**NTNU – Trondheim**
Norwegian University of
Science and Technology

# Implementation and application of an integrated framework for economic and environmental assessment of maritime transport vessels

**Jon Halfdanarson**
**Mats William Snåre**

Master in Industrial Ecology
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Supervisor: Anders Hammer Strømman, EPT
Co-supervisor: Håkon Lindstad, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

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# MASTER THESIS

for

Students:
Jon Halfdanarson
Mats William Snåre

Spring 2015

## *Implementation and application of an integrated framework for economic and environmental assessment of maritime transport vessels*

*Implementering og anvendelse av et integrert rammeverk for økonomisk og miljømessig evaluering av skip*

### Background and objective

From the first days of our civilization sea transport has dominated trades between nations, regions, and continents. Together with telecommunication, trade liberalization and international standardization, the increased efficiency of maritime transport has enabled the globalization of the world (Kumar and Hoffman, 2002). Globalization means that trade is growing faster than the global Gross domestic product (GDP), and that this trade is not only in finished goods and services, but increasingly in components and services that are used within globalized production processes (ECLAC, 2002). The figures show that the growth from 1950 to 2010 has been: Population 180 %, Energy consumption 470 %, GDP 670 %, Maritime transport 1500 %, Trade 3700 % (Lindstad, 2013). This means that maritime transport has increased twice the GDP growth, trade has increased five times as fast as the GDP, and trade in percentage of GDP has increased from 5% in 1950 to 24 % in 2010.

The environmental consequences of the increased trade have become important as a result of the current climate debate. According to the *Second IMO GHG Study 2009* (Buhaug et al., 2009) for the International Maritime Organization (IMO), the maritime transport emitted 1046 million tons of $CO_2$, 25 million tons of NOx and 15 million ton of SOx in 2007, representing 3.3 % of the world's global anthropogenic $CO_2$ emissions, 10-15 % of the NOx and 4-9 % of the SOx. These emissions are assumed to increase by 150-250 % in 2050 if no action is taken, i.e. 'business as usual' (BAU) scenarios with a tripling of world trade.
A series of papers by Lindstad e.t al spanning from 2011 and onwards develops and utilizes a model for power requirements, emissions and costs for different ship classes and designs. The papers analyses different environ-economic tradeoffs associated with different operating conditions, designs and abatement options to mention a few. The results from these assessments were in some instances also implementet at fleet and global levels.

### *Aim*

The primary objective of this work is to implement and integrate the different sub models by Lindstad into Matlab in order to make an implementation that is more flexible and robust that the existing excel based version. The secondary objective is to apply the implementation to demonstrate validate the model towards a selection of Lindstads original results. The tertiary objective is to apply the model to produce novel results in the interface between or beyond Lindstads analysis.

**The following tasks are to be considered:**

1. Motivation and state of the art
2. Theoretical model description
3. Description of model implementation and structure
4. Model validation
5. Case descriptions and model application and analysis
6. Discussion

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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, 26. January 2015

Olav Bolland

Olav Bolland
Department Head

Anders H. Strømman
Academic Supervisor

Haakon Lindstad

Senior Researcher
Haakon Lindstad, Marintek
Co-Supervisor

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

# *Abstract*

Faculty of Engineering Science and Technology
Department of Energy and Process Engineering

Master of Science in Industrial Ecology

## Implementation and application of an integrated framework for economic and environmental assessment of maritime transport vessels

by Jon Halfdanarson
& Mats William Snåre

Global maritime shipping carries out more than 90% of international trade, and accounts for 3.3% of anthropogenic CO2 emissions (IMO, 2011; Buhaug et al., 2009). These emissions are expected to increase by 150-250% by 2050, assuming business as usual. The latest IPCC report states that greenhouse gas (GHG) emissions from transport has to be reduced by at least 50% by 2050, to be able to reach the target of a maximum 2°C temperature increase. This entails that serious measures must be taken within the shipping industry to lower GHG emissions.

Lindstad et al. has published a series of works (Lindstad, 2013; Lindstad et al., 2011a; 2011b; 2012a; 2012b; 2013a; 2013b) addressing these challenges the later years, where he has developed and utilized several models for power requirements, emissions and cost for different ship categories and sizes. We have built a model that implements and integrates these sub models to a holistic package with integrated LCA functionality. The model examines implications on both individual vessel and fleet level for speed reduction scenarios, as well as assessing alternative, more slender hull designs for bulk carriers. In addition, the aspects of shipbuilding, end of life, and emissions from upstream fuel production are accounted for in the LCA segment.

Our results confirm that our model works as intended, and serves as validation for Lindstads results. Our results indicate that a reduction of only one knot from the design speed of all vessels is enough to save over 7% of annual emissions. Furthermore, it is possible to reduce emission by up to 19.7% without additional cost. Speed reduction and lower block coefficient show significant promise to reduce global $CO_2$ fleet emissions. Existing literature on the subject and our findings in this study strengthens this claim. How these measures eventually will be implemented in practice is up to policy makers and governing organs. They are facing an immense challenge in the years to come, considering the complexity and many aspects of putting these measures to good use.

NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET

# *Sammendrag*

Fakultet for ingeniørvitenskap og teknologi
Institutt for energi- og prosessteknikk

Mastergrad i Industriell økologi

## Implementering og anvendelse av et integrert rammeverk for økonomisk og miljømessig evaluering av skip

av Jon Halfdanarson
& Mats William Snåre

Global maritim transport utgjør mer enn 90% av internasjonal handel, og står for 3,3% av menneskeskapte CO2-utslipp (IMO, 2011; Buhaug et al., 2009). Det er forventet at disse utslippene vil øke med 150-250% innen 2050, dersom ingen grep blir gjort. Den siste IPCC-rapporten slår fast at klimagassutslippene fra transportsektoren må reduseres med minst 50% innen 2050, for å kunne nå målet om maksimalt 2°C temperaturøkning. Dette betyr at drastiske tiltak må gjøres innen maritim transport for å redusere klimagassutslippene.

Lindstad et al. har publisert en rekke artikler (Lindstad, 2013; Lindstad et al., 2011a; 2011b; 2012a; 2012b; 2013a; 2013b) som adresserer disse utfordringene i de senere år, der han har utviklet og benyttet flere modeller for motorkraft, utslipp og kostnader for ulike skipskategorier og størrelser. Vi har bygget en modell som implementerer og integrerer disse sub-modellene til en helhetlig pakke med integrert LCA funksjonalitet. Modellen undersøker implikasjoner på både enkeltfartøy og flåtenivå for fartsreduksjon scenarier, samt undersøker alternative, mer slanke skrogdesign for bulkskip. I LCA-segmentet ser vi og på aspektene av skipsbygging, skipsavvikling og oppstrømsutslipp fra drivstoffproduksjon.

Resultatene våre bekrefter at modell fungerer som tiltenkt, og til validering av Lindstads resultater. Våre resultater viser at en reduksjon på kun en knop fra opprinnelig hastighet på alle fartøyer, er nok til å redusere årlige utslipp med over 7%. Det er og mulig å redusere utslipp opp til 19,7% uten ekstra kostnader. Fartsreduksjon

og lavere blokk-koeffisient virker som lovende tiltak til å redusere $CO_2$ utslipp fra den globale skipsflåten. Funn fra både eksisterende litteratur og våre egne funn i denne studien styrker denne påstanden. Hvordan disse tiltakene implementeres i praksis er opp til politikere og styrende organer. De står overfor en enorm utfordring i årene som kommer, med tanke på kompleksiteten og de mange aspektene som må tas stilling til ved å ta i bruk og utnytte disse tiltakene.

## Acknowledgements

We would like to thank our supervisor Professor Anders Hammer Strømman for his contribution to this thesis. His guidance through the process has been very valuable to us. We would also like to use this opportunity to show our gratitude to Dr. Håkon Lindstad at Marintek, for giving us extensive and thorough introduction to marine trade. His previous research has been of outmost importance for this thesis and without his collaboration and supervision; this thesis would not be possible. Last, we also want to thank Petter Jønvik for useful insight on life cycle assessment of marine transport vessels.

# List of Content

# Abbreviations

$CO_2$ – Carbon dioxide
DWT – Dead Weight Tonnage
EEDI – Energy Efficiency Design Index
EEOI – Energy Efficiency Operational Indicator
GHG – Green House Gases
IMO – International Marine Organisation
IPCC – Intergovernmental Panel on Climate Change
LCA – Life Cycle Assessment
LNG – Liquid Natural Gas
LPG – Liquid Petroleum Gas
MARPOL – International Convention for the Prevention of Pollution from Ships
MBM – Market Based Measures
MEPC – Marine Environment Protection Committee
MS – Microsoft Soft
NM – Nautical Mile
RORO – Roll-on Roll-off Transport Vessel
SEEMP – Ship Energy Efficiency Management Plan
UN – United Nations
UNCTAD – United Nations Conference on Trade and Development
UNFCCC – United Nations Framework Convention on Climate Change
USD – United States Dollar

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# 1 Introduction

## 1.1 Global shipping and related emissions

Ever since the dawn of civilization, maritime transportation has been one of the most important means of transportation. Whether it was exploration, conquest, or long distance transportation of men or goods, the waterway was the path. Today, global shipping is more essential than it have ever been. More than 90% of global trade is carried out by the shipping industry (IMO, 2011). In a world where globalization does not seem to have a limit, the same prospect applies to global maritime shipping.

Globalization, population growth, increasing standard of living, rapid industrialization, exhaustion of local resources, road congestion, and elimination of trade barriers are all contributors to the continuing growth in maritime transportation (Christiansen et al., 2007). There is a clear trend that trade is not only in finished products or services, but is also increasing in components and services used in globalized production processes (Kumar & Hoffman, 2002). Table 1 shows how the development in global shipping has been for the major cargo categories, from 1970 and up until 2013. We see that all categories has increased, and that the total amount of cargo transported has nearly quadrupled.

Table 1: Development in global shipping (millions of tonnes transported, UNCTAD, 2014).

| Year | Oil and gas | Main Bulks | Other dry cargo | Total |
|---|---|---|---|---|
| 1970 | 1440 | 448 | 717 | 2605 |
| 1980 | 1871 | 608 | 1225 | 3704 |
| 1990 | 1755 | 988 | 1265 | 4008 |
| 2000 | 2163 | 1295 | 2526 | 5984 |
| 2005 | 2422 | 1709 | 2978 | 7109 |
| 2006 | 2698 | 1814 | 3188 | 7700 |
| 2007 | 2747 | 1953 | 3334 | 8034 |
| 2008 | 2742 | 2065 | 3422 | 8229 |
| 2009 | 2642 | 2085 | 3131 | 7858 |
| 2010 | 2772 | 2335 | 3302 | 8409 |
| 2011 | 2794 | 2486 | 3505 | 8785 |
| 2012 | 2841 | 2742 | 3614 | 9197 |
| 2013 | 2844 | 2920 | 3784 | 9548 |

## 1.1 GLOBAL SHIPPING AND RELATED EMISSIONS

Global warming and climate change has emerged as some of the most important global challenges. The International Panel on Climate Change (IPCC) has thoroughly documented how anthropogenic GHG emissions contribute to increase global warming, and how this can lead to pervasive and irreversible impacts for people and ecosystems (Ribeiro et al., 2007; IPCC, 2014). There is generally a broad international consensus on this area, although there will always be some anachronistic resistance against the undeniably necessary green shift we have ahead of us. In 2010, the UN Framework Convention on Climate Change (UNFCCC) committed to limiting the global temperature rise to 2°C compared to pre-industrial levels. It is clear, that to fulfil this commitment, extreme mitigation measures has to be made. With a business as usual scenario, we have no chance of reaching the 2°C target, but will more likely end up with a temperature increase of 4°C by the end of the century. To be able to reach the 2°C target, annual anthropogenic GHG emissions has to be reduced by at least 50% by 2050 (IPCC, 2014).

As trade and transport related GHG emissions continues to increase, this sector has gotten more attention over the years. The first GHG study (Skjølsvik et al., 2000) by the International Maritime Organization (IMO) was based on emission data from 1996 and estimated emission from international trade to contribute to 1.8% of the world’s total anthropogenic $CO_2$ emissions. The second IMO study (Buhaug et al., 2009) concluded with an increase from 1.8% to 2.7% from international trade, or even 3.3% when including domestic trade. Expected increase at the time was estimated to 150%-250% in 2050 given business as usual (tripling of world trade). The third IMO GHG study (Smith et al., 2014) based on 2012 emission figures, indicated a decrease in net emissions, from 1046 to 950 million tonnes of $CO_2$ but the global contribution of 2.7% stayed the same, along with emission predictions for 2050. The challenge is how to deal with the predicted increase in trade, and still manage to reduce emissions.

## 1.2 Policy

When compared to other modes of cargo transport, we can see from Figure 1 that maritime shipping performs quite well in terms of $CO_2$ emission. Nonetheless, the maritime shipping sector is one of the international transportation means where mandatory measures have been implemented to reduce GHG emissions.

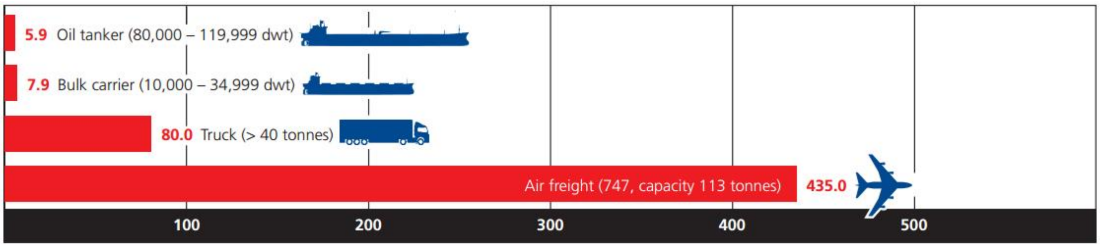


Figure 1: Emission in grams CO2 per tonne-km from different modes of transport (International Chamber of Shipping, 2014; Buhaug et al., 2009).

The United Nations (UN) established the International Maritime Organization (IMO) in 1948. Since then, IMO have been a leading actor in the work of promoting cooperation among governments and the shipping industry to improve maritime safety and minimize international shipping's environmental impacts. The work of IMO serves as a model for other international industry sectors where cooperation across nation's borders is key for making effective environmental regulations (Yamaguchi, 2012). In 1973, the International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted at IMO. MARPOL is a regulatory framework designed to prevent and minimize pollution from ships – both accidental and from routine operations. The convention consists of six different annexes, concerning special areas of a ships operational pattern. Annex VI – the "Prevention of Air Pollution from Ships" was first adopted in 1997, and sets limits to emissions of sulphur oxide, nitrous oxide and particulate matter in ship exhaust. This Annex has been updated several times since 1997.

The Marine Environmental Protection Committee (MEPC) is an organ underlying IMO, which have been a very important actor in the development of the GHG Studies presented by IMO. MEPC was also central in forming the principles of the mandatory Energy Efficiency Design Index (EEDI) for new ships, and a voluntary Ship Energy Efficiency Management Plan (SEEMP), which both were adopted by MARPOL in 2011. The EEDI evaluates the amount of $CO_2$ emitted per unit of cargo transported as a consequence of the ships type, size and technical solutions. As long as the required energy efficiency level is obtained, the shipyard can choose any technical solution available to comply with the regulations. The SEEMP is an operational system that can be used to monitor and manage ship and fleet efficiency over time. This can be done using the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool. The EEOI enables operators to measure the energy efficiency of a ship in operation, and register the effect of changes in operational patterns or technical improvements. Both the SEEMP and the EEOI are useful tools for ship owners and operators seeking to optimise the performance of a ship.

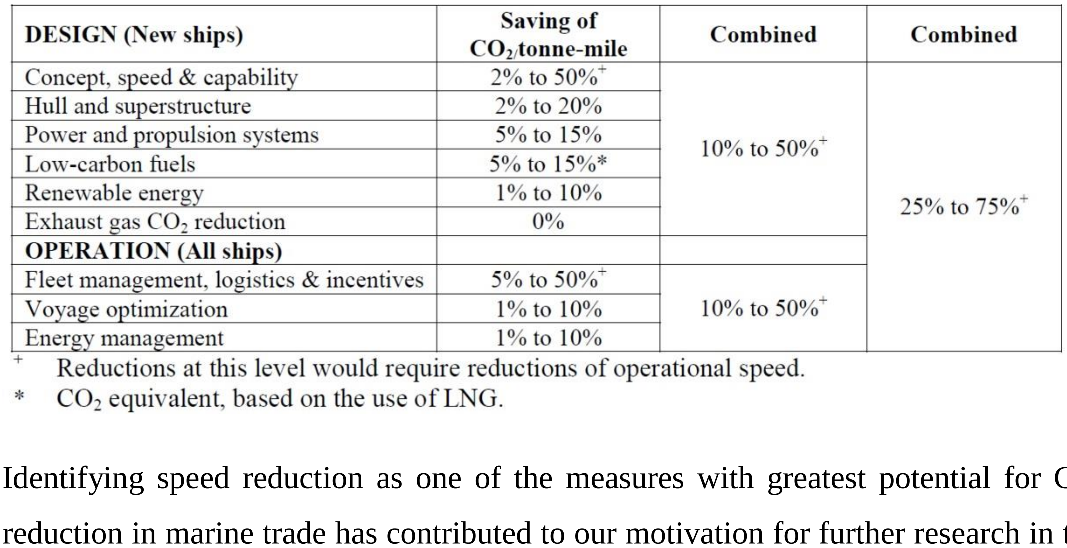
IMO are also considering market based measures (MBM) like emission trading, fuel taxes, and combinations of these two. MBM’s have the strength of full effect from day one, if implemented, as opposed to EEDI, which will take several years before any major effect is registered. The EEDI will only reduce emissions from new vessels, which means that even after 14-15 years, only half of the fleet will have been improved. There are discussions whether MBM’s should be implemented on its own, or if it should be combined with the SEEMP and EEDI, but there is a general consensus that MBM’s have the potential of providing economic incentives for the maritime industry to invest in technology and to seek the best available operational solutions for the best energy efficiency scenario possible.

## 1.3 State of the art

As the international shipping industry and its emissions are getting more and more attention, several studies on the different potential mitigation strategies has been carried out (Buhag et al., 2009; Lindstad, 2013). The main categories of intervention are: operational, market-based, technology and energy. Our main focus has been speed reduction implications on fleet level and design improvement for bulk carriers.

In the fourth assessment report by IPCC, Marintek (2000) estimated that the short-term potential for emission reduction from operational measures to be in the range of 1-40%. This could be achieved by reducing operation speed of vessels, optimizing fleet composition and routing of vessels. On a long-term perspective there was conducted a study on the most fuel consuming vessels of the world fleet, where both operational and implementation of technical measures was considered. The results showed that there was a emission reduction potential of 17.6% in 2010 and 28.2% in 2020 (Marintek, 2000). These reductions are of significance, but unfortunately not large enough to compensate for projected fleet growth within the same time period. Out of the measures considered, they found that speed reductions hold the greatest potential for emission reduction, followed by improvement of technologies. IPCC states that they consider speed reduction to only be economically feasible if policy incentives are implemented. Such policies include but are not limited to $CO_2$-trading and emission taxes.

Table 2: Assessment of potential reductions of $CO_2$ emissions from shipping by using known technology and practices (Buhaug et al., 2009).



| **DESIGN (New ships)** | **Saving of $CO_2$/tonne-mile** | **Combined** | **Combined** |
|---|---|---|---|
| Concept, speed & capability | 2% to 50%$^{+}$ | 10% to 50%$^{+}$ | 25% to 75%$^{+}$ |
| Hull and superstructure | 2% to 20% | | |
| Power and propulsion systems | 5% to 15% | | |
| Low-carbon fuels | 5% to 15%* | | |
| Renewable energy | 1% to 10% | | |
| Exhaust gas $CO_2$ reduction | 0% | | |
| **OPERATION (All ships)** | | | |
| Fleet management, logistics & incentives | 5% to 50%$^{+}$ | 10% to 50%$^{+}$ | |
| Voyage optimization | 1% to 10% | | |
| Energy management | 1% to 10% | | |

$^{+}$ Reductions at this level would require reductions of operational speed.

* $CO_2$ equivalent, based on the use of LNG.

Identifying speed reduction as one of the measures with greatest potential for $CO_2$ reduction in marine trade has contributed to our motivation for further research in this area. The emission reduction potential from other measures, as identified by Marintek (2000) can be seen in table 2.

There has been conducted several studies on different segments of marine transport that has influence on the total $CO_2$ emissions from this sector. The GHG studies conducted by IMO (Skjølvik et al., 2000; Buhaug et al., 2009; Smith et al., 2014) put focus on both operational and technical innovation measures as means to reduce emission, utilizing both top down and bottom up approaches. They all conclude that combustion of hydrocarbons is the main source of emissions, where carbon dioxide, nitrogen oxide, sulphur oxide, water and volatile organic compounds are the main contributing agents considered. Although this study focuses mainly on $CO_2$ emission, it is important to consider these other polluting agents that pose as a challenge for obtaining cleaner transport and protection of the environment. An increase in vessel size and transportation capacity have led to low freight rates and reduced carbon footprint, but there has also been an increase in transit times (loading and unloading as well as waiting for slot time in port). In port and slow zones, all sorts of pollution from ships pose a problem due to the concentrated area where the ships are residing. The international maritime organization as well as governments, port authorities and shipping lines have increased their focus on sulphur emissions and implemented lower limits on emissions in parts of Europe and North America. Several carriers have switched to fuel with low sulphur content when they arrive at heavily polluted ports such as Hong Kong, and local authorities are considering banning the use of bunker fuel with high sulphur content at port. The true source of the challenge lies in the price difference between fuel with high and low sulphur content, as some shipping lines are reluctant to change to low sulphur fuel due to the increase cost of doing so (Drewry, 2015).

It is well established (Alkaner and Zhou, 2006; Buhaug et al., 2009; Smith et al., 2014) that the operation phase of sea transport is responsible for the majority of the $CO_2$ emissions in this sector. This is not to say that raw material extraction, ship construction and end of life treatment is not of significance. On the life cycle side of marine transport, Gratsos et al., (2010) did a comparative study on life cycle $CO_2$ emissions bulk carriers, where they argue for greater robustness in ships to reduce repairs and extend lifetime as measures to mitigate environmental impacts on the life cycle side of marine transport. They concluded that building more robust vessels is beneficial, outweighing the cost of slightly reduced transport capacity. Studies have also shown that vessel size is of great importance, since larger ships are more energy efficient per freight unit compared to ships with smaller transport capacity (Cullinane & Khanna, 1998; 2000). The important thing to understand is that if you double the transport capacity, the increase in power required is only two thirds of that of the increase in size. This implies that by building larger ships you can reduce the fuel consumption per freight work done (Lindstad, 2013).

There is already a positive development in shipping with at least three factors that has been identified in selected sectors to contribute to lowering emissions (Drewry, 2015; Marintek, 2000). The two first factors have been found in containerships, where slow steaming (speed reduction) and a trend towards larger and more fuel-efficient vessels are already starting to take hold. The third; there is also a positive development where governments and IMO have placed stricter emission-restrictions on ships that are coming into ports. The average ship size in the Asia – North Europe route has increased by 40% in a five-year period (2009-2013), and container vessels have increase with an additional 23% between 2013 and 2015 (Drewry, 2015).

With the paper from Lindstad et al. (2011a), *“Reduction in greenhouse gas emission and cost by shipping at lower speeds”*, in additions to Faber et al. (2010, 2012), we have our main starting point for this thesis. Here, the effects of slow steaming are thoroughly investigated and discussed, and serves as framework for our study. Lindstad et al. (2014) *“Assessment of profit, cost, and emissions for slender bulk vessel designs”*, which points out a clear potential for emission reduction within shipping, is our most important reference when investigating the effects of more slender design for bulk carrying vessels.

# 2 Scope and aim

## 2.1 Our contribution to the state of the art

The primary objective of this work is to implement and integrate the different sub models developed by Håkon Lindstad to a flexible and dynamic model. Hence, we have focused mainly on compiling his existing contributions to a holistic package with integrated LCA functionality. His existing research is both thorough and of high quality, but suffers from lacking dynamic functionality as it is based on MS Excel spread sheets. Because of this, it requires a lot of manual labour for making adjustment or implementing new data for new annual reports. By adding dynamic functionality, and test our model with data from his pre-existing work, we are able to both make a model that is more flexible and robust while at the same time validate or disprove the results from his previous work.

Most studies focus either on design and construction of the vessels, or operational improvement. There is a need for work that includes both sides of that challenge in a satisfactory manner.  Our solution to these challenges is to build a calculation model where the input parameters are quickly exchangeable with new data. This way researchers can easily makes changes to sea conditions, fleet composition and vessel specifications, to suit their research question. By including an integrated LCA segment in the calculations, the model can then automatically produce $CO_2$ emissions and costs, normalised to: individual vessels, size classification, vessel category or total fleet, including both operational and upstream emissions. Integrating LCA as a part of our model will provide the opportunity to produce results one step beyond Lindstad existing work, where a simplified LCA based on economic activity in shipyards has been used.

The model is divided into two main scripts where one part of the model calculates emission by making incremental reductions to operational speed. The other calculates emission reductions from altering the ships dimensions and displacement. Both types of emission reduction are obtained primarily by the decreased power requirement.

We have chosen to perform the following scenarios using the model.

1. **Annual total fleet emissions**

In this scenario we have looked at change in annual total fleet emissions by reducing the design speed of the vessel (Vd), one knot at the time, from one knot less (Vd-1) to five knots less (Vd-5) than the design speed. In addition to the speed reduction, we have also calculated the emission levels that occur when vessels are operating with lowest expenses possible (Cost min.). This is done by extracting the emission level for the speed that has the lowest cost for each individual vessels size classification within each vessel category. The same has been done with respect to emission, where we compile the lowest possible emissions for each vessel size and category (e min.).

2. **Emission per tonne nautical mile from individual vessels**

In this scenario, we map the emissions of all vessel size and categories at speeds from 5 knots up the maximum speed they are able to achieve without exceeding the install power. Results are produced as $CO_2$ per tonne nautical mile (in grams), by calculating the total emission from one round trip, and then normalizing the emissions to the freight work performed on that given round trip.

3. **Change in emission from reducing block coefficient**

In the third scenario, we have investigated how emission levels change from a more slender design; either by increasing the beam of the vessel, or by reducing the displacement. We have divided the results in four scenarios; the first being the reference where no alteration to the original design has been made, in the second we have reduced the displacement by 14%, in the third we reduced the displacement by 28%, and in the last scenario we increased the beam (width) by 30%.

4. **Life cycle assessment of cargo vessels**

The last scenario calculates the contribution from different life cycle phases and upstream sources to the overall annual emissions. We assumed a 30 year life time and divided the life cycle into three phases; construction, operation and end of life.

# 3 Methodology

## 3.1 Introduction to solution method

In the following chapter, we want to take you through the process of how we went from the mathematical equations, to the finished model. The model we have developed started out from a set of equations from a paper named "*Reductions in greenhouse gas emissions and cost by shipping at lower speeds*" by H. Lindstad et al., (2011a). This paper provided the fundamental mathematical equations for calculating the power, fuel consumption, cost and emission that were used as a starting point for our model. A set of input parameters was needed to calculate the power usage for each vessel (Ch. 3.4). The power needed depends on sea conditions and ship- and engine size. The calculated power usage is then used as basis for calculating the fuel consumption, which in turn is used for calculating $CO_2$ emission. Fuel consumption is one of three main factors together with time charter and capital investment cost that make up the total cost function.

## 3.2 Mathematical Equations and theoretical approach

Chapter 3.2 describes and assesses the main mathematical equations used in the speed reduction and block coefficient scenario. The emission reduction through speed reduction measure is composed of four main equations; 1. power, 2. fuel, 3. emission and 4. cost. All parameters in the equations are described and explained in depth in chapter 3.4 Empirical basis and application.

### 3.2.1 Power equation

$$P = \frac{1}{n\left(j+k\sqrt{\frac{v}{v_d}}\right)}\left(\left(\frac{\rho C_S S v^3}{2}\right) + \left(\frac{1}{2}\frac{C_W \rho g \left(\frac{H_{\frac{1}{3}}}{2}\right)^2 B^2}{L}(v+u)\right)\right) + P_{aux} \qquad (1)$$

The power function consist of four parts. K is the propeller or propulsion efficiency, which is speed dependent and n defines the efficiency at design speed. This part of the equation works as a factor for calculation of the sum of still water and wave -power required for propulsion. When speed ($v_s$) is lowered, the propulsion efficiency drops according to the efficiancy factors ($j + k$), and some additional power is needed per knot.

$$K = \frac{1}{n\left(j+k\sqrt{\frac{v_s}{v_d}}\right)} \tag{2}$$

$P_s$ is the power required for propulsion in still water sea conditions eq. (3). The biggest contributors to still water power is the constant S, which is the wetted surface of the ship. This constant relates to the size of the ship, thus; the bigger the ship the greater the still water power required. Speed ($v_s$) and the still water coefficient ($C_s$) are the only variables in the equation, and still water power increases from 0 knots and upwards with a factor of speed cubed.

$$P_s = \frac{\rho C_s S {v_s}^3}{2} \tag{3}$$

$P_w$ is the additional power needed to compensate for waves. The factors in this equation is wave drag coefficient ($C_w$) representing the wave resistance, density of water (ρ), gravity ($g$), significant wave height ($H_{1/3}$ ) width of ship ($B$), length of ship ($L$), wave speed ($u$) and vessel speed ($v_s$). The greater the width of the ship, the greater amount of power is needed for propulsion. Length works as a power-reducing factor, but only in wave power, as a longer ship would require greater still water power, due to the increase in wetted surface. In the wave power equation a longer ship means a more slender design with better hydrodynamic performance.

$$P_w = \frac{C_w \rho g \left(\frac{H_{1/3}}{2}\right)^2 B^2}{2L}(u + v_s) \tag{4}$$

$P_{aux}$ is the auxiliary power needed for on-board equipment such as light, heating, computers and navigation systems.

$$P_{aux} \tag{5}$$

The total power is then the sum of each contributor, multiplying the sum of still water power and wave power with the propulsion efficiency factor.

$$P = K(P_s + P_w) + P_{aux} \tag{6}$$

### 3.2.2 Fuel equation

$$F = F_s + F_{p\&s} = K_f((\frac{PD}{v}) + (P_{p\&s}T_{p\&s})) \tag{7}$$

Total fuel consumption ($F$ - eq. 7) can be divided into two main parts. Fuel used during sailing ($F_s$ - eq. 8) and fuel used in ports and slow zones ($F_{p\&s}$ - eq. 9). Power in ports and slow zones ($P_{p\&s}$) is assumed to correspond to the idle engine power ($kW_{min}$ – see eq. 24). The power needed for the different parts of the voyage is multiplied with the time spent in each section ($\frac{D}{v_s}$ during sailing, $T_{p\&s}$ in ports and slow zones), and then multiplied with the fuel coefficient $K_f$. This gives us the total fuel used per round trip ($F$) in tonnes.

$$F_s = K_f(\frac{PD}{v_s}) \tag{8}$$

$$F_{p\&s} = K_f(P_{p\&s}T_{p\&s}) \tag{9}$$

### 3.2.3 Emission equation

$$\varepsilon = (\frac{F}{DM})K_e \tag{10}$$

The emission equation (eq. 10) normalizes the total amount of fuel used per round trip ($F$) to the amount of cargo ($M$) multiplied with the distance of transportation ($D$). It is then multiplied with the emission factor $K_e$, which gives us the emission in tonnes $CO_2$ per tonne nautical mile ($\varepsilon$).

### 3.2.4 Cost equation

$$C = \frac{1}{DM}\left(\left(F_sC_{HFO} + F_{p\&s}C_{MDO}\right) + T_CT + \left(MC_M\frac{1}{2}T\left(\frac{\frac{C_{IR}}{100}}{yr}\right)\right)\right) \tag{11}$$

Equation 11 shows how the total cost ($C$) is calculated. It can be divided into five main parts; normalization factor (eq. 12), fuel cost (eq. 13), time charter (eq. 14) and capital cost due to cargo value (eq. 15).

The normalization is applied to express the cost in dollars per tonne nautical mile.

$$\frac{1}{DM} \tag{12}$$

The amount of fuel needed for sailing ($F_s$) and for ports and slow zones ($F_{p\&s}$) is multiplied with their respective prices (Cost of heavy fuel oil – $C_{HFO}$, Cost of marine diesel oil – $C_{MDO}$)

$$F_s C_{HFO} + F_{p\&s} C_{MDO} \tag{13}$$

Time charter ($T_C$) is the daily cost related to renting a ship, crew and supply expenses (thoroughly explained in chapter 3.4.20). Time charter is multiplied with the number of days the voyage endures, $T$.

$$T_C T \tag{14}$$

The capital investment cost due to cargo value is calculated by multiplying average cargo value ($C_M$) with average weight of cargo ($M$). This value is multiplied with the interest rate ($C_{IR}$), and adjusted to only apply to half of the time spent on the round trip ($\frac{1}{2}T$), as the goods often are transported only one way.

$$M C_M \frac{1}{2} T \left(\frac{\frac{C_{IR}}{100}}{yr}\right) \tag{15}$$

### 3.2.5 Block coefficient

Block coefficient is a parameter usually applied to describe the hull shape of bulk carrying vessels. These vessels have traditionally been designed to maximize cargo carrying capacity at lowest possible construction cost. This practice has resulted in shoebox-looking hulls with very short bow sections and consequently not the best hydrodynamic performances. The hull is usually described as three different parts, the bow section, the block and the stern. For a standard *Panamax Dry Bulker*, the total drag resistance against the water would be distributed like this: bow section 10%, block 85% and stern 5%. This makes it interesting to look at different possibilities to make the hull more slender, and thus reduce the drag resistance.

$$C_b = \frac{\nabla}{LBT} \tag{16}$$

The block coefficient ($C_b$) is defined in eq. 16 where $\nabla$ is the displaced volume, $L$ is Length, $B$ is beam and $T$ is draught.

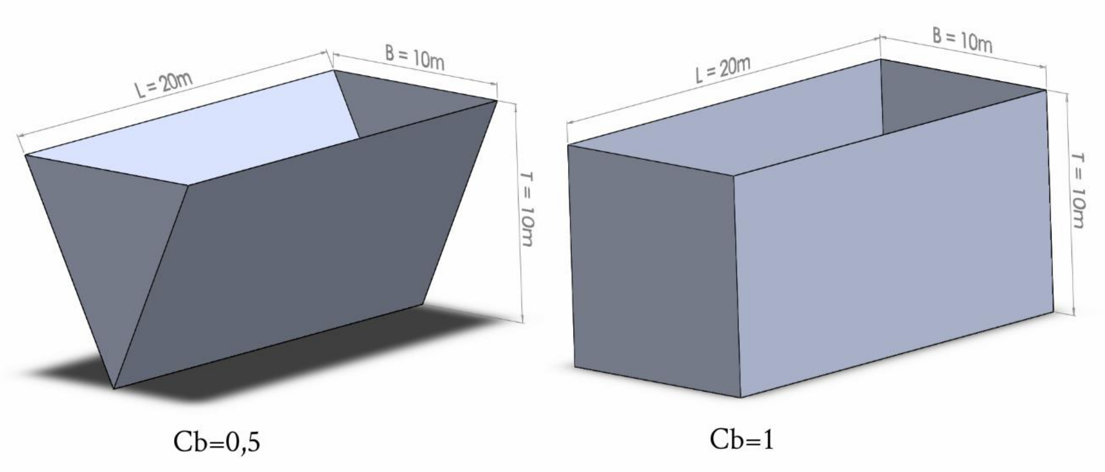


Figure 2: Examples of two types of hull shapes and their corresponding block coefficient

Figure 2 shows us two simplified examples of blocks. These two blocks have the same length ($L$), beam ($B$) and draught ($T$), but the block coefficient ($C_b$) for the block to the left is only half compared to the right one, because of only half as much displaced volume ($\nabla$). The displaced volume, which is the parameter with most impact on the block coefficient, is closely related to the cargo carrying capacity. To reduce the displaced volume, the cargo carrying capacity also has to be lowered. This would not follow the current trend within shipbuilding of increasing the dead weight tonnage ($dwt$), to lower the cost and emission per tonne nautical mile transported. The other opportunity is to increase length, beam and draught. The options to increase length and draught are in many cases limited by ports and canal conditions, so the most feasible way to maintain current levels of cargo carrying capacity and at the same time lower the block coefficient is to increase the beam.

$$P_s = P_{s_{ref}} \frac{S F_n C_b}{S_{ref} F_{n_{ref}} C_{b_{ref}}} \tag{17}$$

The way the block coefficient affects our ships modelled performance is shown in eq. 17. Here, $P_s$ is the power needed for sailing, and $P_{s_{ref}}$ is the corresponding reference value from the baseline scenario. $S$ is wetted surface, $F_n$ is Froudes number, and $C_b$ is the block coefficient. Beneath the fraction line are the corresponding reference values from the baseline scenario.

Froudes number is given in eq. 18, where $v_s$ is vessel speed, $L$ is the lenght of the ship, and $g$ is the gravitational force. The new adjusted power needed for sailing affects the fuel used, the emission, and the cost.

$$F_n = \frac{v_s}{\sqrt{Lg}} \tag{18}$$

## 3.3 Implementation of theoretical model

In chapter 3.3 we will take you through the structure of the model and how we have applied our knowledge from the mathematical equations in converting the equations into a model built on a MATLAB script. Building the model was our primary objective in this study and we have devoted a substantial part of our effort to this section. We wish to emphasize this process in our report by illustrating the effort that lies behind the model. We start by presenting the model as a flowchart, identifying the sections and function that is translated into segments of code, constituting the model. Lastly we will describe the additional changes that were made to create the block coefficient model.

### 3.3.1 Choice of software

For modelling the theoretical equations into a dynamic system, we have chosen to use MATLAB (Matrix Laboratory). MATLAB is a numerical computing environment and programming language initially developed by Cleve Moler in the 1970s, who later co-founded MathWorks in 1984 which currently runs the continuous development of MATLAB. MATLAB is widely used in academic institutions and integrate well with everything from MS office software, such as MS Excel to other programming languages such as C, Java and Python.

### 3.3.2 Model structure

The application of the mathematical formulas are structured in code according to the flowchart show in fig. 3. Although, many calculations occur in parallel, there is some linearity to the model, and the following chapters will take you through the process as linearly as the model allows for. The model is divided into six sections:

1. Input data

2. Propeller efficiency and still water resistance factor

3. Power calculation

4. Fuel consumption calculation

5. Life cycle assessment, emission and cost

6. Results

All sections contain three to five functions that perform different calculations to produce the output that is used in the next section. Please note that the functions are not functions in the classical programming sense, but rather a segment of script we have chosen to call functions for the purpose of dividing up the code.

All functions referring to figure 3 and 4 are written in the following format:
Function X-X – <function name> (abbreviation from figure)

The code for both speed reduction and block coefficient model can be read in its entirety in appendices 7.1 and 7.2.

## 3.3 IMPLEMENTATION OF THEORETICAL MODEL

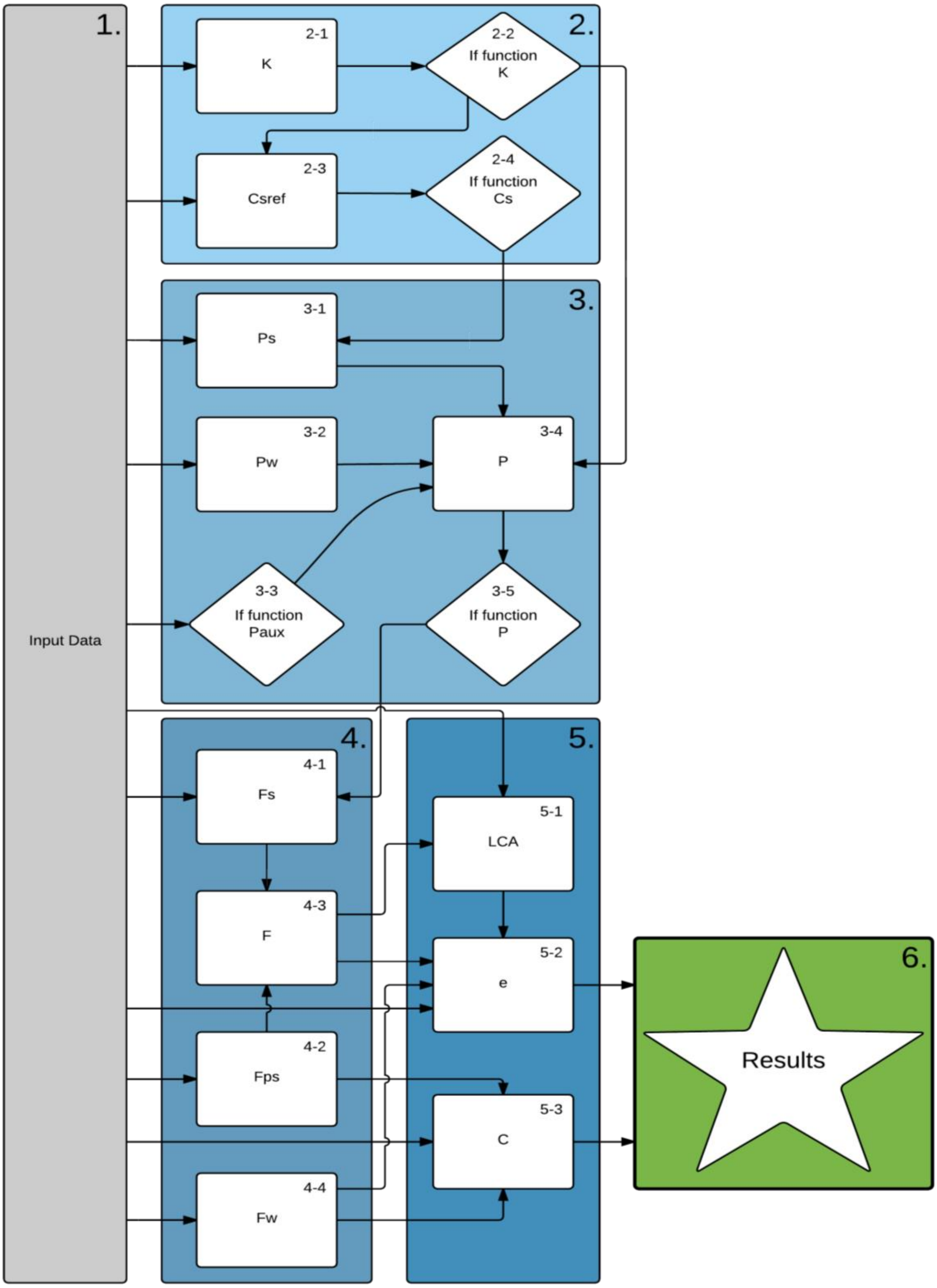


Figure 3: Flow chart of the main components of the speed reduction model

### Section 1 – Input data

The model starts with reading input parameters from a Microsoft excel spreadsheet and assigning them to variables, vectors and matrices in MATLAB (more information on input parameters in Ch. 3.4.2 to 3.4.27). Some input parameters are assigned as vectors and some as matrices. I.e. engine sizes (Ch. 3.4.8) are assigned to a 60x1 vector since engine size is a parameter that does not change and each vessel can only have one engine size each. The vector then holds 60 values of engine sizes, one per vessel in the data set. Other parameters such as propeller efficiency (function 2-1 in fig. 3) are assigned to a 60x30 matrix since this parameter is speed dependent and changes accordingly. The matrix then holds 1800 propeller efficiency values, one value for each speed from 1-30 knots for each of the 60 classes.

### Section 2 – Propeller efficiency and still water resistance factor

*Function 2-1 – Propeller efficiency (K)*

In this function, the model loads the engine efficiency ($n$) from the input data and assigns the default propeller efficiency to be equal to: $\frac{1}{n}$

*Function 2-2 - Changes in propeller efficiency (K) according to speed*

This function takes n from function 2-1, and then loads parameters: $j$, $k$ and $v_d$ from the input data. The code calculates the changes in propeller efficiency for each of the vessels for the speeds 1 through 30 knots (generated by a for-loop and assigned to $v_s$). If the vessel speed ($v_s$) is greater than or equal to the vessel design speed ($v_d$), then $K$ is equal to $\frac{1}{n}$. If the vessel speed is lower than the design speed, then $K$ will be calculated as shown in eq. 2.

$$K = \frac{1}{n\left(j+k\sqrt{\frac{v_s}{v_d}}\right)} \tag{2}$$

*Function 2-3 – Default still water drag coefficient ($C_{s_{ref}}$)*

Each vessel has a reference still water drag coefficient value ($C_{s_{ref}}$), which is the water friction against the hull when traveling at design speed. It is calculated using installed power ($kW$), wetted surface ($S$), and design speed ($v_{\mathrm{d}}$) from the input data. Maximum continuous revolution at design speed ($M_{cr}$), and the density of salt water ($\rho$) are constants given in the script. Propeller efficiency ($K$) taken from function 2-2.

$$C_{s_{ref}} = 2\frac{kWM_{cr}}{K\rho S v_{\mathrm{d}}} \tag{19}$$

*Function 2-4 – Still water drag coefficient for various speeds ($C_s$)*

The still water drag coefficient ($C_s$) is speed dependent, and in this function, a for-loop iterates through the speeds 1-30 knots ($v_s$) and calculates the $C_s$ -values that corresponds with each speed for each vessel, based on the reference value ($C_{s_{ref}}$) from function 2-3. Adjustment factors are equal to: $k_1$ = 0.8 and $k_2$ = 0.2. For speeds ($v_s$) greater than design speed ($v_d$), the still water resistance factor ($C_s$) is equal to:

$$C_s = C_{s_{ref}}\left(k_1 + \left(k_2\left(\frac{v_s}{v_d}\right)^2\right)\right) \tag{20}$$

For vessel speeds lower ($v_s$) lower than design speed ($v_d$), the still water resistance factor (C$_s$) is equal to:

$$C_s = \left(k_3 C_{s_{ref}}\right) + \left(k_4 \frac{v_s}{v_d} C_{s_{ref}}\right) \tag{21}$$

Here the adjustment factors are equal to: $k_3$ = 0.9 and $k_3$ = 0.1. And lastly, as mentioned earlier, when vessel speed ($v_s$) is equal to design speed ($v_d$); $C_s$ is equal to $C_{s_{ref}}$.

### Section 3 – Power calculations

*Function 3-1 – Still water power requirement ($P_s$)*

This function uses the still water drag coefficients ($C_s$) from function 2-4 and wetted surface ($S$) from the input data. Salt water density (ρ) is a constant given in the script. For-loop iteration through the speeds 1-30 knots ($v_s$) and the corresponding still water drag coefficients ($C_s$) calculates the required power for sailing in still water according to eq. 3 in chapter 3.2.1.

$$P_s = \frac{\rho C_S S\, v_S{}^3}{2} \tag{3}$$

*Function 3-2 – Wave power requirement ($P_w$)*

The function loads the parameters significant wave height ($H_{1/3}$), wave speed ($u$) and wave drag coefficient ($C_w$), which represents the sea conditions specified in the input data. In addition, salt water density (ρ), gravity ($g$) and vessel dimensions; width ($B$) and length ($L$). $H_{1/3}$ , $u$ and $C_w$ are interdependent, so for any given wave height, the corresponding speed and wave drag are loaded accordingly. The code then first calculates the relative speed ($v_r = v_s + u$) between wave ($u$) and vessel in m/s for speeds 1-30 knots ($v_s$), which is then used together with the input parameters to calculate the added power required for waves, given by eq. 4 in chapter 3.2.1.

$$P_w = \frac{C_w \rho g \left(\frac{H_{\frac{1}{3}}}{2}\right)^2 B^2}{2L} (v_r) \tag{4}$$

*Function 3-3 – Auxiliary power requirement ($P_{aux}$)*

This function loads the engine size ($kW$) from the input data, as the auxiliary power is a function of engine size. If the engine size ($kW$) is larger than 10 000 kW, then $P_{aux}$ has a base size of 250 kW ($P_{Base}$) plus 2.5% ($P_1$) of the installed capacity:

$$P_{aux} = P_{Base} + (kWP_1) \tag{22}$$

If the engine size ($kW$) is equal to or smaller than 10 000 kW, then $P_{aux}$ is equal to 5% ($P_2$) of the installed capacity:

$$P_{aux} = kWP_2 \tag{23}$$

*Function 3-4 – Total power required during sailing ($P$)*

This function loads propeller efficiency ($K$) from function 2-2, as the total power ($P$) is the sum of power required for still water ($P_s$) and waves ($P_w$) multiplied with the propeller efficiency ($K$) as this will account for the power lost from engine to propeller, and lastly adding the auxiliary power ($P_{aux}$) which is independent of propeller efficiency.

$$P = K(P_s + P_w) + P_{aux} \tag{6}$$

*Function 3-5 – Adjusting for idle power and upper limit power cut off*

This function goes through all power values ($P$) for all vessels and speeds, and checks if there are any values that exceed the installed power ($kW$) on the vessel in question, and if there are values that are lower than the idle power ($kW_{min}$) of the engine. The idle power is assumed to be 15% ($P_{Idle}$ = 0.15) of the installed power capacity, which is the lowest possible power output of the engine.

$$kW_{min} = P_{Idle}kW \tag{24}$$

If the model calculates an engine power requirement that is less than 15% of the installed power, then the aforementioned minimum required power is used instead. All values that exceed the installed power capacity are removed from the dataset, as the speeds are not obtainable in practice.

## Section 4. – Fuel consumption calculations

*Function 4-1 – Fuel during sailing ($F_s$)*

This function loads the round trip distance ($D$) from the data input as well as the fuel consumption factor ($K_f$). The function then takes the power required ($P$) from function 3-4, at each possible speed ($v_s$), and calculates the fuel consumption.

$$F_s = K_f\left(\frac{PD}{v_s}\right) \tag{8}$$

*Function 4-2 – Fuel in ports and slow zones ($F_{ps}$)*

This function loads the time spent in ports and slow zones ($T_{ps}$), fuel consumption factor ($K_f$) from the input data, and power requirement for ports and slow zones ($P_{ps}$), which is set to be equal to the idle power of the vessel engine ($kW_{min}$).

$$P_{ps} = kW_{min} \tag{25}$$

The fuel consumption in port and slow zones ($F_{ps}$) is then equal to the product of fuel consumption factor ($K_f$), power requirement in ports and slow zones ($P_{ps}$) and the time spent in ports and slow zones ($T_{ps}$).

$$F_{ps} = K_f P_{ps} T_{ps} \tag{9}$$

*Function 4-3 – Total fuel consumption ($F$)*

The total fuel consumption ($F$) is the sum of fuel used during sailing ($F_s$ in function 4-1) and the fuel used in port and slow zones ($F_{ps}$ in function 4-2).

$$F = F_s + F_{ps} \tag{7}$$

*Function 4-4 – Freight work factor ($F_w$)*

The model needs to have a number for the freight work ($DM$, distance times weight of cargo) of each vessel in order to normalize cost and emission to tonne per nautical mile. The freight work factor ($F_w$) compensates for the fact that some voyages are done with only ballast water and no cargo. The model first uses the number of cargo voyages ($C_v$)

and ballast voyages ($B_v$) for each vessel to calculate the total number of voyages per year ($Voy_{tot}$).

$$Voy_{tot} = C_v + B_v \tag{26}$$

The freight work factor is then given by the share of cargo voyages out of the total number of voyages.

$$F_w = \frac{C_v}{Voy_{total}} \tag{27}$$

**Section 5. Life cycle assessment, emissions and cost**

*Function 5-1 – Life cycle assessment (LCA)*

The life cycle assessment utilizes the light ship weight of the vessels to determine the amount of steel needed for construction and maintenance of the vessel throughout their lifetime. In addition to this, there is extraction and transport of raw materials, steel fabrication, and scrapping of the vessels along with transport of scrap metal. In the previous figure the LCA is shown as a single function, but in fact, it consist of a set of minor functions as illustrated in fig. 4. Values, coefficients and factors in this part of the study is largely based on a life cycle assessment by Gratsos et al., in 2010, which conducted a life cycle assessment on two *Dry Bulk* vessels (*Panamax* and *Handymax*).

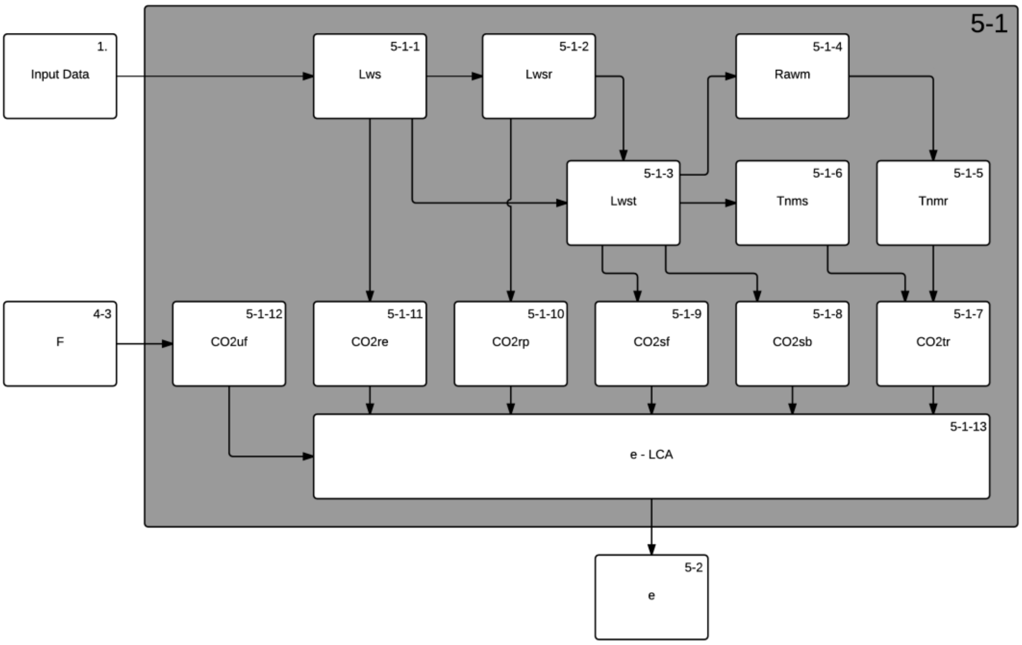


Figure 4: Flow chart of LCA sub model

*Function 5-1-1 – Light ship weight ($L_{ws}$)*

This function performs no calculations; it only loads the light ship weights from the input data spread sheet.

*Function 5-1-2 – Amount of steel need for repair ($L_{wsr}$)*

The amount of steel needed for repairs of the vessel during the 30-year (assumed) lifetime is set to be 10% ($S_{rep}$ = 0.1) of the weight of the ship ($L_{ws}$).

$$L_{wsr} = L_{ws} S_{rep} \tag{28}$$

*Function 5-1-3 – Total amount of steel needed during lifetime ($L_{wst}$)*

The total amount of steel ($L_{wst}$) that is needed throughout the lifetime of each vessel is the sum of steel needed for construction ($L_{ws}$) and the steel need for repairs and maintenance ($L_{wsr}$).

$$L_{wst} = L_{ws} + L_{wsr} \tag{29}$$

*Function 5-1-4 – Raw material needed for steel production ($R_{awm}$)*

From the total amount of steel, we have assumed a raw material factor of 2.66 ($S_{Raw}$). This means that for every tonne of steel that is used in shipbuilding ($L_{wsr}$), 2.66 tonnes of raw materials such as iron ore, coal, limestone etc. needs to be extracted and transported (Worldsteel, 2015).

$$R_{awm} = L_{wsr}S_{Raw} \tag{30}$$

*Function 5-1-5 – Transport of raw materials in tonnes nautical miles ($T_{nmr}$)*

The raw materials ($R_{awm}$) in function 5-1-4 is assumed to be transported by ship over a distance of 3484 nautical miles ($D_{PB}$) which is the distance from Port Hedland, Australia to Busan, Korea.

$$T_{nmr} = R_{awm}D_{PB} \tag{31}$$

*Function 5-1-6 – Transport of steel and scrap materials - tonne nautical miles ($T_{nms}$)*

This function calculates the tonnes nautical miles ($T_{nms}$), distance and amount of steel ($L_{ws}$), which will be scrapped at the end of life of the vessel. The distance from the scrapyard or building yard to the steel mill ($D_{CD}$), where the steel will be re-melted may vary, but we have chosen to use the same distance as chosen by Gratsos et al., (2010); a distance of 4136 nautical miles ($D_{CD}$), which corresponds to the distance between Chittagong Bangladesh, and Dalian in China.

$$T_{nms} = L_{ws}D_{CD} \tag{32}$$

*Function 5-1-7 – $CO_2$ from transport of scrap and raw materials ($CO2_{tr}$)*

This function uses the total freight work from transportation (scrap - $T_{nms}$ and raw materials - $T_{nmr}$) in tonnes nautical miles and we have assumes that raw materials and scrap are transported with a large dry bulker with an average emission of 12 grams of $CO_2$ per tonne nautical mile ($T_{nc}$).

$$CO2_{tr} = (T_{nmr} + T_{nms})T_{nc} \tag{33}$$

*Function 5-1-8 – $CO_2$ emissions due to shipbuilding ($CO2_{sb}$)*

This function uses a shipbuilding $CO_2$ factor ($S_{bc}$ = 0.216) to calculate the amount of $CO_2$ emitted per tonne of steel that is processed at the ship yard. In other words, $CO_2$ emitted due to construction of each ship. The amount of steel processed is given by the total light ship weight ($L_{wst}$) from function 5-1-3.

$$CO2_{sb} = L_{wst}S_{bc} \tag{34}$$

*Function 5-1-9 – $CO_2$ emission due to steel fabrication from raw materials ($CO2_{sf}$)*

This function uses the total amount of steel needed for each vessel ($L_{wst}$) and multiplies it with a steel fabrication factor ($S_{fc}$ = 1.75). Oxera (2004) argues that in a state of the art steel facility, an amount of 1.75 tonnes of $CO_2$ per tonne of steel fabricated is to be expected. Note that this is a conservative value and older facilities will likely represent a higher value than what is used here.

$$CO2_{sf} = L_{wst}S_{fc} \tag{35}$$

*Function 5-1-10 – $CO_2$ emissions from repairs at shipyard ($CO2_{rp}$)*

This function uses the amount of steel need for repairs ($L_{wsr}$), given by function 5-1-2 and multiplies it with a shipyard activity $CO_2$ factor ($R_{pc}$ = 0.303). The $R_{pc}$ factor includes all yard activity such as cutting, transport, welding and direct emissions from sea trials adding up to 0.303 tonnes of $CO_2$ per tonnes of steel replaced.

$$CO2_{rp} = L_{wsr}R_{pc} \tag{36}$$

*Function 5-1-11 – $CO_2$ emissions from disassembly/scrapping of vessel ($CO2_{re}$)*

In this function, we have assumed that cutting one tonne of steel uses roughly 60 kg of propane ($C_3H_8$), which translates into 0.18 tonnes of $CO_2$ per tonnes of steel cut ($R_{ec}$ = 0.18). The amount of steel cut is the light ship weight ($L_{ws}$) of individual vessels. Transportation of the cut steel is accounted for in function 5-1-7, while emissions from re-melting of the steel is excluded in this function.

$$CO2_{re} = L_{ws}R_{ec} \tag{37}$$

*Function 5-1-12 – $CO_2$ emissions from upstream fuel production ($CO2_{uf}$)*

This function takes the amount of fuel per round trip ($F$) calculated in function 4-3 and calculates the amount of $CO_2$ emitted from extraction and refining of the amount of fuel used. The $CO_2$ coefficient was provided by Bengtsson et al. (2011), and is estimated to be 0.25 tonnes $CO_2$ per tonnes of fuel consumed ($F_{us}$ = 0.25).

$$CO2_{uf} = e_{Up} = F_{us}F \tag{38}$$

*Function 5-1-13 – Total life cycle assessment related emissions ($e_{LCA}$)*

The overall LCA-related emissions are the sum of all parts in functions 5-1-7 through 5-1-11. Emissions from upstream fuel production ($CO2_{uf}$) are kept separate from construction and end of life related emissions as the fuel production is affiliated with the operational phase of the vessel life cycle (see eq. 41). Note that this concludes the LCA segment (fig. 4), and the next function refers to function 5-2 in fig. 3.

$$e_{LCA} = CO2_{tr} + CO2_{sb} + CO2_{sf} + CO2_{rp} + CO2_{re} \tag{39}$$

*Function 5-2 – Total emission per tonnes nautical mile ($e_{tot}$)*

In this function we have first calculated the direct emissions ($e_C$) from fuel combustion by using the fuel consumed ($F$) and $CO_2$ per unit fuel combusted ($K_e$)

$$e_C = K_eF \tag{40}$$

The total emission is then the sum of the direct combustion emissions ($e_C$), upstream fuel production ($e_{Up}$) and the LCA related emissions ($e_{LCA}$).

$$e_{tot} = e_C + e_{Up} + e_{LCA} \tag{41}$$

All emissions sources are normalized to the freight work, which consist of distance per round trip ($D$) multiplied by the average weight of cargo ($M$). The freight work is then multiplied with the freight work factor ($F_w$) from function 4-4 (eq. 27) to compensate for the fact that some voyages are made with only ballast water.

$$e = \frac{e_{tot}}{F_w D M} \tag{42}$$

*Function 5-3 – Total cost of fuel consumption, time charter and capital investment*

This function based on the cost equation (eq. 11) and is divided into 5 sub parts: $f_1$ – normalization factor, $f_2$ – fuel cost, $f_3$ – time charter, $f_4$ – value of cargo, $f_5$ – interest rate on capital invested in cargo. The normalization factor $f_1$ is given by

$$f_1 = \frac{1}{F_w D M} \tag{43}$$

The fuel cost ($f_2$) is the sum of heavy fuel oil consumed during sailing ($F_s$), and marine diesel oil consumed in ports and slow zones ($F_{ps}$). The amount of fuel is multiplied with their respective fuel prices to find the total cost of fuel per round trip (Cost of heavy fuel oil – $C_{HFO}$, Cost of marine diesel oil – $C_{MDO}$).

$$f_2 = F_s C_{HFO} + F_{ps} C_{MDO} \tag{13}$$

The cost of time charter ($f_3$) is, the daily cost ($T_c$) multiplied with the number of days per round trip ($T_t$). The number of days is dependent on the speed ($v_s$) and distance of the round trip ($D$).

$$f_3 = T_c T_t \tag{14}$$

Cargo value ($f_4$) is given by the average weight of cargo transported ($M$) and the value of the cargo per tonne ($C_m$). Here we assume that the investment cost is from port to port, and not for a round trip, which means the investment cost only applies to a one way travel distance ($T_t/2$ - half of one round trip; one way with cargo and one way with ballast water).

$$f_4 = \frac{MC_m T_t}{2} \tag{44}$$

Given that the interest rate ($Cir$ = 5) on the cargo value ($f_4$) should only apply to the number of days during travel and not a whole year, the cost of annual interest rate is divided by 365 days ($yr$) to find the daily expense, which is then multiplied with the number of days during travel (one way) in $f_4$.

$$f_5 = \frac{(\frac{Cir}{100})}{yr} \tag{45}$$

The total cost of capital investment ($f_6$) is the product of cargo value, interest rate and the number of days the cargo is under transport.

$$f_6 = f_4 * f_5 = \frac{MC_M T_t}{2} \frac{(\frac{Cir}{100})}{yr} \tag{15}$$

Collectively these parts add up to the total cost ($C$) of transportation for one round trip, normalized to per tonne nautical mile ($f_1$).

$$C = f_1 * (f_2 + f_3 + f_6) \tag{11}$$

**Section 6. Results**

All emission and cost results are by default produced as results for individual vessels per tonne nautical miles. Addition code was added in the model in this section in order to produce additional results for easier analysis.

All emission ($e$) and cost ($C$) results are also produced without the normalization factor ($f_1$, eq. 43) in order to give the total emission and cost of one round trip ($e_{RT}$) and $C_{RT}$).

$$C_{RT} = f_2 + f_3 + f_6 \tag{46}$$

By multiplying $e_{RT}$ and $C_{RT}$ with the number of round trips per year ($RT_{yr}$), we obtain the total annual emission ($e_{yr}$) and cost ($C_{yr}$) for each vessel. Since the cost and emission are calculated the same way, the procedure from here on forward described with $X$ representing $C$ and $e$.

$$X_{yr} = X_{RT}RT_{yr} \tag{47}$$

The annual emission and cost ($X_{yr}$) is in turn multiplied with the respective number of vessels ($N_o$) within that given size classification to get the total cost and emission for that size class (${X_{yr}}_{class}$).

$${X_{yr}}_{class} = X_{yr}N_o \tag{48}$$

These results can then be summed to get the total emission of a vessel category ($X_{category}$ – i.e. *Dry bulker, Container, Oil tanker* etc.).

$$X_{category} = \ {X_{yr}}_{class\ 1} + \ {X_{yr}}_{class\ 2} + \ \dots + {X_{yr}}_{class\ \mathrm{n}} \tag{49}$$

At last, the sum of all categories ($X_{category}$) will give the annual emissions for the world fleet of cargo transporting vessels ($X_{fleet}$).

$$X_{fleet} = X_{category\ 1} + X_{category\ 2} + \ \dots \ + X_{category\ n} \tag{50}$$

### Modelling of the Block coefficient

The block coefficient section is not illustrated in the flow chart (fig. 3), and here we will explain why.

We have run four different scenarios with four different block coefficients. We have chosen the standard *Panamax* for our block scenarios, which is a representative midrange dry bulker, with a block coefficient of approximately 0.87. The adjusted block coefficients have been obtained by lowering the cargo carrying capacity and displacement, and by increasing the beam. First, we have the baseline; the reference scenario where nothing is changed and the ships have the same initial input parameters as in the speed reduction scenario. The first two scenarios are based on a lowering of average cargo carrying capacity and displacement, respectively by 14% and 26%. Here, the wetted surfaces of the vessels are reduced since they travel lighter in the water. Assuming lighter and smaller vessels, the new building prices are expected to drop, which again leads to a reduction in time charter expenses. The third scenario entails a 30% increase of beam. We assume the wetted surface to remain constant as the beam increases, but the keel gets thinner. With an increased beam, the vessel will experience an increase in wave resistance. All scenarios are run with sea conditions reflecting 70% calm sea and 30% 4 meters head waves.

The block coefficient script is based on the same foundation of code as the main script, but for the sake of keeping the code as clear and transparent as possible we choose to keep the speed reduction and block coefficient model separate. Once an early version the main model (speed red.) was in place and functional, we duplicated the code and continued to work on the scripts separately. The block script performs the same calculations as in speed reduction, but as the script loads the input parameters (see chapter 3.3.2), we have coded the model to create the four scenarios described. The different block scenarios are calculated in parallel and the model code can be seen in appendix 7.2.

## 3.4 Empirical basis and application

Chapter 3.4 will provide a more in depth look at the input parameters that were used in the previous chapter, their source of origin or how they were deduced from source data. Here we also state the assumptions that were made considering the input data, as well as the reason behind it. In many cases, we have stayed with the same assumptions as Håkon Lindstad, for the consistency and purpose of validating his results. This chapter primarily serves the purpose of giving the reader insight to the data necessary to utilize the model and perform emission calculations.

The majority of the information in the input parameter sheet has been gathered from Table 5: *Operational and technical characteristics of different vessel types and calculation of bunker consumption figures* in (Lindstad et al., 2012a). This table provided the basic information for all the ships categories and size classifications and is used for feeding all parameter data into the MATLAB -model. The following parameters were directly adapted from the table previously mentioned: No of ships, distance per voyage, design speed, engine size, engine efficiency at design speed, width of ship, length of ship, draft of ship, grams of fuel per kWh, wave height, wave speed, wave drag, $CO_2$ per unit of fuel, average weight of cargo, price of heavy fuel oil, price of marine diesel oil, export value of cargo, annual interest, cargo voyages, ballast voyages. The remaining parameters were either extrapolated based on data from the table, or they were deduced through discussion and consolidation with Lindstad. Where other sources were used, this is specified in the parameter description.

The input parameter sheet can be seen in its entirety in appendix 7.3

## 3.4 EMPIRICAL BASIS AND APPLICATION

### 3.4.1 Vessel categories and classification

Vessels are divided into eleven categories with 4-7 size classifications with each category; e.g., General cargo vessels are divided into size classification ranging from 0-500 tonnes in the smallest category, to 15 thousand tonnes and above for the largest (see table 3).

Table 3: Example of vessel category and size classification.

| | |
|---|---|
| General Cargo | Dry Cargo 15'++ |
| | Dry Cargo 10'-15' |
| | Dry Cargo 5'-10' |
| | Dry Cargo 1'-5' |
| | Dry Cargo 500-1' |
| | Dry Cargo 0-500 |

### 3.4.2 Number of ships

The number of ships used within each ship category and size classification reflects the number of cargo vessels in the global fleet that falls within the ship characterization we have chosen. The total number of vessels represents the global fleet of cargo vessels anno 2007 (Buhaug et al., 2009; Lindstad et al., 2012a). The following ship types are not included in this study: Ferry (pax only), Cruise, Yacht, Offshore, Service, Fishing and other. This fleet represent roughly 50% of the total fleet in term of numbers, but the average dead weight tonnage is only 2.1% of that of cargo vessels.

### 3.4.3 Distance per voyage

The distances used for each ship category and size classification are meant to reflect the average travel distance of one voyage (one way) measured in nautical miles. The round trip distance is hence twice the distance per voyage. The largest *Dry Bulk* ship; *Capesize* can be used as an example to illustrate a sailing pattern. The *Capesize* typically can travel from Australia to Japan/Korea/China with coal or iron ore and then in ballast back, which would give an average sailing distance is 7500 nautical miles one way.

### 3.4.4 Days per voyage

Since we are progressively examining the consequences of different speeds for the vessel fleet, we continuously have to update the amount of time they spend for each voyage. The parameter used in our calculations, $T_t$, is found by dividing the round trip distance ($D$) on the relevant speed ($v_s$), and then again on 24 hours a day ($d$).

$$T_t = \frac{\frac{D}{v_S}}{d} \tag{51}$$

### 3.4.5 Time in ports and slow zones

The average number of days spent in port and slow zones ($T_{ps}$) per round trip, derived from subtracting days at sea ($D_s$) from one year ($yr$) and dividing this number by the number of cargo ($Cv$) and ballast voyages ($Bv$) per year.

$$T_{ps} = \frac{yr - D_S}{Cv + Bv} \tag{52}$$

### 3.4.6 Vessel speed

Default operational vessel speed ($v_s$) is considered to be 95% of design speed ($v_d$). But as we progressively examine the fleet, $v_s$ will vary from 5 to 30 knots.

### 3.4.7 Design speed

Design speed ($v_d$) is the speed the ship is designed to maintain at 75% engine load (75% of installed power $kW$).

### 3.4.8 Engine size

Engine size ($kW$) is defined as the maximum power the engine can produce, measured in kilowatts output.

### 3.4.9 Engine efficiency at design speed

The engine efficiency coefficient ($n$) is a coefficient between zero and one that is used for calculating the power output of the propeller at 75% engine load (design speed in calm water). Typical value resides between 0.6 – 0.7 (Lindstad et al., 2011a)

### 3.4.10 Power required in ports and slow zones

Power required in ports and slow zones ($P_{ps}$) is the amount of power used when the vessel travels very slowly or standing still. For lower speeds ($v_s$), the engine will run at idle load, which will vary depending on engine size. In this study, we have chosen to use 15% of engine load as idle load ($kW_{min}$), which is then also the required power for port and slow zones.

### 3.4.11 Displacement

Displacement ($\nabla$) is the volume of water displaced by the vessel. The volume is equal to the sum of the light ship weight ($L_{ws}$) and the dead weight tonnage ($dwt$) divided by the density of salt water ($\rho$ = 1.025 kg/L).

$$\nabla = \frac{L_{ws}+dwt}{\rho} \tag{53}$$

### 3.4.12 Dimensions

The dimensions of the ship are gathered directly from Lindstad (Lindstad, 2015). Fig. 5 below illustrates how the dimensions are considered. Note that the symbols in the figure do not necessarily coincide with the symbols we have used throughout this study.

All dimensions are measured at waterline. Beam ($B$) and length ($L$) is the front-to-back and side-to-side of the ship at the water line, while the draft ($T$) is the distance from the waterline to the bottom of the keel when ship is fully loaded. All dimensions are measured in standard SI meters. Not all ship categories were covered in Lindstad table, so we have estimated some dimensions using reference vessels from Sea-Web (2015).

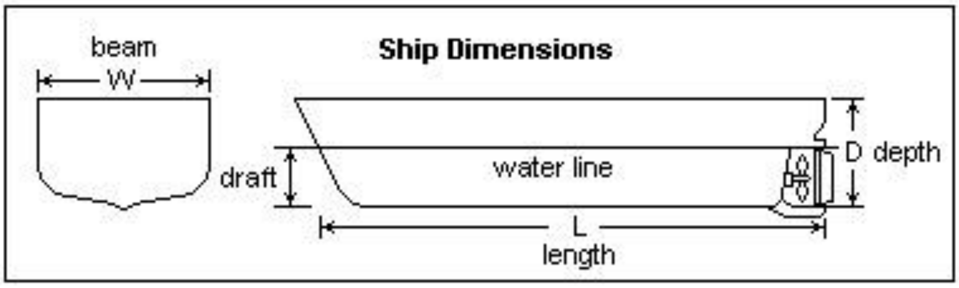


Figure 5: Characterisation of ship dimensions.

### 3.4.13 Wetted surface

The wetted surface ($S$) of the ship is the area of the hull that is in contact with water. The area is estimated from the dimensions in the chapter above and the shape is considered a box, ignoring the front and back, as these are tapered/pointed. Eq. 54 shows how the wetted surface is estimated.

$$S = \frac{B*L}{2*T*L} \tag{54}$$

### 3.4.14 Gram fuel per kWh

This parameter is also known as the brake specific fuel consumption ($K_f$), which is a measure of fuel efficiency. This is a measure of the efficiency of the combustion engine compared to the shaft power output. Values range from 190 grams of fuel equivalents per kWh to 285 grams of fuel equivalents per kWh.

### 3.4.15 Wave characteristics

The wave characteristics consist of three interdependent parameters, namely significant wave height ($H_{1/3}$), wave speed ($u$) and wave drag ($C_w$). Wave height is set by the analyst and the wave speed and wave drag is calculated as function of the given wave height.

**Significant wave height ($H_{1/3}$)**

The significant wave height is given by $H_{1/3}$. This parameter describes a wave where the wave amplitude on average is half that of the value. Two thirds (2/3) of the waves are on average smaller than the given height, while one third (1/3), on average, is larger than the given height with a maximum up to twice that of the given height.

**Wave speed ($u$) and relative wave speed ($v_r$)**

Wave speeds are obtained by dividing length of the wave with peak period of the wave. Wavelength and peak period are characteristics given by the significant wave height. The relative wave speeds ($v_r$) a given by a matrix of values calculated from the significant wave height ($H_{1/3}$) and corresponding wave speed ($u$) and the speed of the vessel ($v_s$). This is due to wave speed being a parameter that is relative to the vessel speed. In this analysis we have chosen to work with head waves and assumed that the average sea conditions have head wave 50% of the distance travelled.

**Wave drag coefficient**

The wave drag coefficient ($C_w$) is a value that is used when calculating the addition power needed due to waves. The value is given by the wave height ($H_{1/3}$) and is independent of the vessel speed ($v_s$). The value is a function of still water resistance factor and ship design, but in this analysis we use a simplified approach with average values calculated from characteristics of a *Panamax* Dry Bulker in different wave heights and apply these for all vessels.

### 3.4.16 $CO_2$ per unit of fuel burned

This $CO_2$ per unit of fuel ($K_e$) parameter is a constant and represents the amount of $CO_2$ emitted from burning one unit of fuel. Different sources specify roughly the same amount, but we have chosen to use the same amount as used by Lindstad et al., (2011a); 3.17 kg of $CO_2$ emitted per 1 kg of heavy fuel oil burned.

### 3.4.17 Average weight of cargo

Average weight of cargo ($M$) is calculated from payload capacity (in tonnes) and the "utilization when loaded" –factor (in percentage). The utilization when loaded factor represent how much of the given payload capacity any given ship is able to utilize. I.e. an oil tanker can utilize 98-99% of the payload capacity, as the cargo is liquid and can fill all the cargo space available. Container ships often have air in between the cargo inside the containers and rarely can utilize more than 70% of the payload capacity due to stacking of the goods. The average weight of cargo is then obtained by multiplying payload capacity with utilization when loaded factor.

### 3.4.18 Cost of heavy fuel oil

The cost of heavy fuel oil ($C_{HFO}$) has a large effect on the overall cost function as heavy fuel oil is the fuel type used by most vessels during sailing, but it also has an effect on for instance the emission/cost minimization point. The market price of heavy fuel oil varies, and has changed a lot the last year, but in this analysis we have chosen to be consistent with Lindstad et al. (2011a), which use a price of 400 USD per tonne heavy fuel oil.

### 3.4.19 Cost of marine diesel oil

This parameter is quite similar in characteristics as $C_{HFO}$, but the main difference is that marine diesel oil is modelled as the fuel type used for port and slow zones. The cost of marine diesel oil ($C_{MDO}$) is higher because it is a more refined fuel type and is thus more expensive than HFO. Lindstad et al. (2011a) used a price of 600 USD per tonne fuel for this parameter.

### 3.4.20 Time charter

Time charter ($T_C$) represents the cost related to renting a ship. This cost is very dependent of the price of building the vessel. The time charter ($T_C$) parameter is calculated from values in table 3 from Lindstad et al. (2012b). This table displays new-building cost per vessel as a function of vessel type and size, both for 2007 and for economies of scale. The average size dead weight tonnage ($dwt$) is also given for the different ship types, for both economic scenarios. This allows us to find a price per $dwt$ for all ship types for both scenarios, and then calculate the average of the two. Price per $dwt$ is then muliplied up to represent the new-building cost of the different relevant ship sizes. The daily time charter cost is estimated as 12% of the new building price, divided by 365 days.

### 3.4.21 Export value

The Export value ($C_M$) parameter is the average price per tonne of the cargo transported by the vessel in question. The value of the cargo has an impact on the overall cost by losing capital interest during sailing. The model considers cargo value as an expense by the losing interest on the potential capital that could be invested while the cargo under transport. The longer the capital is tied up in cargo under transport the greater the expense, similarly; a higher cargo value leads to a higher capital investment and greater expenses.

### 3.4.22 Annual interest of investment capital

Interest rate ($Cir$) is related to export value described above, as this is the assumed interest rate on the capital investment. The interest rate one could get on a capital investment can vary substantially depending on how much capital is invested, whether the capital is invested in stocks or bonds, and for how long the capital is tied up. As in many other cases we have chosen to stick with Lindstads et al. (2011a) proposed value of an interest rate of 5%.

### 3.4.23 Propeller efficiency constants

These parameters ($j + k$) are related to how the efficiency of the propeller (K – eq. 2) changes at different speed. Both are entered as input of 0.5, but $j$ is a speed independent constant that is always 0.5, while $k$ is dependent of speed with a value of 0.5 at design speed or higher and decreases at lower speeds. The sum of the two values is never greater than one ($j + k$ = 1).

### 3.4.24 Cargo and ballast voyages per year

$Cv$ and $Bv$ are the number of voyages the vessels of each class and category travel per year with cargo and ballast water respectively. These numbers are used in calculating freight work factor ($F_w$), and time in ports and slow zones ($T_{ps}$).

### 3.4.25 Dead weight tonnage

Dead weight tonnage ($dwt$) is a common marine vessel terminology used for the load bearing capacity of a vessel. This includes cargo, fuel, people, and water etc., everything except the weight of the vessel itself. Mathematically it can be represented as weight of displaced water when fully loaded minus the weight of the ship.

### 3.4.26 Light ship weight factor

The light ship weight factor ($L_{ws}$-factor) is a parameter used to get more coherent light ship weights. This approach was used due to difference in size classification of vessels by the various sources for dead weight tonnage, light ship weight and displacement. This posed a challenge as incoherence in the data sources caused some very unlikely results and a review of the data was needed. The light ship weight factor was obtained by dividing the light ship weight value by dead weight tonnage of selected vessels in “Kystverksberegninger”, a data set provided by Sintef MarinTek (Lindstad, 2015).

### 3.4.27 Light ship weight

Light ship weight ($L_{ws}$), also know as dry weight or lightweight, is the actual weight of the ship without any fuel, cargo, people or water. Light ship weight values are calculated estimates from multiplying the light ship weight factor ($L_{ws}$-factor) by the dead weight tonnage ($dwt$) of the vessels in question.

# 4 Results and analysis

The results come from four different main scenarios where we have looked at:

- Emissions across the total fleet from reducing speed.
- Effect on individual vessels from reducing speed.
- Effect on bulk carriers from altering vessel design
- Emission contribution from upstream sources (life cycle assessment).

## 4.1 Fleet emissions and the effect of speed reduction

In total, we found that 883.17 mega tonnes of $CO_2$ are emitted annually from all cargo vessels given operation at design speed ($v_d$) and an average sea condition of 2.5 meter head waves for the larger vessels and 1 meter head waves for the smallest vessels in each vessel category.

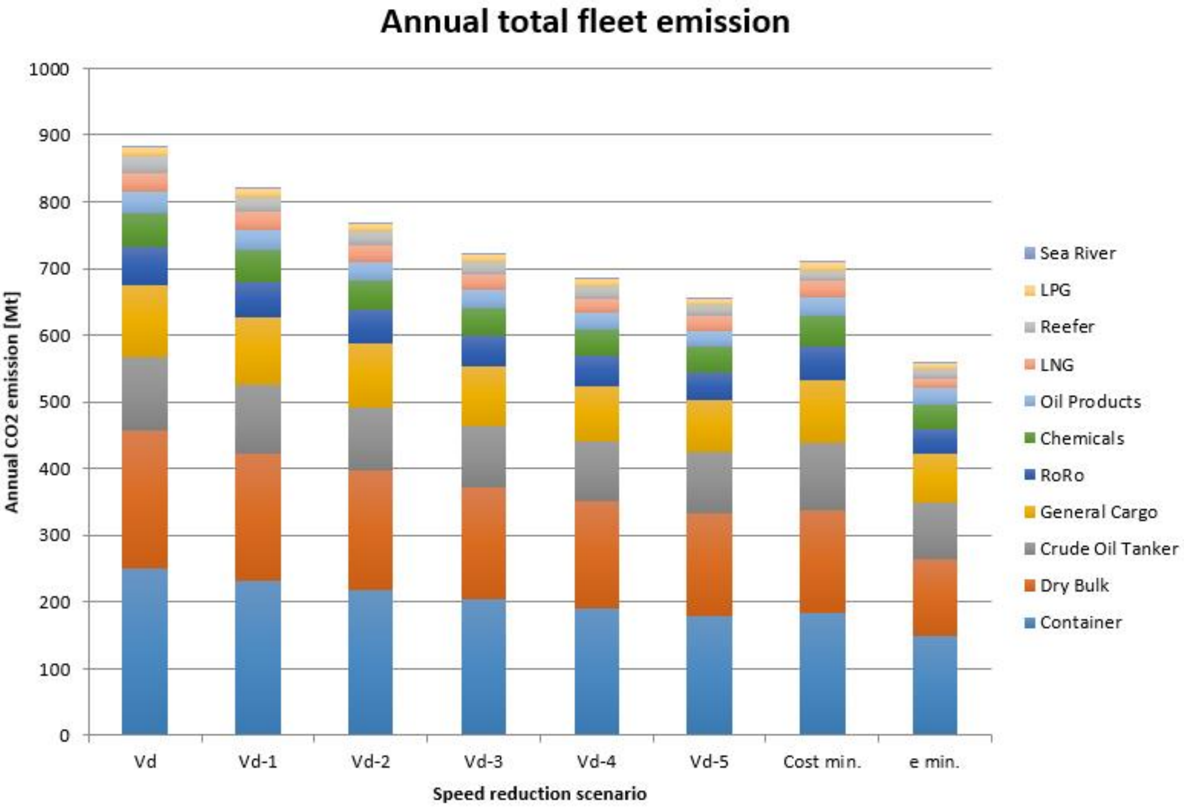
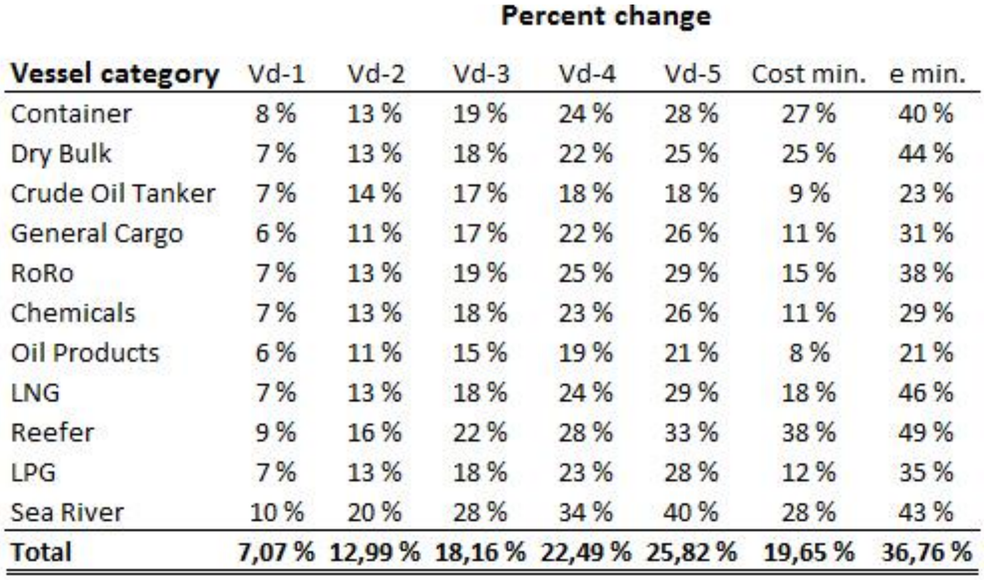


Figure 6: Vessel category break down of annual $CO_2$ emissions.

The emissions include both direct emissions from fuel combustion as well as upstream emissions such as vessel construction, end of life and fuel production. The largest contributors the global annual emissions are by far *Container* and *Dry Bulk* vessels as they collectively emit 456.4 mega tonnes of $CO_2$, as seen in fig. 6. This constitutes roughly 51.6% of the overall emissions, which means that these two vessel categories alone are responsible for over half of the annual emissions. The second most contributing vessel categories are *Crude Oil*, *General Cargo* and *RoRo* with 12%, 12% and 7% relative contribution respectively (fig. 12).

Table 4: Percentage reduction in emission from speed reduction and cost/emission optimization.



**Percent change**

| Vessel category | Vd-1 | Vd-2 | Vd-3 | Vd-4 | Vd-5 | Cost min. | e min. |
|---|---|---|---|---|---|---|---|
| Container | 8 % | 13 % | 19 % | 24 % | 28 % | 27 % | 40 % |
| Dry Bulk | 7 % | 13 % | 18 % | 22 % | 25 % | 25 % | 44 % |
| Crude Oil Tanker | 7 % | 14 % | 17 % | 18 % | 18 % | 9 % | 23 % |
| General Cargo | 6 % | 11 % | 17 % | 22 % | 26 % | 11 % | 31 % |
| RoRo | 7 % | 13 % | 19 % | 25 % | 29 % | 15 % | 38 % |
| Chemicals | 7 % | 13 % | 18 % | 23 % | 26 % | 11 % | 29 % |
| Oil Products | 6 % | 11 % | 15 % | 19 % | 21 % | 8 % | 21 % |
| LNG | 7 % | 13 % | 18 % | 24 % | 29 % | 18 % | 46 % |
| Reefer | 9 % | 16 % | 22 % | 28 % | 33 % | 38 % | 49 % |
| LPG | 7 % | 13 % | 18 % | 23 % | 28 % | 12 % | 35 % |
| Sea River | 10 % | 20 % | 28 % | 34 % | 40 % | 28 % | 43 % |
| **Total** | **7,07 %** | **12,99 %** | **18,16 %** | **22,49 %** | **25,82 %** | **19,65 %** | **36,76 %** |

### 4.1.1 Effects of reducing speed

By reducing the operating speed by one knot, an overall emission reduction of ~7%, from 883.17 to 820.73 mega tonnes was achieved. The relative changes was most profound in the Sea River category where emissions where reduced by 10.35%. Unfortunately, Sea River vessels constitutes less than 0.2% of the annual emissions, so although the changes within the category are large, on a global scale this is of little significance. In the other vessel categories, the speed reduction have somewhat equal effect, with reduction spanning from 5.98% to 7.51% with the exception of reefer with a slightly larger effect of 8.56%. As with the results from the original scenario, container and dry bulk vessels hold the potential for largest net emission reduction. A one knot speed decrease can provide a 33.4 mega tonnes emission reduction, which constitutes 53.5% of the overall achieved reduction from just these two categories. If we include crude oil and general cargo in the accounting, we obtain a reduction of 76.6%, which is over three quarters of the total emission reduction potential from a one knot speed reduction.

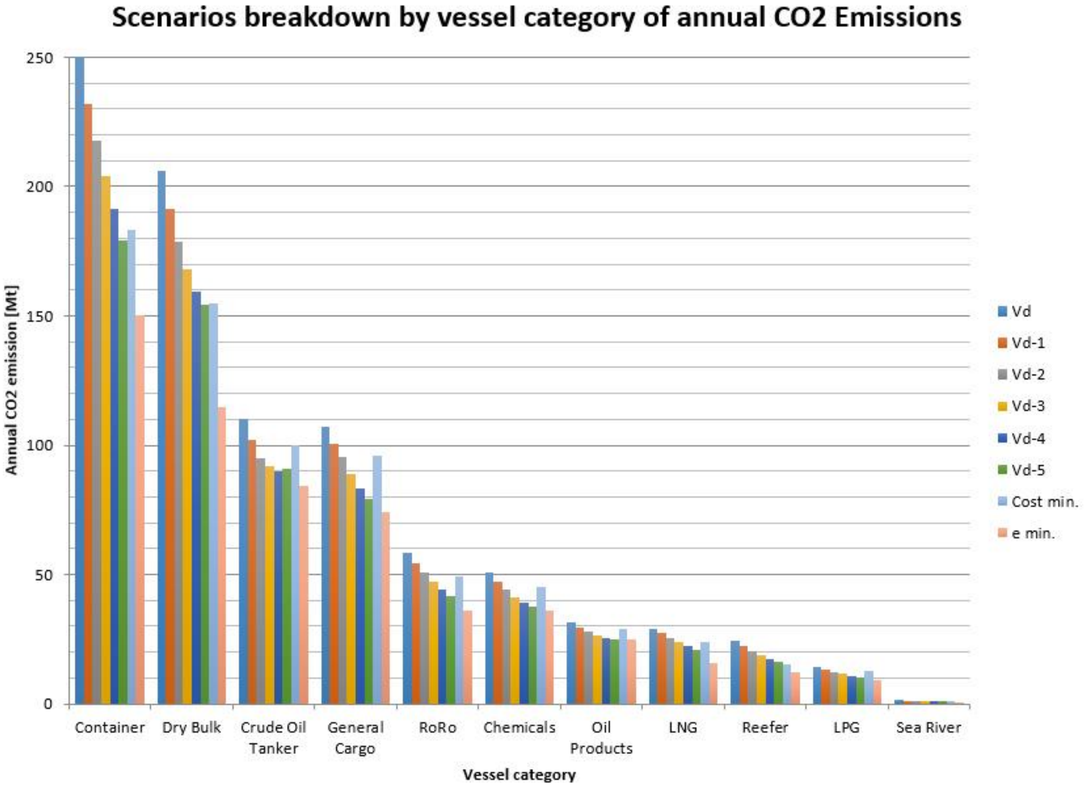


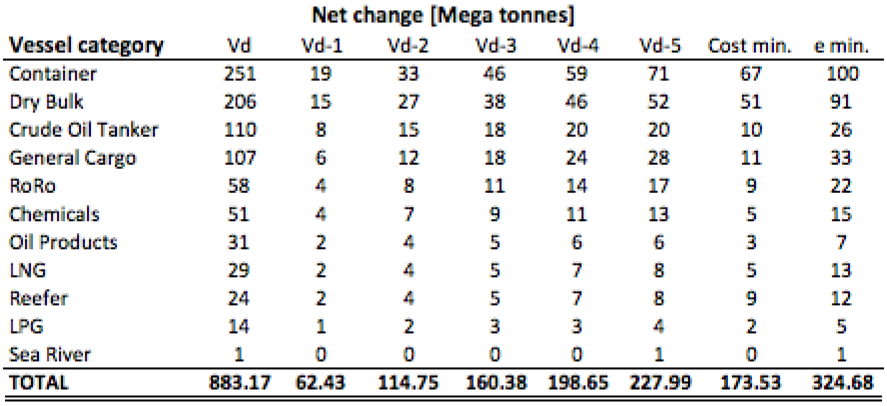
Figure 7: Fleet emissions from all vessel categories in speed reduction scenario 1-5 and cost/emission optimization

When speed is reduced further, a pattern emerges; emissions on fleet level have a diminishing emission return as speed is reduced. The same pattern can be seen in the results from speed reduction on individual ships in chapter 4.2. The gain is greatest in the first reduction step from design speed ($v_d$) to one knot less ($v_d$-1), but there is still much to gain from one knots speed reduction to two knots reduction. Although there is a smaller emission reduction gained from continuous reduction a two knots reduction still holds a significant potential in overall reduction. On the total fleet, a flat two knots speed reduction to all vessels can save the atmosphere from 114 mega tonnes of $CO_2$ emissions (13% from original results). As with the one knots speed reduction scenario, we see the same vessel category distribution in this case as well. The net change in emissions are largest in container and dry bulk vessel, while within each category the relative change is biggest in sea river vessels where the reduction comes close to a 20% emission reduction compared with the original results. By incremental reductions of the speed down to five knots less than the original, it becomes clearer that some vessel categories have a greater reduction potential than others. From table 4 we see that *Crude Oil Tanker* have miniscule emission savings from four to five knots reduction, and *Oil Products* only have two percentage points better emission performance. This is in contrast to for instance *Container* and *LPG*, which increase their emission performance by four and five percentage points, respectively.

### 4.1.2 Cost and emission optimization

In addition to the speed reduction scenarios, we have conducted two more scenarios. One where the model returns the emission of each ship category and size for the lowest possible cost, and another where the model returns the lowest possible emission. In the cost minimization scenario, we see that some vessels have the opportunity to reduce their emission to a much larger degree than others while still saving costs. The categories that can reduce their emissions most while still saving costs are *Reefer, Sea River*, *Container* and *Dry Bulk* in that order (see table 4). Although, if we look at net emission reduction, which is of greatest interest, *Container* and *Dry Bulk* completely dominated with an emission reduction of 67 and 51 mega tonnes (see table 5).

Table 5: Net change in emission from speed reduction and cost/emission optimization.



| | Net change [Mega tonnes] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Vessel category** | Vd | Vd-1 | Vd-2 | Vd-3 | Vd-4 | Vd-5 | Cost min. | e min. |
| Container | 251 | 19 | 33 | 46 | 59 | 71 | 67 | 100 |
| Dry Bulk | 206 | 15 | 27 | 38 | 46 | 52 | 51 | 91 |
| Crude Oil Tanker | 110 | 8 | 15 | 18 | 20 | 20 | 10 | 26 |
| General Cargo | 107 | 6 | 12 | 18 | 24 | 28 | 11 | 33 |
| RoRo | 58 | 4 | 8 | 11 | 14 | 17 | 9 | 22 |
| Chemicals | 51 | 4 | 7 | 9 | 11 | 13 | 5 | 15 |
| Oil Products | 31 | 2 | 4 | 5 | 6 | 6 | 3 | 7 |
| LNG | 29 | 2 | 4 | 5 | 7 | 8 | 5 | 13 |
| Reefer | 24 | 2 | 4 | 5 | 7 | 8 | 9 | 12 |
| LPG | 14 | 1 | 2 | 3 | 3 | 4 | 2 | 5 |
| Sea River | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| **TOTAL** | **883.17** | **62.43** | **114.75** | **160.38** | **198.65** | **227.99** | **173.53** | **324.68** |

This constitutes more than 68% of the overall emission reduction potential in this scenario. The reason for this is the large share of emissions *Container* and *Dry Bulk* make up in the initial scenario (see $v_d$ in figure 6.), thus a low percentage change in these vessel categories will still represent a large net change in the fleet.

The emission minimization scenario serves to give perspective as to what is theoretically possible without necessarily being practical. It provides a theoretical lower limit, where the diminishing returns do not yield any real return anymore. In order to achieve emissions as low as we have in this scenario, the speeds of medium fast vessels such as *Dry Bulk* and *General Cargo* have to be as low as 6-8 knots, and fast moving vessels such as *Container* and *RoRo* have to be as low as 8-10 knots. This is less than half their initial speed, which then results in more than doubling their transport time and consequently cutting their freight work in half.

The difference in number and size of vessels shown in table 6 is of great relevance when considering the results on fleet level. Figure 8. show the annual freight work performed by the different vessels categories.

Table 6: Weighted averages of design speed, voyage distance, engine size and cargo weight for each vessel category.

| **Vessel Cat. [Name]** | **Nr. Ships [#]** | **Design Speed [Knots]** | **Distance [Nm]** | **Engine Size [kW]** | **Cargo Weight [tonnes]** |
|---|---|---|---|---|---|
| Container | 4398 | 20 | 3487 | 22454 | 19151 |
| Dry Bulk | 7523 | 14 | 4131 | 7833 | 48135 |
| Crude Oil | 2053 | 15 | 4259 | 15116 | 137726 |
| General Cargo | 17280 | 12 | 751 | 2037 | 3750 |
| RoRo | 2410 | 15 | 735 | 6725 | 4167 |
| Chemicals | 3868 | 13 | 1598 | 4453 | 12282 |
| Oil Products | 4906 | 12 | 719 | 2636 | 8079 |
| LNG | 265 | 20 | 7325 | 25089 | 68048 |
| Reefer | 1226 | 16 | 1688 | 5009 | 4091 |
| LPG | 1103 | 12 | 484 | 3155 | 5507 |
| Sea River | 1169 | 11 | 224 | 710 | 868 |

The annual freight work adds important insight when looking at results from the fleets' annual $CO_2$ emissions. As we have already established, the largest amounts of emission comes from *Container*, *Dry Bulk*, *Crude Oil Tanker* and *General Cargo* vessels. *Container* ships only perform 18.2% of the annual freight work, but *Container* vessel has on average the highest operational speed and the second largest engine size except for *LNG* vessel. *LGN* might seem similar to *Container* vessels given these characteristics, but the main reason *LNG* vessels has almost ten times lower emission than *Container* vessels, is the fact that the *LNG* has less than sixteen times the number of vessels (see table 6). *Dry Bulk* vessels have the second largest amount of emission but also perform 39.1% of the annual freight work. *Dry Bulk* has moderate characteristics in terms of speed, round trip distance, engine size and cargo weight, but the major contribution from this vessel category lies in number of vessels, which for *Dry Bulk* are the second largest. *Crude Oil Tankers* are the third largest emitter of $CO_2$ but also the vessels category that performs the second most freight work. *Crude Oil Tankers* has by far the largest average weight of cargo, which is primarily due to the convenient cargo type and large vessel size. Since *Crude Oil Tankers* transport a liquid cargo, they can utilize close to 100% of the cargo carrying capacity, thus maximising their freight work capacity. The fourth most emitting vessel categories are *General Cargo* vessels. *General Cargo* vessels completely dominates the other categories in number of vessels (see table 6), but the majority of vessels are small in size and travel short distances, resulting in a low average vessel characteristics. Of the over 17,000 vessels in this category, close to 8,000 vessels is in the size classification: 1-5 thousand tonnes, which becomes small when comparing them to the over 5,000 *Dry Bulk* vessels between 15-85 thousand tonnes (see appendix 7.3). Nevertheless, the sheer number of *General Cargo* vessels results in this vessel category being the fourth largest in both emission and freight work.

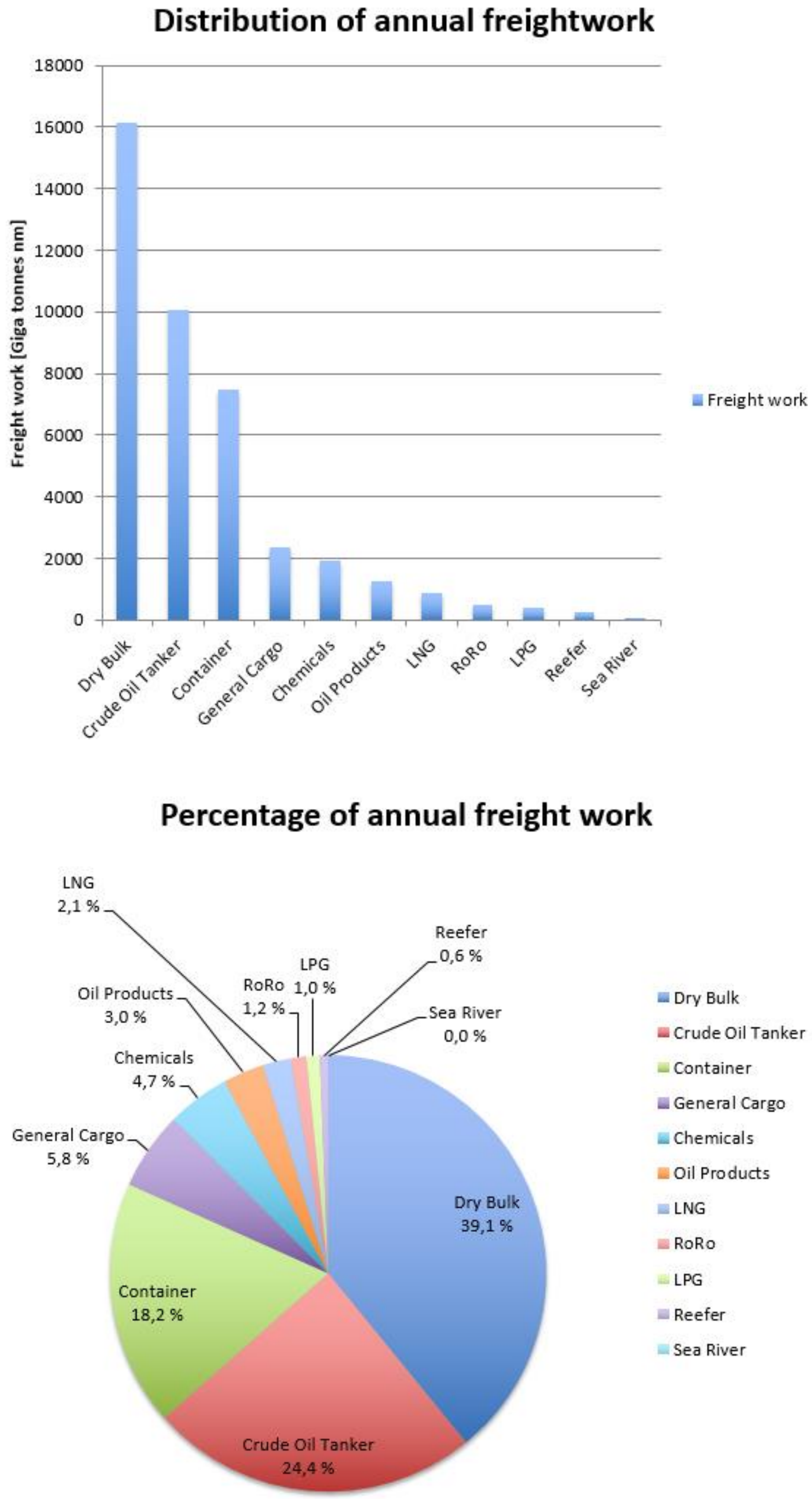


Figure 8: Amount and distribution of freight work by vessel category per year.

## 4.2 Effect of speed reduction on individual vessels

In the scenario with speed reduction on individual vessels we have looked at how cost and emission change when the operating speed of the vessel is decreased. The range of speeds the vessels operate in defines the axes on the graphs. The minimum speed on the x-axis is set to 5 knots, which is considered the absolute lowest speed with any practical application for these transport vessels, up to the various maximum speeds, limited by the installed power of the vessels. The corresponding speed range sets the cost values on the y-axis, and the emissions follow speed and cost.

The speed reduction scenario results are comprised by three figures with three subsets of graphs; emission/cost, speed/cost and speed/emission. The axis on the speed/emission graph is shown with speed in knots (nautical miles per hour) and emission in gram $CO_2$ per tonne nautical mile. Speed/cost is shown with knots versus dollars per thousand tonne nautical mile and lastly, cost/emission is shown with dollars per thousand tonne nautical mile vs. gram $CO_2$ per tonne nautical mile. Emission from the life cycle assessment are included in the results by assuming a vessel lifetime of 30 years, and normalizing the LCA-emissions of one year of operation over the freight work done per round trip.

Emissions consist of contribution from ship manufacturing and material extraction, upstream fuel production and combustion and scrapping of vessels at end of life.

Looking at the cost graphs, there is an increase in cost after a cost-minimum is achieved at a certain speed for all vessels. The speed at which the cost minimum occurs is relative to the design speed of a given vessel. This is due to the fact that fuel consumption increases exponentially at operating at speeds that exceeds design speed and the cost of fuel then increases accordingly.

The cost includes the cost of fuel consumption, time charter, and the capital cost of the cargo value. The reason cost minimum of larger vessels occur at higher speed than that of smaller vessels is because larger vessels can carry more cargo, hence a greater net cargo value. When travel time increases due to reduced operating speed, the capital cost of transported good increases faster than for vessels with a lower carrying capacity.

## 4.2 EFFECT OF SPEED REDUCTION ON INDIVIDUAL VESSELS

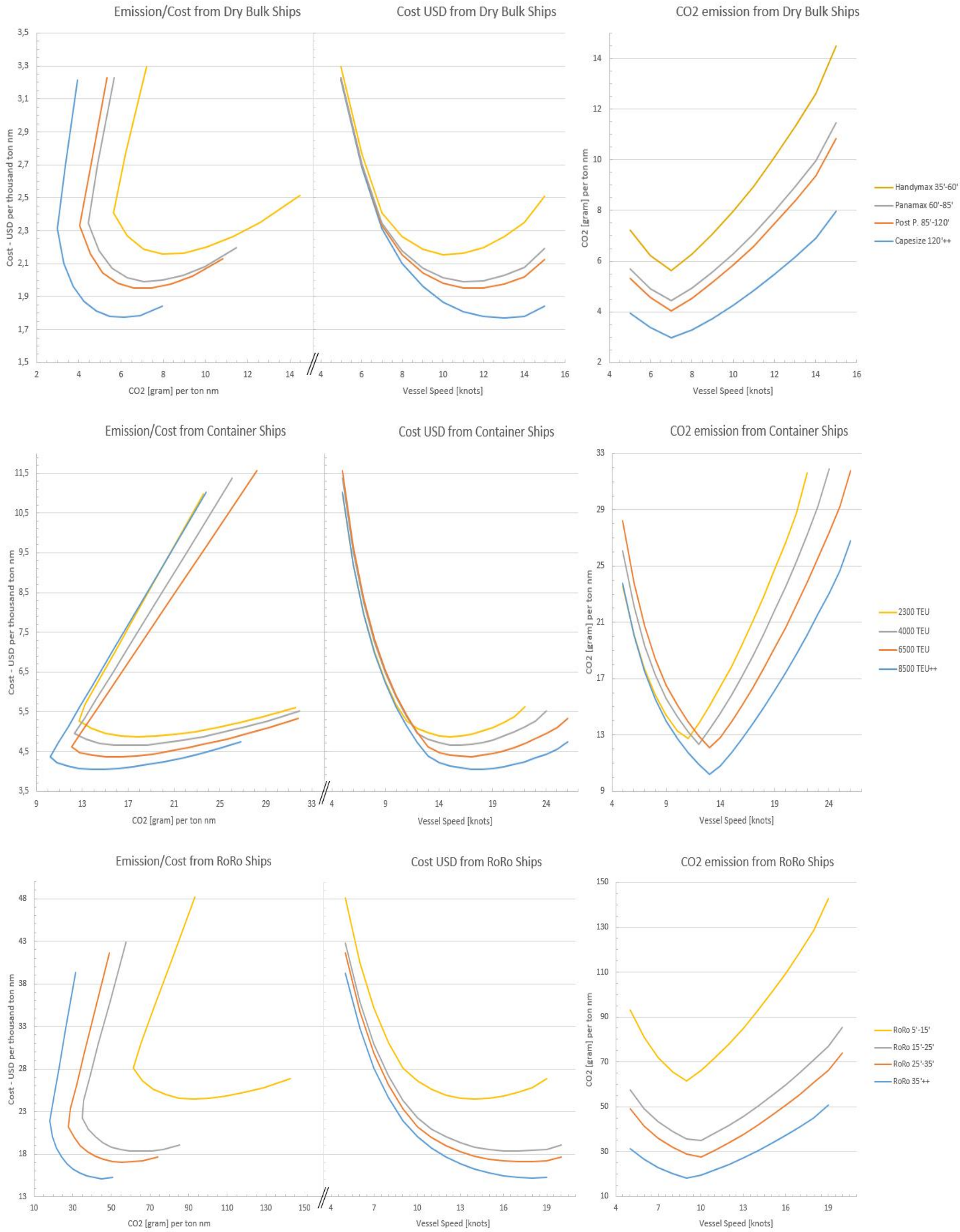


Figure 9: Emission/Cost, Speed/Cost and Speed/Emission graph for Dry Bulk, Container and RoRo vessels.

A generic trend that can clearly be seen from the cost emission graph is that size of the vessel defines the range in both cost and emission the vessels operate in. Using dry bulk ships as an example, a medium size vessel like the *Handymax* have emissions from ~6-14 grams per tonne nautical mile and costs from 2.5-3.3 USD per thousand tonne nautical mile within the speeds of 5-15 knots. A *Capesize* vessel from the same category has emissions from 3-8 grams per tonne nautical mile and costs from 1.8-3.5 USD per thousand tonne nautical mile. This trend with larger vessels having lower emission and costs than smaller vessel is true also for other categories than *Dry Bulk*, although this is only true when results are normalized to freight work. Across all ship categories, larger ships have a lower emission per freight work (tonne nautical mile) than that of smaller ships. Larger ships have larger emissions per year, but normalized to the freight work they perform, they come out on top with up 50-60 % less emission per freight work, than the smaller classes within same category.

These speed reduction scenarios are run with calm sea (0m waves) to easier display the effect of reducing speed. At “average” sea conditions (2,5m waves), the extra power needed to “overwin” the waves leads to many of the different ship classes not reaching their design speed because they exceed their installed power.

Several of the graphs have a characteristic buckling appearance. This applies especially to the speed/emission and cost/emission graphs, and to some degree speed/cost. This significant change of direction is a direct consequence of the lower cut off for the power-equation. When the vessels reach a minimum engine load, which set at 15% of installed motor capacity, the speed/emission graph will no longer continue to decrease. Instead, as the vessel continues to reduce speed, fuel consumption will rise per tonne nautical mile and contribute to a rise in emission and cost since they don’t use any less engine power but they travel for a longer period of time.

The four dry bulk classes displayed have 14 knots as design speed. We can see from figure 9 that they have the capacity to reach 15 knots as operating speed. At maximum operating speed, the *Handymax, Panamax, Post Panamax* and *Capesize* emits close to 15, 12, 11 and 8 grams of $CO_2$ per tonne nautical mile respectively. They all have potential to reduce emission by reducing speed, where the *Handymax* has the biggest emission reduction potential; from 15 to 6 grams $CO_2$ per tonne nautical mile, a reduction of 60%.

We can see that all classes can reduce cost by reducing speed. Smaller classes can reduce speed more than the bigger classes to achieve cost minimum. Smaller dry bulk vessels such as *Handysize* and *Handymax* have emissions close to 15 gram per tonne nautical mile at their operating speed with a reduction potential of 6 and 9 grams per tonne nautical mile respectively. The larger vessels; *Panamax, Post Panamax* and *Capesize* operate with emission values of 12, 11 and 8 grams per tonne nautical mile. As seen by the emission/cost graphs, the smaller vessels have potential of obtaining an emission minimization without additional increase in cost, while the larger vessels will have an increase in cost to reach their emission minimum. It is however obvious that the different ship classes have the potential to lower their operating speed and obtain both a cost-benefit as well as lowering their emissions.

All categories have three graphs showing different size classes, for emission/cost, speed/cost, and speed/emission. For some categories, the smallest classes has been excluded from the graph, since their values deviate to such a degree they fall outside of the plot area of interest for the category (see fig. 13 in appendix 7.4). The trend within international shipping is to build larger vessels, which is another reason we have focused on the larger ship-classes within the different categories.

## 4.3 Effect of reducing block coefficient

The standard *Panamax* is used for our block scenarios, which is a representative midrange dry bulker, with a block coefficient of approximately 0.87. The results for the block coefficient scenarios are presented in fig. 10 and 11. Here we have the baseline, which is the reference scenario with default input parameters. The baseline scenario has the mentioned block coefficient of 0.87. Scenario 1 consists of a reduction of $dwt$ and displacement of 14%, and has a block coefficient of 0,75. Scenario 2 consists of a reduction of $dwt$ and displacement of 26%, and has a block coefficient of 0.65. Scenario 3 comprises an increase of beam by 30%, and has a block coefficient of 0.67.

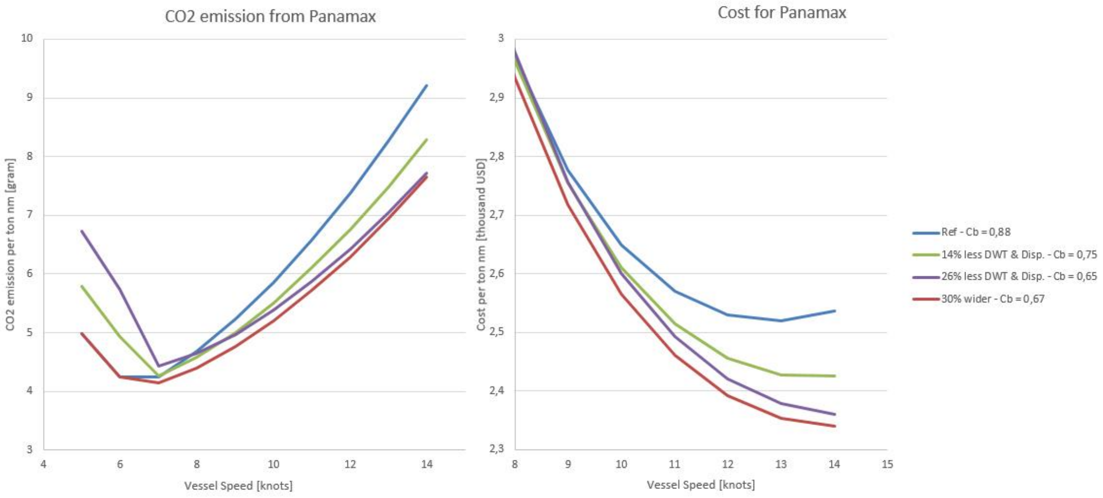


Figure 10: Emission and cost performance of a Panamax vessel for increasing speeds, for each block scenario 1-3.

The block results show us that all our three scenarios have the potential to perform better than our baseline scenario. The speed/emission graph show us that the *Panamax* in the baseline scenario emits 9.2 grams $CO_2$ per tonne nautical mile at operational speed, while our three scenarios emits 8.3, 7.8 and 7.7 grams $CO_2$ per tonne nautical mile respectively. For our two scenarios where we reduce $dwt$ and displacement, we can notice that as the block coefficient is reduced, the fuel consumption and emission per tonne nautical mile decreases even more. Scenario 3 is however where the normalized emissions has decreased the most. Block coefficient is reduced, but cargo carrying capacity is maintained.

## 4.3 EFFECT OF REDUCING BLOCK COEFFICIENT

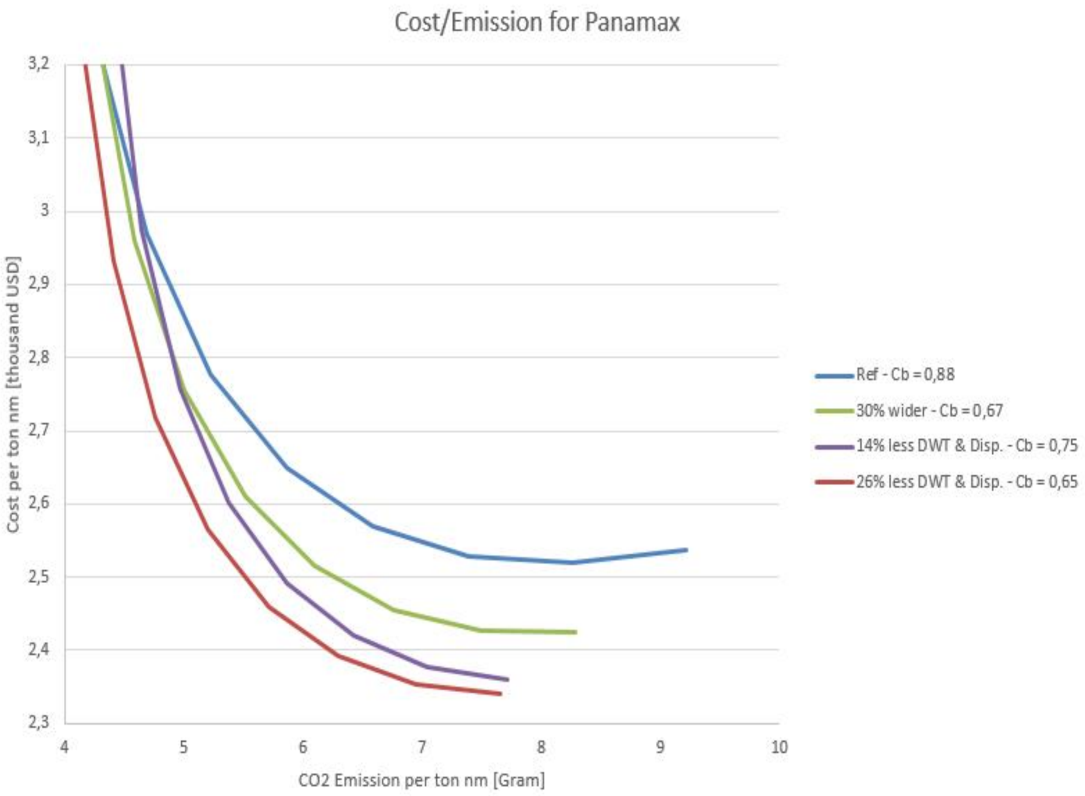


Figure 11: Cost/emission of a Panamax at various speeds, for block scenario 1-3.

We see from the speed/cost graph that the different scenarios all perform better than the baseline. The cost in thousand dollars per tonne nautical mile decreases from 2.54 in the baseline, to 2.42 in scenario 1, to 2.37 in scenario 2, and down to 2.34 in scenario 3. Like with emission, the cost normalized for each tonne transported per nautical mile is reduced for the two scenarios with lowered $dwt$ and displacement. Even though there is less cargo carrying capacity, the normalized cost is reduced. This is due to lower fuel cost, lower new building cost resulting in lower time charter and lower cargo interest cost. Scenario 3 gains from a lower block coefficient, reduces its fuel cost and normalizes over the same cargo capacity, and is the most cost beneficial scenario. The cost/emission graph makes the results from the block scenarios quite clear. At operational speed, scenario 1 yields a 0.9 gram $CO_2$, and 120 USD per tonne nautical mile improvement in emission and cost, compared to the baseline scenario. Scenario 2 presents a potential reduction of 1.4 gram $CO_2$, and 170 USD per tonne nautical mile. The best scenario in terms of cost/emission is number 3, with a reduction potential at operational speed at 1.5 gram $CO_2$, and 200 USD per tonne nautical mile. This demonstrates that the various block coefficient scenarios have a very positive influence on both normalized cost and emission. Scenario 3 is also the easiest one to compare to the reference scenario in a fleet perspective, since the same freight work is performed. Scenario 1 and 2 would yield bigger emission mitigation if total emissions for a year from the bulk carrying categories (Dry bulk, Crude oil and Oil products) were to be compared, but it would represent a much smaller amount of freight work since the $dwt$ has been reduced. In scenario 3, the vessels have the same $dwt$ as in the reference scenario, but have a reduced block coefficient due to increased width and slenderness. Compared to the baseline scenario, scenario 3 could yield a mitigation of 45.2 mega tonnes of $CO_2$ per year for the bulk carrying categories, representing a reduction of 16%.

## 4.4 Life cycle assessment results

The LCA results show that only ~2.5% of annual $CO_2$ emission can be allocated to the construction and end of life phases, while operation dominates with ~97.5% with the assumption of a lifetime of 30 years for each vessel (fig. 12). Fuel production is considered as part of operation, and constitutes 7% of the emissions in the operation phase. This is a major contributor to overall annual emissions and from the life cycle perspective; this is the largest contribution from upstream emission sources. The production of steel for ship materials is the largest emission source in construction. Using a 60-80 thousand tonne *Panamax* as an example, construction emissions normalized to a 30-year lifetime adds up to 1.2 mega tonnes of $CO_2$ per year. Steel production contributes with 1.0 mega tonnes, ship building 0.12 mega tonnes, maintenance 0.015 mega tonnes and transportation of the raw materials to the building site contributes with 0.058 mega tonnes of $CO_2$.

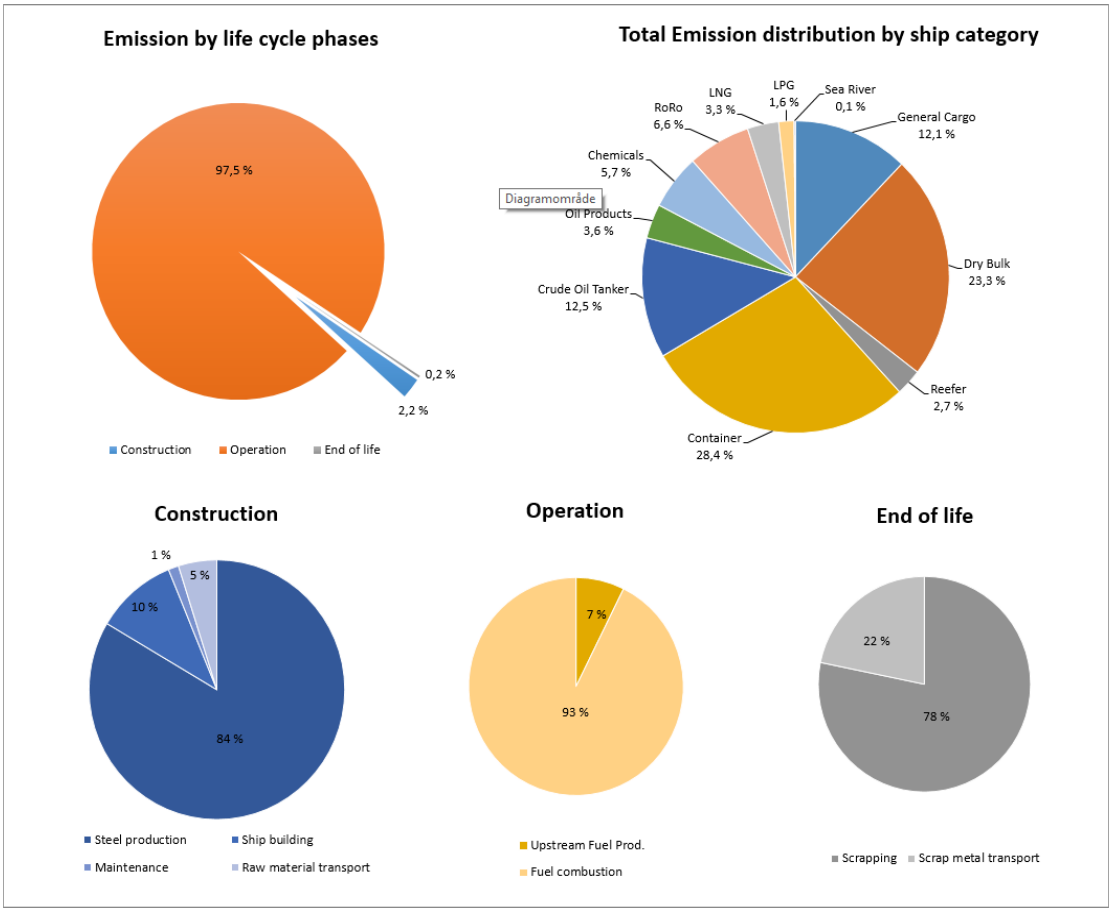


Figure 12: Emissions by life cycle phases with individual breakdown on second row, as well as annual emission distribution from ship categories.

The general trend that can be seen from LCA related emissions is that larger vessels have the greater annual emission contribution from construction and end of life. Although, there are some deviating examples where the smaller vessels have equal or greater relative contribution (i.e. the oil products category), which is believed to be due to weaknesses/inaccuracy in the data. The variation in the results is quite small in the operation phases between vessel size classifications, while somewhat larger in construction and end of life. Direct emission from combustion ranges from 85.6% to 92.6%, upstream fuel production from 6.76% to 7.30%, while construction and end of life ranges from 0.11% to 6.88% and 0.01% to 0.69% respectively. When we look at variations within vessel categories (table 7), the variation is even smaller.

Table 7: Emission distribution between direct and indirect emission sources.

| Vessel category | Construction % | Upstream fuel % | Fuel Comb. % | End of life % |
|---|---|---|---|---|
| General Cargo | 2,39 % | 7,12 % | 97,37 % | 0,24 % |
| Dry Bulk | 2,47 % | 7,11 % | 97,29 % | 0,25 % |
| Reefer | 1,08 % | 7,22 % | 98,81 % | 0,11 % |
| Container | 1,71 % | 7,17 % | 98,12 % | 0,17 % |
| Crude Oil Tanker | 3,13 % | 7,06 % | 96,55 % | 0,31 % |
| Oil Products | 2,97 % | 7,07 % | 96,73 % | 0,30 % |
| Chemicals | 2,38 % | 7,12 % | 97,38 % | 0,24 % |
| RoRo | 1,76 % | 7,17 % | 98,07 % | 0,18 % |
| LNG | 1,81 % | 7,16 % | 98,01 % | 0,18 % |
| LPG | 2,82 % | 7,08 % | 96,90 % | 0,28 % |
| Sea River | 2,97 % | 7,07 % | 96,73 % | 0,30 % |

If we take an in depth look at an example category such a dry bulk, which is the second largest vessel category in terms of total fleet emission with 23.3% contribution we see that within construction operation and end of life, the percentage distributions are identical to that of the global fleet. This is expected due to the way upstream emissions are modelled, which means that within life cycle phases, the emissions distribution in all categories are the same, but the relative emissions on the global fleet will be unequal due to size and weight of each vessel, and the number of vessels in size classification.

# 5 Discussion and conclusion

## 5.1 Objective and validation

The main objective of this study has been to build a holistic dynamic model that integrates the submodel of Håkon Lindstad and validate his results. Our main findings on both speed emissions and design measures are well within the scope of the Lindstads results and complies well with the total fleet emissions estimated by IMO and IPCC. This implies that the submodel integration has worked well and overall works as intended. Some deviation from Lindstads results were expected due to the integration of our sub model on life cycle assessment emissions, and our results are somewhat larger which is a deviation in the expected direction.

We've established that the overall fleet emissions from global trade are in range of what IMO reported in their second and third greenhouse gas study. The 2007 fleet emissions in IMO's second GHG study from 2009, was estimated to 862 million tonnes, but this was later downgraded to 847.5 million tonnes in their third study in 2014 which is a downward adjustment of 8%. In our model we found the global emission to be 883.17 million tonnes, which is 2.4% higher than their first estimate and 4.2% higher than their newest adjusted estimate for the same time period.

A profound similarity in results occurred when we removed the LCA impacts from our results. This was done since it has been difficult to find accurate data on IMO's life cycle assessment. When removing LCA emissions from our results, we ended at 861.97 million tonnes, which is a difference of less than 0.01% from IMO's results. This difference is most likely more coincidental than accurate, as there are so many contributing factors along the way. Assumptions considering sea conditions and calculations of average travel distances, vessel size and cargo capacity are but a few of the sources of error that exist, but the results are nonetheless conspicuously similar. Given more time, we would have liked to put a larger focus on verifying and using more accurate input data, but the most important part for us was that the functionality is in place. Our results are to a large extent one way to verify that our model works as intended. The main objective is still fulfilled, making our model available for further research with newer and/or more accurate data.

## 5.2 Implications of speed reduction

Results from the speed reduction scenario showed to no surprise that reducing speed is a very effective way to reduce emissions as suggested by several other studies before us (Lindstad et al., 2011a; Marintek, 2000; Buhaug et al., 2009; Smith et al., 2014). Our results indicate that a reduction of only one knot from the design speed to all vessels is enough to save over 7% of annual emissions. Furthermore, it is possible to reduce emission by up to 19.7%, which is equal to a speed reduction between 3-4 knots without additional cost. Any greater speed reduction continues to reduce emission but at the expense of increased cost, as travel time increases to such an extent that time charter expenses exceed the savings in fuel cost. The lowest theoretical annual emission can be obtained by customizing the fleet's operation speed to their respective emission minimum. With this custom set up, emissions can be reduced to 558 million tonnes per year, which corresponds to a reduction of 36.8%. This is however very impractical as travel times become very large due to the low speeds and a significant increase in number of vessels are needed to compensate for the reduction in annual freight work by the current fleet.

Using speed reduction as a measure to reduce emissions has proven effective and cost beneficial, but how to achieve the speed reductions in practice still remains a challenge. On the upside, since speed reduction is independent of technology, it has its strengths in the ability to be implement right away. There is no single vessel that does not have the opportunity to reduce their speeds, but identifying the proper incentives and policies needed to apply the measure are still under consideration of UNFCC and the Marine Protection Committee of IMO. Two ways that has been assessed to achieve speed reduction are Energy Efficiency Design Index (EEDI) and the Market Based Measures (MBM) in the form of emission trading and fuel taxation. The EEDI only applies to new vessels, which means that even after a 12-15 year time period, the measure is only applied to half of the vessels in the world fleet (Lindstad et al., 2011a). MBM on the other hand, will have full effect on the entire fleet right away, under the assumption that by increasing fuel prices, you give operators incentive to reduce fuel consumption, which has been studied by Corbet et al. (2009) and concluded to have the desired effect. Another study challenges this view by stating that the relationship between fuel price and operating speed is more complex, and that the effect from increasing fuel price might have been overestimated (Lindstad et al., 2011a).

The current drop in fuel prices is another aspect that sheds light on the importance of policy implementation. The average fleet speed varies with changes in market circumstances, and the low fuel prices works as incentive to increase speed for greater profits. This is a contrast to the development from a few years ago, where an increasing supply of transport vessels combined with increasing fuel prices led to a deceleration in demand for maritime transport (Faber et al., 2012). In this time period speed reduction was popular among shipping lines as the surplus of vessels during the recession could be utilized to compensate for the decrease in freight work when operation speed is lowered to cut costs. With a recovering economy combined with the recent drop in fuel prices, the surplus of vessels is diminishing. Shipping lines that makes use of all their vessels might be enticed to increase the speed of their vessels in order to raise their transport capacity, which makes sense as a business owner, but is harmful to the environment. Without policies that can force the development in maritime transport in the direction we need to go in order to protect the environment, we run the risk of experiencing another case of tragedy of the commons. A classic case where shipping lines are reluctant to "go first" in risk of others not following in their footsteps, effectively handing over revenue to other companies, as their reduced freight work are compensated for by other that choose to not reduce their operating speed.

## 5.3 Importance of policies

Having established the importance of policies in order to achieve speed reductions in practice, we wish to discuss what how the policies can be used as instruments to reach the objective. The first and maybe most self-explanatory way is to introduce speed limits during sailing. There are a few possible ways speed limits can be used, and they all have their strength and weaknesses. One way is to impose a flat speed limit at for instance 16-18 knots. This way one ensures that the higher speeds, that cause the greatest emissions (due to the nature of how power and fuel requirements increase exponentially with higher speeds), are eliminated from marine trade. However, this measure may be considered unfair against vessel categories such as *RoRo* and *Container* vessels, as these operate at speeds from 16-25 knots. Other major vessel categories such as *Dry Bulk* and *General Cargo* typically operate in a range from 12-

15 knots, and would not be affected by an 18 knots limit. The speed limit would have to be as low as 8-12 knots in order to have an effect on all categories in the global fleet. As a consequence, *RoRo* and *Container* vessels freight work capacity would suffer far more from this measure than *General Cargo* and *Dry Bulk*. Additionally, Maersk found that by occasionally sailing at higher speeds, vessels could improve their emissions. This was explained by that fact that; occasional high speed sailing would clean their turbochargers from soot, that build up when sailing at low engine load. Occurrences of fuel pump malfunction and injector nozzle damage due to operating in off-design conditions have also been reported (Faber et al., 2010). Policies prohibiting high speeds entirely exclude selected vessels from “cleaning out” the turbocharger and could prove counterproductive. It is worth mentioning that there is little documentation on the subject, and further studies are needed to back up this claim.

Another approach is to introduce speed limits in the form of averages. During a voyage from port A to port B, a vessel cannot exceed a certain average speed, but remains free to use the whole range of speeds as long as it is within the policy average limits. Automatic identification system (AIS) can be used for tracking vessels and as an instrument to enforce the average speed limits. The possibility for this solution is already partly in place as IMO’s International Convention for the Safety of Life at Sea (IMO SOLAS) requires that all vessels (dwt of 300 tonnes or larger) that operate in international water is fitted with AIS. IMO SOLAS formed this mandate in 2002 and by 2012 approximately 250,000 vessels have been fitted with AIS transceivers, and roughly 1 million vessels are required to install one in the near future.

A third alternative is to differentiate speed limits for different types of vessels. This solution poses an immediate challenge as vessels categories are classified by their cargo handling system, rather than the actual content of the cargo. A possible solution to this proposed by Lindstad et al. (2011a), is to impose limits based on the main cargo type on board the vessel for each voyage. It is obvious that there is no easy solution as to how most efficiently implement a speed reduction policy. The optimal solution is probably a combination of the alternatives considered. For example: policy could implement a general limit of 10 knots, with fuel taxes for speeds higher than 10 knots. This opens the possibility for operation at higher speeds when necessary, while still maintaining strong incentive to lower operational speeds. As an extension, this policy could offer a discount to vessels that are sufficiently energy efficient, reinforcing the trend of building larger and more emission efficient vessels.

## 5.4 Vessel size and design

As mentioned earlier; speed reduction have been identified as one of the most effective measures to reduce emission in maritime trade, but there are also other measure that show some interesting promise. As mentioned in the introduction, we see a trend towards continuously larger vessels, which has contributed to an increase in maritime related emission efficiency. The largest vessels in our study (*Crude Oil, LNG* and *Dry Bulker*) show that these also have the lowest weighted average emission per tonne nautical mile, which validates that larger vessels are more emission efficient (see fig. 14 in appendix 7.4 for comparison of $CO_2$ per tonne nautical mile and annual $CO_2$ emissions). *Crude Oil* and *Dry Bulkers* falls within the overarching term *Bulk Transporters* are also the main vessels categories applicable for design alterations to reduce block coefficient in the future. Combining the reduced block coefficient with larger vessels may prove as a significant measure to reduce overall emissions. Although, size limitations in port and canal locks still pose a challenge to conduct larger alterations.

Many of the larger vessels sizes today are maximizing the capacity of canal locks and size classification are often named after their maximum dimensions (*Suezmax, Panamax* etc.). Comparing two sizes of *Dry Bulk* vessels considered in this study: Handysize (15-35 thousand tonnes) and *Handymax* (35-60 thousand tonnes), the emission per tonne nautical mile is reduced from 20.9 grams per tonne nautical mile to 15.3 grams, meaning that *Handymax* is 26.8% more efficient per freight work than *Handysize*. Our best block scenario resulted in a 16.3% in the *Panamax,* which is on size class larger than *Handymax*, but these solutions also have their drawbacks. They are both technological dependent measures raise the same challenge that occurs with EEDI in speed reductions. Old vessels need to be substituted with larger and more slender vessels in order to have the desired effect. Simply building more new vessels with the new designs elements will only contribute to additional emission, not instead of, which is a requirement in order to have the desired effect. This means that this measure needs to be phased in over time, and following the same projection that was found in EEDI where the measure is only implemented to new vessels, 12-15 years from now, only half of the world fleet will be affected by the changes. Considering that only selected vessel categories are applicable for changes to block, an even longer time may be required.

## 5.5 The path forward

From both literature and our own study we have learned that there is other means than speed reduction that need consideration when determining the path forward. Undoubtedly, the combined efficiency gains from using larger vessels with reduction of block coefficient form a substantial potential for savings in emissions. In the years to come, policies will play an important role for how measures are implemented, and when. This complex issue needs to be subject to careful consideration. It is not possible to just lower speeds, change the design of new vessels, and believe that will fix all problems. Orchestrating changes to fleet logistics will be crucial to compensate the reduction in freight work that follows speed reduction. It is possible that the increase in vessel size is not enough to counteract reduced freight work and vessel production must be increased. We believe that an increased focus on the life cycle of vessels will be of importance if we are to increase vessel production in the future. Our life cycle assessment can contribute to this topic, although more detailed and vessel specific LCAs are recommended as decision-making tools. We built our LCA model to fit any vessel of any size in the fleet, basing our input on vessel-dimensions and weight, which has its drawbacks by lacking in vessel specific accuracy. This is due to fact that our model is based on a general *Panamax*, and hence it might not fit perfectly for other vessel categories with a different structure and material composition. From experience, we have found that this might be particularly true for the smallest vessels sizes, where the data uncertainty is greatest. Our LCA model works best as an overview across the fleet to provide the overall model with a holistic scale.

A last notion to the trend of building larger vessels is the necessary adaptations to ports logistics and infrastructure to handle the increasing size in vessels. For *Container* vessels, this may entail upgrading or even building new cranes that can handle on/off -loading the largest vessels, but also the port-associated infrastructure that will transport of cargo further. Most changes to both operation speed and vessels design trigger chain reactions that needs proper identification by the policy makers, in order to prepare for the knock on effects in the maritime transport market.

## 5.6 Conclusion

Our results confirm that the model we have put together works as intended, and serves as validation for Lindstads results. The model complies with our objective to make a more flexible and robust model with easily exchangeable input data. With our LCA feature, we have also contributed to a more thorough accounting for upstream fuel emissions, shipbuilding and ship's end of life.

We can see from our results that speed reduction is a very effective measure to reduce emissions. A uniform reduction of one knot from the design speed, for all vessels in the world fleet, is enough to reduce over 7% of annual emissions. Furthermore, if speed reduction was individually adapted to the different vessel categories and sizes, an emission reduction potential of 19.7% was identified, without yielding additional cost.

The effects of introducing more slender designs to the fleet of bulk carriers (D*ry bulk, Crude oil and Oil products*) has been investigated, and our best block coefficient scenario indicated a mitigation potential of 16% per year for the bulk carrying fleet. This clearly represents a significant possibility for reducing emissions, as the bulk carrying fleet accounts for roughly 60% of annual freight work and almost 40% of annual total fleet emission.

Our results show a clear trend where the largest vessels within each category clearly are the most cost and energy efficient. Increasing the size of the vessel also increase cost and emission, but not at the same rate. Bigger vessels have lower cost and emission per unit of cargo transported, and this phenomenon is known within the shipping industry, where the trend the later years has been to build bigger and bigger. This is also part of the reason for the bigger ships being most efficient; the biggest ships are also often the newest ones, with the best technology.

Speed reduction and lower block coefficient show significant promise to reduce global $CO_2$ fleet emissions. Existing literature on the subject and our findings in this study strengthens this claim. How these measures eventually will be implemented in practice, is up to policy makers and governing organs. Whether they choose to increase the use of MBM's, EEDI, flat or custom speed limits, or perhaps a combination of all these strategies for the future, remains to be seen. Regardless, the decision makers are facing an immense challenge in the years to come, considering the complexity and many aspects of putting these measures to good use.

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# 7 Appendix

## 7.1 Speed reduction, total fleet and life cycle MATLAB code

```
%% Section 1. File read - Frontend Excel sheet with input parameters
Data =  xlsread('FrontendSpeedRed.xlsx', 2, 'D5:AK64');

% Constants and factors used with input parameters
x    =   60;      % Number of ship type entries in Excel input
document
vmax =   30;      % Number er speed iterations
LT   =   30;      % Expected life time
MCR  =   0.75;    % Maximum continous revolution at design speed
ktms =   1.852;   % Knots to m/s conversion factor
p    =   1.025;   % Density of saltwater
g    =   9.81;    % Earths gravity
v    =   1:vmax;  % Vessel speed, 1 through 30 knots

for i = 1:x
No(i,1)    =   Data(i,1);    % Number of ships
Voy(i,1)   =   Data(i,2);    % Distance per voyage
Day(i,1)   =   Data(i,3);    % Days per voyage
Tpsd(i,1)  =   Data(i,4);    % Time in port and slow zones
vs(i,1)    =   Data(i,5);    % Vessel Speed
vd(i,1)    =   Data(i,6);    % Design Speed
kW(i,1)    =   Data(i,7);    % Engine size (Installed power)
n(i,1)     =   Data(i,8);    % Engine efficiency
Dis(i,1)   =   Data(i,11);   % Displacement of water (tons)
B(i,1)     =   Data(i,12);   % Width of ships at water line
L(i,1)     =   Data(i,13);   % Length of ship at water line
Dft(i,1)   =   Data(i,14);   % Draft - Fully loaded
S(i,1)     =   Data(i,15);   % Wetter surface of ship
Ct(i,1)    =   Data(i,16);   % Drag coefficient
Kf(i,1)    =   Data(i,17);   % Gram fuel per kWh
H13(i,1)   =   Data(i,18);   % Wave height
u(i,1)     =   Data(i,19);   % Wave Speed
Caw(i,1)   =   Data(i,20);   % Wave Drag
Ke(i,1)    =   Data(i,21);   % CO2 per unit fuel
M(i,1)     =   Data(i,22);   % Average weigth of cargo
Chfo(i,1)  =   Data(i,23);   % Cost of heavy fuel oil
Cmdo(i,1)  =   Data(i,24);   % Cost of marine diesel oil
TC(i,1)    =   Data(i,25);   % Time charter cost per day
CM(i,1)    =   Data(i,26);   % Export value per ton
Cir(i,1)   =   Data(i,27);   % Annual interest
j(i,1)     =   Data(i,28);   % Propeller constant, speed independent
k(i,1)     =   Data(i,29);   % Propeller constant, speed dependent
Cv(i,1)    =   Data(i,30);   % Cargo voyages
Bv(i,1)    =   Data(i,31);   % Ballast voyages
Lws(i,1)   =   Data(i,34);   % Lightship weight

% ADDITIONAL DATA
% Distance per roundtrip;
D = 2 .* Voy;

% Time per roundtrip
T = 2 .* Day;
```

```
% Minimum / idle engine load
kWmin = 0.15 .* kW;

% Engine load in ports and slow zones
Pps = kWmin;

%Time in port and slow zones (days to hour conversion)
Tps(i,1) = Tpsd(i,1)*24;
end

% Calculation for time spent per voyage per boat, at different speeds
for i = 1:x %1 to X number of ships
    for h = 1:vmax %1 to vmax number of speeds
        Tt(i,h) =  ((D(i)/h)/24);
    end
end


%% Section 2. Propeller efficiencies and still water resistance
factors
% 2-1 Change in propeller efficientcy for lower speeds
for i = 1:x %1 to X number of ships
    for ij=1:vmax
    if  v(1,ij) > vd(i,1);
        Ku(i,ij) = n(i,1);
    else
        Ku(i,ij) = n(i,1) * (j(i,1) + (k(i,1) *
sqrt(v(1,ij)/vd(i,1))));
    end

        % 2-2 Propeller efficiency
        K(i,ij) = 1 / (Ku(i,ij));
end

% 2-3 Still Water Resistance Factor
Csref(i,1)   =
((kW(i,1))*MCR*(1/(K(i,ij)))*2)/(p*(S(i,1))*((vd(i,1))^3));
end

% 2-4 Calculations for still water drag coefficients
for i = 1:x %1 to X number of ships
    for h = 1:vmax %1 to vmax number of speeds
    if h > vd(i);
       Cs(i,h) = Csref(i) * (0.8 + (0.2*(h/vd(i))^2));
    else
        if h < vd(i);
           Cs(i,h) = (Csref(i)*0.9) + (((h/vd(i))*0.1)*Csref(i));
        else
           Cs(i,h) = Csref(i);
        end
    end
    end
end


%% Section 3. - POWER
%Iterate through 1 to X number of ships
for i = 1:x
```

```
    %Iterate through 1 to vmax number of speeds
    for ij = 1:vmax
        % 3-1 Still water power (Ps)
        Ps(i,ij) = (p*Cs(i,ij)*S(i)*((v(ij))^3))/2;

        %Relative vessel and wave speed (used in wave power (Pw))
        Vr(i,ij) = ((v(ij))/1.94384449)+u(i);

        % 3-2 Wave power (Pw)
        Pw(i,ij) = ((Caw(i)*p*g*(((H13(i))/2)^2)*(B(i))^2)/(2*L(i)))
* Vr(i,ij);

        % 3-3 Auxiliary power (Paux)
    if kW(i) > 10000;
       Paux(i,1) = 250 + (kW(i) * 0.025);
    else
       Paux(i,1) = kW(i) * 0.05;
    end

    % 3-4 Total power (P)
    P(i,ij) = (K(i,ij))*((Ps(i,ij))+((Pw(i,ij))))+(Paux(i));

    % 3-5 Adjusting idle power and upper limit cut off
    if P(i,ij) < kWmin(i);
       P(i,ij) = kWmin(i);

    else if P(i,ij) > kW(i);
            P(i,ij) = NaN;
         end
    end
    end
end

%% Section 4. - FUEL
%Iterate through 1 to X number of ships
for i = 1:x
        %Iterate through 1 to vmax number of speeds
    for ij = 1:vmax
    % 4-1 Fuel during sailing (Fs)
    Fs(i,ij) = (Kf(i))*((P(i,ij))*(D(i))/(v(ij)));

    % 4-2 Fuel used in ports and slow zones (Fps)
    Fps(i) = (Kf(i))*((Pps(i))*(Tps(i)));

    % 4-3 Total fuel (F)
    F(i,ij) = (Fs(i,ij)) + (Fps(i));

    % 4-4 Freight work factor
        % Total number of voyages per year
        Voy_total(i) = ((Cv(i)) + (Bv(i)));

        % Roundtrips per year
        Roundtrips_year(i) = Voy_total(i) / 2;

        % Freight work factor (Fw)
        Fw(i,1) = (Cv(i))/(Voy_total(i));
    end
end
```

```
%% Section 5. - LCA emissions and cost

%Section 5.1 - Life Cycle Assessment of ships (All values in tonnes)
Rps = 0.100;   %Replacement steel factor needed for repairs
Rmf = 2.660;   %Raw material factor
Atdr = 3484;   %Average transport distance of raw materials (Nautical
miles)
Atds = 4136;   %Average transport distance of scrap materials
(Nautical miles)
Sfc = 1.750;   %CO2 Steel fabrication coefficient
Sbc = 0.216;   %CO2 Ship building coefficient
Rpc = 0.303;   %CO2 Repair coefficient
Rec = 0.180;   %CO2 Scrapping coefficient
Tnc = 12.00;   %CO2 gram per ton nm coefficient (from Panamax)
Fus = 0.250;   %CO2 gram emitted upstream per gram fuel used

%Iterate through 1 to X number of ships
for i = 1:x
    %Iterate through 1 to vmax number of speeds
    for ij = 1:vmax

%5-1-2 Amount of steel needed for repairs (Lwsr)
Lwsr(i,1) = (Lws(i,1)) * Rps;
%5-1-3 Amount of steel in ship + steel need for repair over life
time(Lwst)
Lwst(i,1) = (Lws(i,1)) + (Lwsr(i,1));
%5-1-4 Raw materials need for extraction and transport (Rawm)
Rawm(i,1) = Lwst(i,1) * Rmf;
%5-1-5 Tonnes nautical miles (Raw materials) (Tnmr)
Tnmr(i,1) = Rawm(i,1) * Atdr;
%5-1-6 Tonnes nautical miles (Scrap materials) (Tnms)
Tnms(i,1) = Lwst(i,1) * Atds;

%5-1-8 Ship Building
%CO2 emissions from ship building per ship
CO2sb(i,1) = Lwst(i,1) * Sbc;
%Sum of CO2 for number of ships
CO2sb_class(i,1) = CO2sb(i,1) * No(i);
%CO2 emission per year per class
CO2sb_year(i,1) = CO2sb_class(i,1) / LT;

%5-1-9 Steel fabrication
%CO2 emission from steel fabrication per ship
CO2sf(i,1) = Lwst(i,1) * Sfc;
%Sum of CO2 for number of ships
CO2sf_class(i,1) = CO2sf(i,1) * No(i);
%CO2 emission per year per class
CO2sf_year(i,1) = CO2sf_class(i,1) / LT;

%5-1-10 Repairs
%CO2 emissions from repair per ship
CO2rp(i,1) = Lwsr(i,1) * Rpc;
%Sum of CO2 for number of ships
CO2rp_class(i,1) = CO2rp(i,1) * No(i);
%CO2 emission per year per class
CO2rp_year(i,1) = CO2rp_class(i,1) / LT;
```

```
%5-1-11 Scrapping
%CO2 emissions from cutting of steel scrapping per ship
CO2re(i,1) = Lws(i,1) * Rec;
%Sum of CO2 for number of ships
CO2re_class(i,1) = CO2re(i,1) * No(i);
%CO2 emission per year per class
CO2re_year(i,1) = CO2re_class(i,1) / LT;

% Construction related Transport
%CO2 emissions from transportation of raw materials per ship
CO2tra(i,1) = (Tnmr(i,1) * Tnc) / 1000000;
%Sum of CO2 for number of ships
CO2tra_class(i,1) = CO2tra(i,1) * No(i);
%CO2 emission per year per class
CO2tra_year(i,1) = CO2tra_class(i,1) / LT;

% End of life related transport
%CO2 emissions from transportation of scrap materials
CO2tsc(i,1) = (Tnms(i,1) * Tnc) / 1000000;
%Sum of CO2 for number of ships
CO2tsc_class(i,1) = CO2tsc(i,1) * No(i);
%CO2 emission per year per class
CO2tsc_year(i,1) = CO2tsc_class(i,1) / LT;

% Totals
%5-1-7 Total transport
CO2tr(i,1) = CO2tra(i,1) + CO2tsc(i,1); %Total CO2 emission from
transportation
%5-1-13 Total CO2 in tonnes
CO2LCA_tonnes(i,1) = CO2sf(i,1) + CO2sb(i,1) + CO2rp(i,1) +
CO2re(i,1) + CO2tr(i,1);
%Total CO2 in grams
CO2LCA(i,1) = CO2LCA_tonnes(i,1) * 1000000;

% EMISSION INDIVIDUAL PARTS
%5-1-12 CO2 from Upstream fuel production per ship per round trip
e_upstream_roundtrip(i,ij) = F(i,ij) * Fus;
% CO2 from upstream fuel production per year per class
e_upstream_year_class(i,ij) = e_upstream_roundtrip(i,ij) *
Roundtrips_year(i) * No(i);

% CO2 from shipbuilding and EOL per year
CO2LCA_year(i,1) = CO2LCA(i) / LT;
% CO2 from shipbuilding and OEL per roundtrip
CO2LCA_roundtrip(i,1) = CO2LCA_year(i) / Roundtrips_year(i);

% CO2 from combustion per year per ship
e_combustion_year(i,ij) = F(i,ij) * Ke(i) * Roundtrips_year(i) ;
% CO2 from conbustion per year per class
e_combustion_year_class(i,ij) = e_combustion_year(i,ij) * No(i);

% CO2 from combustion normalized to freightwork
e_combustion(i,ij) = (F(i,ij) / (Fw(i)*D(i) * M(i)))  * (Ke(i));
% CO2 from upstream fuel production normalized to freightwork
e_upstream(i,ij) = e_upstream_roundtrip(i,ij) / ( (Fw(i))*(D(i)) *
(M(i)) );
% CO2 from LCA normalized to freightwork
e_LCA(i,1) = CO2LCA_roundtrip(i) / ((Fw(i)) * (D(i)) * (M(i)));
```

```
%Section 5.2 Emission all parts combined
% CO2 emitted per ton nautical mile [gram / ton nm]
e(i,ij) = e_combustion(i,ij) + e_upstream(i,ij) + e_LCA(i);
% CO2 per roundtrip ship [tons]
e_roundtrip(i,ij) =  e(i,ij) * ((Fw(i)) * (D(i)) * (M(i))) / 1000000;
% CO2 per year per ship [tons]
e_year_ship(i,ij) = e_roundtrip(i,ij) * Roundtrips_year(i);
% CO2 per year per ship class [tons]
e_year(i,ij) = e_year_ship(i,ij) * No(i);
% CO2 per life time per ship [tons]
e_lifetime(i,ij) = e_year_ship(i,ij) * LT;
% CO2 per life time per ship class [tons]
e_class(i,ij) = e_lifetime(i,ij) * No(i);

% Section 5.3 Cost
% Normalization factor for ton nautical mile
f1(i,ij) = 1 / ((Fw(i))*(D(i)) * ((M(i))));
% Fuel cost of fuel consumption during sailing & ports and slow zones
f2(i,ij) = ((Fs(i,ij)) * ((Chfo(i))/10^6)) + ((Fps(i)) *
((Cmdo(i))/10^6));
% Time charter cost
f3(i,ij) = (TC(i)) * ((Tt(i,ij)));
% Value of cargo transported
f4(i,ij) = (M(i)) * (CM(i)) * 0.5 * (Tt(i,ij));
% Interest rate on captial invested
f5(i,ij) = ( (Cir(i)) / 100 ) / 365;
% Capital investment cost
f6(i,ij) = f4(i,ij) * f5(i,ij);
%Cost per ship per ton nautical mile
C(i,ij)  = f1(i,ij) * (f2(i,ij) + f3(i,ij) + (f4(i,ij)*f5(i,ij)));
% Cost per ship per round trip
C_roundtrip(i,ij)  = ((f2(i,ij) + f3(i,ij) + (f4(i,ij)*f5(i,ij))));
% Cost per ship per year
C_year(i,ij) = C_roundtrip(i,ij) * Roundtrips_year(i);
% Cost per class per year
C_year_class(i,ij) = C_year(i,ij) * No(i);

        end
end

%%Section 6. - Results
%1 to X number of ships
for i = 1:x
% Emission per ton nm at design speed only
e_vd(i,1) = e(i,vd(i));
end

for i = 1:x %1 to X number of ships
%Lifetime emission at design speed only
e_lifetime_vd(i,1) = e_lifetime(i,vd(i));
e_class_vd(i,1) = e_class(i,vd(i));
% e_upstream_year_max(i,1) = max
end

% Emission reduction scenarios at Vd, Vd-1, Vd-2
for i = 1:x %1 to X number of ships
        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e_year(i,ij))== false
            e_year_max(i,1)=e_year(i,ij);
```

```
            end
        end

        for ij = 1:25
            if  isnan(e_year(i,ij+1))== false
            e_year_middle(i,1)=e_year(i,ij);
            end
        end

        for ij = 1:25
             if  isnan(e_year(i,ij+2))== false
            e_year_best(i,1)=e_year(i,ij);
             end
        end

        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e_combustion_year_class(i,ij))== false

e_combustion_year_class_max(i,1)=e_combustion_year_class(i,ij)/
1000000;
            end
        end

         for ij = 1:25
            if  isnan(e_combustion_year_class(i,ij+1))== false

e_combustion_year_class_middle(i,1)=e_combustion_year_class(i,ij)/
1000000;
            end
        end

        for ij = 1:25
             if  isnan(e_combustion_year_class(i,ij+2))== false

e_combustion_year_class_best(i,1)=e_combustion_year_class(i,ij)/
1000000;
             end
        end

        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e_upstream_year_class(i,ij))== false

e_upstream_year_class_max(i,1)=e_upstream_year_class(i,ij)/ 1000000;
            end
        end

        for ij = 1:25
            if  isnan(e_upstream_year_class(i,ij+1))== false

e_upstream_year_class_middle(i,1)=e_upstream_year_class(i,ij)/
1000000;
            end
        end

        for ij = 1:25
             if  isnan(e_upstream_year_class(i,ij+2))== false

e_upstream_year_class_best(i,1)=e_upstream_year_class(i,ij)/ 1000000;
             end
```

```
        end

end

%Annual freightwork
for i = 1:x
    Freighwork_year(i,1)  = Fw(i) * D(i) * M(i) * Roundtrips_year(i)
* No(i);
end
```

## 7.2 Block coefficient MATLAB code

```
%File read - Parameters
Data =  xlsread('FrontendBlock.xlsx', 2, 'D5:AH64');

%Constants
x    =   60;      % Number of ship type entries in Excel document
vmax =   30;      % Number or speed iterations
MCR  =   0.75;    % Maximum continous revolution at design speed
ktms =   1.9438;   % Knots to m/s conversion factor
p    =   1.025;   % Density of saltwater
g    =   9.81;    % Gravity
v    =   1:vmax;  % Vessel speed, 1 through 30 knots

for i = 1:x
No(i,1)    =   Data(i,1);          % Number of ships
Voy(i,1)   =   Data(i,2);          % Distance per voyage
Day(i,1)   =   Data(i,3);          % Days per voyage
Tps(i,1)   =   (Data(i,4))*24;     % Time in port and slow zones
vs(i,1)    =   Data(i,5);          % Vessel Speed
vd(i,1)    =   Data(i,6);          % Design Speed
kW(i,1)    =   Data(i,7);          % Engine size (Installed power)
n(i,1)     =   Data(i,8);          % Engine efficiency
Paux(i,1)  =   Data(i,9);          % Aux. Power
Dis(i,1)   =   Data(i,11);         % Displacement of water (tons)
B(i,1)     =   Data(i,12);         % Width of ships at water line
L(i,1)     =   Data(i,13);         % Length of ship at water line
Dft(i,1)   =   Data(i,14);         % Draft - Fully loaded
Ct(i,1)    =   Data(i,16);         % Drag coefficient
Kf(i,1)    =   Data(i,17);         % Gram fuel per kWh
H13(i,1)   =   Data(i,18);         % Wave height
u(i,1)     =   Data(i,19);         % Wave Speed
Caw(i,1)   =   Data(i,20);         % Wave Drag
Ke(i,1)    =   Data(i,21);         % CO2 per unit fuel
M(i,1)     =   Data(i,22);         % Average weigth of cargo
Chfo(i,1)  =   Data(i,23);         % Cost of heavy fuel oil
Cmdo(i,1)  =   Data(i,24);         % Cost of marine diesel oil
TC(i,1)    =   Data(i,25);         % Time charter cost per day
CM(i,1)    =   Data(i,26);         % Export value per ton
Cir(i,1)   =   Data(i,27);         % Annual interest
j(i,1)     =   Data(i,28);         % Propeller constant, speed
independent
k(i,1)     =   Data(i,29);         % Propeller constant, speed
dependent
Cv(i,1)    =   Data(i,30);         % Cargo voyages
Bv(i,1)    =   Data(i,31);         % Ballast voyages
end

% ADDITIONAL DATA
% Distance per roundtrip;
D    =   2 .* Voy;

% Time per roundtrip
T    =   2 .* Day;

% Minimum / idle engine load
kWmin = 0.15 .* kW;
```

```
% Time in ports and slow zones
Pps = kWmin;

% Calculation for time spent per voyage per boat, at different speeds
for i = 1:x %1 to X number of ships

    for h = 1:vmax %1 to vmax number of speeds

        Tt(i,h) =  ((D(i)/h)/24);

    end
end


%% BLOCK COEFFICIENT SCENARIO MODIFICATIONS

for i = 1:x %1 to X number of ships
    for h = 1:vmax %1 to vmax number of speeds

       %Reference Values
% Frouds Number, Initial
Fnref(i,1)   =   ((vd(i,1))/ktms)/(sqrt(g*(L(i,1))));

% Wetted surface, initial
Sref(i,1) = ((B(i,1)*L(i,1)) + (2*L(i,1)*Dft(i,1)));

% Block coefficient, initial
Cbref(i,1) = Dis(i,1) / (L(i,1) * (B(i,1)) * (Dft(i,1)));

% Scenario 1 - 14% reduction in DWT and Displacement
% Reduced displacement
Dis2(i,1) = (Dis(i,1)) * 0.86;
% Reduced Cargo capacity
M2(i,1) = (M(i,1)) * 0.86;
% Reduced Time Charter
TC2(i,1) = TC(i,1) * 0.86;
% Reduced Wetted surface
S2(i,1) = (((B(i,1)*L(i,1)))*0.72) + (2*L(i,1)*Dft(i,1));

%Scenario 2 - 26% reduction in DWT and Displacement
% Reduced displacement
Dis3(i,1) = (Dis(i,1)) * 0.74;
% Reduced Cargo capacity
M3(i,1) = (M(i,1)) * 0.74;
% Reduced Time Charter
TC3(i,1) = TC(i,1) * 0.74;
% Reduced Wetted surface
S3(i,1) = (((B(i,1)*L(i,1)))*0.52) + (2*L(i,1)*Dft(i,1));

%Scenario 3 - Increased Beam
% Increased width
B1(i,1) = (B(i,1)) * 1.3;

% Corresponding  new block coefficients
Cb1(i,1) = Dis(i,1) / (L(i,1) * (B1(i,1)) * (Dft(i,1)));
Cb2(i,1) = Dis2(i,1) / (L(i,1) * (B(i,1)) * (Dft(i,1)));
```

```
Cb3(i,1) = Dis3(i,1) / (L(i,1) * (B(i,1)) * (Dft(i,1)));

    end
end


%% Section 2 - Propeller efficiencies and still water resistance
factors


% 2-1 Change in propeller efficientcy for lower speeds
for ij=1:vmax
    if  v(1,ij) > vd(i,1);
        Ku(i,ij) = n(i,1);
    else
        Ku(i,ij) = n(i,1) * (j(i,1) + (k(i,1) *
sqrt(v(1,ij)/vd(i,1))));
    end

        % 2-2 Propeller efficiency
        K(i,ij) = 1 / (Ku(i,ij));
end

% 2-3 Still Water Resistance Factor
Csref(i,1)=((kW(i,1))*MCR*(1/(K(i,ij)))*2)/(p*(Sref(i,1))*((vd(i,1))^
3));

% 2-4 Calculations for still water drag coefficients
for i = 1:x %1 to X number of ships
    for h = 1:vmax %1 to vmax number of speeds
    if h > vd(i);
        Cs(i,h) = Csref(i) * (0.8 + (0.2*(h/vd(i))^2));
    else
        if h < vd(i);
            Cs(i,h) = (Csref(i)*0.9) + (((h/vd(i))*0.1)*Csref(i));
        else
            Cs(i,h) = Csref(i);
        end
    end
    end
end


%% Section 3 - Power
%Iterate through 1 to X number of ships
for i = 1:x
    for ij = 1:vmax %1 to vmax number of speeds

% 3-1 Still water power (Ps)
% Reference still water power
Psref(i,ij) = (p*Cs(i,ij)*Sref(i)*((v(ij))^3))/2;

% Still water power Scenario 1
Ps2(i,ij) =
Psref(i,v(ij))*(((S2(i))*(Cb2(i)))/((Sref(i))*(Cbref(i))));
% Still water power Scenario 2
Ps3(i,ij) =
Psref(i,v(ij))*(((S3(i))*(Cb3(i)))/((Sref(i))*(Cbref(i))));
```

```
% Still water power Scenario 3
Ps1(i,ij) =
Psref(i,v(ij))*(((Sref(i))*(Cb1(i)))/((Sref(i))*(Cbref(i))));

% Relative vessel and wave speed
vr(i,ij) = ((v(ij))/1.94384449)+u(i);

% 3-2 Wave power (Pw)

% Reference wave power
Pwref(i,ij)=((Caw(i)*p*g*(((H13(i))/2)^2)*(B(i))^2)/(2*L(i))) *
vr(i,ij);

% Adjusted wave coefficient for Scenario 3
Caw1(i) = (Caw(i)) * ((sqrt((B1(i))/(L(i)))) /
(sqrt((B(i))/(L(i)))));
% Wave power Scenario 3
Pw1(i,ij)=((Caw1(i)*p*g*(((H13(i))/2)^2)*(B1(i))^2)/(2*L(i))) *
vr(i,ij);

% 3-4 Total power (P)
% Initial total power
Pref(i,ij) = (K(i,ij))*((Psref(i,ij))+((Pwref(i,ij))))+(Paux(i));
% Total power Scenario 1
P2(i,ij) = (K(i,ij))*((Ps2(i,ij))+((Pwref(i,ij))))+(Paux(i));
% Total power Scenario 2
P3(i,ij) = (K(i,ij))*((Ps3(i,ij))+((Pwref(i,ij))))+(Paux(i));
% Total power Scenario 3
P1(i,ij) = (K(i,ij))*((Ps1(i,ij))+((Pw1(i,ij))))+(Paux(i));


% 3-5 Adjusting idle power and upper limit cut off for all scenarios
    if Pref(i,ij) < kWmin(i);
       Pref(i,ij) = kWmin(i);

       P1(i,ij) < kWmin(i);
       P1(i,ij) = kWmin(i);

       P2(i,ij) < kWmin(i);
       P2(i,ij) = kWmin(i);

       P3(i,ij) < kWmin(i);
       P3(i,ij) = kWmin(i);

    else if Pref(i,ij) > kW(i);
            Pref(i,ij) = NaN;

            P1(i,ij) > kW(i);
            P1(i,ij) = NaN;

            P2(i,ij) > kW(i);
            P2(i,ij) = NaN;

            P3(i,ij) > kW(i);
            P3(i,ij) = NaN;
        end
    end
```

```
%% Section 4 - Fuel
% 4-1 Fuel during sailing (Fs)
% Fuel during sailing reference scenario
Fsref(i,ij) = (Kf(i))*((Pref(i,ij))*(D(i))/(v(ij)));
% Fuel during sailing scenario 1
Fs2(i,ij) = (Kf(i))*((P2(i,ij))*(D(i))/(v(ij)));
% Fuel during sailing scenario 2
Fs3(i,ij) = (Kf(i))*((P3(i,ij))*(D(i))/(v(ij)));
% Fuel during sailing scenario 3
Fs1(i,ij) = (Kf(i))*((P1(i,ij))*(D(i))/(v(ij)));

% 4-2 Fuel used in ports and slow zones (Fps)
Fps(i) = (Kf(i))*((Pps(i))*(Tps(i)));

% 4-3 Total fuel (F)
% Reference scenario
Fref(i,ij) = (Fsref(i,ij)) + (Fps(i));
% Scenario 1
F2(i,ij) = (Fs2(i,ij)) + (Fps(i));
% Scenario 2
F3(i,ij) = (Fs3(i,ij)) + (Fps(i));
% Scenario 3
F1(i,ij) = (Fs1(i,ij)) + (Fps(i));

% 4-4 Freight work

Fw(i) = (Cv(i))/((Cv(i)) + (Bv(i)));



%% EMISSION
%  CO2 emitted per ton nautical mile
eref(i,ij) = ( (Fref(i,ij)) / ( (Fw(i))*(D(i)) * (M(i)) ) ) *
(Ke(i));
e1(i,ij) = ( (F1(i,ij)) / ( (Fw(i))*(D(i)) * (M(i)) ) ) * (Ke(i));
e2(i,ij) = ( (F2(i,ij)) / ( (Fw(i))*(D(i)) * (M2(i)) ) ) * (Ke(i));
e3(i,ij) = ( (F3(i,ij)) / ( (Fw(i))*(D(i)) * (M3(i)) ) ) * (Ke(i));

% Total number of voyages per year
Voy_total(i) = ((Cv(i)) + (Bv(i)));

% Roundtrips per year
Roundtrips_year(i) = Voy_total(i) / 2;

% CO2 per roundtrip ship [tons]
eref_roundtrip(i,ij) =  eref(i,ij) * ((Fw(i)) * (D(i)) * (M(i))) /
1000000;
e1_roundtrip(i,ij) =  e1(i,ij) * ((Fw(i)) * (D(i)) * (M(i))) /
1000000;
e2_roundtrip(i,ij) =  e2(i,ij) * ((Fw(i)) * (D(i)) * (M2(i))) /
1000000;
e3_roundtrip(i,ij) =  e3(i,ij) * ((Fw(i)) * (D(i)) * (M3(i))) /
1000000;
% CO2 per year per ship [tons]
eref_year_ship(i,ij) = eref_roundtrip(i,ij) * Roundtrips_year(i);
e1_year_ship(i,ij) = e1_roundtrip(i,ij) * Roundtrips_year(i);
e2_year_ship(i,ij) = e2_roundtrip(i,ij) * Roundtrips_year(i);
e3_year_ship(i,ij) = e3_roundtrip(i,ij) * Roundtrips_year(i);
```

```
% CO2 per year per ship class [tons]
eref_year(i,ij) = eref_year_ship(i,ij) * No(i);
e1_year(i,ij) = e1_year_ship(i,ij) * No(i);
e2_year(i,ij) = e2_year_ship(i,ij) * No(i);
e3_year(i,ij) = e3_year_ship(i,ij) * No(i);


% COST
% Reference scenario
f1ref(i,ij) = 1 / ((Fw(i))*(D(i)) * ((M(i))));
f2ref(i,ij) =
((Fsref(i,ij))*((Chfo(i))/10^6))+((Fps(i))*((Cmdo(i))/10^6));
f3ref(i,ij) = (TC(i)) * ((Tt(i,ij)));
f4ref(i,ij) = (M(i)) * (CM(i)) * 0.5 * (Tt(i,ij));
f5ref(i,ij) = ( (Cir(i)) / 100 ) / 365;
f6ref(i,ij) = f4ref(i,ij) * f5ref(i,ij);
Cref(i,ij)  = f1ref(i,ij) * ((f2ref(i,ij) + f3ref(i,ij) +
(f4ref(i,ij)*f5ref(i,ij))));

% Scenario 1
f12(i,ij) = 1 / ((Fw(i))*(D(i)) * ((M2(i))));
f22(i,ij) = ((Fs2(i,ij))*((Chfo(i))/10^6)) + ((Fps(i)) *
((Cmdo(i))/10^6));
f32(i,ij) = (TC2(i)) * ((Tt(i,ij)));
f42(i,ij) = (M2(i)) * (CM(i)) * 0.5 * (Tt(i,ij));
f52(i,ij) = ( (Cir(i)) / 100 ) / 365;
C2(i,ij)  = f12(i,ij) * ((f22(i,ij) + f32(i,ij) +
(f42(i,ij)*f52(i,ij))));

% Scenario 2
f13(i,ij) = 1 / ((Fw(i))*(D(i)) * ((M3(i))));
f23(i,ij) = ((Fs3(i,ij))*((Chfo(i))/10^6)) + ((Fps(i)) *
((Cmdo(i))/10^6));
f33(i,ij) = (TC3(i)) * ((Tt(i,ij)));
f43(i,ij) = (M3(i)) * (CM(i)) * 0.5 * (Tt(i,ij));
f53(i,ij) = ( (Cir(i)) / 100 ) / 365;
C3(i,ij)  = f13(i,ij) * ((f23(i,ij) + f33(i,ij) +
(f43(i,ij)*f53(i,ij))));

% Scenario 3
f11(i,ij) = 1 / ((Fw(i))*(D(i)) * ((M(i))));
f21(i,ij) = ((Fs1(i,ij))*((Chfo(i))/10^6)) + ((Fps(i)) *
((Cmdo(i))/10^6));
f31(i,ij) = (TC(i)) * ((Tt(i,ij)));
f41(i,ij) = (M(i)) * (CM(i)) * 0.5 * (Tt(i,ij));
f51(i,ij) = ( (Cir(i)) / 100 ) / 365;
C1(i,ij)  = f11(i,ij) * ((f21(i,ij) + f31(i,ij) +
(f41(i,ij)*f51(i,ij))));
    end
end

% Extraction of emission values for maximum speeds for the different
% scenarios

for i = 1:x %1 to X number of ships
    for ij = 1:vmax %1 to vmax number of speeds
      if  isnan(eref_year(i,ij))== false
      eref_year_max(i,1)=eref_year(i,ij);
      end
```

```
        end

        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e1_year(i,ij))== false
            e1_year_max(i,1)=e1_year(i,ij);
            end
        end

        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e2_year(i,ij))== false
            e2_year_max(i,1)=e2_year(i,ij);
            end
        end

        for ij = 1:vmax %1 to vmax number of speeds
            if  isnan(e3_year(i,ij))== false
            e3_year_max(i,1)=e3_year(i,ij);
            end
        end
end



%% Results

% Dry Bulk(Panamax) - Emission
xlswrite('BlockResults.xlsx', eref(9,1:30), 'RawData', 'D3');
xlswrite('BlockResults.xlsx', e1(9,1:30), 'RawData', 'D4');
xlswrite('BlockResults.xlsx', e2(9,1:30), 'RawData', 'D5');
xlswrite('BlockResults.xlsx', e3(9,1:30), 'RawData', 'D6');

%Crude Oil(75'-120') - Emission
xlswrite('BlockResults.xlsx', eref(27,1:30), 'RawData', 'D10');
xlswrite('BlockResults.xlsx', e1(27,1:30), 'RawData', 'D11');
xlswrite('BlockResults.xlsx', e2(27,1:30), 'RawData', 'D12');
xlswrite('BlockResults.xlsx', e3(27,1:30), 'RawData', 'D13');

% Oil Products(15'-25') - Emission
xlswrite('BlockResults.xlsx', eref(33,1:30), 'RawData', 'D17');
xlswrite('BlockResults.xlsx', e1(33,1:30), 'RawData', 'D18');
xlswrite('BlockResults.xlsx', e2(33,1:30), 'RawData', 'D19');
xlswrite('BlockResults.xlsx', e3(33,1:30), 'RawData', 'D20');

% Dry Bulk - Cost
xlswrite('BlockResults.xlsx', Cref(9,1:30), 'RawData', 'D24');
xlswrite('BlockResults.xlsx', C1(9,1:30), 'RawData', 'D25');
xlswrite('BlockResults.xlsx', C2(9,1:30), 'RawData', 'D26');
xlswrite('BlockResults.xlsx', C3(9,1:30), 'RawData', 'D27');

%Crude Oil(75'-120') - Cost
xlswrite('BlockResults.xlsx', Cref(27,1:30), 'RawData', 'D31');
xlswrite('BlockResults.xlsx', C1(27,1:30), 'RawData', 'D32');
xlswrite('BlockResults.xlsx', C2(27,1:30), 'RawData', 'D33');
xlswrite('BlockResults.xlsx', C3(27,1:30), 'RawData', 'D34');

% Oil Products(15'-25') - Cost
xlswrite('BlockResults.xlsx', Cref(33,1:30), 'RawData', 'D38');
xlswrite('BlockResults.xlsx', C1(33,1:30), 'RawData', 'D39');
```

```
xlswrite('BlockResults.xlsx', C2(33,1:30), 'RawData', 'D40');
xlswrite('BlockResults.xlsx', C3(33,1:30), 'RawData', 'D41');


% Reference scenario maximum emission
xlswrite('BlockResults.xlsx', eref_year_max(7:13,1), 'RawData',
'D46');
xlswrite('BlockResults.xlsx', eref_year_max(25:30,1), 'RawData',
'D53');
xlswrite('BlockResults.xlsx', eref_year_max(31:36,1), 'RawData',
'D59');

% Maximum emission scenario 1
xlswrite('BlockResults.xlsx', e2_year_max(7:13,1), 'RawData', 'F46');
xlswrite('BlockResults.xlsx', e2_year_max(25:30,1), 'RawData',
'F53');
xlswrite('BlockResults.xlsx', e2_year_max(31:36,1), 'RawData',
'F59');

% Maximum emission scenario 2
xlswrite('BlockResults.xlsx', e3_year_max(7:13,1), 'RawData', 'G46');
xlswrite('BlockResults.xlsx', e3_year_max(25:30,1), 'RawData',
'G53');
xlswrite('BlockResults.xlsx', e3_year_max(31:36,1), 'RawData',
'G59');

% Maximum emission scenario 3
xlswrite('BlockResults.xlsx', e1_year_max(7:13,1), 'RawData', 'E46');
xlswrite('BlockResults.xlsx', e1_year_max(25:30,1), 'RawData',
'E53');
xlswrite('BlockResults.xlsx', e1_year_max(31:36,1), 'RawData',
'E59');
```

## 7.3 Input parameter sheet

|  | Number | Ship type | No. of ships [Nr. #] | Distance per voyage [Nautical Miles] | Days per voyage [Days] | Tps - Time in ports and slow zones [days] | Vessel speed | Design speed [knots] | Engine size [kW] | n - Engine efficiency at vd [0-1] | Paux - Aux. Power [kW] | Pps - Power req. Ports & slow zones [kW] | Displacement [ton] | B - Width of ship at WL [m] | L - Length of ship [m] | Draft - Fully Loaded [m] | S - Wetted surface [m2] | Ct - Drag coeff. [dimensionless] | Gram fuel per kWh [g/kWh] | H13 - Wave height | u - Wave speed | Caw - Wave drag | Ke - CO2 per unit fuel | M - Average weight of cargo | Chfo - Cost of hfo | Cmdo - Cost of mdo | TC - Time charter cost per day | CM - Export value per ton | Cir - Annual interest | j - Constant | k - Constant | Cargo Voyages [Nr. #] | Balast Voyages [Nr. #] | dwt - dead weight tonnage [t | LWS-factor | LWS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **General Cargo** | 1 | Dry Cargo 15'++ | 1215 | 3000 | 16 | 7,783 | 14,25 | 15 | 8080 | 0,65 | 404 | 404 | 35477,4 | 23 | 150 | 10 | 6450 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 21600 | 400 | 600 | 14413 | 250 | 5 | 0,5 | 0,5 | 15 | 8 | 25341 | 0,4 | 10136 |
|  | 2 | Dry Cargo 10'-15' | 710 | 2000 | 11 | 5,206 | 14,25 | 15 | 5666 | 0,65 | 283,3 | 283 | 17485,3 | 19 | 135 | 8 | 4725 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 10260 | 400 | 600 | 7072,1 | 250 | 5 | 0,5 | 0,5 | 22 | 12 | 12434 | 0,4063 | 5051 |
|  | 3 | Dry Cargo 5'-10' | 2654 | 1000 | 6 | 3,411 | 12,35 | 13 | 3280 | 0,65 | 164 | 164 | 9855,75 | 16,5 | 120 | 7 | 3660 | 0,00045 | 210 | 2,5 | 10,9 | 1,67 | 3,17 | 5440 | 400 | 600 | 3956,9 | 250 | 5 | 0,5 | 0,5 | 36 | 20 | 6957 | 0,4167 | 2899 |
|  | 4 | Dry Cargo 1'-5' | 7806 | 500 | 5 | 3,507 | 11,4 | 12 | 1328 | 0,65 | 66,4 | 66,4 | 3658,44 | 11 | 78 | 4,5 | 1560 | 0,00045 | 230 | 2,5 | 10,9 | 1,67 | 3,17 | 1955 | 400 | 600 | 1447,5 | 250 | 5 | 0,5 | 0,5 | 44 | 25 | 2545 | 0,4375 | 1113 |
|  | 5 | Dry Cargo 500-1' | 2482 | 350 | 5 | 3,653 | 9,5 | 10 | 560 | 0,65 | 28 | 28 | 1034,84 | 9,5 | 53 | 3,3 | 853,3 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 510 | 400 | 600 | 405,53 | 250 | 5 | 0,5 | 0,5 | 46 | 26 | 713 | 0,4514 | 321,8 |
|  | 6 | Dry Cargo 0-500 | 2413 | 200 | 2 | 2,519 | 9,5 | 10 | 369 | 0,65 | 18,45 | 18,5 | 287,535 | 8,4 | 36 | 2,1 | 453,6 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 127,5 | 400 | 600 | 111,48 | 250 | 5 | 0,5 | 0,5 | 68 | 40 | 196 | 0,467 | 91,53 |
| **Dry Bulk** | 7 | Capesize 120'++ | 782 | 7500 | 33 | 11,45 | 13,3 | 14 | 15427 | 0,65 | 635,7 | 636 | 194890 | 45 | 280 | 18,2 | 22792 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 163930 | 400 | 600 | 26899 | 250 | 5 | 0,5 | 0,5 | 6 | 5 | 172251 | 0,1314 | 22639 |
|  | 8 | Post P. 85'-120' | 119 | 6500 | 29 | 11,58 | 13,3 | 14 | 11969 | 0,65 | 549,2 | 549 | 108426 | 38 | 225 | 14,5 | 15075 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 88270 | 400 | 600 | 14641 | 250 | 5 | 0,5 | 0,5 | 7 | 5 | 93752 | 0,1565 | 14674 |
|  | 9 | Panamax 60'-85' | 1447 | 5500 | 28 | 12,23 | 13,3 | 14 | 9801 | 0,65 | 490,1 | 490 | 83051,9 | 32,2 | 220 | 14,5 | 13464 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 65550 | 400 | 600 | 11278 | 250 | 5 | 0,5 | 0,5 | 8 | 5 | 72219 | 0,15 | 10833 |
|  | 10 | Handymax 35'-60' | 1937 | 5000 | 25 | 11,64 | 13,3 | 14 | 8214 | 0,65 | 410,7 | 411 | 55282,8 | 32,2 | 175 | 12,2 | 9905 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 41800 | 400 | 600 | 7194,3 | 250 | 5 | 0,5 | 0,5 | 9 | 5 | 46069 | 0,2 | 9214 |
|  | 11 | Handysize 15'-35' | 1920 | 3000 | 16 | 7,864 | 13,3 | 14 | 6656 | 0,65 | 332,8 | 333 | 31980,4 | 25 | 150 | 10 | 6750 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 22500 | 400 | 600 | 4071,4 | 250 | 5 | 0,5 | 0,5 | 15 | 7 | 26071 | 0,2267 | 5909 |
|  | 12 | Coastal 5'-15' | 464 | 1500 | 10 | 6,333 | 12,35 | 13 | 3565 | 0,65 | 178,3 | 178 | 12113,4 | 20 | 120 | 7,5 | 4200 | 0,00045 | 210 | 1 | 4,7 | 1,6 | 3,17 | 7310 | 400 | 600 | 1455,1 | 250 | 5 | 0,5 | 0,5 | 22 | 11 | 9318 | 0,3 | 2795 |
|  | 13 | Small Bulk 0-5' | 854 | 400 | 4 | 3,768 | 10,45 | 11 | 1071 | 0,65 | 53,55 | 53,6 | 2113,33 | 11 | 66 | 4,4 | 1307 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 1190 | 400 | 600 | 247,52 | 250 | 5 | 0,5 | 0,5 | 44 | 25 | 1585 | 0,3333 | 528,3 |
| **Reefer** | 14 | Reefer 15'++ | 22 | 4000 | 14 | 6,154 | 19,95 | 21 | 14972 | 0,65 | 624,3 | 624 | 22772,9 | 25,1 | 176,3 | 9,3 | 7704 | 0,00045 | 210 | 2,5 | 10,9 | 1,67 | 3,17 | 12325 | 400 | 600 | 12102 | 250 | 5 | 0,5 | 0,5 | 16 | 10 | 16075 | 0,4167 | 6698 |
|  | 15 | Reefer 10'-15' | 203 | 3000 | 11 | 5,108 | 19 | 20 | 11037 | 0,65 | 525,9 | 526 | 16805,8 | 21,8 | 136 | 9,2 | 5467 | 0,00045 | 230 | 2,5 | 10,9 | 1,67 | 3,17 | 8925 | 400 | 600 | 8801,9 | 250 | 5 | 0,5 | 0,5 | 20 | 13 | 11691 | 0,4375 | 5115 |
|  | 16 | Reefer 5'-10' | 372 | 2000 | 9 | 4 | 17,1 | 18 | 6387 | 0,65 | 319,4 | 319 | 10384,7 | 19 | 116 | 7,7 | 3990 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 5440 | 400 | 600 | 5386,8 | 250 | 5 | 0,5 | 0,5 | 25 | 17 | 7155 | 0,4514 | 3230 |
|  | 17 | Reefer 0-5' | 629 | 1000 | 6 | 3,263 | 12,35 | 13 | 1901 | 0,65 | 95,05 | 95,1 | 2863,61 | 13 | 78 | 4,2 | 1669 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 1445 | 400 | 600 | 1469,6 | 250 | 5 | 0,5 | 0,5 | 34 | 23 | 1952 | 0,467 | 911,6 |
| **Container** | 18 | 8500 TEU++ | 206 | 11000 | 31 | 10,36 | 23,75 | 25 | 67369 | 0,65 | 1934 | 1934 | 147025 | 42,8 | 350 | 15 | 25480 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 59500 | 400 | 600 | 38332 | 5000 | 5 | 0,5 | 0,5 | 11 | 0 | 105995 | 0,3871 | 41030 |
|  | 19 | 6500 TEU | 175 | 11000 | 31 | 10,45 | 23,75 | 25 | 60277 | 0,65 | 1757 | 1757 | 111421 | 38 | 310 | 14 | 20460 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 44800 | 400 | 600 | 28962 | 5000 | 5 | 0,5 | 0,5 | 11 | 0 | 80084 | 0,3913 | 31337 |
|  | 20 | 4000 TEU | 1068 | 7000 | 24 | 9,929 | 21,85 | 23 | 37208 | 0,65 | 1180 | 1180 | 73729,3 | 32,2 | 280 | 13,5 | 16576 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 30800 | 400 | 600 | 19998 | 5000 | 5 | 0,5 | 0,5 | 14 | 0 | 55297 | 0,3333 | 18432 |
|  | 21 | 2300 TEU | 789 | 2500 | 10 | 4,688 | 19,95 | 21 | 20000 | 0,65 | 750 | 750 | 44324 | 31 | 195 | 11 | 10335 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 18900 | 400 | 600 | 12022 | 5000 | 5 | 0,5 | 0,5 | 32 | 0 | 33243 | 0,3333 | 11081 |
|  | 22 | 1400 TEU | 832 | 1000 | 8 | 4,244 | 18,05 | 19 | 12662 | 0,65 | 566,6 | 567 | 29742,4 | 25,6 | 160 | 10 | 7296 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 11480 | 400 | 600 | 7418 | 5000 | 5 | 0,5 | 0,5 | 45 | 0 | 20512 | 0,45 | 9230 |
|  | 23 | 700 TEU | 1161 | 700 | 7 | 4,438 | 16,15 | 17 | 6794 | 0,65 | 339,7 | 340 | 14647,5 | 21 | 120 | 7,6 | 4344 | 0,00045 | 210 | 1 | 4,7 | 1,6 | 3,17 | 5600 | 400 | 600 | 3624,4 | 5000 | 5 | 0,5 | 0,5 | 48 | 0 | 10022 | 0,4615 | 4626 |
|  | 24 | 200 TEU | 167 | 300 | 5 | 4,691 | 12,35 | 13 | 2319 | 0,65 | 116 | 116 | 4620 | 16 | 110 | 5,5 | 2970 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 1610 | 400 | 600 | 1113,9 | 5000 | 5 | 0,5 | 0,5 | 55 | 0 | 3080 | 0,5 | 1540 |
| **Crude oil tanker** | 25 | Crude oil 200'++ | 506 | 9000 | 42 | 11,44 | 14,25 | 15 | 24829 | 0,65 | 870,7 | 871 | 335237 | 60 | 324 | 21,1 | 33113 | 0,00045 | 200 | 2,5 | 10,9 | 1,67 | 3,17 | 286110 | 400 | 600 | 37855 | 250 | 5 | 0,5 | 0,5 | 4,5 | 4,5 | 295237 | 0,1355 | 40000 |
|  | 26 | Crude oil 120'-200' | 356 | 6000 | 29 | 9,375 | 14,25 | 15 | 17162 | 0,65 | 679,1 | 679 | 175442 | 48 | 265 | 17,2 | 21836 | 0,00045 | 200 | 2,5 | 10,9 | 1,67 | 3,17 | 145530 | 400 | 600 | 19455 | 250 | 5 | 0,5 | 0,5 | 6,4 | 6,4 | 151734 | 0,1563 | 23708 |
|  | 27 | Crude oil 75'-120' | 660 | 2500 | 16 | 6,696 | 14,25 | 15 | 12728 | 0,65 | 568,2 | 568 | 121386 | 38 | 230 | 14,7 | 15502 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 99000 | 400 | 600 | 13258 | 250 | 5 | 0,5 | 0,5 | 12 | 12 | 103403 | 0,1739 | 17983 |
|  | 28 | Crude oil 50'-75' | 198 | 1000 | 11 | 5,735 | 14,25 | 15 | 10571 | 0,65 | 514,3 | 514 | 79169 | 32,2 | 216 | 13,2 | 12658 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 63360 | 400 | 600 | 8495,9 | 250 | 5 | 0,5 | 0,5 | 17 | 17 | 66261 | 0,1948 | 12908 |
|  | 29 | Crude oil 15'-50' | 212 | 800 | 10 | 5,75 | 13,3 | 14 | 7707 | 0,65 | 385,4 | 385 | 46898,8 | 27 | 175 | 11 | 8575 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 37125 | 400 | 600 | 4953,2 | 250 | 5 | 0,5 | 0,5 | 18 | 18 | 38631 | 0,214 | 8268 |
|  | 30 | Crude oil 0'-15' | 121 | 300 | 6 | 5,1 | 11,4 | 12 | 1929 | 0,65 | 96,45 | 96,5 | 4487,77 | 16 | 98 | 6,5 | 2842 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 3430 | 400 | 600 | 466,46 | 250 | 5 | 0,5 | 0,5 | 25 | 25 | 3638 | 0,2336 | 849,8 |

# 7 APPENDIX

|  | Number | Ship type | No. of ships [Nr. #] | Distance per voyage [Nautical Miles] | Days per voyage [Days] | Tps - Time in ports and slow zones [days] | Vessel speed | Design speed [knots] | Engine size [kW] | n - Engine efficiency at vd [0-1] | Paux - Aux. Power [kW] | Pps - Power req. Ports & slow zones [kW] | Displacement [ton] | B - Width of ship at WL [m] | L - Length of ship [m] | Draft - Fully Loaded [m] | S - Wetted surface [m2] | Ct - Drag coeff. [dimensionless] | Gram fuel per kWh [g/kWh] | H13 - Wave height | u - Wave speed | Caw - Wave drag | Ke - CO2 per unit fuel | M - Average weight of cargo | Chfo - Cost of hfo | Cmdo - Cost of mdo | TC - Time charter cost per day | CM - Export value per ton | Cir - Annual interest | j - Constant | k - Constant | Cargo Voyages [Nr. #] | Balast Voyages [Nr. #] | dwt - dead weight tonnage [t | LWS-factor | LWS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Oil Products** | 31 | Products 75'++ | 47 | 5000 | 29 | 11,12 | 14,25 | 15 | 14582 | 0,65 | 614,6 | 615 | 132971 | 44 | 239 | 14,8 | 17590 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 91800 | 400 | 600 | 36471 | 250 | 5 | 0,5 | 0,5 | 8,5 | 4 | 112054 | 0,1867 | 20917 |
|  | 32 | Products 25'-75' | 630 | 4000 | 24 | 9,793 | 14,25 | 15 | 9532 | 0,65 | 476,6 | 477 | 61344 | 32,2 | 173 | 13 | 10069 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 41650 | 400 | 600 | 16639 | 250 | 5 | 0,5 | 0,5 | 9,5 | 5 | 51120 | 0,2 | 10224 |
|  | 33 | Products 15'-25' | 107 | 1500 | 15 | 8,435 | 13,3 | 14 | 5616 | 0,65 | 280,8 | 281 | 22838,3 | 26,2 | 152 | 7 | 6110 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 14400 | 400 | 600 | 5994,7 | 250 | 5 | 0,5 | 0,5 | 15 | 8 | 18418 | 0,24 | 4420 |
|  | 34 | Products 10'-15' | 98 | 700 | 13 | 7,893 | 12,35 | 13 | 3847 | 0,65 | 192,4 | 192 | 16013,4 | 22 | 128 | 7 | 4608 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 9600 | 400 | 600 | 4009,3 | 250 | 5 | 0,5 | 0,5 | 18 | 10 | 12318 | 0,3 | 3695 |
|  | 35 | Products 5'-10' | 471 | 400 | 11 | 7,125 | 11,4 | 12 | 2742 | 0,65 | 137,1 | 137 | 8782,29 | 19 | 102 | 6,5 | 3264 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 4960 | 400 | 600 | 2128,6 | 250 | 5 | 0,5 | 0,5 | 20 | 12 | 6540 | 0,3429 | 2242 |
|  | 36 | Products 0'-5' | 3553 | 100 | 7 | 6,643 | 10,45 | 11 | 1118 | 0,65 | 55,9 | 55,9 | 2510,93 | 11,5 | 65 | 3,5 | 1203 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 1200 | 400 | 600 | 557,22 | 250 | 5 | 0,5 | 0,5 | 26 | 16 | 1712 | 0,4667 | 798,9 |
| **Chemicals** | 37 | Chemical 40'++ | 533 | 5000 | 25 | 9,185 | 14,25 | 15 | 9361 | 0,65 | 468,1 | 468 | 57136,8 | 32,2 | 175 | 12,7 | 10080 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 38250 | 400 | 600 | 22698 | 250 | 5 | 0,5 | 0,5 | 11 | 3 | 47614 | 0,2 | 9523 |
|  | 38 | Chemical 25'-40' | 469 | 4000 | 22 | 8,71 | 14,25 | 15 | 8930 | 0,65 | 446,5 | 447 | 43010,6 | 27 | 170 | 11 | 8330 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 26400 | 400 | 600 | 16535 | 250 | 5 | 0,5 | 0,5 | 13 | 3 | 34686 | 0,24 | 8325 |
|  | 39 | Chemical 15'-25' | 370 | 1500 | 21 | 7,636 | 13,3 | 14 | 6409 | 0,65 | 320,5 | 320 | 24683,1 | 24 | 145 | 9,5 | 6235 | 0,00045 | 260 | 2,5 | 10,9 | 1,67 | 3,17 | 14560 | 400 | 600 | 9051,3 | 250 | 5 | 0,5 | 0,5 | 11 | 5,5 | 18987 | 0,3 | 5696 |
|  | 40 | Chemical 5'-15' | 1028 | 700 | 9 | 5,528 | 12,35 | 13 | 3695 | 0,65 | 184,8 | 185 | 12301,9 | 19 | 112 | 7,8 | 3875 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 7040 | 400 | 600 | 4367,2 | 250 | 5 | 0,5 | 0,5 | 24 | 12 | 9161 | 0,3429 | 3141 |
|  | 41 | Chemical 0'-5' | 1468 | 250 | 6 | 4,37 | 11,4 | 12 | 1278 | 0,65 | 63,9 | 63,9 | 2909,87 | 12 | 65 | 4,5 | 1365 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 1440 | 400 | 600 | 945,8 | 250 | 5 | 0,5 | 0,5 | 36 | 18 | 1984 | 0,4667 | 925,9 |
| **RoRo** | 42 | RoRo 35'++ | 20 | 8500 | 31 | 4,652 | 17,1 | 18 | 20226 | 0,65 | 755,7 | 756 | 69265,8 | 32,3 | 250 | 12,5 | 14325 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 26600 | 400 | 600 | 47805 | 5000 | 5 | 0,5 | 0,5 | 12 | 12 | 44603 | 0,5529 | 24663 |
|  | 43 | RoRo 25'-35' | 49 | 4000 | 18 | 3,825 | 18,05 | 19 | 19492 | 0,65 | 737,3 | 737 | 47338,3 | 32,3 | 218 | 11,5 | 12055 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 16800 | 400 | 600 | 30442 | 5000 | 5 | 0,5 | 0,5 | 20 | 20 | 28403 | 0,6667 | 18935 |
|  | 44 | RoRo 15'-25' | 360 | 1500 | 10 | 2,957 | 18,05 | 19 | 13854 | 0,65 | 596,4 | 596 | 33004,4 | 32,2 | 185 | 11,3 | 10138 | 0,00045 | 190 | 2,5 | 10,9 | 1,67 | 3,17 | 10920 | 400 | 600 | 19898 | 5000 | 5 | 0,5 | 0,5 | 35 | 35 | 18565 | 0,7778 | 14439 |
|  | 45 | RoRo 5'-15' | 678 | 700 | 6 | 2,49 | 17,1 | 18 | 9735 | 0,65 | 486,8 | 487 | 17719,2 | 25 | 150 | 7 | 5850 | 0,00045 | 210 | 2,5 | 10,9 | 1,67 | 3,17 | 5670 | 400 | 600 | 10551 | 5000 | 5 | 0,5 | 0,5 | 50 | 50 | 9844 | 0,8 | 7875 |
|  | 46 | RoRo 0'-5' | 1303 | 300 | 3 | 1,337 | 11,4 | 12 | 2502 | 0,65 | 125,1 | 125 | 2368,67 | 15,6 | 85 | 4,5 | 2091 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 700 | 400 | 600 | 1384,7 | 5000 | 5 | 0,5 | 0,5 | 95 | 95 | 1292 | 0,8333 | 1077 |
| **LNG** | 47 | LNG 60'++ | 229 | 8000 | 31 | 9,25 | 19 | 20 | 27087 | 0,65 | 927,2 | 927 | 104021 | 40 | 250 | 11 | 15500 | 0,00045 | 285 | 2,5 | 10,9 | 1,67 | 3,17 | 74250 | 400 | 600 | 56977 | 250 | 5 | 0,5 | 0,5 | 6 | 6 | 76346 | 0,3625 | 27675 |
|  | 48 | LNG 30'-60' | 18 | 5000 | 24 | 7,625 | 17,1 | 18 | 15969 | 0,65 | 649,2 | 649 | 64632,3 | 39 | 220 | 10 | 12980 | 0,00045 | 285 | 2,5 | 10,9 | 1,67 | 3,17 | 42570 | 400 | 600 | 33266 | 250 | 5 | 0,5 | 0,5 | 8 | 8 | 44574 | 0,45 | 20058 |
|  | 49 | LNG 15'-30' | 8 | 1500 | 14 | 6,893 | 17,1 | 18 | 12536 | 0,65 | 563,4 | 563 | 37493,5 | 25 | 165 | 9,2 | 7161 | 0,00045 | 285 | 1 | 4,7 | 1,6 | 3,17 | 22770 | 400 | 600 | 18199 | 250 | 5 | 0,5 | 0,5 | 14 | 14 | 24386 | 0,5375 | 13107 |
|  | 50 | LNG 0'-15' | 10 | 700 | 9 | 7,361 | 15,2 | 16 | 5798 | 0,65 | 289,9 | 290 | 13774,4 | 18 | 119 | 8 | 4046 | 0,00045 | 285 | 1 | 4,7 | 1,6 | 3,17 | 8118 | 400 | 600 | 6424,9 | 250 | 5 | 0,5 | 0,5 | 18 | 18 | 8609 | 0,6 | 5165 |
| **LPG** | 51 | LPG 45'++ | 118 | 5000 | 21 | 4,889 | 16,15 | 17 | 13401 | 0,65 | 585 | 585 | 71698,8 | 37,2 | 222 | 11,2 | 13231 | 0,00045 | 230 | 2,5 | 10,9 | 1,67 | 3,17 | 50490 | 400 | 600 | 31519 | 250 | 5 | 0,5 | 0,5 | 9 | 9 | 53262 | 0,3462 | 18437 |
|  | 52 | LPG 25'-45' | 68 | 2500 | 15 | 5,077 | 16,15 | 17 | 11398 | 0,65 | 535 | 535 | 46481,5 | 31 | 180 | 10,8 | 9468 | 0,00045 | 230 | 2,5 | 10,9 | 1,67 | 3,17 | 31680 | 400 | 600 | 19866 | 250 | 5 | 0,5 | 0,5 | 13 | 13 | 33570 | 0,3846 | 12912 |
|  | 53 | LPG 15'-25' | 60 | 1500 | 11 | 4,824 | 15,2 | 16 | 8657 | 0,65 | 432,9 | 433 | 27740,2 | 23 | 150 | 10,5 | 6600 | 0,00045 | 230 | 2,5 | 10,9 | 1,67 | 3,17 | 18117 | 400 | 600 | 11400 | 250 | 5 | 0,5 | 0,5 | 17 | 17 | 19264 | 0,44 | 8476 |
|  | 54 | LPG 5'-15' | 205 | 700 | 7 | 5,171 | 14,25 | 15 | 4857 | 0,65 | 242,9 | 243 | 11977,5 | 19,8 | 112 | 8,8 | 4189 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 7524 | 400 | 600 | 4725,4 | 250 | 5 | 0,5 | 0,5 | 24 | 17 | 7985 | 0,5 | 3993 |
|  | 55 | LPG 0'-5' | 652 | 200 | 4 | 3,932 | 12,35 | 13 | 1825 | 0,65 | 91,25 | 91,3 | 3385,6 | 16 | 88 | 6 | 2464 | 0,00045 | 260 | 1 | 4,7 | 1,6 | 3,17 | 1980 | 400 | 600 | 1252,2 | 250 | 5 | 0,5 | 0,5 | 37 | 37 | 2116 | 0,6 | 1270 |
| **Sea River** | 56 | Sea River 5'++ | 24 | 500 | 7 | 2,719 | 11,4 | 12 | 2224 | 0,65 | 111,2 | 111 | 10023,5 | 16 | 132 | 5 | 3432 | 0,00045 | 210 | 1 | 4,7 | 1,6 | 3,17 | 6300 | 400 | 600 | 4406,4 | 250 | 5 | 0,5 | 0,5 | 38 | 19 | 7446 | 0,3462 | 2577 |
|  | 57 | Sea River 1'-5' | 433 | 400 | 6 | 2,717 | 10,45 | 11 | 1214 | 0,65 | 60,7 | 60,7 | 3429,69 | 13,5 | 108 | 4,2 | 2365 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 1870 | 400 | 600 | 1465,8 | 250 | 5 | 0,5 | 0,5 | 40 | 20 | 2477 | 0,3846 | 952,7 |
|  | 58 | Sea River 500-1' | 50 | 200 | 4 | 3,04 | 9,5 | 10 | 915 | 0,65 | 45,75 | 45,8 | 974,88 | 15 | 95 | 3,5 | 2090 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 510 | 400 | 600 | 400,64 | 250 | 5 | 0,5 | 0,5 | 50 | 25 | 677 | 0,44 | 297,9 |
|  | 59 | Sea River 100 - 500 | 156 | 100 | 3 | 2,758 | 9,5 | 10 | 472 | 0,65 | 23,6 | 23,6 | 381 | 7,5 | 34 | 2 | 391 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 170 | 400 | 600 | 150,31 | 250 | 5 | 0,5 | 0,5 | 65 | 30 | 254 | 0,5 | 127 |
|  | 60 | Sea River 0 - 100 | 506 | 100 | 2 | 2,148 | 11,4 | 12 | 261 | 0,65 | 13,05 | 13,1 | 12,8 | 3 | 10 | 1 | 50 | 0,00045 | 230 | 1 | 4,7 | 1,6 | 3,17 | 4,25 | 400 | 600 | 4,7342 | 250 | 5 | 0,5 | 0,5 | 100 | 42 | 8 | 0,6 | 4,8 |

## 7.4 Additional figures

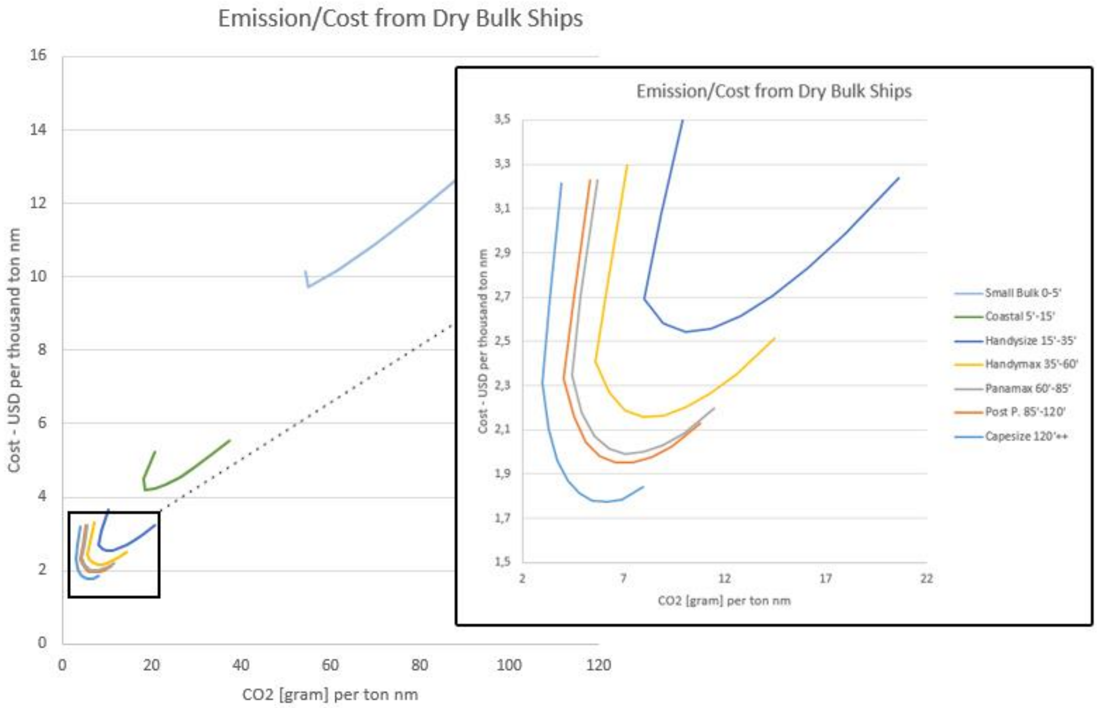

Figure 13: Emission cost graph of Dry Bulk vessels, in full scale and zoomed in to area of interest

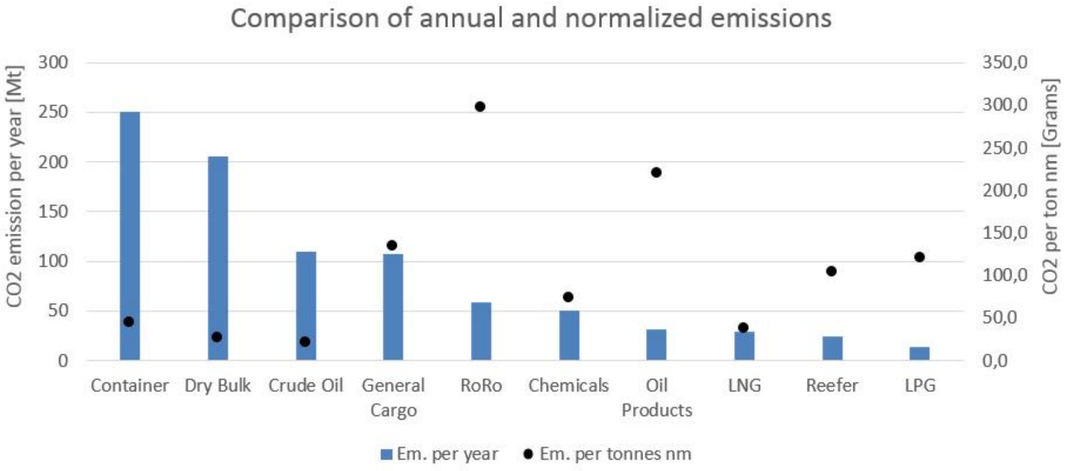

Figure 14: Comparison of weighted averages of annual and normalized emissions.