (LCA) model for the container fleet and (ii) a fleet development model, which generates prospective fleet compositions for five different scenarios until 2050. In the next chapter, *Method*, the LCA methodology is systematically laid out and a literature review of approaches to generating fleet development scenarios is conducted. The LCA model and fleet development model are presented in the chapters *Life Cycle Inventory* and *Scenario Development*, respectively, and the other chapters also follow the dual structure. The *Results* chapter first looks at how the impacts for the fleet in the base year, i.e. 2016, are distributed in the foreground structure and across different size bins. Subsequently, the results for the climate impact in future scenarios are explored. The *Discussion* examines the implications of the reported results and considers the strengths and limitations of the approach. Finally, the main findings are reiterated in the *Conclusion* and suggestion for further research is provided.

# 2 Method

This section presents the main methodological aspects of the thesis. The contents fall into two main parts: Firstly, the life cycle assessment methodology is presented, and then follows a review of the scientific literature on fleet development.

## 2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a modelling tool for quantifying the environmental impacts of a product or service. As the name alludes to, the goal of the assessor is to account for all impacts compounding throughout the product's lifetime, not just the ones that are discernible to the consumer. There are four main steps to the procedure: *Goal and scope definition*, *Inventory analysis*, *Impact assessment* and *Interpretation* (ISO, 2006). It is an iterative process where each step informs and influences the others, see Figure 2-1.

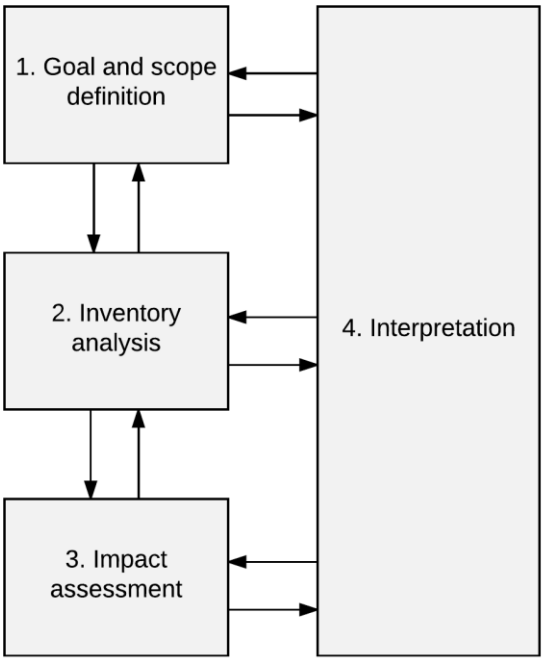



*Figure 2-1: The life cycle assessment framework, modified from ISO 14040 (2006)*

### 2.1.1 Goal and scope definition

Defining the functional unit and system boundaries is the initial step of an LCA. The functional unit is a quantitative measure of the function the system is meant to deliver. The focus on function rather than any inherent physical property of the system allows for consistent benchmarking across products with varying characteristics.

In this thesis, the global containership fleet is modelled from 2016 to 2050. The functional unit is one year of operating the fleet, i.e. a fleet of sufficient capacity to fulfil the transport demand for a given year. Each ship in the fleet is modelled individually from construction to final disposal. The energy requirements for the propulsion of a ship is the most detailed part of the model since this process is dominant for several impact categories, including climate change. The functional unit, system boundaries and reference flows are presented in Figure 2-2.

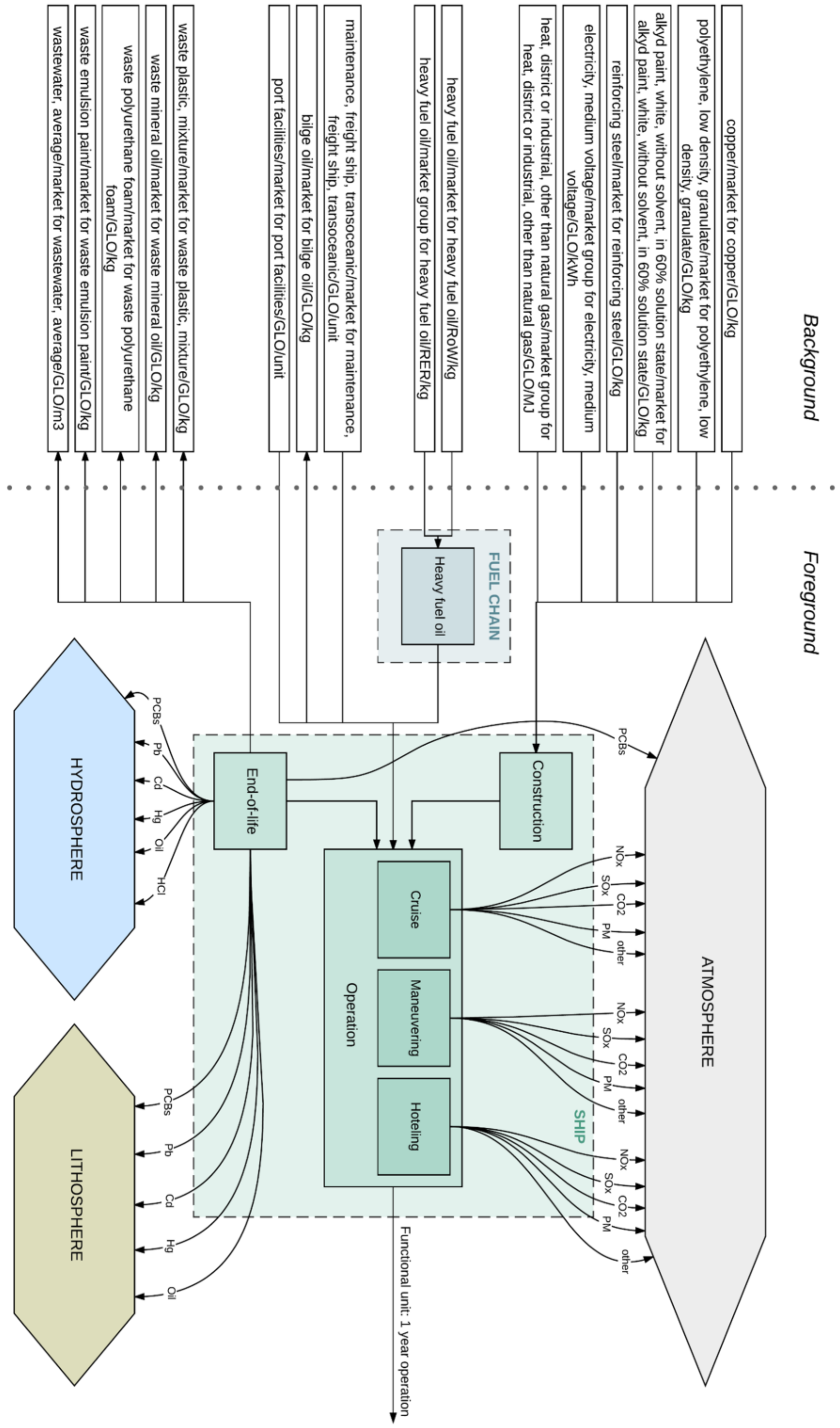



*Figure 2-2: Ship-wise life cycle inventory, showing annual flows. Waste flows are negative in Ecoinvent 3.2 and are here symbolised by arrows pointing from the foreground system to the background system.*

#### 2.1.1.1 Programming Tools

The programming code that reads the external data and executes the LCA calculations is written in Python 3.6.0 64bits on Windows. The program is available under GNU General Public Licence at https://bitbucket.org/ringviolence/anna-ringvold-master-thesis/overview.

### 2.1.2 Inventory analysis

Compiling the life cycle inventory is the second step in the LCA procedure: Information about the material and energy flows necessary to fulfil the desired function are collected and systematised in the requirements matrix, $A$. Each entry, $a_{ij}$, is the quantity of input from process $i$ needed for one unit of output from process $j$. When connected to a system output, the total amount required from each process can be determined. The output can be intermediate or final, represented by the total output vector, $x$, and final demand vector, $y$, respectively. The final demand is the required direct output from the system, which leads to one or more indirect demands that in turn incur their own claims, leading to demands further up in the value chain. E.g. for a final demand of one year of operation of the container fleet, a number of containerships are needed whose construction require an input of steel, a steel mill is necessary to produce the steel, etc. The total output from the system is the sum of intermediate and final demand (Strømman, 2010), see Equation 2-1.

$$\underbrace{x}_{\text{total output}} = \underbrace{Ax}_{\text{intermediate demand}} + \underbrace{y}_{\text{final demand}}$$

*Equation 2-1: Production balance*

The Leontief inverse matrix, L, can be derived from the production balance in Equation 2-1. The coefficients in this matrix, $l_{ij}$, show how the direct and indirect, i.e. life cycle, requirements from process $i$ to satisfy one unit of final demand for process $j$ (Strømman, 2010). How to obtain he Leontief inverse is shown in Equation 2-2.

$$x - Ax = y$$

$$(I - A)x = y$$

$$x = (I - A)^{-1}y = Ly$$

*Equation 2-2: Deriving the Leontief inverse*

The $A$-matrix consists of two methodically equivalent, but conceptually distinct sections: The *foreground system* and the *background system*, see Equation 2-3 (Strømman, 2010). The processes in foreground system are carefully examined and vetted to accurately depict the system under investigation. The background system, on the other hand, are average values associated with economic activities for processes where high resolution is not considered necessary. The delineation between the foreground and background in the present analysis can be seen in Figure 2-2.

$$A = \begin{bmatrix} A_{\mathrm{ff}} & A_{\mathrm{fb}} \\ A_{\mathrm{bf}} & A_{\mathrm{bb}} \end{bmatrix}$$

*Equation 2-3: Structure of the four submatrices of the requirement matrix. The subscript notation now refers to systems,* f *for foreground and* b *for background, instead of processes.*

In this thesis, the foreground consists of the inventory for each ship in blocks along the diagonal. The foreground processes are the same for each ship, but with unique values depending on the ship's characteristics. The sample matrix in Equation 2-4 visualises the foreground structure.

$$A_{\mathrm{ff}} = \begin{bmatrix} \begin{matrix} s_{1,11} & s_{1,12} \\ s_{1,21} & s_{1,22} \end{matrix} & 0 & \cdots & 0 \\ 0 & \begin{matrix} s_{2,11} & s_{2,12} \\ s_{2,21} & s_{2,22} \end{matrix} & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \begin{matrix} s_{n,11} & s_{n,12} \\ s_{n,21} & s_{n,22} \end{matrix} \end{bmatrix}$$

*Equation 2-4: Sample foreground matrix with two foreground processes for n ships.*

Outputs from processes that do not contribute to the value-adding activity of the supply chain must also be accounted for. These flows are called *stressors* and refer to environmental pressures such as emissions and land use, and are collected in the stressor intensity matrix, $S$. The entries, $s_{ij}$, quantify how much of stressor $i$ is incurred for each unit of output from process $j$. Equation 2-5 shows how the total amount of stressors for a given final demand is calculated.

$$e = Sx = SLy$$

*Equation 2-5: Vector of stressors, e, due to a vector of final demand, y.*

#### *2.1.2.1 Ecoinvent*

Ecoinvent, «the largest transparent unit-process LCI database worldwide», is the background database used in this thesis (Wernet et al., 2016). Ecoinvent 3.2 contains 12,916 processes and 25,950 stressors, as well as the interactions between processes and between processes and stressors.

### 2.1.3 Impact assessment

Having determined the total amount stressors, the final step in the quantification is to convert the long list of stressors into a manageable number of environmental impacts. This is a two-stage procedure consisting of classification and characterisation (ISO, 2006). In order to calculate total impacts, one must classify what stressors contribute to which impacts and by how much. E.g. well-mixed greenhouse gases, i.e. $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$) and halocarbons, uniquely contribute to the climate change impact indicator global warming potential (GWP), meaning other stressors are excluded from the calculation (De Schryver and Goedkoop, 2013, Myhre et al., 2013). The stressors included in the calculation need to be converted to a common unit when gathered in one impact category; $CO_2$-equivalents ($CO_2$ eq) for GWP. The coefficients, $c_{ij}$, of the characterisation factor matrix, $C$, tell how much of impact $i$ is generated per unit output of stressor $j$. E.g. with a 100-year time horizon, methane has a GWP of 28 kg $CO_2$ eq per kg (Myhre et al., 2013). After classification is completed for all impact categories, characterising can be done, i.e. calculating the environmental impacts of the investigated system, see Equation 2-6.

$$d = CSLy$$

*Equation 2-6: Vector of environmental impacts, $d$, due to a vector of final demand, $y$.*

Transitioning from quantifications of stressors that are tangibly linked to the product or service to impacts, for which the connection to the initial activity is more abstract, involves several value judgements. E.g. whether or not to include stressors that have been indicated to be relevant for an impact category by preliminary research or what time horizon one considers for each impact category. In ReCiPe, cultural perspectives are employed to handle this issue. The hierarchist perspective, which is the most commonly used, is the one applied in this thesis.

#### *2.1.3.1 ReCiPe*

ReCiPe v1.11 is the impact assessment method used in this thesis. It provides characterisation factors for 18 impact categories. Results are provided for three different *cultural perspectives* to account for various possible value choices: Egalitarian, hierarchist and individualist. The hierarchist perspective is used in this thesis because it is based on the most common policy principles and represents the scientific consensus (Heijungs et al., 2013).

### 2.1.4 Interpretation

Whereas the first three steps are somewhat sequential, interpretation of the results is conducted throughout the entire process. Debugging and gauging the plausibility of results should be done when establishing the goal, modelling all the system flows and during the calculation of impacts.

One way to examine the results is to look at how all impacts, both those caused directly and indirectly, are distributed across their respective foreground processes. This is an *advanced contribution analysis* and yields insight into which foreground processes pull on the most environmentally taxing ones in the background. Disaggregating the impacts, either in the LCA analysis itself, like an advanced contribution analysis, or by dividing the system being analysed into segments for which each one an LCA procedure is performed, provides the analyst with more information than the single value for an impact. If there are any unexpected findings, it is then possible to check whether the unanticipated results are due to erroneous assumptions or if any mistakes were made in the modelling process.

In addition, it is important to evaluate the robustness of the results. This can be done by comparison with outside sources, or by statistical tools, e.g. sensitivity analysis, Monte Carlo simulation or structural path analysis.

## 2.2 Generating Fleet Development Scenarios

Fleet development models vary greatly in detail and scope. There are simplistic models used to investigate economic levers of the system, like that of Psaraftis and Kontovas (2010) which imagines a fleet of uniform ships and Cariou (2011) who differentiates between different size segments of containerships. Also, more complex models that incorporates different ship types and rules for entry to and departure from the fleet exist, such as Kalli et al. (2013) that look at individual ships with spatial resolution of emissions and Eide et al. (2011) who also have additional resolution of size segments within each type. The currently largest and most authoritative work on scenarios of fleet development is the *Third IMO GHG Study 2014* (Smith et al., 2014). Their efforts showcase the process to forecast emissions in an industry with several moving parts and influences from many sides, where all the detail of the aforementioned studies is incorporated and the future demand for ships is driven by an external factor, not fixed rates.

In Smith et al. (2014), future transport demand shapes the fleet, which together with efficiency increases and penetration of new fuels predict emission levels in future years. For non-fossil-fuel transport, such as container shipping, the demand is projected based on GDP. Ships are removed from the fleet when they reach a lifetime of 25 years. Another approach to fleet development is to have fixed growth rates. In Kalli et al. (2013) an annual growth rate in traffic growth for each ship type is coupled with a lifetime for each ship type, which directs the development of the fleet until 2040. Alternatively, Eide et al. (2011) combine fixed growth rates with fixed scrap rates for different ship types to compute an emission trajectory until 2030.

When investigating future fleet compositions, the resolution of the fleet make-up is an important feature. Differentiating between different ship types introduces a useful level of detail, and is commonly done since the ships of a given type share characteristic traits. Granularity within ship types may also be valuable as there can be economies of scale-effects with increasing ship size for example. With this approach, ships of a certain type and within a predetermined size range are apportioned and the averaged characteristics across these allotted *size bins* are used as example ships that exist in the future fleet. For containerships, the most common demarcation feature is the twenty-foot equivalent unit (TEU) (Smith et al., 2014, Eide et al., 2011, Cariou, 2011, Lindstad et al., 2012), which is a capacity attribute used specifically for containerships that designates how many twenty-foot long ISO containers a ship can maximally hold.

Both Smith et al. (2014) and Eide et al. (2011) differentiate ships in the future fleet along both type and size axes: In Eide et al. (2011) the size distribution of the fleet is constant throughout the modelling period, while in Smith et al. (2014) the size bins for the containership segment evolve from 2012 to 2050, where the development of the distribution is established based on a literature review.

The model developed in this thesis is a life cycle analysis, computing the total environmental impact of the global container fleet in 2016 for 11 different impact categories. 2016 also serves as the base year for the further analysis of the development of the environmental impact of the container fleet until 2050. It is similar to the *Third IMO GHG Study 2014* (Smith et al., 2014) in that estimated future transport demand is used as a starting point for the analysis, based on long-term economic projections. It likens Smith et al. (2014) and Eide et al. (2011) in that size bins are used as an architectural structure for the future fleet. It differs from the above fleet development approaches in that it handles only one ship type, i.e. containerships, which permits more detail within the model. Also, a differentiated operational profile is developed and utilised in this thesis, see section 2.2.1.

### 2.2.1 Slow steaming

A phenomenon named *slow steaming* became a widely adopted strategy in international shipping after fuel prices rose drastically in 2007 (Smith et al., 2014, Cariou, 2011, Beverelli et al., 2010).

Due to the prevailing overcapacity in the containership market and low freight rates, slow steaming is still used by carriers today as a tool to absorb capacity and keep shipping costs down (UNCTAD, 2016). It is the phenomenon that ships go at lower speeds to save fuel, often significantly below design speed, since the power requirement of the motor, and thus the fuel consumption, is non-linearly correlated with speed: A useful rule of thumb is that the engine power is a cubic function of the speed (Psaraftis and Kontovas, 2010). Since containerships carry high-value goods, as opposed to raw materials, they have historically been built to run at higher design speeds than other ship types. In turn, this means that they also have the highest potential for saving costs by slow steaming (Smith et al., 2014, Psaraftis and Kontovas, 2010). The debate over whether slow steaming will continue or not is not settled, but the practice is being upheld at the moment and therefore necessary to include in the model.

# 3 Life Cycle Inventory

The environmental impact of the current fleet is calculated by constructing a life cycle inventory (LCI) for each individual ship in the existing fleet and then performing a life cycle impact assessment (LCIA) for the entire fleet. By keeping the full resolution of the fleet until the final step of impact calculation the model is flexible and makes it possible to calculate the impact of any subdivision of the fleet.

The life cycle inventory of a ship includes all the materials used and disposed of during its lifetime as well as any direct emissions happening during the activities occurring in the lifespan of the ship. An activity that lead to environmental impact occur in one of five life cycle phases:

- Construction
- Operation, propulsion
- Operation, other
- End-of-life
- Fuel

An overview of which processes and stressors occur in each phase for an individual ship is found in Table 3-5 and Table 3-6 at the end of this chapter, respectively.

Below are presented short introductions to the data sources used in the thesis.

## 3.1 Ship Data

The core data in the analyses in this thesis are from IHS Maritime & Trade's Sea-web™ Database. It was previously named *IHS Fairplay Database*, and as of 10 May 2017 it was integrated into IHS's Maritime Portal (IHS Markit, 2017). Information for all containerships in the database with a construction date after 1 January 1980 was extracted, and serves as the cornerstone for all calculations. To compose the inventory for a ship the relative values given in Table 3-5 and Table 3-6 are multiplied with the appropriate ship feature. To calculate the environmental impacts at fleet level, the impacts from each individual ship is summed.

### 3.1.1 Missing Data Points

From the dataset obtained from the Sea-web™ Database, only ships with status *In Service/Commission* were included in the analysis, a total of 5003 containerships. However, there were some characteristics where data was missing, see Table 3-1. The most problematic were the large amount of missing values for light displacement tonnage (LDT). LDT is used in the LCI to calculate the impacts from life cycle phase *Construction*. Missing values were estimated by regressing LDT against other ship features. Scatter plots of LDT and the other ship features and the linear regression statistics for the correlations are presented in Figure 3-1 and Table 3-2, respectively. A new parameter, *Box*, the product of *Draught, Length and Breadth,* was created because it intuitively makes sense that such a parameter would correlate strongly with LDT.

*Table 3-1: Overview of missing values in the ship database. The characteristics in bold type are those necessary to run the analysis.*

| *Characteristic* | *Non-null entries* | *Missing entries* |
|---|---|---|
| **IMO ship number** | **5003** | **0** |
| Name of ship | 5003 | 0 |
| **Year of build** | **5003** | **0** |
| **Gross tonnage (GT)** | **5003** | **0** |
| **Deadweight (DWT)** | **5003** | **0** |
| **Lightweight displacement tonnage (LDT)** | **3705** | **1298** |
| **Twenty-foot equivalent units (TEU)** | **4982** | **21** |
| Draught | 4996 | 7 |
| Length | 4967 | 36 |
| Breadth | 5002 | 1 |
| **Main engine total kW** | **4999** | **4** |
| **Auxiliary engine total kW** | **3261** | **1742** |
| Service speed | 4945 | 58 |

As observed in Figure 3-1 and Table 3-2, the *Box* parameter is the one with the highest R-value and lowest standard deviation. Therefore, the coefficients for the linear regression analysis between *LDT* and *Box* were used to estimate the 1267 missing values there were *Box* values for, leaving 31 instances where the second-most ideal parameter, *DWT*, was used.

Table 3-1 shows that many values for *Auxiliary engine total kW* also are missing. This characteristic is less central to the calculation: Pre-set auxiliary engine power usage is checked against this figure, and the power usage is decreased to the auxiliary engine capacity if it is lower than the pre-set value. Missing entries are added using a similar approach as for LDT: Based on the plots in Figure A-1 in the appendix, it was determined that the missing auxiliary engine data should be determined by a second order polynomial regression of the *DWT* parameter.

The other ship characteristics have much fewer missing values, therefore it would not make sense to split the estimation of missing between different features. Hence, parameters with all values present were chosen for these regressions: *DWT* was used for both *Main engine total kW* and *TEU*. A second order polynomial regression was used for the latter.

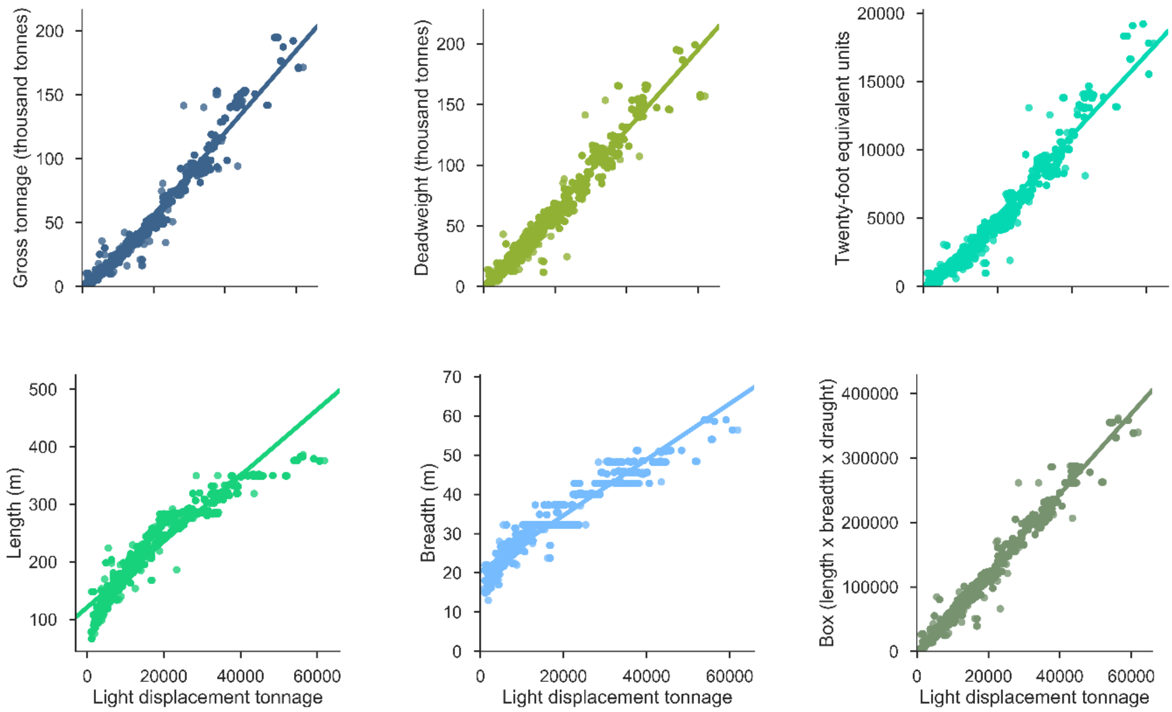



*Figure 3-1: Scatter plots of LDT against other parameters. The plots were made to find a good predictor variable for LDT to fill missing values in the dataset.*

*Table 3-2: Values for linear regression of other ship characteristics against LDT, accompanying the plots in Figure 3-1.*

| *Predictor* | *Slope* | *Intercept* | *R-value* | *P-value* | *Standard error* |
|---|---|---|---|---|---|
| GT | 3.03E-01 | 2.97E+03 | 0.987 | 0 | 7.87E-04 |
| DWT | 2.93E-01 | 1.64E+03 | 0.987 | 0 | 7.70E-04 |
| TEU | 3.28E+00 | 2.97E+03 | 0.984 | 0 | 9.84E-03 |
| Length | 1.60E+02 | -1.81E+04 | 0.959 | 0 | 7.85E-01 |
| Breadth | 1.31E+03 | -2.55E+04 | 0.965 | 0 | 5.83E+00 |
| Box | 1.59E-01 | 9.58E+02 | 0.994 | 0 | 2.92E-04 |

## 3.2 Construction

Ship construction inputs are generated from the transoceanic freight ship modelled in Ecoinvent 3.2 (Wernet et al., 2016). This is an approximately 50,000 DWT dry bulk carrier (Spielmann et al., 2007). Due to design differences between dry bulk carriers and containerships the input values were scaled based on LDT, calculated as the sum of material inputs, rather than DWT.

The most significant input, accounting for more than 99% of the weight of the ship, is steel. Production of steel requires large amounts of energy, and the industry is responsible for almost 7% of global $CO_2$ emissions (World Steel Association, 2017).

## 3.3 Operation, propulsion

The majority of greenhouse gas emissions in a ships lifetime stem from the propulsion of the ship, commonly called the operational phase, see section 5.1. The ship engine combusts fuel, and the released energy is used to move the ship. The emission of greenhouse gases and other pollutants to the atmosphere is proportional to the amount of fuel the engine consumes. Therefore, it is important to increase the motor fuel efficiency, measured in specific fuel oil consumption (SFOC) most often reported with the unit g/kWh, to reduce emissions in the future. Greenhouse gas emissions can also be reduced by minimising water resistance through improved hull shape designs, since this reduces the ship's fuel consumption.

Continuous progress is being made in ship efficiency measures: "A standard ship built today will have an improved performance relative to a ship built to standard 5 years ago with no additional cost to the buyer" (Eide et al., 2011). The International Maritime Organisation (IMO) has implemented the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SSEMP) for already existing ships to ensure continued improvement (IMO, 2017a). More energy efficient ships improve both profits and environmental performance, so further innovations and implementation of existing technologies are expected to persist. Thus, the fuel efficiency of the global fleet has been increasing the past decades as the ships that replace the ones removed from the fleet have improved fuel efficiency (UNCTAD, 2015), and it is expected to continue to improve in the future. In the model employed in this thesis, SFOC reductions of 10 and 5 g/kWh from one decade to the next are meant to simulate these improvements, see Table 3-3.

The data inputs for the operational phase are provided by the shipping chapter in the European Monitoring and Evaluation Programme (EMEP) and the European Environmental Agency's (EEA) *Air Pollutant Emission Inventory Guidebook 2016* (Trozzi and De Lauretis, 2016). The emission intensities are relative to the fuel consumption of the ship, with a higher resolution for pollutants that depend on the engine combustion technology than for those who are decided by which fuel is used.

*Table 3-3: Improvement of SFOC over time. Ships with earlier build-years are assumed to have lower fuel efficiency than newer ships. The quantification is based on Cariou (2011) and in-house knowledge.*

| *Decade when ship was built* | *Specific fuel oil consumption, SFOC (g/kWh)* |
|---|---|
| 1980 | 205 |
| 1990 | 195 |
| 2000 | 185 |
| 2010 | 180 |
| 2020 | 175 |
| 2030 | 170 |
| 2040 | 165 |
| 2050 | 155 |

### 3.3.1.1 Fuel-specific emissions

$CO_2$, sulphur oxides ($SO_x$), heavy metals and toxic chlorinated aromatic substances are pollutants whose emissions are determined by their contents in the fuel used. These are called Tier I pollutants and are calculated by multiplying the emission factor for the appropriate pollutant and fuel type by the fuel consumption:

$$E_i = FC_{tot,m} \times EF_{i,m}$$

*Equation 3-1: The emission, $E$, of a fuel-specific pollutant $i$ is the product of fuel consumption, $FC$, of fuel type $m$ and the fuel-specific emission factor, $EF$.*

It is assumed that all ships run on heavy fuel oil (HFO), also called residual fuel. This is the most common fuel in maritime transportation: About 85% of the fuel used for international shipping activity in 2011 was HFO (Smith et al., 2014). Residual fuel is the heaviest fraction left in crude oil refining and contains high levels of sulphur (Bengtsson et al., 2011). In this model, the sulphur content of the fuel is one that complies with the limits established for ships moving outside Sulphur Emission Control Areas (SECAs), outlined in IMO Regulation 14: 3.50% by mass before 1 January 2020 and 0.50% after that date (IMO, 2017c).

#### *3.3.1.2 Engine-specific emissions*

Nitrogen oxides ($NO_x$), non-methane volatile organic compounds (NMVOC) and particulate matter (PM), in addition to being dependent on the type of fuel, are pollutants whose emission intensities are also reliant on what engine type is analysed as well as the operational profile of the ship.

Marine engines are typically categorised as one of two types: Slow-speed engines and medium-speed engines. The slow-speed engines comprise the majority of installed power on a ship as main propulsion engines, while auxiliary engines, which are used for operations other than moving the ship, are medium-speed engines (Spielmann et al., 2007). In the present analysis, this separation of engine types is assumed for all ships.

EMEP and EEA's guidebook identifies three different operational profiles, with unique emission intensities: Cruising, manoeuvring and hoteling. The time a ship spends in each of those trip phases is based on aggregate data for nine size segment of container ships from Lindstad et al. (2012), see section 3.3.1.4.

The calculation of engine-specific emissions is done after the most detailed level outlined in EMEP and EEA's guidebook: Tier III-modelling. The emissions for each phase of the trip are calculated by multiplying fuel consumption with an effect factor that is unique for each pollutant, engine type, trip phase and fuel type (Trozzi and De Lauretis, 2016), shown in Equation 3-2.

$$E_i = \sum_{e,p} FC_{e,p,m} \times EF_{i,e,p,m}$$

*Equation 3-2: The emission, $E$, of an engine-specific pollutant $i$ is the fuel consumption, $FC$, of engine $e$ in trip phase $p$ and of fuel type $m$ multiplied by the engine-specific effect factor, $EF$, summed across the possible combinations of engine types and trip phases.*

As well as control requirements for sulphur, IMO also imposes $NO_x$ control requirements. Since these are mainly dependent on the engine type, the restrictions only apply to newbuilds (IMO, 2017b). If a ship is completed after 1 January 2000, Tier I regulations apply. It is estimated that an engine meeting Tier I-standards has about 17% lower NOx-emissions than an engine built before the requirements came into effect (Trozzi and De Lauretis, 2016), and this emission reduction is included in the model in this thesis, see Equation 3-3. Ships with a construction date after 1 January 2011 must comply with Tier II regulations, which is a 15% tightening of the total weighted cycle emission limit compared to Tier I (IMO, 2017b). Hence, a further 15% NOx-emission reduction is modelled for ships built 2011 and after, see Equation 3-4. Tier III regulations apply to ships built after 1 January 2016 and that are operating in Nitrogen Emission Control Areas (NECAs); these ships are not included in the model. For ships built after 1 January 2016 that are operating outside NECAs, Tier II regulation apply (IMO, 2017b).

$$E_{NO_x}(2000 \leq b < 2011) = E_{NO_x}(b > 2000)\times(1 - 17\%)$$

*Equation 3-3: $NO_x$ emissions of ships with a build date, $b$, between 2000 and 2011 are 17% lower than for ships constructed before 2000.*

$$E_{NO_x}(b \geq 2011) = E_{NO_x}(2000 \leq b < 2011)\times(1 - 15\%)$$

*Equation 3-4: A further 15% reduction in $NO_x$ emissions, relative to Tier I engines, are applied to ships with a build date, b, in or after 2011.*

#### 3.3.1.3 Other emissions

Some stressors are present in Ecoinvent 3.2, but not covered in EMEP and EEA's guidebook. In Ecoinvent they are reported per tkm, so the yearly emissions are found by multiplying the emission intensities with the annual transport work, shown in Equation 3-5.

$$E_i = TW \times EF_i$$

*Equation 3-5: Emission, $E$, of pollutant $i$ is the product of a ship's transport work, $TW$, and the emission factor, $EF$, for the transoceanic freighter in Ecoinvent 3.2.*

#### 3.3.1.4 Fuel consumption and transport work

To be able to calculate emissions related to propulsion, information about a ship's operational profile is needed. In lieu of data about speed and trade routes served by each ship, aggregate operational data for different size bins from Lindstad et al. (2012) was used. For calculation of the pollutants covered in EMEP and EEA's guidebook information about the time spent in each of the trip phases of cruising, manoeuvring and hoteling is needed, while those listed in Ecoinvent requires information about the annual transport work of each ship. The data from Lindstad et al. (2012) is found in Table 3-4.

A ship's fuel consumption is calculated as follows:

$$FC_{tot,s} = \sum_{e,p} t_p \times P_{e,p} \times SFOC_{b(s)}$$

*Equation 3-6: Fuel consumption, $FC$, of ship $s$ is the product of time, $t$, spent in trip phase $p$, the power requirement, $P$, in that trip phase and for engine $e$, and the specific fuel oil consumption, $SFOC$, dependent of the ship's year of build, $b$. The total fuel consumption, $FC_{tot}$, is found by summing the results across all engine types and trip phases.*

As previously mentioned, there are two engine types installed on a containership: The main engine used for propulsion and auxiliary engines for other purposes. The power requirement is calculated differently for the two types. For auxiliary engines, power required in each trip phase is as reported in Jalkanen et al. (2009): 750 kW in cruise phase, 1250 kW while manoeuvring and 1000 kW while hoteling. However, the power requirement cannot exceed the capacity of the auxiliary engine. For main engines, the power requirement is a percentage, commonly called *load factor*, of the maximum continuous rating (MCR), a measure of the total installed main power, see Equation 3-7. When a ship travels at design speed the load factor lies between 70% and 90% (Cariou, 2011), so a load factor of 80% was chosen for the cruise phase. It is assumed to be 25% when manoeuvring and the main engines are assumed to be off when hoteling.

$$P_{main,s,p} = MCR_s \times LF_p$$

*Equation 3-7: The power requirement, $P$, of the main engine of ship $s$ for trip phase $p$ is the product of the ship's maximum continuous rating, $MCR$, and the load factor, $LF$, for that trip phase.*

*Table 3-4: Data about operational profiles for containerships of varying sizes (Lindstad et al., 2012).*

| *Ship size (TEU)* | *Days at sea at service speed, $t_{sea}$* | *Days per voyage, $d_{voy}$* | *Voyages, $n_{voy}$* | *Distance per voyage, $l_{voy}$ (nm)* | *Payload percentage, PL* | *Cargo utilisation, u* |
|---|---|---|---|---|---|---|
| 8500+ | 251 | 31 | 11 | 11000 | 80% | 70% |
| 6500 | 250 | 31 | 11 | 11000 | 80% | 70% |
| 4000 | 226 | 24 | 14 | 7000 | 80% | 70% |
| 2300 | 215 | 10 | 32 | 2500 | 80% | 70% |
| 1400 | 174 | 8 | 45 | 1000 | 80% | 70% |
| 700 | 152 | 7 | 48 | 700 | 80% | 70% |
| 200 | 107 | 5 | 55 | 300 | 75% | 70% |

The time spent in each trip phase are calculated from data provided in (Lindstad et al., 2012) in the following manner:

$$t_{cruise} = t_{sea}$$
$$t_{manoeuvre} = d_{voy} \times n_{voy} - t_{cruise}$$
$$t_{hotel} = 365.25 - t_{cruise} - t_{manoeuvre}$$

*Equation 3-8: Time calculation for the ships' trip phases. $t$ is the time spent in each trip phase in days. $t_{sea}$ are the days at sea at service speed, $d_{voy}$ are the number of days spent per voyage and $n_{voy}$ are the number of voyages in a year. Values are found in Table 3-4.*

The transport work conducted by each ship, which is used to estimate emissions of pollutants in the Ecoinvent inventory, is calculated as follows:

$$TW_{s,z} = u_z \times DWT_s \times PL_z \times l_{voy,z} \times n_{voy,z}$$

*Equation 3-9: The annual transport work, $TW$, by ship $s$ in size bin $z$ is the product of cargo utilisation, $u$, the ship's deadweight tonnage, $DWT$, the ratio of DWT used for payload cargo, $PL$, distance per voyage, $l_{voy}$, and the annual number of voyages for the ship, $n_{voy}$. When the distance per voyage is given in nautical miles, a conversion factor of 1.825 must be applied to calculate tonne-kilometres.*

## 3.4 Operation, other

There are activities occurring throughout a ship's lifetime that are not associated with propulsion. Here are included the same activities as in Ecoinvent 3.2: Ship maintenance, disposal of bilge oil waste and the use of port facilities. In Ecoinvent, the values for these activities are given per tkm, and the demand for maintenance and disposal of bilge oil waste is rescaled by a ship's annual transport work in the model in this thesis. The use of port facilities is outsized with this approach, however, so this demand was rescaled based on the figure for port infrastructure demand per throughput of cargo in port provided in the Ecoinvent documentation (Spielmann et al., 2007). By calculating how much throughput each ship contributes per year, a more accurate figure for port infrastructure demand was attained.

## 3.5 End-of-Life

When a ship reaches the end of its economic life it is taken out of service and discarded. There are three main ways of disposing of a ship: (i) Dismantling at a recycling facility that follows strict regulations and has negligible releases of hazardous substances to the surrounding environment, these standard recycling yards are typically located in China or Turkey; (ii) dismantling at a substandard recycling yard on beaches in South Asia where lack of regulations or enforcement results in releases of large amounts of hazardous materials; or (iii) create an artificial reef by sinking the ship (Choi et al., 2016). Since the primary component of ships are high-quality steel, ship owners make a profit when they sell them to recycling yards, and only a very small percentage of ships are disposed of by the final method. Not having to comply with strict and often costly waste disposal, substandard recycling yards can outbid the standard ones: 70% to 80% of oceangoing vessels are scrapped at beaches in Bangladesh, India and Pakistan (Sarraf et al., 2010).

The data on the emissions that occur when breaking a ship apart are from the 2010 World Bank report by Sarraf et al. on shipbreaking in Pakistan and Bangladesh. Ships are brought onto beaches that slope about 10 degrees by the tides and are dismantled from front to back on the spot (Hiremath et al., 2016). Lack of formal waste disposal and treatment sites in these countries leads much of the hazardous material to be spilled on the beaches, while some is embodied in the sold off scrap and disseminates through society and the environment depending on its second-hand use (Sarraf et al., 2010), see Table A-1.

Relying on the pollution inventories for merchant vessels established by Sarraf et al. (2010), the amount of hazardous material has been estimated per ship based on their gross tonnage. Asbestos is not included in the inventory because there is no stressor- or waste process for it in Ecoinvent 3.2. The rest of the stressors were distributed among the environmental compartments based on the information in Table A-1. It is assumed that all ships are beached when they are scrapped.

## 3.6 Fuel value chain

This foreground process refers to the impacts related to the extraction and production of heavy fuel oil, which is assumed used for all ships and engine types in this thesis. It does not include the emissions from burning the fuel, which are accounted for in *Operation, propulsion*. The market distribution of heavy fuel oil used for the transoceanic freighter in Ecoinvent 3.2 is employed: 17% from the European market and the remaining 83% from the rest of the world (RoW) (Spielmann et al., 2007).

*Table 3-5: Life cycle inventory processes for a ship modelled in this thesis*

| *Life cycle phase* | *Process name* | *Quantity* | *Unit* | *Source* |
|---|---|---|---|---|
| Construction | Copper | 9.97E-01 | kg/LDT | (Spielmann et al., 2007) |
| | Polyethylene | 2.09E-01 | kg/LDT | (Spielmann et al., 2007) |
| | Alkyd paint | 1.46E+00 | kg/LDT | (Spielmann et al., 2007) |
| | Reinforcing steel | 9.97E+02 | kg/LDT | (Spielmann et al., 2007) |
| | Electricity | 4.07E-01 | kWh/LDT | (Spielmann et al., 2007) |
| | Heat | 1.25E+01 | MJ/LDT | (Spielmann et al., 2007) |
| Operation, other | Maintenance | 1.54E-11 | unit/tkm | (Spielmann et al., 2007) |
| | Bilge oil | -1.25E-05 | kg/tkm | (Spielmann et al., 2007) |
| | Port facilities | 3.18E-09 | unit/tonne throughput at port | (Spielmann et al., 2007) |
| End-of-life | Waste plastic | -2.09E-01 | kg/LDT | (Spielmann et al., 2007) |
| | Waste mineral oil | -2.99E+00 | kg/GT | (Sarraf et al., 2010) |
| | Waste polyurethane foam | -1.87E+00 | kg/GT | (Sarraf et al., 2010) |
| | Waste emulsion paint | -4.34E-01 | kg/GT | (Sarraf et al., 2010) |
| | Wastewater | -1.28E+00 | m3/GT | (Sarraf et al., 2010) |
| Fuel | Heavy fuel oil, RoW | 8.29E-01 | kg/kg fuel | (Spielmann et al., 2007) |
| | Heavy fuel oil, Europe | 1.71E-01 | kg/kg fuel | (Spielmann et al., 2007) |

*Table 3-6: Life cycle inventory stressors for a ship modelled in this thesis. All emissions in the Operation, propulsion phase are atmospheric releases, while the environmental compartment in the End-of-life phase are given in the name*

| *Life cycle phase* | *Stressor name* | *Quantity* | *Unit* | *Source* |
|---|---|---|---|---|
| Operation, propulsion | $NO_x$ | See section 3.3.1.2 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | NMVOC | See section 3.3.1.2 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Particulates, >10 µm | See section 3.3.1.2 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Particulates >2.5 µm and <10 µm | See section 3.3.1.2 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Particulates, <2.5 µm | See section 3.3.1.2 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | $CO_2$ | 3.11E+03 | kg/tonne fuel | (IMO, 2005) |
| | $SO_x$ | 20 × %S | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Lead | 1.80E-04 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Cadmium | 2.00E-05 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Mercury | 2.00E-05 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Arsenic | 6.80E-04 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Chromium | 7.20E-04 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Copper | 1.25E-03 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Nickel | 3.20E-02 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |

| | | | | |
|---|---|---|---|---|
| | Selenium | 2.10E-04 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | Zink | 1.20E-03 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | PCB | 5.70E-07 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | PCDD/F | 4.70E-10 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | HCB | 1.40E-07 | kg/tonne fuel | (Trozzi and De Lauretis, 2016) |
| | CO | 1.76E-05 | kg/tkm | (Spielmann et al., 2007) |
| | Ammonia | 1.00E-06 | kg/tkm | (Spielmann et al., 2007) |
| Operation, propulsion | PAH | 5.00E-09 | kg/tkm | (Spielmann et al., 2007) |
| | Benzene | 1.22E-07 | kg/tkm | (Spielmann et al., 2007) |
| | Hydrogen chloride | 1.44E-07 | kg/tkm | (Spielmann et al., 2007) |
| | Methane, fossil | 1.55E-07 | kg/tkm | (Spielmann et al., 2007) |
| | Toluene | 5.15E-08 | kg/tkm | (Spielmann et al., 2007) |
| | Hydrogen fluoride | 1.44E-08 | kg/tkm | (Spielmann et al., 2007) |
| | Xylene | 5.15E-08 | kg/tkm | (Spielmann et al., 2007) |
| | Dinitrogen monoxide | 2.00E-07 | kg/tkm | (Spielmann et al., 2007) |

*Table 3.6 continued*

| *Life cycle phase* | *Stressor name* | *Quantity* | *Unit* | *Source* |
|---|---|---|---|---|
| End-of-life | PCBs, atmosphere | 7.65E-07 | kg/GT | (Sarraf et al., 2010) |
| | PCBs, lithosphere | 7.65E-07 | kg/GT | (Sarraf et al., 2010) |
| | PCBs, hydrosphere | 1.70E-07 | kg/GT | (Sarraf et al., 2010) |
| | Lead, lithosphere | 1.05E-03 | kg/GT | (Sarraf et al., 2010) |
| | Lead, hydrosphere | 1.60E-04 | kg/GT | (Sarraf et al., 2010) |
| | Cadmium, lithosphere | 1.65E-03 | kg/GT | (Sarraf et al., 2010) |
| | Cadmium, hydrosphere | 2.52E-04 | kg/GT | (Sarraf et al., 2010) |
| | Mercury, lithosphere | 3.82E-05 | kg/GT | (Sarraf et al., 2010) |
| | Mercury, hydrosphere | 5.84E-06 | kg/GT | (Sarraf et al., 2010) |
| | Oils, lithosphere | 3.07E+00 | kg/GT | (Sarraf et al., 2010) |
| | Oils, hydrosphere | 2.91E+00 | kg/GT | (Sarraf et al., 2010) |
| | Hydrochloric acid, hydrosphere | 1.39E-04 | kg/GT | (Sarraf et al., 2010) |

# 4 Scenario Development

The makeup of the future containership fleet is modelled by discarding and replacing individual ships. The base year is 2016, and the scenarios run to 2050. The fleet for a given year is comprised by already existing ships as well as new ones:

$$fleet_y = fleet_{y,old} + fleet_{y,new}$$

*Equation 4-1: The fleet for year $y$ consists of the ships remaining from the previous year and newbuilds.*

This section goes through the critical parts of the fleet development model, providing a rationale for the judgements that have been made.

## 4.1 Removing ships from fleet stock

Each year ships that have reached the end of their economic life are removed from the fleet. How many ships are scrapped is determined by an annual scrap rate, which is estimated to be a flat rate of 3% of the TEU capacity of the fleet (Eide, year).

$$fleet_{y,old} = fleet_{y-1} - fleet_{y,scrapped}\left(TEU = SR * fleet_{y-1}\right)$$

*Equation 4-2: The old part of the fleet in year $y$ is the fleet from the previous year minus the ships that are scrapped, where the sum of the TEUs of the scrapped ships equals the scrapping rate proportion, $SR$, of the TEU total of the previous year's fleet. $SR$ is 3% for all years.*

### 4.1.1 Lifetime distribution

There are two rules by which ships are scrapped. Firstly, ships older than 45 years are removed from the fleet, then subsequently, the age of remaining ships needed to fill the TEU quota follow a normal distribution with a mean of 25 years and standard deviation of 5 years, see Figure 4-1. In the *Third IMO GHG Study 2014* all ships have a uniform lifetime of 25 years (Smith et al., 2014), while Kalli et al. (2013) use differentiated lifetimes for different ship types, with 25 years for containerships. Which ship of a given age is removed from the fleet is random.

$$fleet_{y,scrapped} = ships(b = y - 45) + ships\left(b = y - N(25,5)\right)$$

*Equation 4-3: The part of the fleet that is scrapped in year y is composed of ships with build-year, b, 45 years ago and ships which ages follow a normal distribution with mean 25 years and standard deviation 5 years. The oldest ship in the dataset was built in 1980, and since the fleet development simulation starts in 2016, an age roof of 45 years ensures that all ships are at one point removed.*

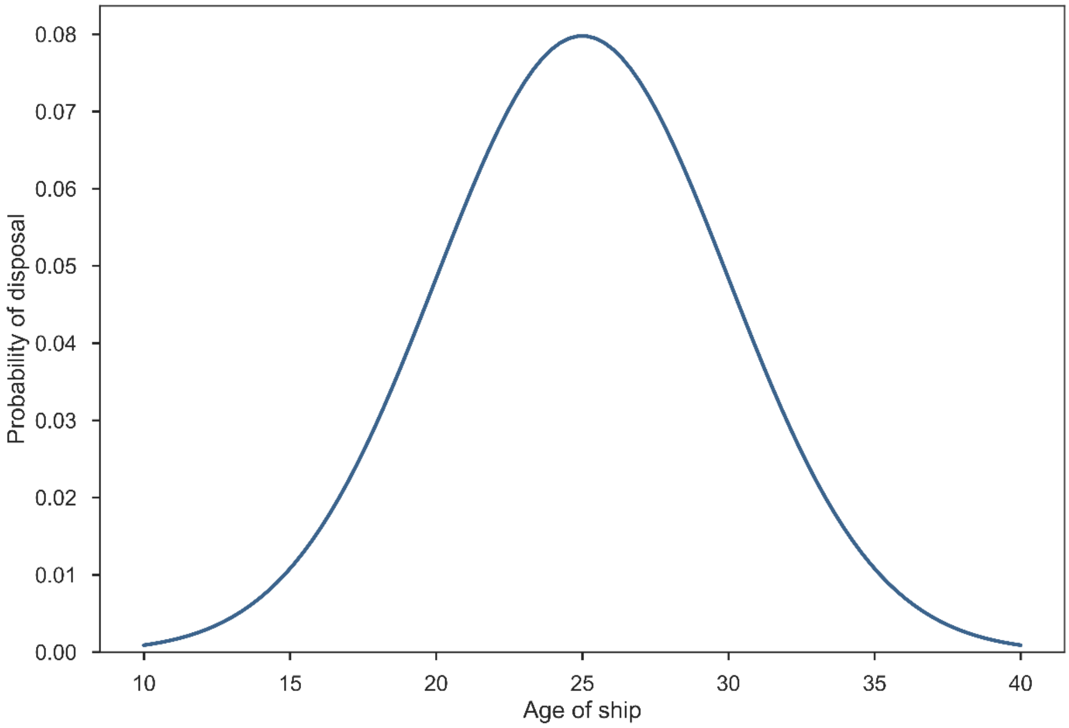



*Figure 4-1: Probability distribution from which scrapped ships are sampled; a normal distribution with mean 25 years and standard deviation 5 years.*

## 4.2 Adding new ships to fleet stock

The other half of the development of the containership fleet each year is the building of new ships. Future ships exist in the dataset as example ships, divided into size bins whose distribution follow a path determined by the development in fleet distribution since 2000, see section 4.2.2.1 and 4.2.2.2, respectively. The driver of additions to the fleet is the forecasted economic development until 2050, see 4.2.1, where the new ships must satisfy the remaining transport demand for that year, i.e. that which is not covered by the old part of the fleet. If the transport work performed by the old part of the fleet exceeds the total transport work demand, no new ships are added.

$$fleet_{y,c,new} = new\ ships\left(TW = TW_{y,tot(c)} - TW\left(fleet_{y,old}\right)\right) \geq 0$$

*Equation 4-4: The new part of the fleet in year $y$ consist of ships that fill the demand for transport work, $TW$, of scenario $c$ not performed by the fleet remaining from the previous year.*

To determine how many new ships of each size segment are added in a given year, both the information about the size division of the fleet and the transport work of the ships within those size buckets is required. With nine size buckets, the predictions of the division of the fleet in Figure 4-8 yields nine equations of the form:

$$x_{z,y} = P_{z,y} x_{y,new}$$

*Equation 4-5: The amount of ships, $x$, in size bin $z$ built in year $y$ equals the proportion $P$ of ships of size $z$ of the total amount of new ships that year.*

The transport work adds the following line, which removes the singularity of the system. This assumes that the projected demand is exactly met.

$$\sum_z TW_{z,y} x_{z,y,new} = TW_{new\ ships,y} = TW_{y,tot(c)} - TW\left(fleet_{y,old}\right)$$

*Equation 4-6: The product of the transport work, $TW$, in year $y$, summed over all size bins, $z$, equals the outstanding transport work of scenario $c$ in year $y$.*

The ten equations presented above yield the following non-singular linear system, whose solution gives how many ships are added in each size bin for the given year, as well as the total number of newbuilds.

$$\begin{bmatrix} 1 & 0 & \cdots & 0 & -P_1 \\ 0 & 1 & \cdots & 0 & -P_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & -P_9 \\ TW_1 & TW_2 & \cdots & TW_9 & 0 \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_9 \\ x_{new} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ TW\left(fleet_{y,new}\right) \end{bmatrix}$$

*Equation 4-7: The solution to this linear system yields how many newbuilds in each size bin and in total are required to meet the transport demand for a given year.*

### 4.2.1 Transport demand

Developments in shipping demand are have historically tracked changes in global GDP (UNCTAD, 2016). Since both the global population and global productivity have been jointly increasing the past half century the per capita GDP is also a good predictor of shipping transport work: Both measures have R-values of 0.96. Looking forward, population growth is expected to start diminishing toward the middle of the century (UN DESA, 2015). Therefore, the GDP per capita measure is used in this thesis to predict future transport work in the shipping sector, the reasoning being that GDP per capita, as well as an indicator of increases or decreases in productivity, is also a gauge of the purchasing power of the populace, which is considered a better predictor of trade and container shipping than GDP alone.

The prediction variable data used for training and prediction are from the Shared Socioeconomic Pathways (SSP) Database (IIASA, 2016), which are described further in section 4.2.1.1. The historic data used for training are from The World Bank's World Development Index (WDI) Database. The future economic scenarios are generated by OECD, and the future population scenarios are made by the International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR). The per capita GDP projections until 2100 is shown in Figure 4-4.

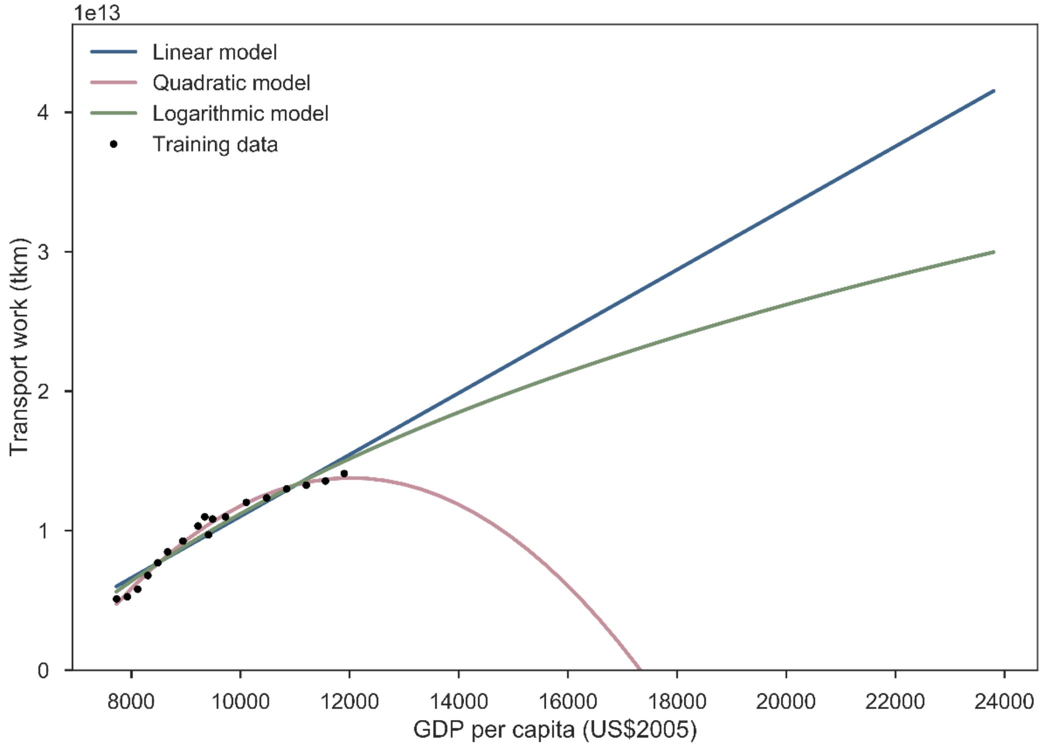



*Figure 4-2: Three regression models were examined to explore predictive potential of per capita GDP for transport work. All models are a good fit within the training set, but considering extraneous factors the logarithmic model is chosen.*

The response variable data used for model training is from UNCTAD's *Review of Maritime Transport* (2016), where estimated transport work of the container fleet is reported since 2000. The data in the SSP Database is reported quinquennially from 1980. In addition, data exists for the year 2008. For the historic data, every five years plus 2008, just five data points from 2000 to 2016, is not enough to train the model, therefore a linear interpolation between each successive data point in the SSP database was done to match with the annually reported transport work data in UNCTAD's *Review of Maritime Transport*.

Three regression models were explored, linear, quadratic and logarithmic, see Figure 4-2. It can be observed that all models are a good fit in the training set. However, when extrapolating the prediction variable to three times the maximum value in the training set, just below the mean value of the scenarios in 2050, we see that the quadratic model peaks too early, and is therefore not useful. UNCTAD (2016) reports that the expansion of shipments in 2015 followed a pace «notably slower than the historic average», which might be symptomatic of a weakening of the trade-GDP relationship: Even though the 2009 recession is still influencing shipping, the crisis is not ongoing, and reduced elasticities outside such periods may point to structural changes being contributing factors. Considering these observations, the logarithmic model was chosen to model future transport work. The forecast of transport work from 2010 till 2050 is presented in Figure 4-3.

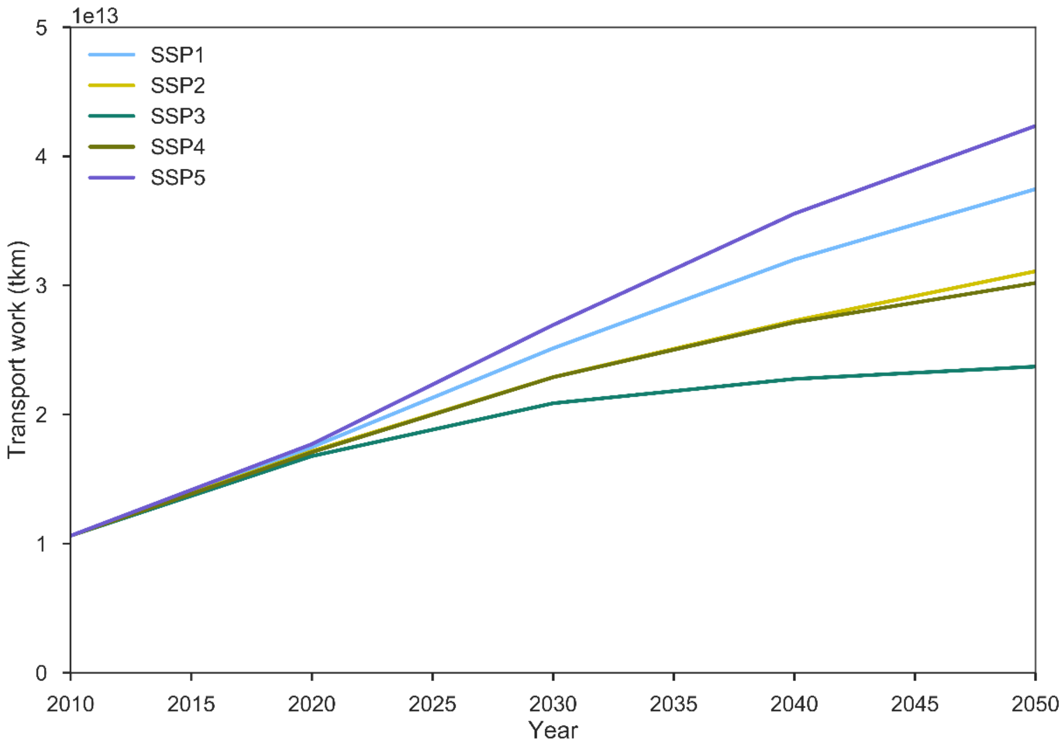



*Figure 4-3: Predicted transport work demand for containerships until 2050. Based on the logarithmic model shown in Figure 4-2.*

#### 4.2.1.1 Shared Socioeconomic Pathways

The SSPs are quantified descriptions of how socioeconomic aspects of the global collective might evolve towards 2100, following five possible storylines. It is assumed that no new climate policies will be put in place and that there are no significant climate feedbacks (Ebi et al., 2014). In this regard, the five pathways are all baseline scenarios, or business-as-usual (BAU), and do not map out what will happen based on varying climate efforts, but they tell the narratives of five different futures which may all occur. Using multiple stories communicate the inherent uncertainty in making quantified projections for the future, and the narratives «guide the choice of assumptions» in the modelling (Dellink et al., 2017). They may not describe plausible futures since they do not include climate policies or impacts (O'Neill et al., 2017), and this uncertainty propagates with time. Therefore, the scenario development only extends to 2050. The GDP per capita development of the five SSPs until 2100 can be found in Figure 4-4 .

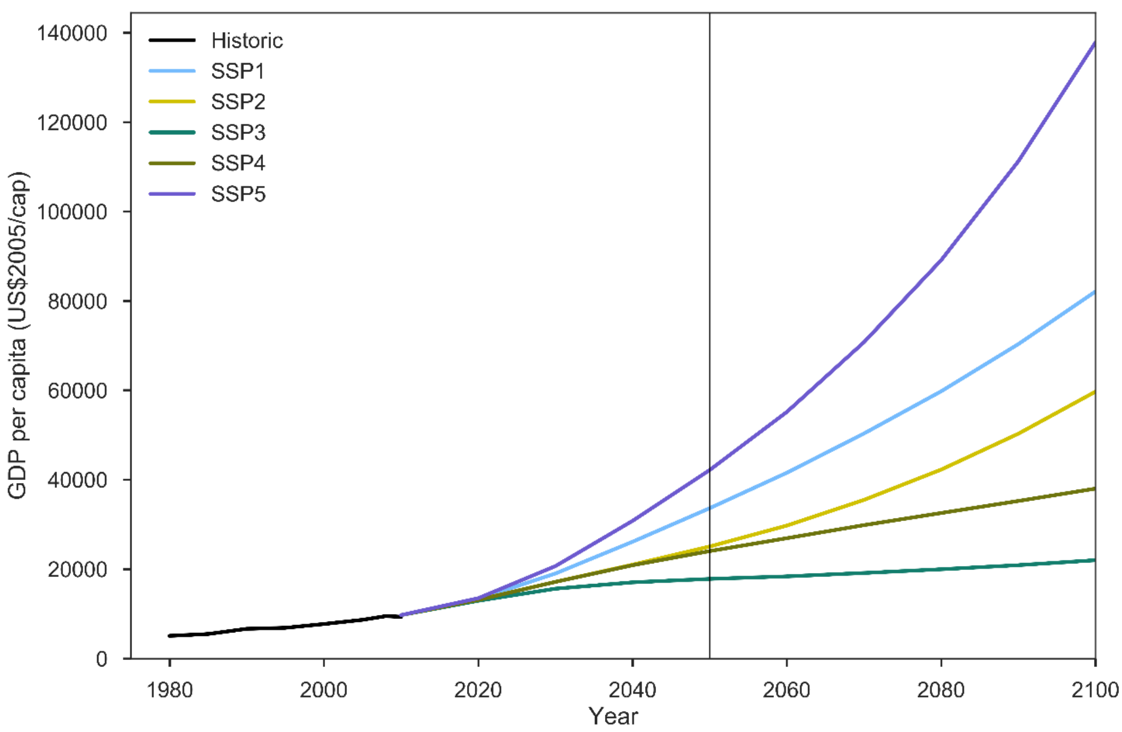



*Figure 4-4: Historic and future developments in per capita GDP. A vertical line shows the year 2050, the year the scenario modelling runs to.*

The narratives are placed within a cartesian space of increasing challenges to adaptation and mitigation, see Figure 4-5, and are simply named SSP1 to SSP5. The first pathway, SSP1, is one where there are few socioeconomic challenges to both mitigation and adaptation, which means that «sustainable development proceeds at a reasonably high pace» and there is rapid technological progress. In the opposite corner of the quadrant, the SSP3 pathway is a world where there are considerable challenges to both mitigation and adaptation, due to moderate economic growth and slow technological change. It is a regionalised world with high inequality which leads to reduced trade flows and «large numbers of people vulnerable to climate change». SSP2 is an intermediate case between these two extremes. SSP4 is «a mixed world», where challenges to adaptation are high while those to mitigation are low: Low-carbon technologies see rapid growth where it matters most, but other regions are isolated and with limited adaptive capacity. Lastly, SSP5 is the pathway where high energy demand is met with carbon-based fuels, yet economic growth and more equitable distribution of resources means that people are more equipped to adapt to the impacts of climate change. (O'Neill et al., 2017)

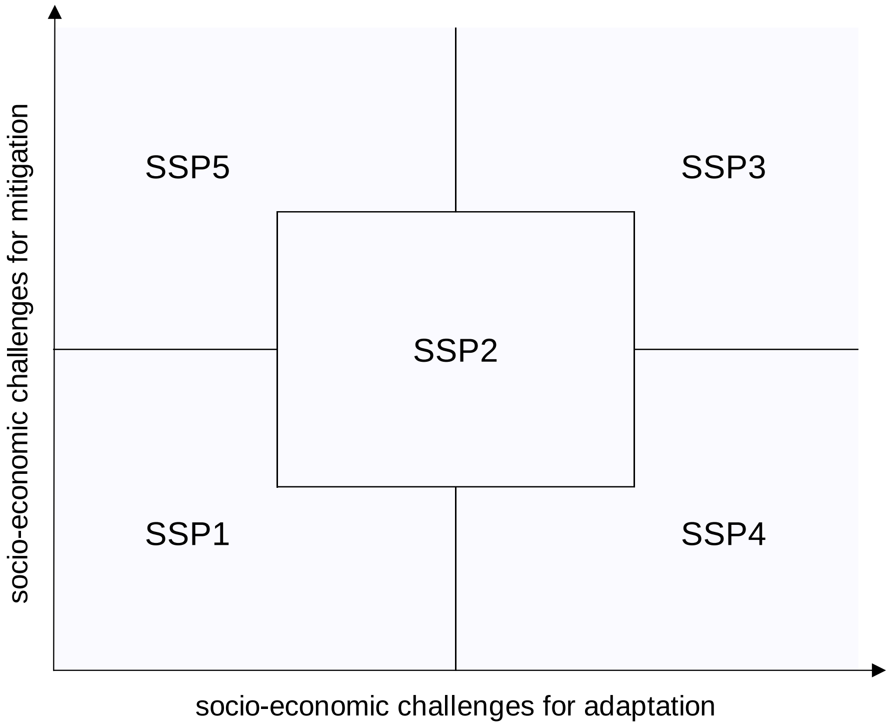



*Figure 4-5: Space of challenges spanned by the Shared Socioeconomic Pathways. Adapted from (O'Neill et al., 2017).*

For GDP, there are three alternative interpretations of the SSPs. Here, GDP projections from the OECD team are used (Dellink et al., 2017), which are chosen as *illustrative* SSPs in the SSP Database (IIASA, 2016).

#### *4.2.1.2 Transport work calibration and slow steaming*

UNCTAD (2016) estimates that the transport work conducted by containerships in 2016 was 1.36E+13 tkm. When applying the operational profiles outlined in Lindstad et al. (2012) to all ships in the current fleet, the transport work of the fleet is overestimated by 83%. Given that the figures in Lindstad et al. (2012) are based on data from 2007, it stands to reason that the transport work of the fleet will be overstated if slow steaming has been widely adopted since then. In the description below it is assumed that all ships run at design speed in 2007, which is referred to as a normal year.

Slow steaming was simulated by reducing load and number of trips in a year for a certain size segments when calculating transport work, see Equation 4-8. The values were adjusted so that the error relative to the figure for transport work in 2016 reported by RMT16 came within 10%. To achieve this, in 2016, all ships have 60% utilisation and ships larger than 2300 TEU travel only two thirds of the trips they do in a normal year. Adjusting the number of trips while keeping the distance per trip constant is meant to simulate that a ship of a given size still travel the same routes as in 2007, but at reduced speed. Vessels below 2000 TEU are small containerships, used as feeder vessels between ports, while those of size 2000-3000 TEU are intermediate vessels used for transport in smaller regions, e.g. the Mediterranean (Lindstad et al., 2012). In 2012 there were signs that smaller vessels were less prone to be operated at lower speeds (Smith et al., 2014), these are therefore not affected by slow steaming in the model. It is assumed that the slow steaming will end in 15 years, by linearly scaling up the reduced values to the original figures, i.e. from 2031 to 2050 all ships sail at the speeds used in 2007.

Sailing at lower speeds incurs significant fuel savings, which is much of the motivation for the practice. A 33% speed reduction, which is used in this analysis, yields «hourly main engine fuel oil savings» of 75% (Wiesmann, 2010). This alters the calculation of fuel consumption in the following manner:

$$FC_{s,e=main,p=cruise}(TEU \geq 2300) = FC_{old,s,e=main,p=cruise} \times \left(0.25 + f\left(0, 0.75, \frac{n_{voy,y}}{n_{voy,old}}\right)\right)$$

*Equation 4-8: The fuel consumption, $FC$, of the main engine of ship $s$, for ships of capacity 2300 TEU or above, in the cruising operating phase is the calculation at original conditions, $FC_{old}$, multiplied by a factor that spans from 0.25 to 1.00 based on the proportion between the number of voyages, $n_{voy}$, the ship makes in year $y$ and the number of trips made in a normal year, $n_{voy,old}$. Fuel consumption is a convex parabolic function of increasing speed (Wiesmann, 2010), but will here follow a linear function since the number of voyages are linearly scaled. This will result in a slight overestimation of fuel consumption in the period when slow steaming is ended, i.e. the first 15 years of the modelling period.*

It is assumed that the time spent in each trip phase stays constant for all years.

### 4.2.2 New ships

Future ships exist in the dataset as example ships. They follow the size division used in Lindstad et al. (2012) with the addition of one extra segment in the top tier, due to the introduction of ultra large container vessels in the '10s. For each year there are nine example ships in the following nine size classes, with exclusive lower limits and inclusive upper limits. The largest containership in the database is 19224 TEU, thus the following bins encompass the entire fleet.

1. 0 to 200 TEU
2. 200 to 700 TEU
3. 700 to 1400 TEU
4. 1400 to 2300 TEU
5. 2300 to 4000 TEU
6. 4000 to 6500 TEU
7. 6500 to 8500 TEU
8. 8500 to 12500 TEU
9. 12500 to 20000 TEU

#### *4.2.2.1 Characteristics*

The characteristics needed for calculation of life cycle impacts must be estimated for the example ships. Looking at Table 3-1 reveals that these are gross tonnage (GT), deadweight tonnage (DWT), lightweight displacement tonnage (LDT), twenty-foot equivalent units (TEU), main engine maximum continuous rating (MCR) and auxiliary engine MCR. The figures are estimated based on the mean of the ships in the same size bin that were built the past 15 years, i.e. for a ship built in 2020, the means of the ships built since 2005 are used. It can be observed in Figure 4-6 that this approach introduces some unevenness in future ship characteristics, where the patterns of previous years are repeated. Additionally, a clear decreasing trend in main engine MCR in recent years can be observed. For this feature, the mean for the ships built in the past three years was used. Since the dataset only consists of ships currently in use, it is possible that figures from scrapped ships diverge greatly and there are important tendencies that are concealed by the lack of this data. However, this is not expected to introduce a large amount of uncertainty since seagoing vessels have a significantly higher life expectancy than 15 years.

#### *4.2.2.2 Distribution*

The future distribution of new ships is based on the trends of relative size distribution of newbuilds since 2000, see Figure 4-7: Developments in relative size distribution of newbuilds. For the segments with low and relatively stable percentages, 0-200, 200-700 and 6500-8500 TEU, this percentage was kept constant until 2050. The other segments were either linearly increased or decreased from 2016 to 2050. It is assumed that the two largest segments, 8500-12500 TEU and 12500-20000 TEU, will not keep growing at such a rapid pace as they have the past five years, but that the growth will taper off and these ships will become the new normal, growing to the previous levels of the largest container ship size of the ‘00s: 35% and 25%, respectively. It is assumed that a ceiling has been reached when it comes to vessel size, and that a class of even larger vessels will not be introduced in the modelling period (Drewry, 2016). Nonetheless, even in a fleet which exists primarily of ultra-large container vessels, some amount of smaller ships is still needed. It is therefore assumed that the mid-size vessels will continue to decrease towards a floor of 5% of newbuilds in 2050. The development of all size segments from 2016 to 2050 can be seen in Figure 4-8.

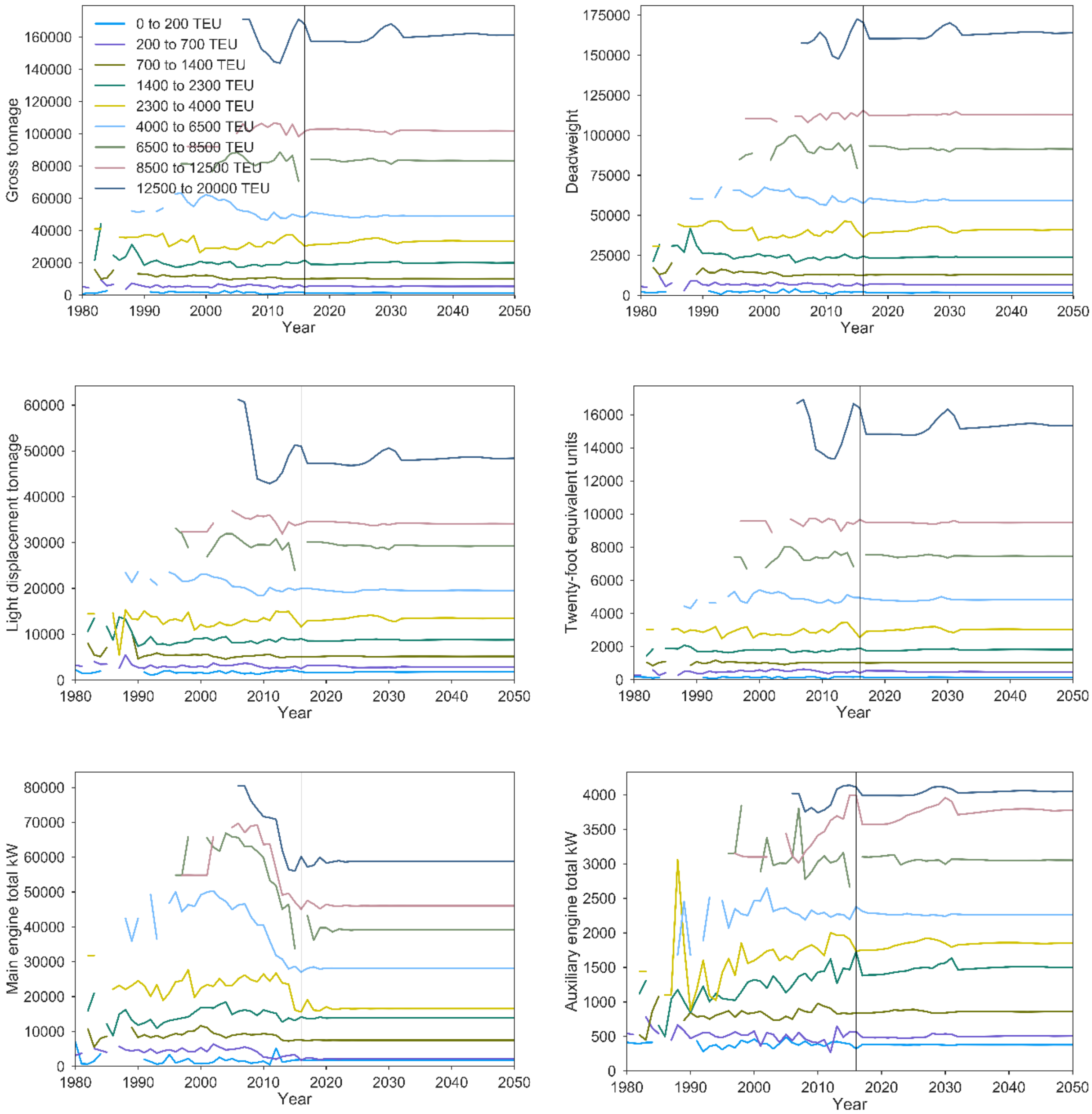



*Figure 4-6: Development in mean values for characteristics of newbuilds over time, broken down per size bin. 2016, the scenario base year, is identified by a vertical line. The values for the example ships of each size bin, used to model the future fleet, are based on the mean for the size bin the past 15 years. The exception is the main engine capacity, where the main of the previous 3 years.*

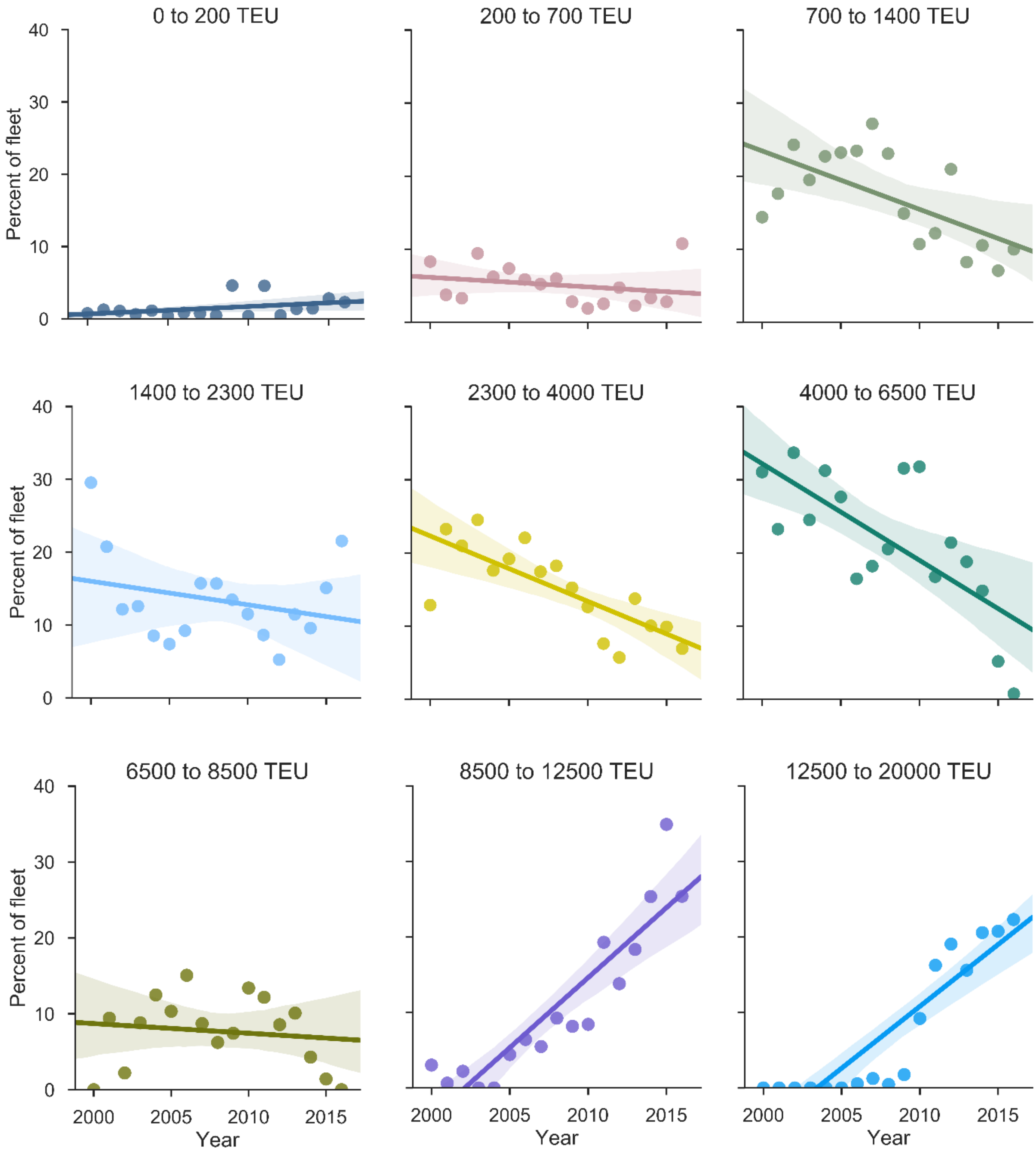



*Figure 4-7: Developments in relative size distribution of newbuilds. A linear trend line and error bands for this regression are included to give an intuition of the direction of the developments as well as the accompanying uncertainty. The error bands show the 95% confidence interval, and are calculated using a bootstrap method (Waskom, 2015).*

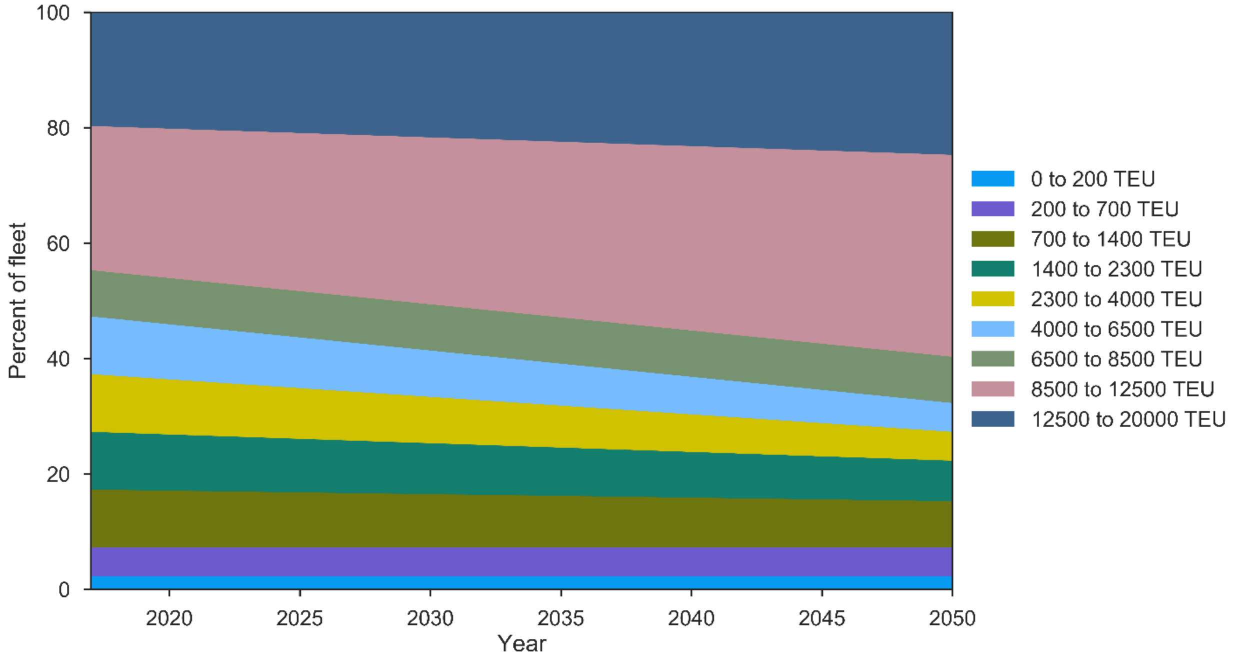



*Figure 4-8: Percentage distribution of newbuilds from 2016 to 2050.*

# 5 Results

In this section, the results of the life cycle analysis of the current fleet of containerships and the modelled future fleet are presented. For the current fleet, a deeper dive into the details of 11 impact categories are presented and an advanced contribution analysis is performed, while for the future fleet the focus is narrowed, and developments over time in a single impact category, global warming potential (GWP), is explored.

## 5.1 The current fleet

11 of the 18 midpoint impact categories calculated in ReCiPe are reported here; those that are most relevant to shipping. An overview is found in Table 5-1. The functional unit is one year of operation of the containership fleet, so the results investigated in this section are the total impacts of all ships in the database, before any of them are scrapped and future ships are added. The size bins used in the scenario development are used to group ships of the same size and aggregate results. For the advanced contribution analysis, three size bins where chosen to represent the fleet, one small, medium and large segment. All advanced contribution plots are found in Figure A-2.

*Table 5-1: Characterisation factors for the 11 impact categories investigated in this section (Heijungs et al., 2013). Stated impacts values are for the hierarchist perspective.*

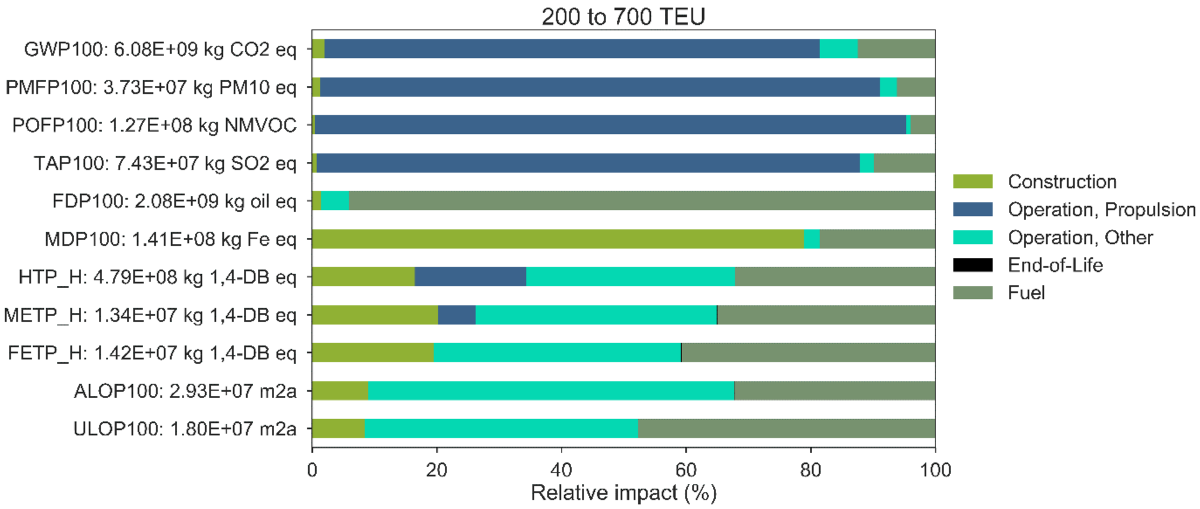
| *Characterisation factor name* | *Code* | *Unit* | *2016 impacts* |
|---|---|---|---|
| Global warming potential | GWP100 | kg CO2 eq | 2.46E+11 |
| Particulate matter formation potential | PMFP100 | kg PM10 eq | 4.39E+09 |
| Photochemical oxidant formation potential | POFP100 | kg NMVOC | 5.05E+09 |
| Terrestrial acidification potential | TAP100 | kg SO2 eq | 2.97E+09 |
| Fossil depletion potential | FDP100 | kg oil eq | 8.42E+10 |
| Mineral depletion potential | MDP100 | kg Fe eq | 7.57E+09 |
| Human toxicity potential | HTP_H | kg 1,4-DB eq | 1.82E+10 |
| Marine ecotoxicity potential | METP_H | kg 1,4-DB eq | 5.05E+08 |
| Freshwater ecotoxicity potential | FETP_H | kg 1,4-DB eq | 5.31E+08 |
| Agricultural land occupation potential | ALOP100 | m2a | 9.86E+08 |
| Urban land occupation potential | ULOP100 | m2a | 6.25E+08 |

Observing the results from the advanced contribution analysis in Figure 5-1 it is discovered that the 11 impact categories fall into four segments of impacts with similar behaviour. Firstly, there are the ones where the fuel combustion in the operational phase is the major contributor: GWP, PMFP, POFP and TAP. This is due to the fact that the pollutants that add to these impacts are the ones released during sailing when fuel is burnt. Secondly, the measure for depletion of fossil fuels, FDP, is dominated by the process of the fuel value chain. This is because the activity of bringing fossil fuels out of the ground occurs in this value chain and the annual fuel consumption of the ships greatly exceed those occurring elsewhere in the life cycle, e.g. in ports and during steel production. Thirdly, the ferrous counterpart to the previous impact type, is MDP, where the steel-heavy construction process makes the most substantial contribution. Lastly, there are the remaining five toxicity and land use impacts. These have in common that the three main processes contributing to these impacts are construction, the non-propulsion activities in the ships' use phase and the fuel value chain.

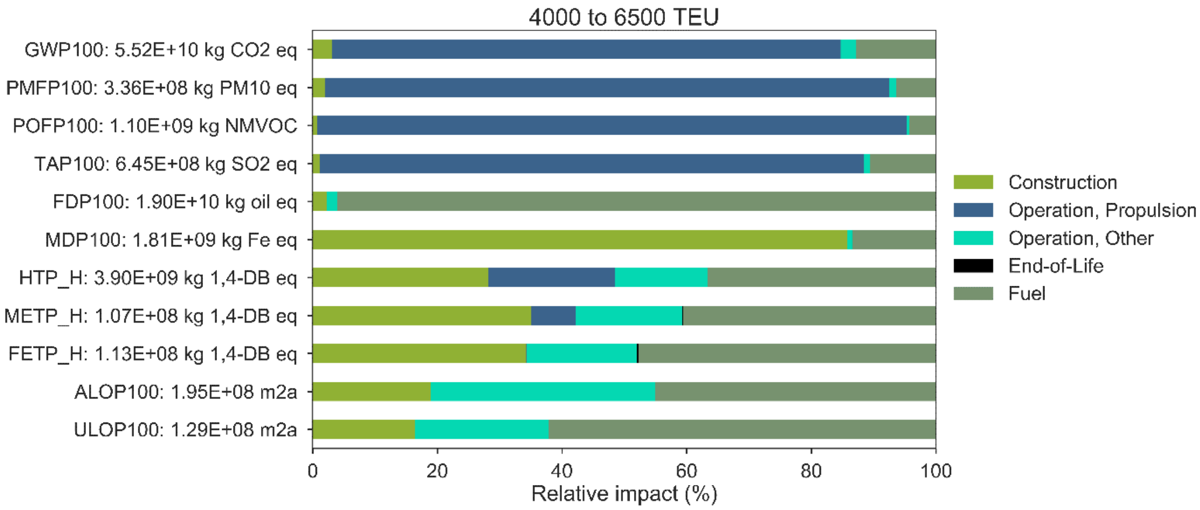
Examining how the relative impacts vary between different size bins reveals that the importance of the construction phase increases with expanding ship size. As expected, the transport work dependent process *Operation, other* plays a larger role in the life cycle of the small ship in 2016, since these ships are not slow steaming.

It is interesting to note that the scrapping of ships is insignificant in comparison with the other processes. Especially since all ships are modelled as being beached in South Asia, an industry with a reputation of inflicting a large negative impact on the environment and human health, the biggest problem being mismanagement of hazardous materials and their release to the environment (Chang et al., 2010, Demaria, 2010, Sarraf et al., 2010, Choi et al., 2016). It is important to keep in mind, however, that LCA does not include any risk assessment mechanisms: Even though the impact of beaching is shown to be proportionately inconsequential in this thesis, Deshpande et al. (2012) has shown that the activity pose a risk to the health of the workers and the ecological systems at the beaches where the dismantling is performed.

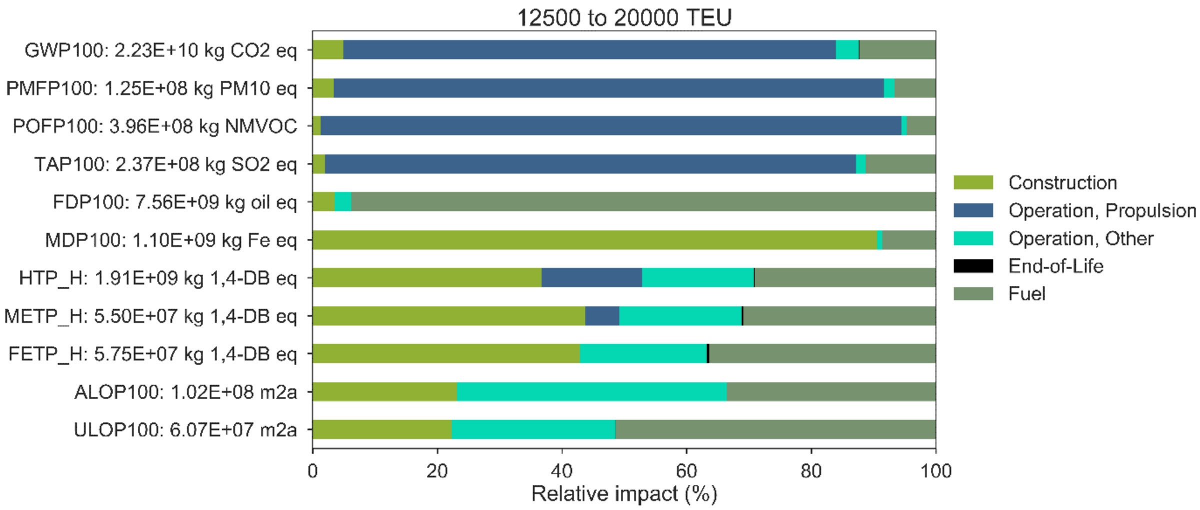
In Figure 5-2 each size bin's relative contribution to GWP, number of ships in the fleet and fleet capacity is shown. The distributions of the other impact categories are the same as for GWP, except MDP which more closely resemble the distribution in terms of capacity. It can be seen that a small number of large ships, those with TEU capacity exceeding 8500, are responsible for much of the fleet's impact on global warming. However, when looking at the carrying capacity rather than the number of ships, it is revealed that the large ships that comprise less than 20% of the fleet in terms of numbers, make up more than 40% of the fleet's TEU capacity. For ships between 2300




*(a)*




*(b)*




*(c)*

*Figure 5-1: Normalised advanced contribution results for three bin sizes; (a) small ships ranging from 200 to 700 TEU, (b) ships of medium size falling within 4000 and 6500 TEU, and (c) very large container vessels with capacity to carry between 12500 and 20000 TEU.*

and 8500 TEU, the relative climate impact is the same as the capacity they constitute in the fleet. While for ships smaller than 2300 TEU, their relative climate impact is much larger than their share of the fleet in terms of capacity, which is due to the fact that there are many of them, almost 30% of ships in the 2016 fleet are below 2300 TEU. These numbers show that there exists an economy of scale-effect in terms of environmental impacts in container shipping, i.e. the impact of the marginal added capacity does not scale linearly, meaning that a greater share of large ships in the fleet leads to a reduction of emission intensity.

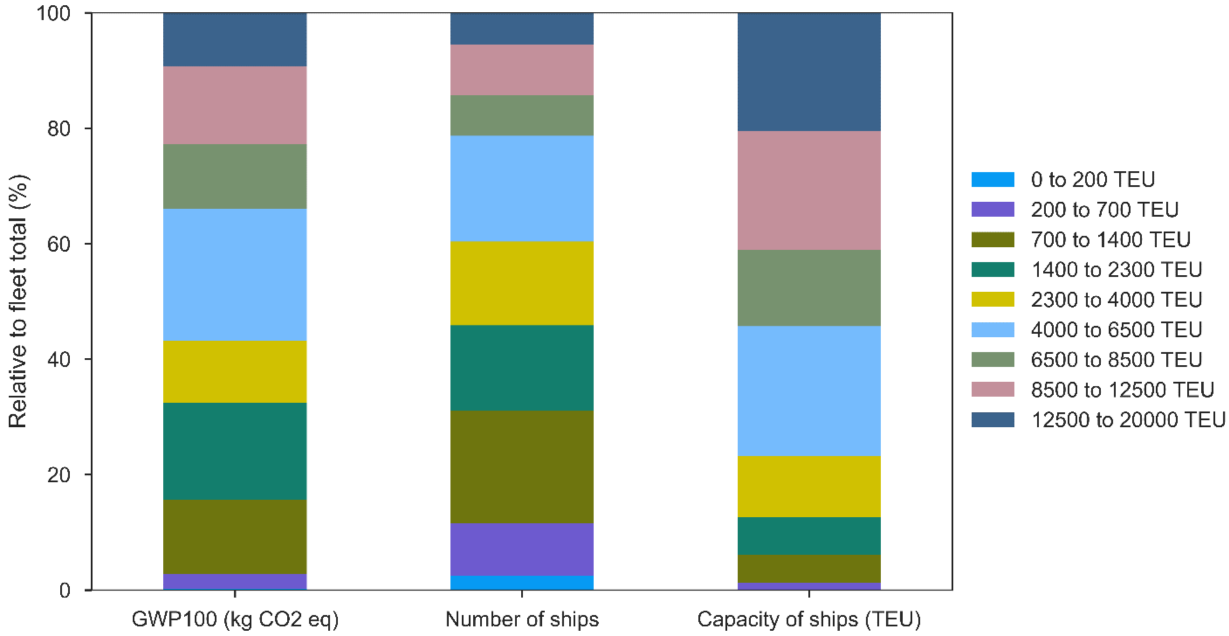



*Figure 5-2: Distribution of climate impacts, number of ships and ship capacity of the containership fleet in 2016.*

## 5.2 Future scenarios

In Figure 5-3 to Figure 5-7, GWP projections for the five SSP scenarios are displayed. They show that for all scenarios, the climate change impact from container shipping is lower than in 2016 for all years until 2050 even though the demand for transport is expected to rise, see Figure 4-3.

A distinct downward trend is observed the first 15 years, which is a result of the end to the slow steaming practice: Each year, when the speed of the ships in the fleet increases a little, new capacity is gained from the existing fleet, reducing the need for new ships. Then, when the ships sail at design speed and this source of unused capacity is depleted, new ships are required and the emission trend turns. In SSP3 the emissions flatten out but continue slightly downward, ending at 1.43E+11 kg CO2-eq in 2050, with a cumulative impact of 1.36E+12 kg $CO_2$ eq over the 34-year modelling period. SSP2 and SSP4 have very similar trajectories since the projected transport work is similar in both scenarios, as seen in Figure 4-3. After the trend reversal in 2031 the emissions start growing slightly, landing at respectively 1.74E+11 and 1.70E+11 kg $CO_2$ eq in 2050, and with cumulative $CO_2$ equivalent emissions of respectively 1.47E+12 kg and 1.46E+12 kg. In the remaining two scenarios, SSP1 and SSP5, the climate change impact starts growing when the slow steaming ends, driven by rapid economic growth, see Figure 4-4. It is apparent that annual GWP would surpass the 2016-level within the end of the century if the upwards trend in these scenarios continues. The climate impact in 2050 is 2.00E+11 and 2.19E+11 kg $CO_2$ eq, respectively, and the cumulative impact from 2016 to 2050 is respectively 1.57E+12 and 1.65E+12 kg $CO_2$ eq. This means that the savings potential of cumulative emissions between SSP3, with the lowest cumulative emissions, and SSP5, which have the highest, is 17.5%. Values for all impact categories in 2050 and cumulative impacts from 2016 to 2050 are found in Table A-2 and Table A-3, respectively.

The shift to building larger ships is also manifested in Figure 5-3 to Figure 5-7. Ships above 8500 TEU, i.e. the two largest bin sizes, which accounted for 22% of emissions in 2016, are responsible for more than half the emissions in 2050: 52% in SSP3 and 63% in SSP5. The introduction of larger, less emission intensive ships is a contributing factor to the decrease of emissions and subsequent slow growth after 2030. They enable the fleet to conduct more transport work with a smaller environmental footprint.

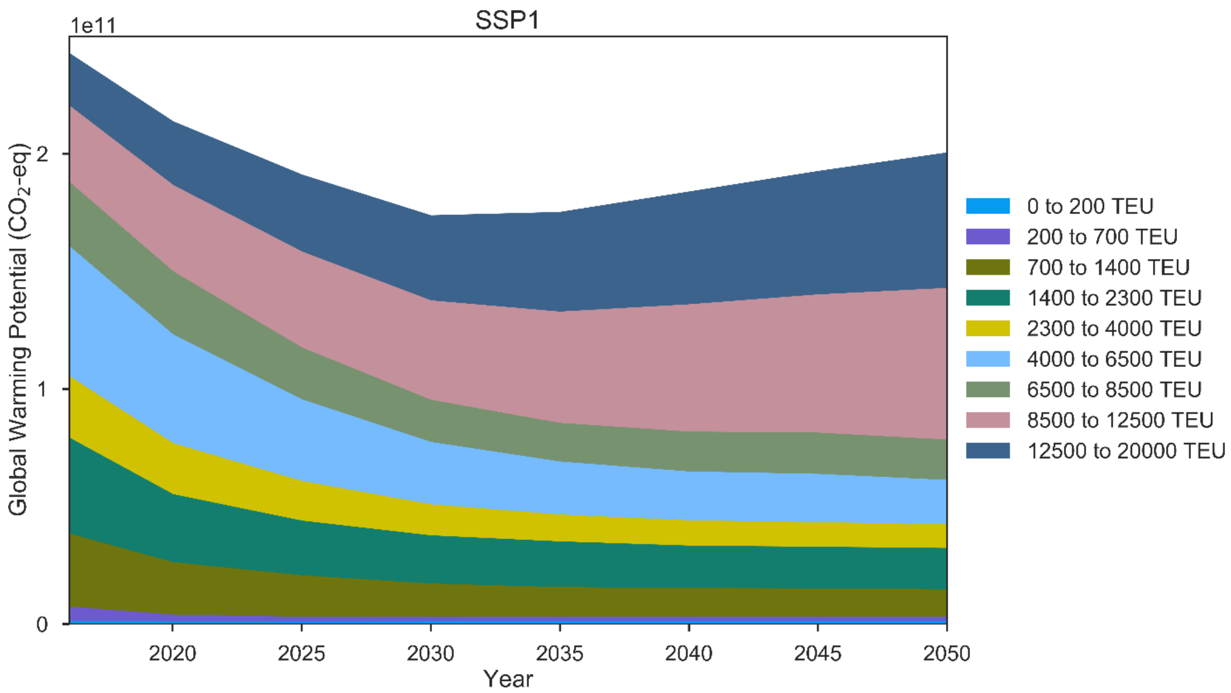



*Figure 5-3: Development of GWP from 2016 to 2050 in SSP1.*

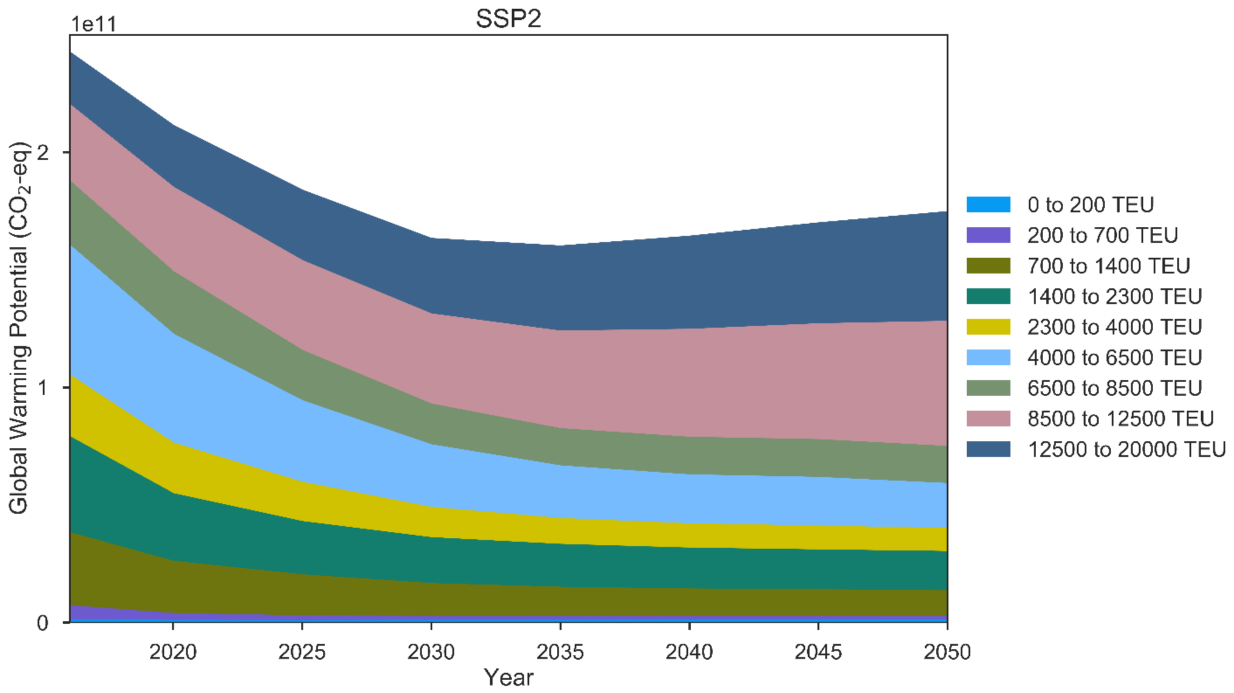



*Figure 5-4: Development of GWP from 2016 to 2050 in SSP2.*

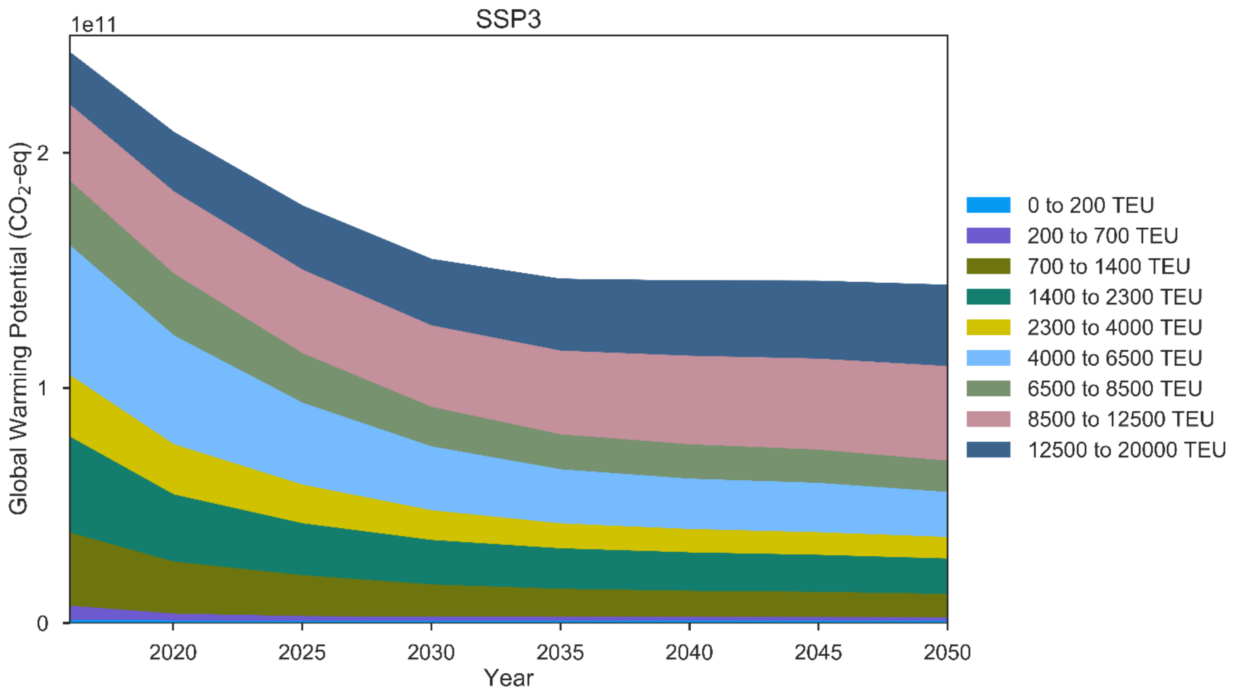



*Figure 5-5: Development of GWP from 2016 to 2050 in SSP3.*

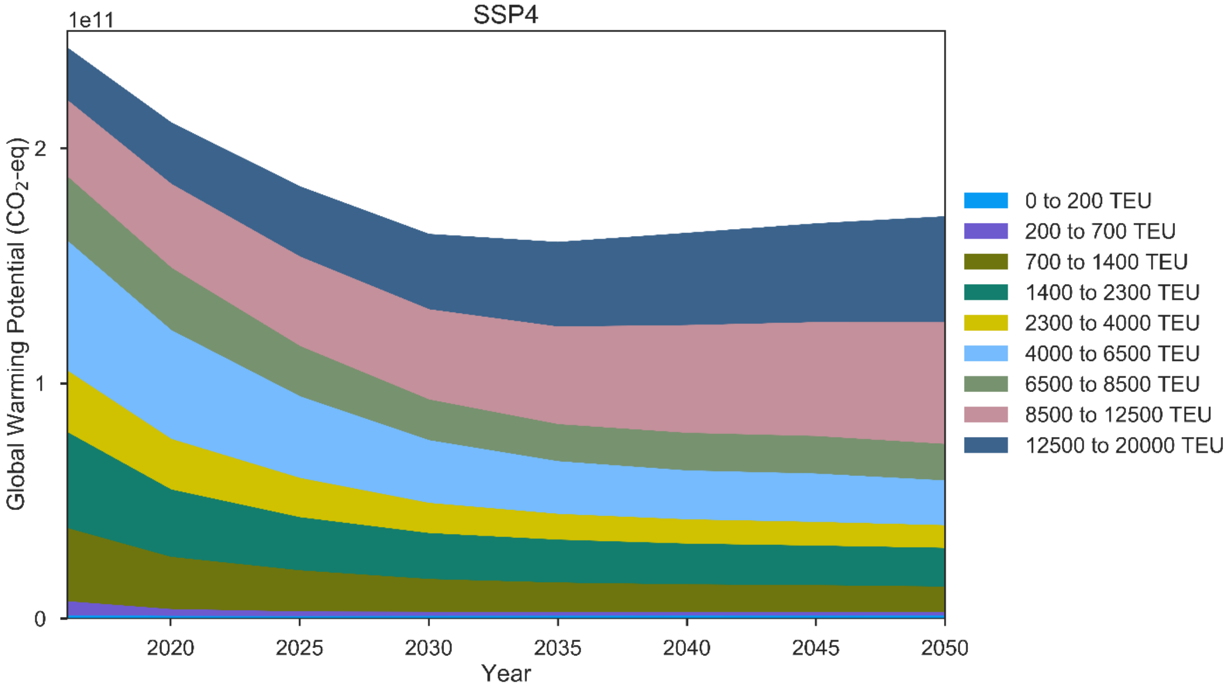



*Figure 5-6: Development of GWP from 2016 to 2050 in SSP4.*

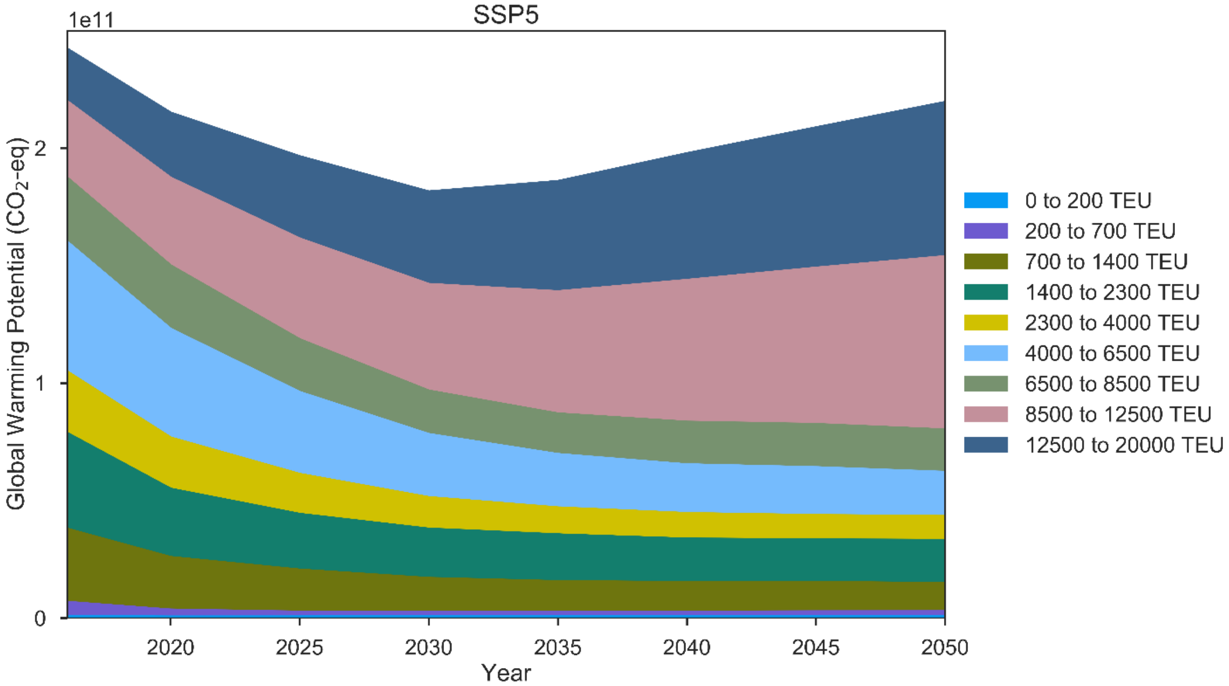



*Figure 5-7: Development of GWP from 2016 to 2050 in SSP5.*

# 6 Discussion

The two main takeaways from the previous chapter are the economies of scale-effect when it comes to environmental impacts, i.e. that there is potential for greater emission efficiency in the fleet by deploying larger ships, and how the penetration of large ships in the fleet will impact future emissions. With a relatively slight ship efficiency increase, modelled as a 5 g/kWh reduction in specific fuel oil consumption (SFOC), and that a significant share of newbuilds are ships with a capacity surpassing 8500 TEU, following the trend from recent years, the greenhouse gas emissions of the containership fleet stay below the 2016-level for all years in the modelling period in all scenarios.

Looking at emissions and emission efficiency, expressed in kg $CO_2$ eq per tkm, in 2050, listed in Table 6-1, it can be seen that the scenarios with low emissions also have lower efficiency, while the scenario with the highest absolute emissions of greenhouse gases has the highest efficiency. This is due to the constant scrap rate: In scenarios with a more rapid increase in per capita GDP, and by extension future transport work, a larger fleet is required than in scenarios with slower GDP growth. Assuming that scrapped ships are a fixed proportion of a fleet's capacity in a given year means that more older ships are retired when the fleet is larger. This presents an interesting dynamic where the driver of emissions is also the driver of introducing ships that can carry more cargo for lower emissions.

*Table 6-1: Absolute climate impacts and climate impacts per unit transport work in 2050 for each scenario.*

| *Scenario* | *Climate impact (kg $CO_2$ eq)* | *Transport work demand (tkm)* | *Climate impact per unit transport work (kg $CO_2$ eq/tkm)* |
|---|---|---|---|
| SSP1 | 2.00E+11 | 3.75E+13 | 5.33E-03 |
| SSP2 | 1.74E+11 | 3.11E+13 | 5.59E-03 |
| SSP3 | 1.43E+11 | 2.37E+13 | 6.03E-03 |
| SSP4 | 1.70E+11 | 3.02E+13 | 5.63E-03 |
| SSP5 | 2.19E+11 | 4.24E+13 | 5.17E-03 |

A feature that is modelled differently in this thesis than other works tackling fleet development is the size distribution of the future fleet. Eide et al. (2011) keeps the distribution constant over the modelling period, while in Smith et al. (2014) the future size distribution of containerships is predicted «based on a literature review, taking into account historical developments in distribution, expected structural changes in the markets and infrastructural constraints». The data from Smith et al. (2014) about the size distribution of the container fleet in 2012 and their predictions for 2050 are found in Table 6-2 along with the distribution in 2016, calculated from the dataset used in this study. The launch of more than 70 container vessels greater than 14500 TEU since 2012 has resulted in a 1000% growth in the proportion of this ship size in terms of numbers of ships the last four years. Also, the proportion of ships between 12000 and 14500 TEU have doubled in the same time span. These developments were not anticipated beforehand and are too recent to have yet been assimilated into the literature, therefore the future size distribution of the containership fleet is based on the statistics from the existing fleet in this thesis, and not a literature review. However, this does not account for restraints in port capacity or other factors that might cause a drop in the construction of large ships (Drewry, 2016). That said, there are circumstances that suggest continued investments in large vessels, such as consolidation and alliances among carriers (IHS Markit and JOC.com, 2017) and the size distribution within the current orderbook (World Maritime News, 2016).

*Table 6-2: Size distribution of containership fleet in 2012 and the assumed distribution in 2050 in (Smith et al., 2014), as well as the distribution of the dataset used in this thesis, i.e. the 2016 fleet.*

| *Bin size (TEU)* | *2012 (%)* | *2050 (%)* | *2016 (%)* |
|---|---|---|---|
| 0-999 | 22 | 22 | 19 |
| 1000-1999 | 25 | 20 | 25 |
| 2000-2999 | 14 | 18 | 12 |
| 3000-4999 | 19 | 5 | 16 |
| 5000-7999 | 11 | 11 | 11 |
| 8000-11999 | 7 | 10 | 11 |
| 12000-14500 | 2 | 9 | 4 |
| 14500+ | 0.2 | 5 | 2 |

The scenario with the lowest greenhouse gas emission level in 2050 and the lowest cumulative emissions from 2016 to 2050 is SSP3, where the narrative is one of a regionalised world with lower economic growth than the other pathways as well as slow technological progress and low investments in human capital (O'Neill et al., 2014). This story is vastly different from the one painted by world leaders of global unity, collectively tackling the challenges we face as inhabitants on this planet, and a better world for all, which is epitomised in the Sustainable Development Goals (SDGs) (United Nations, 2017). This is to show that the scenario with the best outcome in terms of climate change impact may be undesirable in many other aspects. Given that seaborne transport is a cornerstone of global trade, carrying everything from building equipment to technological gadgets and medical supplies, and historically closely correlated with growth in world GDP, perhaps less stringent emission reduction requirements should be applied to the shipping industry. This approach of differentiating obligations between sectors is suggested in the European Union's *2050 Roadmap to a Low-Carbon Economy*, where the transport sector is expected to contribute less in comparison to other sectors such as buildings and power generation (European Commission, 2017).

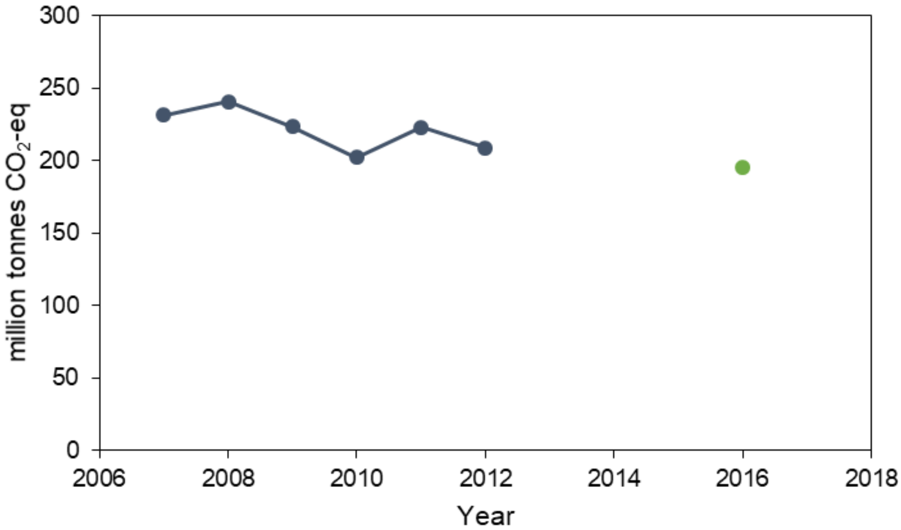



*Figure 6-1: Greenhouse gas emissions from the containership fleet; 2007-2012 and 2016. The blue series is from the* Third IMO Greenhouse Gas Study *(Smith et al., 2014), where the bottom-up estimates of greenhouse gas emissions from international shipping were scaled by 25.6%, the proportion of $CO_2$-emissions attributed to containerships in international shipping in 2012. The green data point is the global warming potential in the life cycle phase* Operation, propulsion *in 2016 from the model in this thesis.*

Comparing the climate change impact results for 2016 in this model with data from 2012 reported in the *Third IMO GHG Study 2014* (Smith et al., 2014) it is seen that the result in this thesis, 1.95E+11 kg $CO_2$ eq, is within 10% of the result of Smith et al. (2014), 2.09E+11 kg $CO_2$ eq. As is seen in Figure 6-1, the development in emissions from the containership fleet between 2007 and 2012 was varied, with no clear trend after the global economic downturn in late 2008. UNCTAD (2015) reveals that although containerised trade has increased the steadily since 2012, overcapacity in the market has led to low freight rates and the persistence of slow steaming, even when the bunker fuel prices fell 46% between June and December in 2014. This fact, together with the introduction of very large ships to the fleet in recent years, means that the result falls within the space of possible outcomes. The results in this thesis are substantiated by that they fall within a reasonable range of the results in a large and well-respected work such as the *Third IMO GHG Study 2014* (Smith et al., 2014).

Due to time constraints, there are several aspects of the current debate on shipping and environment that the model in this thesis does not account for. Firstly, there are some things that are left out of the model altogether: The energy consumption of refrigerated containers is not included, neither are exhaust gas scrubbers, which most likely are needed to some extent after the requirements for maximum emissions of sulphur oxides are tightened in 2020. There are other parts of the model, such as the use of only one fuel and only one method of scrapping, that would benefit from expansion. The current implementation prevents the exploration of the effect penetration of alternative maritime fuels would have on future environmental impacts. However, using heavy fuel oil out at sea and cleaner fuels close to shore has been suggested as an avenue to keep shipping costs down and avoid higher climate impacts, which is a risk since optimising for low emissions of $NO_x$ and $SO_x$ may increase greenhouse gas emissions (Lindstad et al., 2015). If this were to become reality, the present analysis is thought to be a good approximation of future emission patterns.

Another limitation in the present model is the lack of spatial dimension. Acquisition of such data is outside the scope of this thesis, and transport work averages for each size bin were used instead. Consequently, the results are not well suited to be used for regional analyses, which in turn makes it hard to assess the harm to humans. The emissions in Ecoinvent are categorised as *high stack, non-urban*, which makes sense for an aggregated analysis: The bulk of emissions are at the high seas, far away from people, where the ships spend the most time. For the same reason, neither SECAs or NECAs are modelled in this thesis. Thus, for detailed, location-specific modelling with a focus on how shipping emissions close to shore poses a risk to human health, the work by Kalli et al. (2013) is a better fit. It is due to this limitation that the focus of the prospective life cycle impact assessment is primarily focused on climate impacts.

And this is the strength of the present model: It can inform the container shipping community about the trend of greenhouse gas emissions for their sector, and whether or not they will be able to meet the goals with current trends. The results give both hope and warning. With the continued increases in efficiency and ship size, containerships will be able to deliver more shipping services with less emissions. However, the slow steaming phenomenon can give a false sense of accomplishment because when it tapers off new capacity is delivered by the already existing fleet.

# 7 Conclusion

In this thesis, the life cycle environmental impacts of the current and future container shipping fleet are investigated. To be able to meet international climate targets, global $CO_2$ emissions must come down (IPCC, 2015). Seaborne transport has lower greenhouse gas emissions per unit mass transported than all other forms of transport, but the industry has large absolute emissions, 2.1% of total greenhouse gas emissions in 2012, and meets expectations to become more energy efficient and environmentally friendly (Smith et al., 2014). World GDP and trade is anticipated to rise in the coming decades, and as the backbone of international trade, this means that shipping in general and container shipping in particular are expected to deliver more transport work while at the same time reducing absolute emissions. IMO has taken measures to ensure continued improvement in ship's emission intensities (IMO, 2017a), and there also exists a potential for efficiency gains by building larger ships (Bouman et al., 2017).

A prospective environmental impact assessment model was developed for this thesis, which takes a dataset of the current fleet of containerships and calculates the life cycle environmental impacts of the current fleet as well as for five scenarios until 2050, following the Shared Socioeconomic Pathways. The results show that with the assumed efficiency increases in engine technology and fleet size distribution, the environmental impacts of the containership fleet will go down in the coming decades and will not go above the 2016-level in any of the scenarios, even with a quadrupling in transport demand. However, the industry should be wary of the trend reversal apparent in the scenarios: When the slow steaming practice of the current fleet ends, which in the model is projected to be 15 years after the base year, the downward trajectory of the impacts shifts and starts growing. If all sectors were to contribute the same percentage reductions in greenhouse gases to meet the climate targets in the Paris agreement, it means a 50% reduction compared to 2010 levels by 2050 (IPCC, 2015). For the containership fleet this translates to a maximum of 1.01E+11 kg $CO_2$ eq in 2050 (Smith et al., 2014). For all investigated scenarios in this thesis total emissions are significantly higher. It is paramount to prepare for further diligent efforts towards reducing climate impacts, even as innovation and progress is celebrated.

The phenomenon of slow steaming is great example for why the consideration of life cycle impacts is crucial for comparing varying scenarios: When a ship is operating at lower-than-usual speed, the direct emissions are reduced, but new ships are required to maintain the same service level. Even though when accounting for the direct emissions from these additional ships the total emissions of the fleet are still lower than when running at design speed, but the emissions incurred by the fleet requiring additional ships is left out. The large amount of steel a ship demands might counteract the emission savings due to slow steaming. The containership LCI and the model for generating fleet development scenarios constructed in this thesis, facilitates the further research of this topic.

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# A Appendix

This section features figures and tables not included in the main section because they are peripheral to the thesis' principal arguments. They are provided here for refence and to give a more complete picture for those who want to investigate the statements in the thesis more carefully. All elements are referenced in the main section, and the heading is provided at the end of each caption.

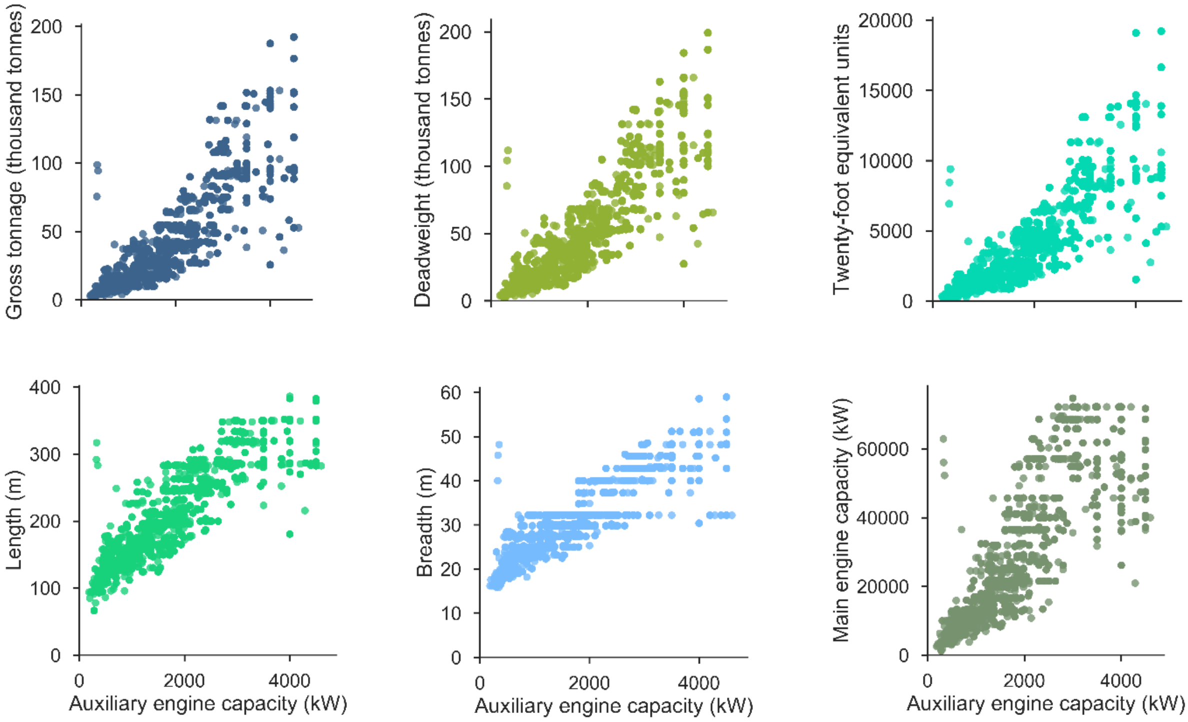


*Figure A-1: Scatter plots of auxiliary engine capacity against other parameters . The plots were made to find a good predictor variable for the auxiliary engine to fill missing values in the dataset. (3.1.1 Missing Data Points)*

*Table A-1: Expected distribution of hazardous wastes from 2010 to 2030 from the ship breaking industries in Bangladesh and Pakistan (Sarraf et al., 2010). (3.5 End-of-Life)*

| | *Unit* | *Remain at yard/in beach sediment* | *Sold with equipment or as item* | *Re-rolling mills* | *Formal waste disposal site* | *Unknown or informal waste disposal site* |
|---|---|---|---|---|---|---|
| Asbestos | tonnes | 50% | 5% | 0% | 0% | 45% |
| PCBs | tonnes | 10% | 90% | 0% | 0% | 0% |
| PU foam | tonnes | 25% | 1% | 0% | 0% | 74% |
| Paints | tonnes | 5% | 5% | 85% | 0% | 5% |
| Heavy metals | tonnes | 27% | 27% | 47% | 0% | 0% |
| Waste liquid organic | m3 | 100% | 0% | 0% | 0% | 0% |
| Miscellaneous | m3 | 100% | 0% | 0% | 0% | 0% |
| Waste liquids, inorganic | tonnes | 26% | 50% | 0% | 0% | 23% |
| Reusable liquid organics | tonnes | 5% | 90% | 0% | 0% | 5% |


*Figure A-2: Normalised advanced contribution results for all size bins . The figure continues on the next two pages. (5.1 The current fleet)*


*Figure A-2 continued*


*Figure A-2 continued*

*Table A-2: Impact totals for the containership fleet in 2050. (5.2 Future scenarios)*

| *Impact category* | *SSP1* | *SSP2* | *SSP3* | *SSP4* | *SSP5* |
|---|---|---|---|---|---|
| GWP100 | 2.00E+11 | 1.74E+11 | 1.43E+11 | 1.70E+11 | 2.19E+11 |
| PMFP100 | 1.11E+09 | 9.76E+08 | 8.09E+08 | 9.55E+08 | 1.22E+09 |
| POFP100 | 3.52E+09 | 3.10E+09 | 2.58E+09 | 3.04E+09 | 3.85E+09 |
| TAP100 | 2.10E+09 | 1.85E+09 | 1.54E+09 | 1.81E+09 | 2.30E+09 |
| FDP100 | 6.78E+10 | 5.92E+10 | 4.87E+10 | 5.79E+10 | 7.44E+10 |
| MDP100 | 8.86E+09 | 7.48E+09 | 5.85E+09 | 7.28E+09 | 9.92E+09 |
| HTP_H | 1.68E+10 | 1.45E+10 | 1.16E+10 | 1.41E+10 | 1.86E+10 |
| METP_H | 4.81E+08 | 4.13E+08 | 3.31E+08 | 4.02E+08 | 5.34E+08 |
| FETP_H | 5.04E+08 | 4.33E+08 | 3.47E+08 | 4.22E+08 | 5.59E+08 |
| ALOP100 | 9.15E+08 | 7.86E+08 | 6.31E+08 | 7.67E+08 | 1.01E+09 |
| ULOP100 | 5.50E+08 | 4.75E+08 | 3.85E+08 | 4.64E+08 | 6.07E+08 |

*Table A-3: Cumulative impact totals for the containership fleet, 2016 to 2050. (5.2 Future scenarios)*

| *Impact category* | *SSP1* | *SSP2* | *SSP3* | *SSP4* | *SSP5* |
|---|---|---|---|---|---|
| GWP100 | 1.57E+12 | 1.47E+12 | 1.36E+12 | 1.46E+12 | 1.65E+12 |
| PMFP100 | 8.99E+09 | 8.45E+09 | 7.89E+09 | 8.41E+09 | 9.40E+09 |
| POFP100 | 2.89E+10 | 2.72E+10 | 2.55E+10 | 2.71E+10 | 3.02E+10 |
| TAP100 | 1.71E+10 | 1.61E+10 | 1.51E+10 | 1.61E+10 | 1.79E+10 |
| FDP100 | 5.34E+11 | 5.00E+11 | 4.64E+11 | 4.98E+11 | 5.61E+11 |
| MDP100 | 6.03E+10 | 5.49E+10 | 4.93E+10 | 5.45E+10 | 6.44E+10 |
| HTP_H | 1.25E+11 | 1.16E+11 | 1.06E+11 | 1.15E+11 | 1.32E+11 |
| METP_H | 3.53E+09 | 3.26E+09 | 2.98E+09 | 3.24E+09 | 3.73E+09 |
| FETP_H | 3.70E+09 | 3.42E+09 | 3.13E+09 | 3.40E+09 | 3.92E+09 |
| ALOP100 | 6.77E+09 | 6.26E+09 | 5.73E+09 | 6.23E+09 | 7.16E+09 |
| ULOP100 | 4.17E+09 | 3.87E+09 | 3.56E+09 | 3.85E+09 | 4.39E+09 |