Assessing Alternative Fuel Types for ULCVs in Face of Uncertainty

SDPO.20.037.m

Kaan Terün

Technische Universiteit Delft

Assessing Alternative Fuel Types for ULCVs in Face of Uncertainty

SDPO.20.037.m

by

Kaan Terün

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday December 2, 2020 at 1:30 PM.

Student number:	4233085	
Project duration:	January 29, 2020 – December 2, 2020	
Thesis committee:	Prof. dr. ir. J. J. Hopman,	TU Delft, chair
	Dr. A. A. Kana,	TU Delft, supervisor
	Dr. ir. J. H. Kwakkel,	TU Delft
	Dr. V. Reppa,	TU Delft
External member:	Prof. dr. ir. R. Dekker,	EUR, advisor

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Abstract

The International Maritime Organization forecasts that greenhouse gasses produced by ships will increase rapidly in the near future, unless precautions are taken now. This will require all ships to reduce their emissions, especially container vessels which are producing the most emissions. One way of reducing emissions, with existing technology, is to switch to alternative fuels. Making this switch is risky as there are many economic and regulatory uncertainties, which the ship has to survive over its lifetime. This makes it difficult to see which alternative fuel is a better option or not. There is no existing study which makes a comparison between alternative fuels which also takes future uncertainty into account.

The aim of this study is to develop an approach to assess alternative fuel types for robust ultra large container vessels, while taking economic and regulatory uncertainty into account. For this purpose, Robust Decision Making was chosen as the most suitable method. A method which has been used in different areas, but will be implemented for the first time for a subject relating to ship design. Implementing this method required the development of a parametric design tool for ultra large container vessels.

Results show that liquefied natural gas is the most robust option amongst the considered alternative fuels. It would have a good economic performance, while reducing emissions. Non-carbon fuels, such as hydrogen and ammonia, would practically eliminate emissions but do not perform well financially.

Preface

I am proud and honoured to present you this thesis, which is the product of my academic endeavours. I have attended many courses throughout my Bachelor and my Master. During this process I have learned a lot about the different aspects of the maritime world. This thesis made me combine all of this knowledge and made me appreciate the education that I got at the TU Delft.

Writing this thesis was not always easy, I had my rough patches as many, undoubtedly, had before me and will have in the future. Starting with this thesis was one of these rough patches. Finding a topic, which interests me personally and would be a valuable contribution to society was not easy, but I am glad that I did it. It resulted in a thesis with which I can identify myself and of which I am proud. I can only advise to all master students, who are in search for a thesis topic, to find a topic, which they personally find interesting, instead of taking the first available one. It is tempting to do so, because it is easier and quicker but I doubt that it will be as satisfactory as doing a subject that you truly find interesting.

Besides combining the knowledge that I have gathered during my studies, I have also learned a lot during the period of writing this thesis. Naturally, I learned many theoretical things that were not directly linked with my studies, such as uncertainty modelling and programming. But I have also learned more general skills. I learned that you have to come to acceptance to limit your work, that you can not include every aspect. This was not always easy as I tend to be a perfectionist and would like to make everything as accurate as possible, but you also have to follow a planning such that you can achieve the goals that you have set.

I would like to express my gratitude to my supervisor Dr. Austin Kana. His guidance and feedbacks were invaluable and insured the success of this thesis. I could not have wished for a better supervisor. I would like to thank Prof. Hans Hopman for his valuable comments. I would like to acknowledge Prof. Rommert Dekker who gave me the initial idea for this thesis and helped me with his remarks. I would also like to thank Dr. Jan Kwakkel and Dr. Vasso Reppa for being in my thesis committee.

Furthermore, I would like to thank my dear friend Ali, who was always kind enough to answer my questions regarding programming. My gratitude also goes to Can and Nazlı, who have supported me throughout my studies and were always available for inspiring discussions. My Master's Degree would have been boring without my friends Lorenzo, Pietro, Daniel, Spyros, and Alfredo. I am thankful for your support and all the joyful time that we had together. Finally, I would like to thank my parents and my family for their unconditional support throughout my life. I would not be here, nor be the man that I am without them. They gave me all possible opportunities and encouraged me in pursuing my dreams and goals, for this I am truly grateful and deeply indebted.

Kaan Terün
Delft, November 2020

Contents

Nomenclature

AFC	Alkaline Fuel Cell
BAU	Business-as-usual
CAPEX	Capital Expenses
CCS	Carbon Capture and Storage
DWT	Deadweight Tonnage
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
GT	Gross Tonnage
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
LBP	Length Between Perpendiculars
LCV	Lower Calorific Value
LNG	Liquefied Natural Gas
LOA	Length Overall
LPG	Liquefied Petroleum Gas
LS-HPDF	Low Speed - High Pressure Dual Fuel
MDO	Marine Diesel Oil
NPV	Net Present Value
NT	Net Tonnage
PEMFC	Proton Exchange Membrane Fuel Cell
RD&D	Research, Design and Development
SCFI	Shanghai Containerized Freight Index
SFOC	Specific Fuel Oil Consumption
SGC	Specific Gas Consumption
SOFC	Solid Oxide Fuel Cell

SPOC	Specific Pilot Oil Consumption
STS	Ship to Shore
TTW	Tank-to-Wake
ULCV	Ultra Large Container Vessel
VLSFO	Very Low Sulphur Fuel Oil
WTT	Well-to-Tank
WTW	Well-to-Wake

Institutions

DNV GL	Det Norske Veritas Germanischer Lloyd
EU	European Union
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
LR	Lloyd's Register
MARIN	Maritime Research Institute Netherlands
MEPC	Marine Environment Protection Committee
T&E	Transport & Environment
UMAS	University Maritime Advisory Services
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WLPGA	World Liquefied Petroleum Gas Association

Methods

AHP	Analytic Hierarchy Process
EEA	Epoch-Era Analysis
EOA	Engineering Option Analysis
IG	Info-Gap Theory
MDP	Markov Decision Process
MORDM	Many Objective Robust Decision Making
RDM	Robust Decision Making
ROA	Real Option Analysis

Symbols

δ	Fullness of ship
η_H	Hull efficiency
η_O	Open water efficiency
η_R	Relative rotative efficiency

η_S	Shaft efficiency
π	Profit
A_{BT}	Transverse sectional area of the bulb
B_{est}	Estimated length of ship
C_{ABT}	Cross-section parameter
C_{FAE}	Conversion factor between fuel consumption and CO_2 emission auxiliary engine
C_{FME}	Conversion factor between fuel consumption and CO_2 emission main engine
C_{WP}	Waterplane area coefficient
D	Distance
F_n	Froude number
f_c	Cubic capacity correction factor
f_{eff}	Factor of each innovative energy efficiency technology
f_i	Capacity factor for technical/regulatory limitation on capacity
f_j	Ship specific design elements
f_l	Factor for general cargo ships equipped with cranes and other cargo-related gear
f_w	Factor for speed reduction at sea
h_B	Height of the centre of the transverse sectional area of the bulb
h_{TEU}	Height of a 20 feet container, 2.59 m
L_{bh}	Horizontal length of a bulkhead
L_{dh}	Horizontal length of the deckhouse
L_{engine}	Horizontal length of the engine
L_{est}	Estimated length of ship
L_{fs}	Length of the foreship section
L_{funnel}	Horizontal length of the funnels
L_{oa}	Length overall
L_{pp}	Length between perpendiculars
L_{tank}	Length of the fuel tank
l_{TEU}	Length of a 20 feet container, 6.1 m
lcb	Longitudinal centre of buoyancy
n_{TEU}	Number of TEUs on ship, Capacity
P_B	Brake power
P_E	Effective towing power
P_{AE}	Power of auxiliary engines
P_{AEeff}	Innovative mechanical energy efficient technology for auxiliary engine

P_{eff}	Innovative mechanical energy efficient technology for main engine
P_{fuel}	Price of fuel
P_{ME}	Power of main engines
P_{PTI}	Power of shaft motor
P_{PTO}	Power of shaft generator
R	Ship resistance
r_f	Freight rate
SFC_{AE}	Specific fuel consumption of auxiliary engines
SFC_{ME}	Specific fuel consumption of main engines
t	Thrust deduction
v_s	Ship speed
V_{ref}	Ship speed
w	Wake factor
w_{TEU}	Width of a 20 feet container, 2.44 m
x_b	Number of bays
x_r	Number of rows
Cap	for container ships 70% of DWT

Units

J	Joule
nm	Nautical miles
rpm	Rotations per Minute
t	tonnes
TEU	Twenty-foot Equivalent Unit
uE	Unit of Energy
uM	Unit of Mass
USD	United States Dollar

1
Introduction

In ancient times, when civilizations started to grow and centralized governments started to rise, transportation and logistics became more important. Capitals needed to send commands to the outskirts of the empire and resources had to come to the capital to nourish it and to make it grand. On land, this was done by horses and the invention of the wheel was groundbreaking. On water, ships were used, not only for nourishment but also for grandeur. The ancient Egyptians built the pyramids with the granite stones, which had been transported by ships/barges [18].

Figure 1.1: A Phoenician torpedo jar found in a shipwreck [43]

As empires grew, they started trading. One of the greatest traders were the Phoenicians who built a thalassocratic empire through their superior merchant fleet. They also changed how trade was done by standardizing the containers with which the products were transported. They introduced torpedo jars [43], one example can be seen in Figure 1.1. These jars guaranteed a volume of 4 hekats (1 hekat = 4.8 litres), the standard liquid trade unit of the time. Many centuries later, a similar standardization would be made: the container. The container not only changed how goods were transported, but also created a new type of ship: the container vessel. With time these ships also grew and some contemporary container ships are 400 m long, can carry more than 23,000 TEU and are called ultra large container vessels (ULCV) [63].

Today, container vessels are an essential part of world trade and logistics, as 90% of non-bulk cargo is transported by container ships worldwide [78]. Subsequently, container shipping is a large, competitive market. Having insight on the mechanics of container ships and a good forecast for the future is valuable for any economist, shipbuilder or shipper.

There is no doubt that container ships will form the future. However they are also part of a problem, which will shape the future and have an impact on how shipping is going to be done. Ships and other anthropogenic sources produce a lot of emissions. These emissions create a greenhouse effect, which causes the atmosphere and the planet to warm up. This is also known as "global warming" or "climate change". Global warming will cause an increase in weather extremes, i.e., heat waves, heavy precipitation, tropical cyclone intensity, etc. Furthermore, due to climate change, ecosystems will change and cause some animal species (up to 30%) to go extinct; as polar ice melts, water levels will rise. Obviously, humans will also be affected by this. Food production will be affected from climate change and global food shortages could be caused. Additionally, morbidity and mortality will increase due to heat waves, floods, and droughts [140].

The imminent danger and consequences of global warming have been acknowledged by many states and institutions, and they are taking a stance to combat this global crisis. The first step was taken as early as 1992, with the foundation of the United Nations Framework Convention on Climate Change (UNFCCC), which has 197 parties [151]. It has lead the way to international treaties such as the Kyoto Protocol and the Paris Agreement.

Even though steps are being taken, there are a lot of uncertainties involved. Political uncertainties concern policies and regulations, which got worse with the United States of America (USA) declaring that they would quit the Paris Agreement [98]. Nonetheless, new policies will be introduced, but it is uncertain how fast and how harsh. Besides political uncertainties, there are also technical and economic uncertainties. Technical uncertainties concern the rate of development of emerging technologies, i.e., how fast a specific invention will improve, such that it can be applied on bigger scale. Fuel cells are a good example for this, they are being used on smaller scale but they will not reach a point where it is feasible to use them on larger scale, in the foreseeable future [9]. This brings us to economic uncertainties, because feasibility can be technical and/or economic. Fuel prices, trade growth and demand, and freight rates are economic uncertainties, which have an influence on investments, operational measures, etc.

Former United States Secretary of Defense Donald Rumsfeld once famously said [129]:

> "... there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know."

The topic at hand has many known unknowns; we know that there will be new policies, we know that technology will develop, we know that prices will change, but we do not know exactly when and how. Then, there are also unknown unknowns; we do not know if there will be a new groundbreaking technology, we do not know if there will be an economic crisis, we do not know if politicians that support environmental policies, will be elected. These unknowns or uncertainties make it so difficult to make a good forecast on this topic or give advice on it. Simply running deterministic models about the future of shipping will not give accurate results, as there are to many unknowns to make good assumptions. The problem at hand requires a good method for handling uncertainty.

There are many ways of reducing anthropogenic emissions, some indirectly (through policies) and some directly (through technology, operational improvements and fuels). Policies can motivate or force stakeholders to do certain things, which would reduce emissions. While technology and operational improvements can improve the overall efficiency of ships and reduce emissions, as the same job is done with less energy/fuel. Alternative fuels can be "cleaner" and thus cause less emissions. Research has been conducted in all of these fields, but this thesis shows that there is a gap in the literature, on a method to compare different alternative fuel types, which have the potential of reducing emissions, for ULCVs and which also takes future uncertainties into account. This must be done with an emphasis on robustness, as this will guarantee a higher level of success. The research questions which will lead to fill this gap are as follows:

- ***What is an adequate approach to assess alternative fuel types for robust ultra large container vessels in face of uncertainty, regarding the goals of IMO for the year 2050?***
- *What are the implications of the IMO goals for 2050 on container ship requirements?*
- *Which uncertainties can be identified in this subject?*
- *What will be the effect of different alternative fuel types on the design of ULCVs?*
- *What will be the effects of fuel choice on the ship's performance in combination with changes in markets and regulations during the lifetime of the ship ?*
- *How much emission reductions will different fuel types offer and with what certainty?*

The stakeholders of this subject include shipping companies, shipyards, financiers, policymakers, and researchers (for more details see Section 2.3). All stakeholders can benefit from the results of this study and/or the method which will be developed for uncertainty modelling. Shipping companies will profit the most, among all stakeholders, as they are the ones who make profit or losses with buying and operating ships.

The following chapters will explain in detail why the questions above are important and how they were reached. Chapter 2 gives background information on ULCVs and the climate crisis, and describes the interests of the stakeholders. Chapter 3 gives an overview of the uncertainties, which are involved in this subject as well as an insight into forecasts, regarding the next 30 years of the maritime sector made by different prominent companies. Chapter 4 gives an overview of possible solutions for reducing emissions produced by ships. Chapter 5 defines the problem at hand and the scope of the project. Chapter 6 discusses how the research was planned to be conducted and available methodologies for handling uncertainties, of which one was chosen. Chapter 7 explains how the parametric design tool for ULCVs was developed. The designs generated by this tool were tested through the Robust Decision Making method. The methodology and its results have been discussed in Chapter 8. The thesis is concluded by summarizing the whole thesis and answering all research questions in Chapter 9.

2

Background

Chapter 1 has mentioned some aspects, which concern this project. This chapter will give background information on the two main aspects of the project: ULCVs and climate change. The relevancy of ULCVs will be clarified. Further, information on the climate crisis and how the global community tries to mitigate it will be explained. This provides a better understanding on why this topic is significant and relevant, which will also answer the first sub-question (see Section 5.3). Subsequently, the stakeholders of this topic will be introduced.

2.1. Ultra Large Container Vessels

As mentioned above, with the beginning of containerization the rise of container ships started. While the first container ships could only carry approximately 600 TEU, over the years ships grew. Nowadays, there are ships which can carry more than 20,000 TEU. The evolution of container ships over the decades can be seen in more detail in Figure A.1 in Appendix A.

One of the most recent subclass of container vessels is the ULCV-class. There are many definitions for what an ULCV is, but for this project any container ship which can carry more than 14,000 TEU is considered an ULCV, similarly to other references [119][145][88]. This class is growing rapidly, as can be seen from Figure 2.1. This has to do partly with economies of scale and as Haralambides [53] argues with the increasing port efficiency and productivity, which enables the (un-)loading of larger vessels quickly and efficiently.

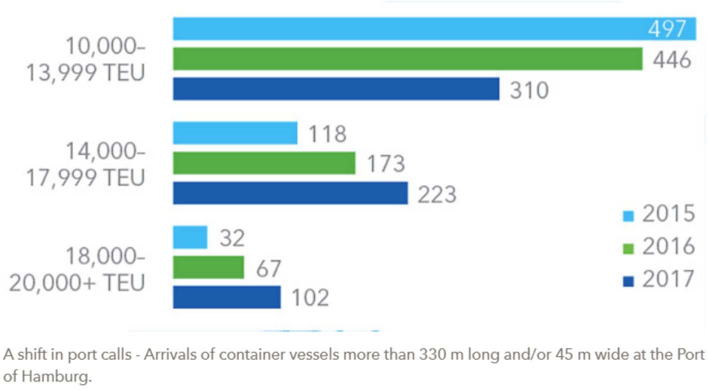


Figure 2.1: Port calls in Hamburg according to ship size [120]

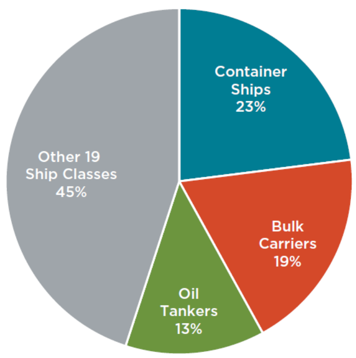


Figure 2.2: Annual CO_2 emissions by ship type [109]

As container ships' sizes increase, so do the emissions that they produce. According to IMO, ships are responsible for 2.2% of anthropogenic CO_2 on a global level [138]. Once this is divided among ship types, Figure 2.2 shows that with 23% container ships are the biggest pollutants [109], i.e., 0.5% of global CO_2 emissions. ULCVs are not necessarily more polluting than smaller container vessels, but they are the fastest growing and also fastest sailing class [109]. This is why special attention should be given to this class. Additionally, 35% of all ships consume roughly 80% of the fuel in the maritime sector, which consequently leads to proportional emissions. Container ships form a substantial part of this with 35% [34].

2.2. Climate Crisis

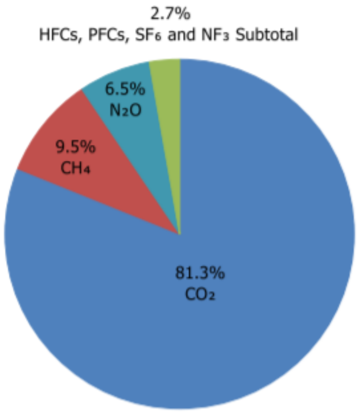


Figure 2.3: 2018 U.S. Greenhouse Gas Emissions by Gas [40]

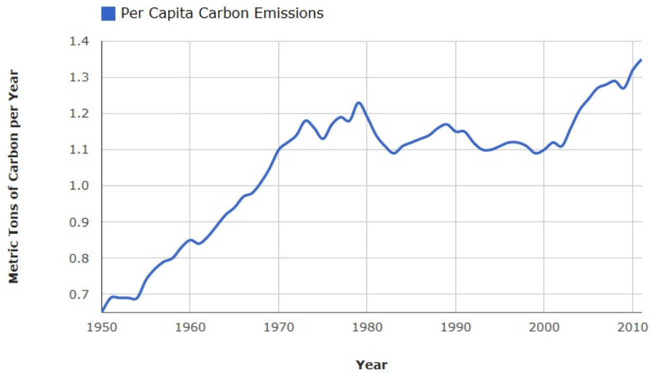


Figure 2.4: Global carbon emissions per capita over the decades [19]

As mentioned above, pollution became an issue with the advent of industrialization. There are many types of pollution, but gas pollution, which is caused by an increase in greenhouse gasses (GHG), has the most severe global effects. Figure 2.4 visualizes how carbon emissions, which are also GHG, have increased over the decades. GHG are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), chlorofluorocarbons, and hydrofluorocarbons. Figure 2.3 shows the distribution of anthropogenic U.S. GHG of the year 2018. Since 1750 the concentration of carbon dioxide, methane, nitrous oxide, and ozone in the troposphere have increased by 43%, 154%, 21%, and 42%, respectively [17]. Out of these four, ozone has the smallest global warming potential (GWP) due to its short lifespan. Nitrous oxide, on the other hand, has the highest GWP; an order of magnitude higher than methane, which can be seen in Table 2.1. The main anthropogenic sources of nitrous oxide are connected to fertilizers and manure. However, carbon dioxide and methane emissions can be tied to the maritime sector, as was mentioned above.

Table 2.1: Lifetime and GWP relative to carbon dioxide [102]

Chemical	Lifetime [Years]	GWP 20-year	GWP 100-year
Carbon dioxide (CO_2)	No Single Lifetime	1	1
Methane (CH_4)	12.4	84	28
Nitrous Oxide (N_2O)	121	264	265
Ozone (O_3)	0.06	Not Significant	Not Significant

As GHG emissions are skyrocketing and causing the globe to warm up, serious mitigation steps must be taken. The biggest step, so far, was taken on December 12, 2015, when parties to the UNFCCC made an agreement to combat climate change, also know as the "Paris Agreement". The main goal for the agreement is to keep the global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further down to 1.5°C [110].

The Paris Agreement did not set any targets for the maritime sector, but the Kyoto Protocol, which was signed in 1997, gave the responsibility for limiting GHG from ships to the International Maritime Organisation (IMO) [103].

IMO forecasts that if no measures are taken now, by the year 2050, CO_2 emissions could rise by 50 to 250% [138]. Therefore, in accordance with the Paris Agreement, during the 72nd session of IMO's Marine Environment Protection Committee (MEPC), a strategy to reduce total GHG from the maritime sector was agreed on. The goal is to reduce GHG emissions by 50% by 2050 and CO_2 emissions by 40% by 2030, and 70% by 2050 (all compared to 2008). IMO's projections for CO_2 emission according to different scenarios can be seen in Figure 2.5.

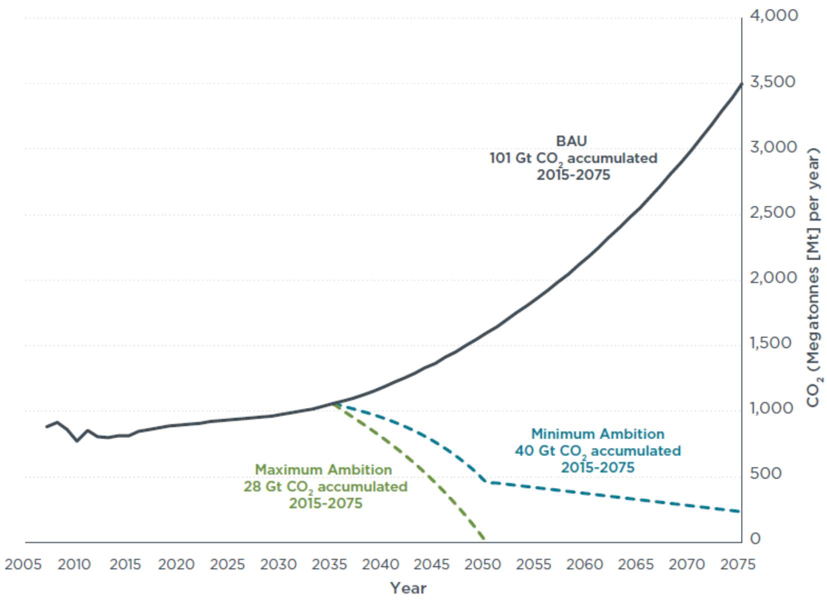


Figure 2.5: CO_2 emissions from international shipping from business-as-usual (BAU) (black) and under IMO's initial GHG strategy (blue and green) [130]

$$\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right)}{f_i \cdot f_c \cdot f_l \cdot Cap \cdot f_w \cdot V_{ref}} + \frac{\left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot f_c \cdot f_l \cdot Cap \cdot f_w \cdot V_{ref}} \tag{2.1}$$

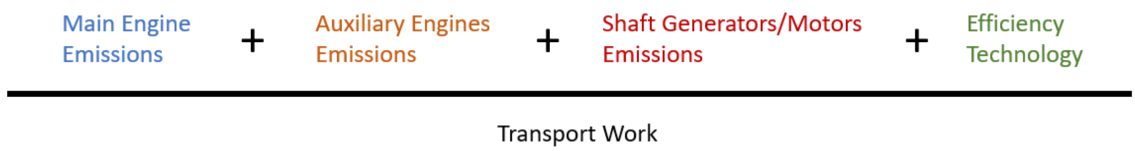


Figure 2.6: Energy Efficiency Design Index summary according to Hon and Wang [56]

IMO has introduced the Energy Efficiency Design Index (EEDI) for this purpose. The formula can be seen in Equation 2.1 [56](for the symbols, please consult the nomenclature). The EEDI has been simplified in Figure 2.6. IMO uses EEDI to reduce GHG emissions and, in accordance with the Paris Agreement, has defined phases. The most recent phase, Phase 3, will be adopted in the next session of MEPC, which was planned for the first half of 2020, but got cancelled due to the COVID-19 pandemic [60]. According to this, from 2022 on, newly built container ships will have to reduce their EEDI. Reduction rates depend on ship size, as can be seen in Table 2.2. By comparing deadweight tonnage (DWT) of ULCVs (see Appendix A, Table A.1), it has been established that they have more than 120,000 DWT, which puts ULCVs in the upper two categories in the table below. New phases of the EEDI will be reviewed by the MEPC in the future [130] but it is unknown when and what reductions these phases will bring.

Table 2.2: EEDI reduction rates according to ship size [60]

Size [DWT]	EEDI reduction
x ≥ 200000	50%
200000 >x ≥ 120000	45%
120000 >x ≥ 80000	40%
80000 >x ≥ 40000	35%
40000 >x ≥ 15000	30%

T&E [146] has analyzed 258 container ships, built between 2013 and 2017, on their EEDI performance. Results show that 71% of all container ships are already 30% below (i.e., better than) the reference line. The reference line for container vessels represents the average efficiency of container ships built between 2000 and 2010 [150]. Furthermore, as can be seen from Figure 2.7, for ULCVs (i.e., DWT larger than 120,000 t) the mean distance to the reference line is 50%. Figure 2.7 shows Phase 3 as a 30% reduction, but (as can be seen from Table 2.2) this is outdated for the bigger ships. Nonetheless, as the distance for the larger ships is still 50% from the reference line, they meet requirements, for **now**. This must be emphasized, because as mentioned above Phase 3 will be implemented in the near future, but to consider the introduction to Phase 4 has also been agreed on [60]. And further phases may also be introduced in the future, which would require bigger decreases. These decreases will be reached by more efficient ships or by cleaner ships. The analysis also shows that ULCVs are significantly technologically advanced compared to smaller container vessels [146].

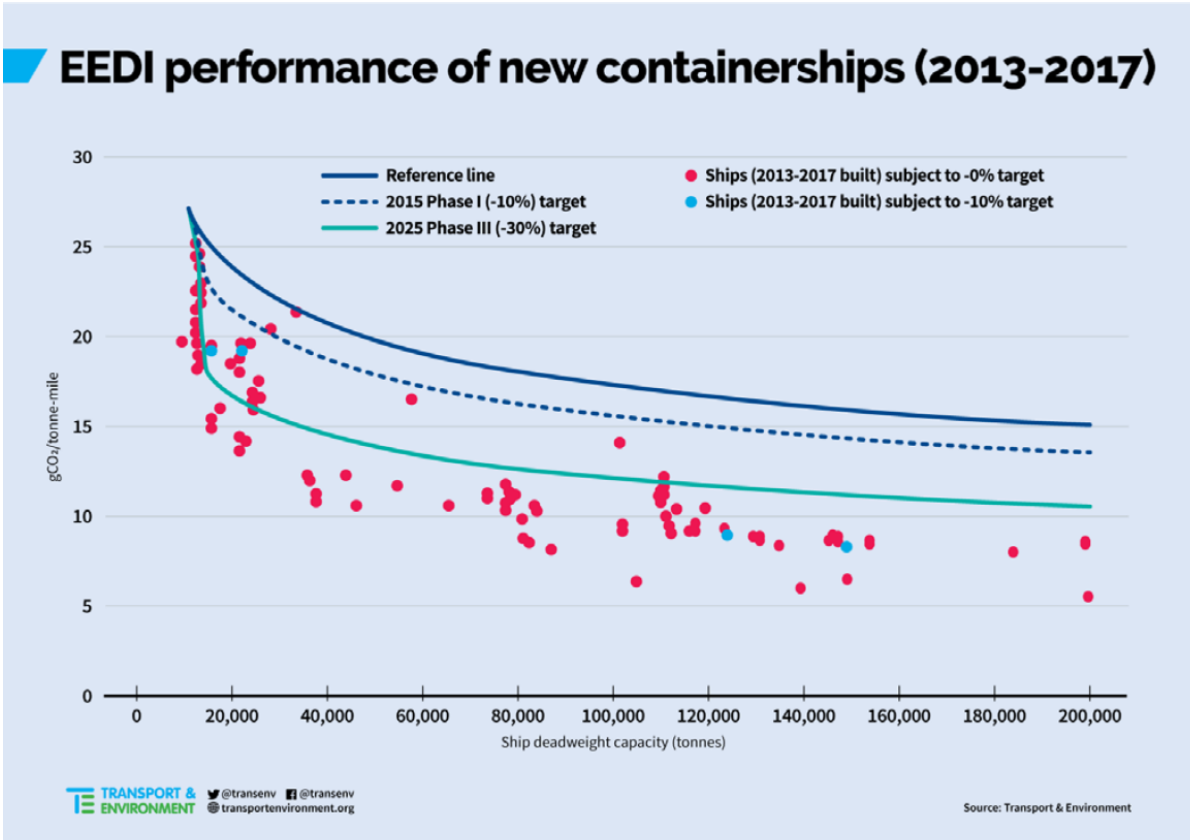


Figure 2.7: EEDI performance of newly-built container ships [146]

In addition to EEDI, there is also the Energy Efficiency Operational Index (EEOI). While the EEDI only focuses on the design of the ship, the EEOI focuses on the operational performance of the ship. The EEOI has been introduced by IMO, but its use is completely voluntary. The EEOI is calculated as seen in Equation 2.2 [59].

$$EEOI = \frac{\sum_i \sum_j (FC_{ij} \cdot C_{Fj})}{\sum_i (m_{cargo,i} \cdot D_i)} \tag{2.2}$$

Where i is the voyage number, j the fuel type, FC_{ij} the mass of consumed fuel j at voyage i, C_{Fj} the fuel mass to CO_2 mass conversion factor for fuel j, $m_{cargo,i}$ the amount of cargo (in TEUs) carried at voyage i, and D_i the distance (in nautical miles) the cargo was transported at voyage i. The unit of EEOI is tonnes CO_2 per TEU times nautical miles.

The problem with the EEDI is that it only focuses on the design of the ship, but it does not indicate anything about how the ship then operates. The EEOI, on the other hand, only considers the operational part, thus has a more direct result. The reason why the EEDI is preferred is, most likely, the fact that it can be enforced more easily.

2.3. Stakeholders

The previous sections have given a general background on the topic. This already gave a first impression of the possible stakeholders. This section will give a detailed overview of different stakeholders, who are tied to this topic and would benefit from the results of this project.

2.3.1. Shipping Companies

Shipping companies and ship owners are the ones who operate the ships, with the goal of making profits. They will also make orders for new ships in the near future. It is in their interest to own ships which can survive turbulent times and stay profitable, regardless of what may come. Thus, knowing what kind of fuel type is robust is valuable information for them.

2.3.2. Shipyards

Shipyards are going to design and build the ships according to the wishes of the shipping companies. The better their designs are, i.e., the more profitable for the shipping company, the better their reputation will be. A shipyard with a superior reputation will attract more customers and the company will benefit from this. Furthermore, knowing which fuel type might become dominant in the future can help in adjusting production in that way and acquire know-how in producing these types of systems.

2.3.3. Financiers

Financiers, financial institutions, and investors have started to adopt plans to finance 'green' projects and shrink their carbon footprint [86]. These financiers would like to know which 'greener' fuel types have a future. With this insight they can make decisions on whether to invest in a project, i.e., ship, or not.

2.3.4. Policymakers

Policymakers and politicians, who have the power to make new regulations for a more environmental friendly future, would benefit from knowing which alternative fuel type is a better option. Hence they could introduce subsidies to incentivize the industry to switch to robuster fuel types or as they know that reducing emission profitably is still possible, they could introduce harsher policies to cut emissions even more.

2.3.5. Researchers

Researchers can be academics or employees of institutions which conduct research in the fields of container shipping, green shipping or uncertainty modelling. Researchers from the first two fields could use the results of this study for further research, as well as applying the demonstrated model to other fields.

3
Uncertainty

The previous chapter has given an overview of the background of the subject and has shown that there are some aspects which are inherently uncertain. Uncertainty is closely tied to risk, the objectified uncertainty as to the occurrence of an undesired event [157]. Risks make it so interesting for many of the stakeholders, as they have much to lose if they make wrong decisions. For this purpose it is important to have a good understanding of the involved uncertainties. Once this has been achieved, statements of possible futures can be made. Many stakeholders are interested in methods to reduce uncertainty or are in search for forecasts, which can tell them how the future will look like, as this aids them to make better decisions. This chapter gives an answer to the second sub-question (see Section 5.3) by giving an overview of the uncertainties which are involved in this subject. Subsequently, forecasts of some of the leading institutions will be presented to evaluate how they handle the defined uncertainties.

3.1. Overview of Uncertainties

In order to get a good overview of the uncertainties, it is important to categorize them. This way, it is possible to achieve a clear vision of their effects and their relations to other aspects. Uncertainties regarding this subject can be divided into 3 main categories: political, technical, and economic. These will be discussed in more detail below.

3.1.1. Political Uncertainties

Political uncertainties or regulatory uncertainties have been partly discussed in the previous chapter. There is a general knowledge that in the upcoming years new policies will be introduced globally (by IMO) and/or locally (by sovereign states) [34]. As there are many parties involved in the creation of new policies, each with their own interests, and all lobbying for their own cause, it is uncertain how these new policies will look like. Each party is advocating their own plan, which gives an insight into the potential outcomes.

In Section 2.2, it has been mentioned that IMO will introduce new phases to reduce the EEDI more. It is unknown when it will happen and how big the reduction will be. Furthermore, reducing the speed of ships is also considered as a good measure to reduce emissions. This can be done by implementing speed limits or bunker levy, but there are discussions on which option is better, how it should be done, and when [121]. Other policy options are subsidies for new technologies or cleaner fuel types, which would encourage the investment in these. These policy options will be discussed in more detail in Section 4.2.

3.1.2. Technical Uncertainties

Technical uncertainties mainly concern the availability and the development of technologies. There are many emerging technologies which either reduce emissions directly or increase overall efficiency of ships and, thus, help to reduce emissions indirectly. Some of these have been successfully implemented on smaller scale, but are not feasible on larger scale, yet. It is uncertain either how fast these technologies will develop, which determines when technology would be ready for use or its performance, which would directly influence its uptake [34]. Different emerging technologies are discussed in detail in Chapter 4. In the same chapter, alternative fuels are also discussed. Technologies regarding their production are also important and are heavily linked to the next category of uncertainties, as production methods will determine the availability of the fuels and the price.

3.1.3. Economic Uncertainties

Economic uncertainties are related to different markets, which are connected to shipping. Some of the major uncertainties, as mentioned above, are the prices of fuels and their availability, i.e., the infrastructure of production, distribution, and storage [147]. Figure 3.1 shows how volatile oil prices can be, such as in the USA where in April 2020 negative prices where reached [137]. Furthermore, uncertainties which are directly connected to container shipping are also very important, such as trade growth, trade demand, freight rates, etc [50]. These determine the profitability of shipping and affect the uptake of new technologies and the investments made in them. They are also related to political uncertainties, as they have direct effects on profitability.

Figure 3.1: US oil prices over the years [137]

3.2. Forecasts

The above mentioned uncertainties make it difficult for decision makers to make plans for the future. This is the reason why many institutions develop their own methods/models to handle these uncertainties and make forecasts for their customers (i.e., shipping companies, shipyards, etc.) who use this information for investments or other decisions.

There are many forecasts, some publicly available, some not. Some forecasts are made by governmental agencies and focus on national goals [44], some by inter-governmental organizations [62], and some by commercial institutions, especially classification societies. Two of these forecasts will be discussed in detail below, specifically the forecasts of Det Norske Veritas - Germanischer Lloyd (DNV GL) and Lloyd's Register (LR), as their main focus is on ships.

3.2.1. Det Norske Veritas - Germanischer Lloyd (DNV GL)

DNV GL is the world's largest ship classification society, but also offers technical advice and risk management to companies. 70% of their business is connected to energy, i.e., Oil&Gas, and Renewables&Power. Therefore, the energy transition (from "dirty" to "clean") and the transport of energy are key interests of DNV GL and their customers. This is the reason why DNV GL has made an extensive forecast for 2050 with a focus on the energy transition [32]. In this research, energy transition is discussed on a global level. In combination with this, a forecast focused on the maritime sector has also been published [33].

DNV GL has made many assumptions to handle the uncertainties involved. DNV GL acknowledges that there are many different forecasts for gross domestic product (GDP) and propose their own method. DNV GL has divided the world in 10 regions, for which forecasts for population and productivity growth are done.

By multiplying population with productivity, the GDP of the regions is calculated. DNV GL assumes that productivity slows down as economies reach maturity, while fertility is linked with urbanization and socio-economic development of the regions, where non-urban, less developed regions have a higher fertility. DNV GL does not take technological breakthroughs into account, while the uptake of emerging technologies is taken partly. DNV GL assumes that new policies to encourage the transition to "greener" energies will be introduced, on regional levels. Carbon pricing will increase in all regions, but will remain lower than USD 60/t CO_2, globally, until 2050.

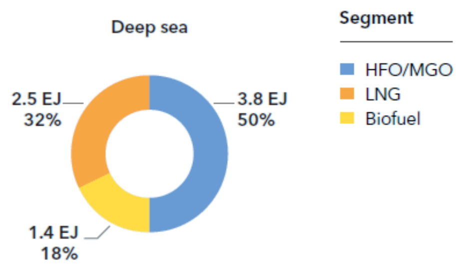


Figure 3.2: Fuels types used by deep sea-going ships in 2050 [33]

The model that DNV GL uses is a deterministic model. DNV GL uses historical data and "good judgement" to determine important parameters. Parameters, which are both uncertain and important, are tested in sensitivity analyses. DNV GL acknowledges that the future will not be precisely as forecasted, but believes in a "most likely" scenario.

According to their forecast, ship speed on average will decrease by 5%, which will also reduce fuel consumption by 10%, compared to 2015. The specific reason for the speed reduction is not given in the report, but it can be assumed that it is due to slow steaming in order to reduce emissions. Fuel consumption in general will decrease by 18% due to more efficient ships. In the year 2050, it is expected that 50% of deep seagoing vessels will be using HFO/MDO, 32% LNG/LPG, and 18% biofuel, as seen in Figure 3.2. Batteries will not be an actor for deep seagoing vessels, but a small actor in short sea shipping. This comes from their assumption, that batteries are only capable of powering smaller vessels with low fuel consumption [34]. All this will lead to approximately 25% decrease in CO_2 emissions, which can be seen in Figure 3.3. This will not suffice to achieve the goals of the Paris Agreement. As mentioned, the average speed will decrease, which would require more ships to accommodate the lost capacity, on the other hand, ships grow in size which annuls the effect of the former. There will be a decrease in ship numbers, but this will be due to the increase in utilization of ships, as it has been visualized in Figure 3.4.

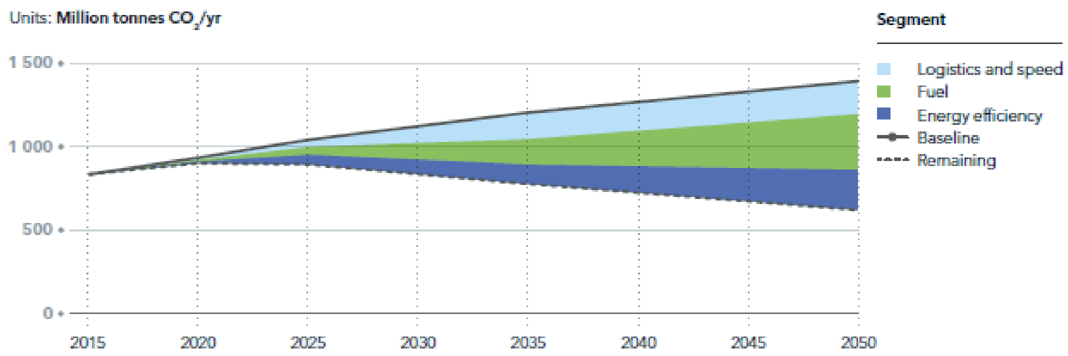


Figure 3.3: Effect of different aspects on CO_2 emissions due to ships [33]

Container trade will grow with 3.2% until 2030 and from there on with 2.1%. This growth is directly linked with the growth of economies globally. The container fleet (in DWT) will grow by 66% by 2030, and by 143% by 2050. This growth will be possible with a growth in number of ships, but also the average size of a container vessel will grow by 30%.

A key aspect with which DNV GL concludes their report is carbon robustness and carbon robust ships. Any ship which will be built today or in the near future will have to adapt to drastic changes. These changes could be, for example, due to market or regulatory changes or due to a technological breakthrough. Their advice for companies is to build carbon robust ships, which can be flexible in fuel, speed, cargo, etc. in order to adjust and mitigate the risks. Their definitions of robustness and flexibility slightly differ from the ones made in Section 6.2.

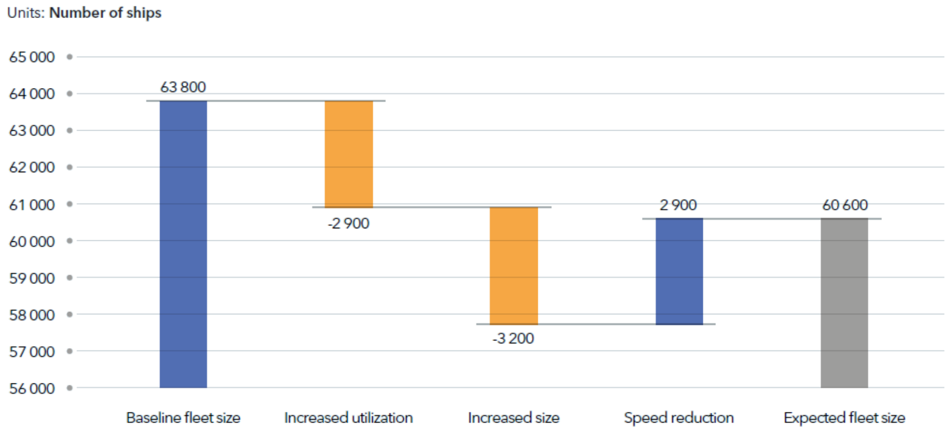


Figure 3.4: Fleet size by the year 2050 [33]

3.2.2. Lloyd's Register (LR)

LR in combination with the University Maritime Advisory Services (UMAS) have written about pathways which lead to zero-emission ships [84]. LR has a different approach compared to DNV GL, which is already made clear at the beginning of their report:

> "**At this point in time, there is too much uncertainty to decide on one route for the future transition of the shipping industry.** So, to reduce uncertainty, one way is to look at future projections and explore the potential of a combination of different technologies and fuels."

This is why LR has chosen to describe different pathways/scenarios. LR has used the method 'backcasting', first proposed by Dreborg [39]. To summarize what the method does; one starts with an initial position in the future, typically a desired goal, and then reaches today by taking steps backwards. By doing so different pathways are created, according to the proposed initial positions.

There are some main assumptions, made for all pathways. LR assumes that fossil fuels will gradually phase out and zero-carbon fuels will dominate the market. By 2030, zero-carbon fuel prices will become competitive with fossil fuels, which will have an additional carbon price. As alternative fuels are less energy dense than conventional fuels, it is assumed that rather than losing a lot of space to storage, vessels will store less energy and stop more frequently to refuel. Furthermore, LR does not see batteries playing a big role on larger scale due to high storage cost of batteries, i.e., fully electric vessels will not be competitive on larger scale. LR also expects that IMO will become more stringent with regulations and that the number of "climate-aligned" financiers, i.e., financiers who see the risk of climate change and invest accordingly, will increase.

LR envisions three possible pathways to zero-emission vessels, the main results can be seen in Figure 3.5. The first one is dominated by renewable energy sources (in 2050). This means that more than 50% of the consumed fuel will be hydrogen, ammonia, methanol, etc. which is produced by renewable electricity, while the rest is biofuels, and hydrogen and ammonia, produced by LNG with carbon capture and storage (CCS) technologies. Fuel cells and storage systems are seen as the biggest challenges. The development of these will determine the dominance of fuel cells or internal combustion engines and the fuel type. Furthermore, LR emphasises, for all pathways, that batteries play a small role, especially in deep sea shipping, due to high costs and low energy volumetric density.

The second pathway is dominated by bio-energy, i.e., bio-gas oil, bio-methanol, and bio-LNG. Thus, about 60% of energy sources will be bio-energy and the rest will be renewable electricity and fossil fuels with(out) CCS (in 2050). Key issue in this pathway is the reduction of biofuel prices. This reduction should be approximately 22% by 2030 with a carbon price of 50 $/tonne or about 41% without a carbon price.

The last pathway is equally dominated by zero-carbon fuels; renewable energy, bio-energy, and natural gas with CCS dominate the market, while fossil fuels without CCS have about 10% of the market share (in 2050). Key element of this pathway is the consistent growth of all alternative energy sources. Another important aspect is the development of CCS technologies, such that natural gas can stay a sustainable energy source.

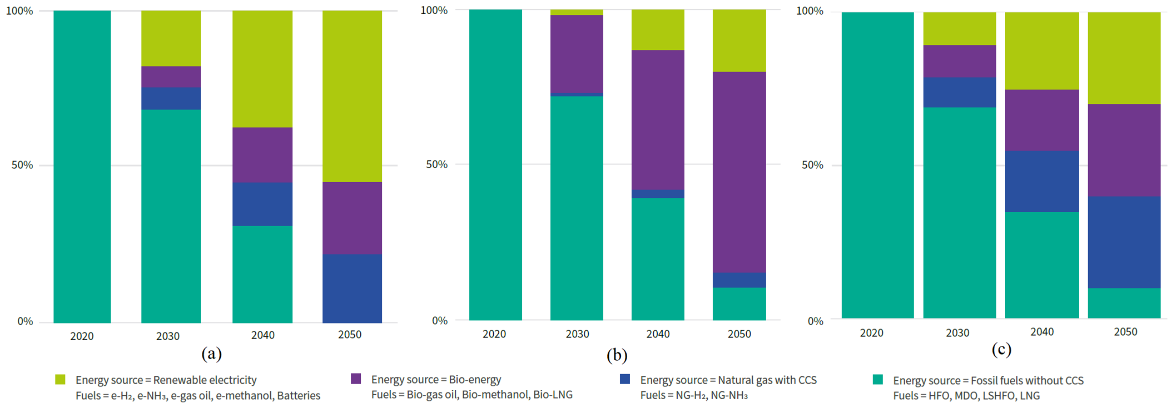


Figure 3.5: Energy source and marine fuels mix of LR's pathways: Renewables dominates (a), Bio-energy dominates (b) , Equal mix (c) [84]

LR concludes with saying that the uncertainty surrounding the fuel of the future, its price, and credentials of sustainability delays critical decisions, which will shape the future of the maritime world. One big contributor to this process will be policymakers, as their policies encourage investments, and research, design and development (RD&D).

3.2.3. Conclusion

DNV GL and LR, both, acknowledge the fact that the future of the maritime world is highly uncertain. LR goes one step further and rather than making a forecast, suggests possible pathways. DNV GL, on the other hand, has developed a deterministic model to forecast the future, but underline the fact that their results are only a more likely outcome and not necessarily precise.

LR's pathways are possible scenarios. LR heavily depends on the goal of each pathway. LR defines what would liked to be reached and then sees what pathway would lead to that point. The pathways might not be accurate, furthermore these points may never be reached. LR's work is limited by their own judgement, which is also the same for DNV GL. DNV GL has developed a deterministic model, which relies on historic data and their own "best judgement". DNV GL has experts in this field, without a doubt, but history has shown that experts' judgements have often misled them and understanding the future may be much more complex than expected [16][144].

This makes it clear that the most critical part of any study which concerns the future of the maritime sector (or any other sector for that matter), is a rigorous treatment of uncertainty. Especially in cases, such as this one, where there are many uncertainties (i.e., economic, technical, political) involved.

4
Emission Abatement

Chapter 3 has mentioned the uncertainties regarding this topic. Uncertainties which have a more direct effect on the reduction of emissions are technical and political. Therefore, it is important to have a good understanding of the technical and regulatory aspects. There are many possible ways to reduce GHG emissions produced by ships. Some solutions are more evolved, while others show great potential, but are still in their early beginnings. An overview of the main emission abatement options can be seen in Figure 4.1. First operational and technical abatement will be discussed, then new policies, and lastly alternative fuels. The last part will answer a part of the third sub-question, as defined in Section 5.3.

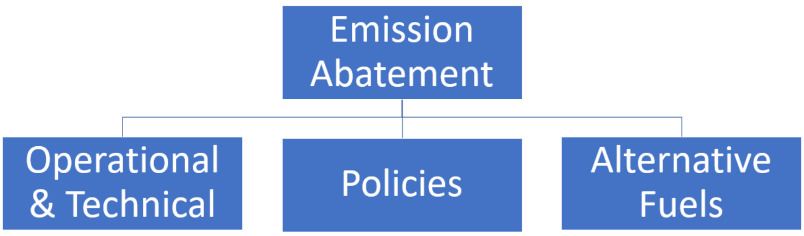


Figure 4.1: A general overview of emission abatement options

Before evaluating different options, it is important to know the magnitude of propulsion power. This will allow to make a judgement of the technical feasibility of an option. Looking at a selection of ULCVs (see Appendix A, Table A.1), it can be seen that the average main engine power is about 64,000 kW. T&E [146] supports this with similar results. This also puts the claims, made in Chapter 3, that batteries do not have an immediate future in deep sea going vessels into perspective. Due to the low energy volumetric density of batteries, the lost cargo capacity to batteries, in combination with its high cost make it economically unfeasible. For example, CMA CGM Benjamin Franklin (about 18,000 TEU) carries approximately 17 million litres of HFO [45], which is the equivalent of 69.8 TJ of energy. Even with the most energy dense lithium-ion battery, which have an energy density of 1,400 MJ/m^3 [80], it would require a volume of about 500,000 m^3 of batteries, which is the equivalent of 15,000 TEU (1 TEU = 33.2 m^3). The equivalent of the HFO is approximtely 510 TEU, which shows why batteries are not feasible.

4.1. Operational and Technical Abatement

This category contains operational and technical improvements which improve the overall efficiency of a ship and thereby help save fuel and thus reduce emissions. Technical improvements, would be measures such as air lubrication, hull coating, improved hull shape, improved propeller design, etc. Operational improvements, on the other hand, can be technical but are not as tangible. They are measures which improve how certain aspects are being done during the operation of a ship, these can be done by optimization or by changing whole procedures. Examples would be slow-steaming, weather rooting, trim/draft optimization, etc.

van den Berg [152] has done a study in which he considers some of the above mentioned options to develop a support tool for the implementation of CO_2 abatement technologies. Similarly, Schwartz et al. [133] look in the potential of abatement technologies and their profitability. They find that with a combination of technical and operational solutions it is possible to reduce CO_2 emissions by about 75% and that half of the considered measures have a positive net cash flow. In this study, slow steaming and NO_x emissions are not considered. There are a couple of reasons why cost effective or even profitable solutions are not implemented. There is fear of hidden costs, effectiveness of options depend on the ship type, not all stakeholders have access to capital for implementation, charter types have influence on incentive, and conservatism are among these reasons [122]. Hu et al. [57] have developed a decision making method for the implementation of mitigation methods. The method takes also the interdependence of some of the measures into account and a sensitivity analysis has been conducted, in order to asses the effect of fuel prices and discount rates.

4.1.1. Wind Propulsion

Another option to reduce emissions is an old, reinvented technology. In the past, ships were mainly propulsed by wind with the use of sails. It took a long time to replace sails with engines, especially on routes which aligned with trade winds. It is still attractive today, as it is "free" propulsion. Implementing wind propulsion does not necessarily mean a fully wind propulsed ship, but can also mean a wind assisted ship. This can be done with the use of sails, kites or Flettner rotors[92]. With the assistance of one of these options it is possible to save fuel by 10-50%, this heavily depends on ship speed, route, and time of the year [139]. The reasons why wind propulsion is not implemented are similar to the reasons mentioned here above [123]. Karslen et al. [66] explore possible policies, such as carbon pricing, which would encourage stakeholders, mentioned here above, to implement wind propulsion.

4.2. New Policies

Policies are not directly reducing emissions; they are rather encouraging or sometimes forcing stakeholders to implement some of the solutions which have been discussed above. In a profit-driven world, in which greed often overpowers common sense and integrity, policies are important weapons of the public to lead the way for those who need guidance.

As discussed above, there are already policies and regulations by IMO or different states. One of IMO's measures is the EEDI, but according to [153] there are loopholes, which affect the cutting of CO_2 emissions. This is also supported by Stevens et al. [142], who found that the EEDI did not result in implementation of better engines or alternative fuels, but a reduction in design speed. Wan et al. [153] also argue that the regulations of now will not be sufficient to meet the goals of the Paris Agreement. A laissez-faire approach, in which the market deals with the problem alone, will not be successful; more regulations are required.

One operational measure which is discussed a lot is slow steaming. Slow steaming is the practice of sailing below the design speed of the vessel. By doing so, one is able to save fuel and thus reduce emissions considerably without making any capital investments, but it has to be noted that there are repercussions for the profits. A 10% reduction in ship speed can reduce emissions by 10-15% [25]. As container ships are one of the fastest sailing classes, the effect of slow steaming is larger compared with other classes, e.g., tankers. Slow steaming has been adapted by some ship owners, since 2008, initially to reduce operating cost associated with high fuel prices, but it has also reduced emissions [26]. IMO, in the 72nd session of MEPC has taken speed reduction and optimization into consideration for reducing GHG emissions.

A policy could also enforce a speed reduction. Psaraftis [121] argues that a speed limit would mandate a speed reduction while a bunker levy would induce it. He argues that, while a speed limit is more popular with some stakeholders, i.e., shipping companies, states; at the moment, the better choice would be a bunker levy, which applies the "polluter pays" principle. Speed limits are more popular thanks to the fact that they are more profitable for shipping companies than bunker levies, while bunker levies would induce bigger reductions in emissions. He also emphasises that there are loop holes for speed limits and enforcing such limits would be highly difficult.

4.3. Alternative Fuels

It is common knowledge that conventionally used heavy fuel oil (HFO) or marine diesel oil (MDO) are not "clean fuels". Both are residual products of oil refineries, such as asphalt [54]. Thus, it seems logical that one of the first solutions, which comes to mind, is to reduce emissions by using a "cleaner" fuel.

One important aspect when comparing different fuel types is the assessment of full life-cycle emissions or well-to-wake (WTW) emissions. Gilbert et al. [48] draws attention to this in his work, in which he compares many fuels' WTW emissions. To make it clearer, one could compare it to buying an electric car in order to help the environment. While the car does not emit any emissions, it makes it crucial how the electricity is being produced. If, for example, the electricity is being produced in coal plants, one has not helped the environment but has actually harmed it more. Thus, the same principle applies to ships, i.e., it is not sufficient to only consider tank-to-wake (TTW) emissions.

4.3.1. Liquefied Natural Gas

Liquefied natural gas (LNG) is a mixture of dominantly methane (CH_4) and some ethane (C_2H_6). The gas is liquefied by lowering its temperature down to -162°C (at 1 bar). As methane is the simplest alkane, LNG is the fossil fuel with the smallest carbon footprint. Due to its density and the temperature at which it is stored, the tank volume is 3-4 times bigger than HFO, for the same energy [1]. LNG, compared to HFO, has a potential of reducing CO_2 emissions by 26%, this is the highest potential amongst hydrocarbons[35].

One crucial aspect of using LNG as fuel in an internal combustion engine (ICE) is the methane slip. This phenomenon occurs when unburnt methane escapes the combustion chamber and leaks to the atmosphere. The effects of methane as a GHG over a 100-year period are 25 times greater than CO_2 [140].

Sharafian et al. [136] has assessed the emission reduction potential of LNG in maritime use. This is being done by comparing different internal combustion engine types to assess TTW emissions. Additionally, by considering the origin of the LNG, well-to-tank (WTT) emissions are are also accounted for. This assures that all emission are accounted for, i.e., WTW emissions are considered. They conclude that, for reducing GHG emissions, LNG is only viable for large ocean-going vessels, which use low speed high pressure dual fuel (LS-HPDF) engines. LS-HPDF engines reduce the methane slip so much that it becomes negligible and reduces WTW GHG emissions by 10%, compared to low speed diesel engines.

The economical feasibility of a LNG fueled container ship has been proven by Adachi et al. [3]. They have also shown that a LNG fueled ship would be more profitable than a conventional ship with a selective catalytic reactor (SCR) on the long run. In their work, they have chosen to make the ship bigger in order to accommodate the LNG tanks, rather than accepting the loss of cargo space. Kana and Harrison [65] have shown that some of the challenges for wider implementations of LNG fueled ships are the development of bunkering infrastructure, availability of LNG as a fuel, and fuel prices, where the ultimate is the main driver. They have also found that the uncertainty regarding the coverage of emission control area (ECA) regulations has not a significant effect. Schinas and Butler [132], on the other hand, name bunkering infrastructure, the availability of LNG as fuel, the availability of an after market, and regulatory uncertainty as the main challenges. The first 2 items will increase when the demand for LNG increases and there are already political initiatives to increase these in Europe and North America [132]. An after market for LNG fueled ships cannot exist if there is not a large fleet of LNG fueled ships, which makes it sort of a chicken or egg dilemma, however once more LNG fueled ships are built this market will establish itself. Which leaves the uncertainty in regulations, which is hard to comment on as it depends highly on world and regional politics.

4.3.2. Liquefied Petroleum Gas

Liquefied petroleum gas (LPG), similar to LNG, is a mixture of propane (C_3H_8) and butane (C_4H_{10}). It boils at -26.2°C (at 1 bar) and has a potential of reducing CO_2 emissions by 15.6% compared to HFO. LPG requires 3 times the storage volume compared to HFO, for the same energy, but it does not need an cyrogenic tank such as LNG[1].

LPG, similar to LNG, can be used in a 2-stroke Diesel-cycle engine, 4-stroke Otto-cycle engine or even a gas turbine. While using LPG produces more CO_2 emissions compared to LNG, LPG produces less GHG emissions than LNG due to methane slip. LNG has 17.5% less GHG emissions compared to HFO, while LPG has 18.5% less [21].

There are not many sources about the implementation of LPG as a marine fuel. As mentioned, LPG is very similar to LNG. While LNG gets a lot of attention from the scientific and the commercial world, LPG is more in the background. Nonetheless, institutions such as DNV GL and World LPG Association (WLPGA) see LPG as a strong option for alternative fuels [21][158].

4.3.3. Methanol

Methanol (CH_3OH) or methyl alcohol is not a fossil fuel but still a carbon based fuel. It is in liquid form at room temperature and has a potential of reducing CO_2 emissions by 11% compared to HFO. Methanol needs roughly 2.5 times the tank volume compared to HFO, for the same energy. Methanol is a corrosive material, but with an engine specifically built for methanol it does not cause any problems [1].

Methanol can be used in 2-stroke Diesel-cycle engines or in a 4-stroke Otto-cycle engine. TTW CO_2 emissions are 10% lower than HFO; WTT emissions heavily depend on the way of production. Methanol, produced with natural gas, has WTW CO_2 emissions higher than HFO. The number for methanol produced from natural gas varies from 2% to 15% depending on sources [6][35][48]. Methanol can also be produced from renewable sources. If produced by means of renewable sources WTW emissions would be much lower. This will be discussed in detail in Section 4.3.6.

According to Ammar [5], a container ship that uses methanol as a dual fuel, with the ratio 89% methanol to 11% MDO, would decrease CO_2 emissions by about 18%. It is not specified if these are WTW or TTW emissions, but considering other sources, it should be TTW. It is also stated that, while fuel prices for methanol are lower than diesel, due to higher fuel consumption, annual fuel costs would be higher by approximately 28%.

4.3.4. Hydrogen

Hydrogen (H_2) is an alternative fuel, which has the potential of reducing CO_2 emissions by 100%. It boils at -253°C (at 1 bar). There are different ways of storing hydrogen, but the most common ways are compressed hydrogen or liquefied hydrogen. Liquefied hydrogen requires 4 to 5 times the tank volume of HFO, for the same energy [1][35]. In case of compressed hydrogen this can be between 10 to 15 times, depending on pressure [35].

As mentioned, TTW CO_2 emissions of hydrogen are 0%, but WTT emission vary drastically depending on means of production. If produced with renewable energy WTW CO_2 emissions can be reduced by more than 80%, compared to HFO [48]. But at the moment 95% of hydrogen is produced from fossil fuels [1]. This kind of hydrogen would increase WTW emissions by roughly 60%, compared to HFO [48].

Hydrogen can be used in an internal combustion engine, as a single or dual fuel (with HFO). If used as a dual fuel, WTW CO_2 emissions are reduced by approximately 45%, this becomes about 82% when used as a single fuel [14][15]. In both sources, dual fuel is used with a 50/50 ratio but neither is explained why this ratio is preferred nor the (dis)advantages of using hydrogen as a single or dual fuel. It is believed that hydrogen's true potential will be achieved with fuel cells, but these are not mature yet, for the application at bigger scale [35].

4.3.5. Ammonia

Ammonia (NH_3), similar to hydrogen, has a potential of reducing CO_2 emissions to 0%. Its boiling point is at -33°C (at 1 bar). Ammonia can be stored in liquid form in low temperature or under pressure. Low temperature storage needs energy to keep ammonia in liquid form, but has lower capital costs than pressurized tanks, as it requires less steel. Ammonia requires 2.5 times the tank volume of HFO, for the same energy [1].

Ammonia can be used in gas or steam turbines, internal combustion engines (spark- or compression-ignition) or fuel cells. de Vries [28] has made an extensive research on the applicability of ammonia as a maritime fuel. He does not consider turbines as a feasible option for ships due to their low efficiency. He also makes a comparison between different fuel cell types, i.e., proton exchange membrane (PEMFC), alkaline (AFC), and solid oxide (SOFC). AFC and SOFC have a lower efficiency than ICE, which is more robust, cheaper, and has a better load response capability. SOFC has the highest efficiency, but, similar to the other fuel cell types, it has problems with power density and load response capability, and is more expensive. Therefore, at the moment the most feasible option are combustion engines.

Using ammonia alone in ICE is feasible, but due to its low flame velocity it is used in combination with a pilot fuel [1]. This could be conventional HFO or ammonia can be cracked before injection, such that a hydrogen-ammonia mixture is created. If pure ammonia is used, WTW CO_2 emissions are reduced by approximately 55%, if used as a dual fuel (50% ammonia, 50% HFO) about 29% [14][15]. There are no sources on the WTW emissions of an ammonia-hydrogen mixture. But TTW CO_2 emissions are definitely zero. If, to create the mixture, ammonia is cracked before injection, WTW emissions are equal to those of pure ammonia. The only difference will occur during the cracking of ammonia, which should result in slightly higher WTW emissions, compared to pure ammonia. Burning ammonia results in nitrogen and NO_x [1], so higher NO_x emissions can be expected.

4.3.6. Biofuels

Biofuels are fuels (liquid or gaseous), which are created by processing biomass. There exists a wide variety of biofuels, from biodiesel and biogas to biomethanol. Biofuels can be produced from soy, sugarcane, corn, etc. This way of production can be problematic as it is directly competing with food production, which gets more vital as the human population increases. It can also be produced from algae or plant dry matter (i.e., trees, bushes, corn stalks, etc.)[1], which is more sustainable.

Biodiesels can be (non-)edible vegetable oils, waste and recycle oil, and animal fats. Biodiesel can be used pure or can be blended with conventional diesel [116]. The ratio of the blend directly affects produced emissions. The reduction of CO_2 emissions depends on the blend ratio and the type of biodiesel, but it can also be seen as carbon-neutral as the biomass, which is required to produce it, absorbs a lot of carbon during its growth [100]. For example, biodiesel produced from rapeseed can decrease WTW CO_2 emissions by 57%, while soy can reduce it by approximately 75%. Biogas (BioLNG) reduces emissions by 40% [48].

Biofuels are more corrosive than conventional fuels, therefore tanks have to be designed accordingly. When stored for a longer period, they oxidize and degrade, which makes them even more corrosive. If not drained frequently microbial growth can occur [1].

4.3.7. Comparison

As it can be seen from above, there are many references on different fuel types. These usually only handle one specific fuel type and one specific aspect of it (emissions, design, etc). Some studies compare emissions of different fuel types, but do not look into other aspects, such as profitability, feasibility, etc [48][15]. These studies are valuable to see which fuel type has what potential of reducing emissions, but to make decisions stakeholders need more information, regarding the above mentioned aspects or the risks that are associated with the different fuel types.

Table 4.1: Comparison of different fuel types, adapted from ABS [1]

Fuel Type	**Boiling Point [°C] (at 1 bar)**	**Tank Volume for Equal Amount of Energy (Compared to HFO)**	**CO_2, kg CO_2/kWh Reduction (Compared to HFO)**
HFO	300 - 700 [91]	1	0%
LNG	-162	3 - 4	26%
LPG	-26.2	3	15.6%
Methanol	65	2.5	11%
Hydrogen (Liquefied)	-253	4 - 5	100%
Hydrogen (Compressed)	-253	10 - 15	100%
Ammonia	-33	2.5	100%

As mentioned, different fuel types have different requirements, which will have an impact on the design of the ships and costs. The main differences have been summarized in Table 4.1, biofuels are not in this table as there are many types of biofuels and their values change accordingly. Ideally, reducing emissions as much as possible should be the goal, but usually monetary aspects play a bigger role when decisions have to be made. Studies which compare more than one property are required to get a better overview.

Deniz and Zincir [29] compare diesel, ethanol/methanol, LNG, and hydrogen. They defined 12 criteria (e.g, safety, global availability, costs, durability, etc.) and use the Analytic Hierarchy Process (AHP). Their results show that hydrogen is the best option among the named fuel types. One of the biggest obstacles associated with hydrogen is the large volume required for storage. In this study, it has been decided that hydrogen would not be stored on ship, but produced by electrolysis from pure water, which is stored or produced by a water purifier. This makes the assumption that the production of hydrogen will be sufficient for the direct use in the engine. This assumption is not explained in the article. Furthermore, it is not explained where the energy for the purifying process and the electrolysis would come from. These aspects make the article's results questionable.

AHP is a valid approach for decision making, but it does not necessarily take future uncertainty into account. Deniz and Zincir [29] make a comparison regarding the situation of now and (mostly) disregard changes that might come in the future, regarding policies, prices, etc.

4.4. Conclusion

It can be seen in the literature that IMO's goals for 2050 challenge many researchers in finding solutions from different perspectives. It has been shown that in the fields of operational and technical emission abatement, and emission abatement policies substantial work has been done. The literature contains assessment of numerous fuel types with respect to their suitability. Many of these studies only look at one specific fuel type. Some studies assess the potential of combinations of the above mentioned solutions under different scenarios [9][11].

There is one gap in the literature, which has been mentioned in the previous section. There is limited comparison of alternative fuel types, which also takes future uncertainty into account. There are some who investigate the performance of a single fuel in combination with future uncertainties, these use some of the methods mentioned in Section 6.3 [2][64][65]. As ships which will be built in the near future will have a lifetime of approximately 25 years, it is rather important to make this comparison. They have to be robust to "survive" the upcoming period.

There are many technical options, some are less developed, some more. How quick these will reach maturity, how fast their uptake will be, or which one will be dominant is uncertain. Politically, i.e., in terms of policies, there is also more than one policy option. This is also, most likely, the most uncertain aspect of all mentioned, as political decisions tend to be the least transparent decisions.

5
Problem Definition

The gap in the literature has been established in Chapter 4. This chapter will give a detailed explanation of the problem. It will describe the benefits of solving the problem. Furthermore, the main research question and sub-questions which lead to the main question will be presented. Lastly, the scope of the project will be defined.

5.1. Objective

The objective of the present work is a comparison of alternative fuel types, which will meet IMO's 2050 goals for emissions, accounting for future uncertainty. This will involve looking at the effects that the different fuel types have on the design of ULCVs. Furthermore, uncertainties which are tied to the upcoming 30 years will also be taken into account. While reducing emissions is the main ambition, doing so should not turn shipping into an unprofitable business. Therefore, it is imperative that economics is part of the evaluation process, such that idealism does not overshadow realism.

Regarding uncertainties, it is not possible to consider all of them, as this would exceed the capability and time of this project. In the previous chapter it has been stated that batteries and fuel cells are emerging technologies, but are not currently deemed feasible on larger scale and therefore will not be considered. Their development in the future will also be neglected, as it will not directly affect the performance of ships which were constructed in the past. The focus will be on ICE, which is a mature technology. Another important aspect regarding alternative fuels is their availability and the commercial readiness level of their infrastructure. But as the objective is to compare alternative fuel types, to consider the latter would lead to an unfair comparison. Once it has been established that one fuel type is superior, infrastructure can be developed by private investors and governments. Ships used to burn mainly coal, but gradually switched to oil as the infrastructure transitioned as more and more ships switched to oil. Hence, technical uncertainties will not be considered in general.

The focus will be on political and economic uncertainties, which are believed to have a bigger impact on the uptake of alternative fuels. The switch to an alternative fuel will only occur if investors can profit from it. While implemented policies will have effects on the profitability of shipping.

5.2. Problem Statement

One might question why it is important to compare alternative fuel types and why to do this specifically for ULCVs. Both are valid questions and have been partly answered in the previous chapters. Ships which are going to be built in the near future are expected to survive through a period of transformation with respect to the climate crisis. Any ship built at any time of history went through many changes as markets tend to rise and fall. The key difference between the past and now is the fact that there was never an environmental catastrophe as the climate crisis. A catastrophe, which is caused by humans and can only be stopped by humans. This is the reason why IMO has set goals for maritime emissions.

Literature has shown that existing regulations will not be sufficient to reach the climate goal. New policies will be introduced or maybe even the goals will be replaced with for more ambitious goals. This in combination with markets and other aspects makes the future much more uncertain than other periods of the past. This is also why DNV GL [34] emphasizes the concept of 'carbon robustness'.

This strategy is very similar to what has been described by Doerry and Koenig [38]. Figure 5.1 visualizes different design strategies according to requirements. When requirements are fixed, it is possible to optimize a design. However, when requirements change there are 2 possible design strategies. One can have a fixed design, which is robust and can survive in many circumstances or a flexible design, which is modular and can adapt to the circumstances. In this case, this would mean a ship that is designed in such a way that retrofitting in the future is easier and less expensive. This is a valid approach for handling the uncertainty regarding IMO's regulations, but retrofits are always expensive and in a market, as competitive as container shipping, it could become problematic. That is why robustness seems like a better and safer approach, as mentioned by DNV GL.

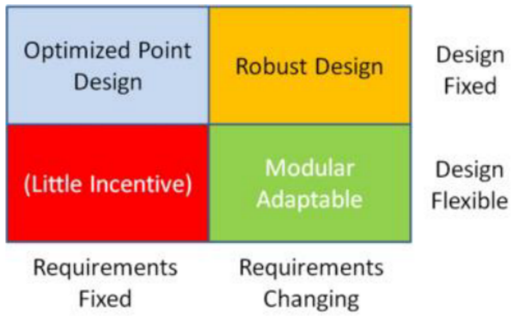


Figure 5.1: Taxonomy of design strategies according to Doerry and Koenig [38]

One of the major aspects of a robust ship design is the choice of fuel. As shown in Chapter 4, different fuel types have different requirements, which will have significant effects on the design of a vessel. Thus, the choice of fuel is important. To make a good choice one has to know the strengths and weaknesses of the fuel types and how they perform compared to others.

Secondly, as it has been established in Chapter 1, container vessels, especially ULCVs, are the biggest pollutants in the maritime sector. Furthermore, ULCVs are the class of the future and these ships are usually the flagships of the shipping companies. If it can be proven that these ships are able to switch to "greener" fuels and are still profitable and competitive, most likely the rest of the sector can also act accordingly.

These are more pragmatic reasons why this research is important, but the ethical aspects should also be considered. Naturally, everyone wishes that the economies thrive, that everyone gets wealthier, and has a comfortable life, but this should not happen at the expense of the environment. In the end, we only have one planet and destroying it will benefit no one. Making profits today at the cost of "destroying" the planet for the upcoming generations is selfish and unethical. Global warming has become such a serious problem that even public figures, such as Pope Francis, feel the urge to call people to stand up against it [46]. Sustainable growth should be everybody's goal, but especially of engineers and other decision-makers, who have the power to influence how things are done. Creating a low or no emissions shipping market would not solve the climate crisis, but it would get us one step closer to doing so.

5.3. Research Questions

The main research question of this project is as follows:

"What is an adequate approach to assess alternative fuel types for robust ultra large container vessels in face of uncertainty, regarding the goals of IMO for the year 2050?"

Sub-questions, which will lead to the answer of the main research question are listed below:

(i) *What are the implications of the IMO goals for 2050 on container ship requirements?*

(ii) *Which uncertainties can be identified in this subject?*

(iii) *What will be the effect of different alternative fuel types on the design of ULCVs?*

(iv) *What will be the effects of fuel choice on the ship's performance in combination with changes in markets and regulations during the lifetime of the ship ?*

(v) *How much emission reductions will different fuel types offer and with what certainty?*

5.4. Scope

- The capacity of ships, which will be used for the evaluation and comparison, will be the kept roughly the same for each fuel type.
- The economic assessment will be limited to one major route. As this is an European project and the major container shipping route for Europe is between China and Northern Europe, the focus will be on this route.
- NO_x and SO_x emissions will be neglected. The focus will be on GHG, especially CO_2. As this is also the main focus of IMO's regulations for 2050.
- The importance of WTW emissions are acknowledged, but only TTW emissions will be considered.
- Batteries and fuel cells are not taken into account. Only fuels for ICE will be considered.
- Development of new technologies will not be considered, as they will not directly affect ships' performances which were built before the development of a specific technology.
- Operational and technical abatement options will not be considered.
- Different policies will be taken into account for scenario creation.
- Economic uncertainties, such as fuel prices and trade demand will be considered.

6
Methodology

This chapter describes the structure of the project and the methodology which will be used. In the first part, a description of the initial research will be given. In the second part, methods to handle uncertainty will be evaluated according to the research's requirements and one method will be chosen.

6.1. Structure

The structure of the thesis follows the order of the sub-questions. The first and third sub-questions, presented in Chapter 5, directly concern the design aspect of the thesis. They have been answered in Chapter 2 and 4, respectively. Answers of both questions have to be incorporated in the design of the vessels. As there are several alternative fuels, several designs have to be made. Therefore, it is beneficial to create a parametric design tool for ULCVs, which can calculate all relevant values for the design (e.g., fuel consumption, cargo capacity, emissions, etc.), according to the choice of fuel type. This will also create flexibility for changes, which might be required in later stages of the project. Parametric design for container vessels has been done before, by Priftis et al. [118] and Köpke et al. [69]. This tool will be utilized to create designs for each fuel type, which will then be evaluated.

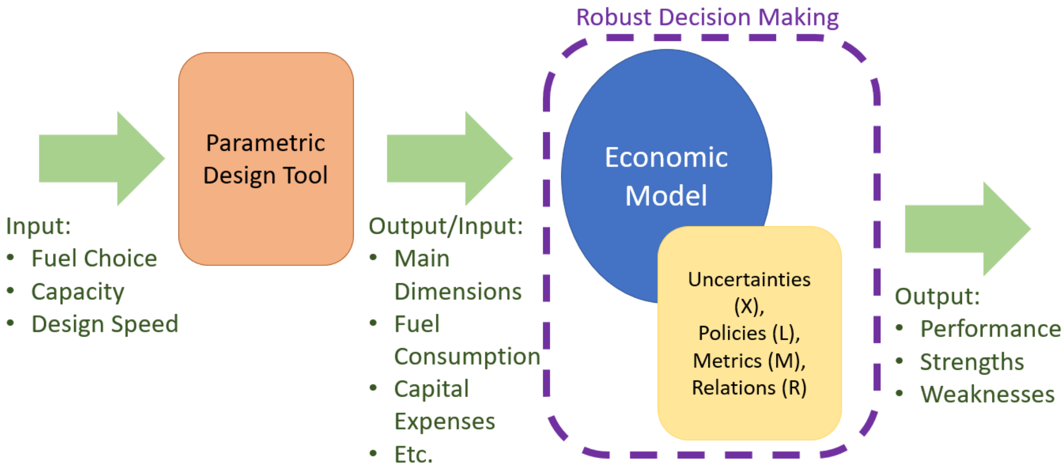


Figure 6.1: Structure of the Research

The second sub-question, which has been answered in Chapter 3, is concerning the uncertainty of the future, while the last two are defining the criteria for the evaluation, which will help to answer the main research question. The performance of different designs over the lifespan of the vessel should be compared, such that the main research question can be answered. This requires a decision-making method, which can handle the uncertainties involved in this topic. The main design evaluation criteria will be emissions and profit, as specified in the last sub-questions. An overview of the structure can be seen in Figure 6.1, how the decision-making method was chosen will be explained below.

6.2. Method requirements

In order to choose the right decision-making method, the requirements for the method and what sort of results are expected should be defined adequately. The method should:

- handle a **level of uncertainty** higher than 2.
- make a **comparison** between results of many different scenarios.
- be able to make an **evaluation** according to multiple criteria.
- **aim** to find a robust design/solution, i.e., not an optimal solution.

The level of uncertainty has been decided according to the definition of Marchau et al. [94]. The lowest level of uncertainty is complete certainty, a situation where everything is known precisely. Level 1 uncertainty is the situation where there is a slight uncertainty but there is no need or necessity to measure the magnitude of uncertainty. Level 2 uncertainty is when there are few future scenarios, which can be predicted or a probabilistic model can be developed for a representation of the situation. Level 3 uncertainty represents the situation when there are more possible future outcomes but it is not possible to assign any probabilities to them. Level 4 uncertainty is the deepest level of recognized uncertainty. It is divided in two: the ability to put limits for possible futures exist (4a) and the only knowledge there is, is the knowledge of the unknown (4b). Beyond this level is total ignorance. An overview of these definitions can be seen in Figure 6.2.

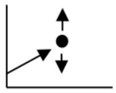
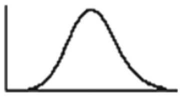
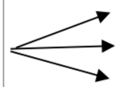
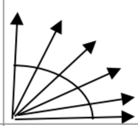
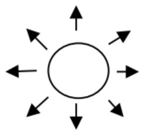
	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future 	Alternate futures (with probabilities) 	A few plausible futures 	Many plausible futures 	Unknown future 	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 6.2: Levels of uncertainty [94]

The level of uncertainty for this subject is higher than 2, because there are many uncertainties involved and it is not possible to assign probabilities to certain scenarios. This means that neither deterministic nor stochastic models can be options. On the other hand, there is a general understanding of the possible futures and how certain aspects function. Therefore, the level of uncertainty is smaller than 4b. Thus, the level of uncertainty, for this subject, should be 3 or 4a.

Similarly, a clear difference between flexibility and robustness must be made, as these terms are similar and could cause some confusion. Flexibility is the ability to adapt to new, different, or changing requirements; while robustness is the ability of performing without failure under a wide range of conditions [96]. To put it in other words, flexibility means changing, according to situations, to perform good; robustness is performing good, regardless of the situation.

6.3. Methods

There are many decision-making methods, which have been used for different researches [93]. In accordance with the method requirements, a selection of possible methods has been done. These methods have been studied in more detail to see if they fulfil all defined requirements. The selected methods are the following:

- Real Option Analysis (ROA)

- Engineering Option Analysis (EOA)
- Info-Gap Theory (IG)
- Robust Decision Making (RDM)
- Many Objective Robust Decision Making (MORDM)
- Epoch-Era Analysis (EEA)
- Markov Decision Process (MDP)

Out of these methods, EOA, and EEA have been used in subjects about ship design [113][47]. ROA, and MDP have been used in subjects about alternative fuels for ships [2][64][65]. An overview of these methods can be seen in Table 6.1. The table is based on the work of Moallemi et al. [99] and has been adopted and extended to see how the methods fulfil the requirements, which have been established in the previous section. The table gives a short explanation of the method, the level of uncertainty which it handles, the criteria with which the evaluations are made, on what basis the comparisons are made, the main aim of the results, and the main references for these methods.

6.4. Method Choice

To decide which method is the most suitable for this project, a comparison between the requirements from Section 6.2 and Table 6.1, has been made. ROA, and MDP are not suitable, as their level of uncertainty is too low. It would require to assign probabilities to different scenarios, which is believed to be very difficult for this topic. Nonetheless, it has been done for MDP by Kana and Harrison [65]. They use historic data to model economic uncertainties, but mention that modelling regulatory uncertainties is more difficult. Regardless, they use uniform distribution to examine the sensitivity of regulatory uncertainties regarding ECA coverage and underline that this is not necessarily how it would develop. Furthermore, the results do not aim for robustness, which is also a reason for deciding against these methods. This is also why EOA, and MORDM are not selected. IG will not be considered, because it is meant for cases with higher uncertainty than the problem at hand. It is believed that, as there is more knowledge about the situation, it would give less reliable solutions than a method with a lower level of uncertainty. This leaves two methods, which fulfill the requirements, for consideration: RDM and EEA.

The two main differences which can be seen from the table are the level of uncertainty and the aim of the results. Moallemi et al. [99] have compared both methods by applying them to the same problem and analyzing the results. They show that the level of uncertainty of RDM is higher, as with RDM there is no probability assigned to the scenarios. Myriad scenarios are run and used for stress testing the decisions/designs. This helps to identify the strengths and vulnerabilities of the options, subsequently the robustness. EEA, on the other hand, deals with uncertainties with known probability distributions (level 2 uncertainty) or when there is a limited amount of possible futures (level 3 uncertainty). In the second case probabilities are not assigned, but the developer still defines the rules for epoch transitions, which inadvertently create epochs which the developer believes are plausible, based on his judgement [47]. The outcome heavily depends on this judgement. RDM, in contrast, is not looking at the possibility of the scenarios, but is using the scenarios to stress test options and define in which circumstances the option fails/succeeds or does (not) perform well. Then, through comparing all the options, it identifies the most robust option.

The second difference is in the aim of the results. RDM, as the name indicates, aims for the most robust option. EEA is proposed as a method for seeking more robust outcomes [47]. But Moallemi et al. [99] argues that it has also been used for incorporating flexibility in design and, when compared with RDM, is focused more on optimality rather than robustness. The options are measured according to a framework of expected utility.

Taking these points into consideration, it has been decided that RDM is the most suitable method for the given subject. It fulfills all specified requirements and when compared to the rest of the methods has more advantages, considering the uncertainties which are involved in this subject.

6.5. Robust Decision Making

RDM is a method which has been used for different topics with a high level of uncertainty, but especially for topics related to climate change. The uncertainty levels in these cases are so high that it is not possible to

Table 6.1: Overview of the considered methods, based on Moallemi et al. [99]

Method	Description	Level of Uncertainty	Evaluation	Comparison	Aim	Sources
Real Option Analysis (ROA)	It aims to evaluate the value of investment opportunities by quantifying a single monetary value for candidate decisions given that the investment uncertainty can be sufficiently estimated.	2	Profits	Defined scenarios	Profitability	Bowman and Moskowitz [20]
Engineering Option Analysis (EOA)	It quantitatively analyses the value of including flexibility in planning, design, and management of engineering systems under uncertainty. EOA presents the benefits of multiple options to decision-makers in terms of different measures (e.g., average expectation and initial capital expense).	3	Multiple criteria	Defined scenarios	Flexibility	de Neufville and Smet [27]
Info-Gap Theory (IG)	It uses a non-probabilistic model to evaluate pre-specified decisions under severe uncertainty, and then to prioritise and choose decisions based on two decision concepts: (1) robustness (i.e., the greatest uncertainty up to which the candidate decision meets critical outcome requirements) and (2) opportuneness (i.e., the lowest uncertainty at which the candidate decision leads to better-than-expected outcomes).	4b	Multiple criteria	Multiple scenarios	Robustness & Opportuneness	Ben-Haim [12]
Robust Decision Making (RDM)	It uses a problem formulation framework and a set of computational tools to stress test a set of candidate decisions over a myriad of policy-relevant scenarios in order to suggest robust adaptive decisions.	4a	Multiple criteria	Multiple scenarios	Robustness	Lempert [74] Moallemi et al. [99]
Many Objective Robust Decision Making (MORDM)	MORDM is a framework that combines RDM with Multi-objective evolutionary optimization. The framework initiates competing problem formulations using well-characterised uncertainties endogenous to the optimization search. Many decision alternatives with good trade-offs among planning objectives are generated (based on known probability distributions of model parameters) in an optimization search. The impact of deep uncertainty on generated decisions is tested in likelihood and regret based performance through stress testing over many future states of the world.	4a (probability distribution for parameters)	Multiple criteria	Multiple scenarios	Optimality	Kasprzyk et al. [67]
Epoch-Era Analysis (EEA)	It aims to suggest engineering design options by considering short-term and long-term uncertainty conditions over time and constructing pathways towards future scenarios to inform a design option that could yield robust performance over the life- cycle of the system.	3	Multiple criteria	Multiple scenarios	Robustness[47] / Optimality [99]	Gaspar et al. [47] Moallemi et al. [99]
Markov Decision Process (MDP)	A method to solve dynamic decision making problems under stochastic conditions. It can be used to evaluate performance of designs, by looking at their lifetime performance and how they adapt to changing environments, policies, etc.	2	Multiple criteria	Defined scenarios	Flexibility	Kana et al. [64] Niese and Singer [105]

define probability distributions or reliable models [49]. RDM searches for the most robust strategy/design by running a myriad of scenarios, comparing its performances and hereby identifies vulnerabilities [99].

The method, which has been visualized in Figure 6.3, can be divided into 4 steps:

(i) The first step is defining the key uncertainties concerning the studied system, the decisions/designs, and objectives. Usually the XLMR framework is used in a participatory process to specify the exogenous uncertainties (X), policy levers (L), metrics (M), and relationships (R) [77].

(ii) In the second step the performance of the different designs are assessed in different scenarios, according to the defined uncertainties.

(iii) The third step is to use statistical machine learning algorithms to search for conditions in which the options show vulnerabilities.

(iv) In the forth step trade-off analyses are made, where the performances are compared according to the objectives. The process can be stopped here or turned into an iterative process by starting again at the first step with the newly acquired knowledge with the pursuit of finding a robuster design [72].

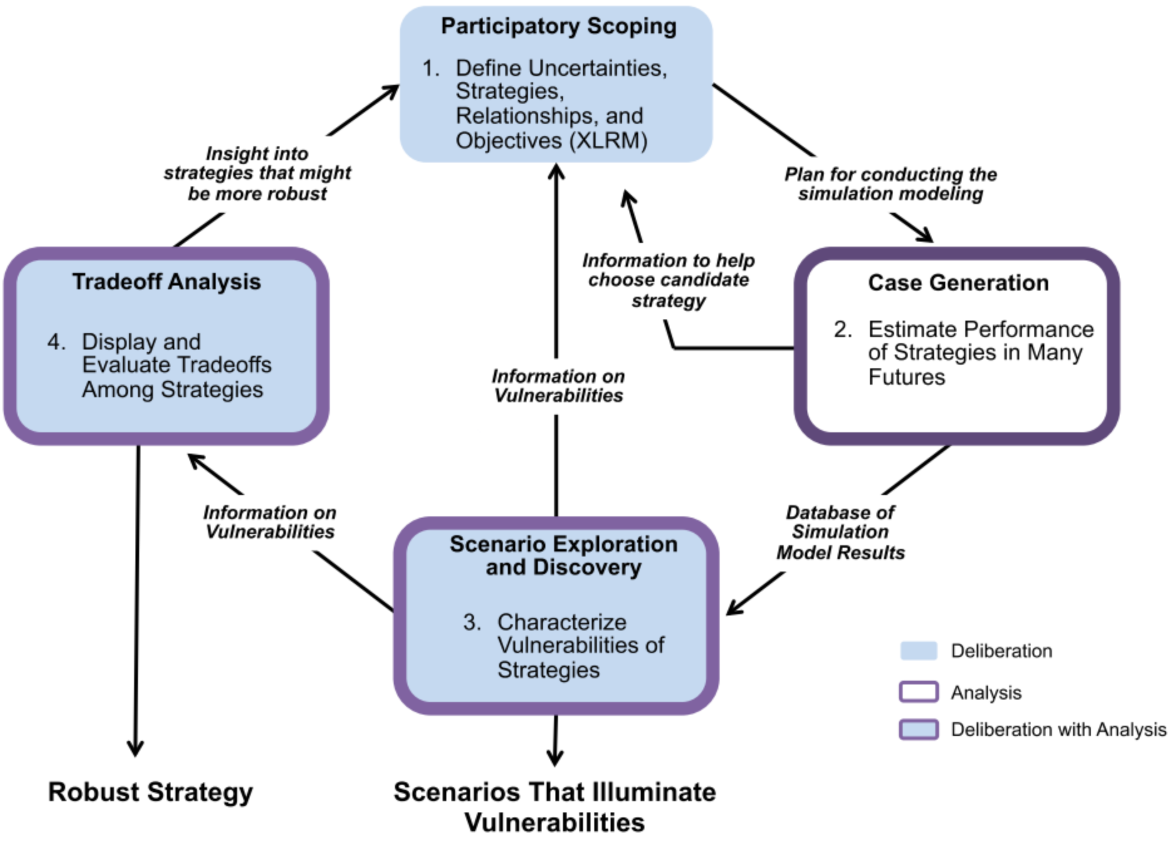


Figure 6.3: Steps of Robust Decision Making [77]

One of the key aspects of RDM is the scenario creation in step 2 and 3. The scenarios are utilized to stress test the options. The probability of one scenario occurring is not important, if it is (im)possible can be discussed afterwards. What is important is to find the circumstances under which the option fails or succeeds, this will indicate how robust the option is. It will show a range of circumstances under which the option will have an acceptable performance. This is why the scenario creation part is crucial. There are some scenario discovery methods available, which have been used successfully in combination with RDM [23][71]. This aspect will be discussed in more detail in Section 6.7. Furthermore, there are many applications of RDM in the literature, which can be used as an example for this study [72][75][76][99].

6.6. Proof of Concept

In order to better explain how the method will be implemented, a simple example can be shown. The values may not be realistic and the assumptions may not be very accurate, but the main purpose is to show how the method works. The investigated parameters are not necessarily the same which will be investigated in the project.

(i) Suppose there are two fuel types: Fuel A and Fuel B. Fuel A has a higher energy density but produces more emissions when burned, while Fuel B has a low energy density and produces less emissions. This means that using Fuel B causes a loss of cargo, as it requires more volume for storing the same amount of energy. Suppose that implementing these fuels only affects the cargo capacity and emissions that are produced. Furthermore, there is an emission rate for each fuel type, which is the relation of produced mass of emissions per used amount of energy [uM/uE]. Assume that there is an exogenous uncertainty (X) regarding the prices of the fuel, Fuel A can vary between 140 and 170 USD per unit of Energy [USD/uE] and Fuel B between 110 and 140 [USD/uE]. In both cases 10000 [uE] is required to make one trip. Furthermore, there is a fixed freight rate for each container [USD/TEU]. These values have been summarized in Table 6.2.

Table 6.2: Main parameters of Fuel A and B

	Fuel A	**Fuel B**
Cargo Capacity [TEU]	21000	17000
Emission Rate [uM/uE]	0.7	0.5
Energy Consumption [uE]	10000	10000
Price [USD/uE]	140-170	110-140
Freight Rate [USD/TEU]	80	80

For simplicity assume a very basic economic model. Operational costs per trip are assumed to be equal to the fuel consumption, other expenses such as crew wages, insurance, etc. are ignored, and income per trip is calculated by multiplying the amount of TEUs with the freight rate (the ships always sail at full capacity). Profit is calculated by subtracting the operational cost from the income. These simple calculations would form the model or relations (R) of this example. Assume that a ship can make 20 trips per year but there is a possible policy (L) for speed limits, which could reduce the trips per year to 15 or 10. The main objectives (M) are making big profits and producing a low amount of emissions. For simplicity only one year will be looked at. With these definitions made it is possible to move to the second step of RDM.

(ii) With one policy lever and one exogenous uncertainty, the amount of generated scenarios will be limited. Let us vary the fuel price in steps of 10, which generates 12 scenarios per fuel type. It can be seen that the amount of scenarios increase exponentially with additional uncertainties or policy levers. In this case only two discrete ranges where looked at, but even this resulted in 12 scenarios per option. With these scenarios it is possible to calculate the total profit of one year and the total emissions of one year.

(iii) It could be possible to generate even more scenarios by varying the parameters to fulfil step 3, but this will be skipped for this simple example.

(iv) The trade-off of the two main objectives has been visualized in Figure 6.4. Two clusters can be seen in the figure, a blue one (Fuel A) to the right and an orange one (Fuel B) to the left, representing the performances. It can be seen that Fuel A generally produces more emissions than Fuel B. It can also be seen that in some cases both fuels can cause losses. If the data is analyzed in detail (see Table A.2 and A.3 in Appendix A), it can be seen that this occurs when the fuel price for Fuel A is 170 [USD/uE] and for Fuel B is 140 [USD/uE], which are vulnerabilities for both. It can also be seen that the amount of trips determines emissions and the range of profits. From detailed analysis, it can also be deduced that in similar scenarios Fuel A is more profitable than Fuel B but also produces more emissions than Fuel B. The Pareto optimality front can be seen in red in Figure 6.4. This would conclude step 4. Now it could be decided to start an iterative process or to make a choice between the 2 options.

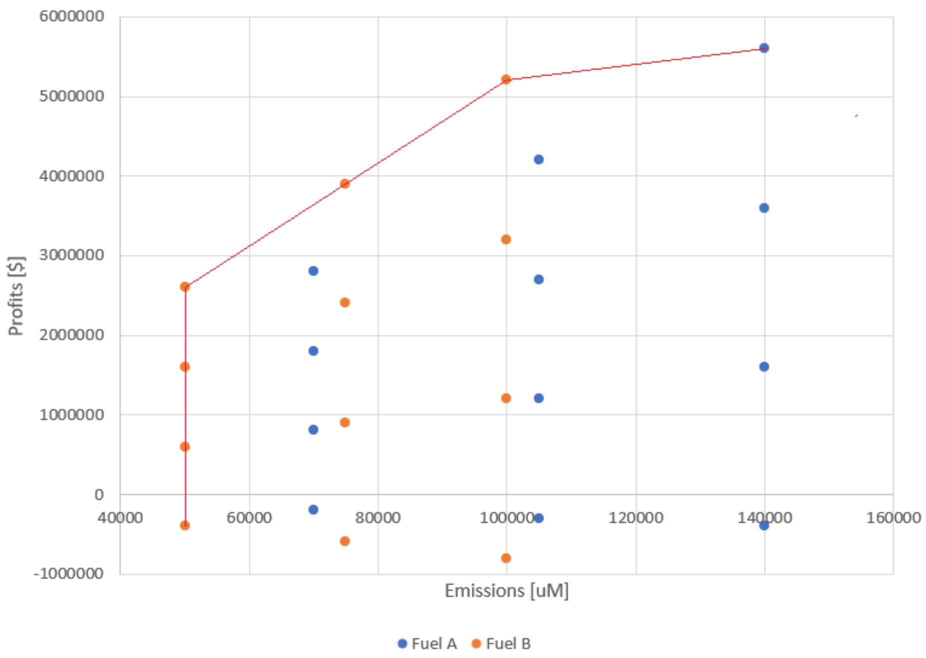


Figure 6.4: Total profit against total emissions of Fuel A (blue) and Fuel B (orange)

6.7. Discussion

Looking at the example above, one could ask what the difference between RDM and multi-objective optimization is. The above used type of graph is just one example, naturally other types of graphs such as box plots can also be used. Furthermore, with multi-objective optimization, only the area near the Pareto optimality front would be interesting, as the goal is optimization. RDM, on the other hand, is interested in all parts of the graph, because areas near the Pareto front indicate where the strengths of each solution lies, but areas which are farther away indicate the weaknesses, which are equally important. The area of a cluster of one solution shows how volatile its performance, i.e., its certainty, is and how robust it is. This aspect of RDM has been demonstrated in the last part of the previous section.

The most critical part of RDM is the first step, in which the XLMR framework is used. The relation, i.e., the model, which will be made will determine how accurate the results are. Furthermore, the defined uncertainties and policies will decide how many scenarios are possible. As has been mentioned before, the amount of scenarios can increase rapidly, which is not necessarily bad. The strength of RDM comes from the vast amount of scenarios, which stress test each option. Naturally, this can become overwhelming, but manageable as has been demonstrated by Kwakkel et al. [72].

As RDM is an iterative method, it is possible to start with a simple model, such as in Section 6.6, and change it with each iteration. By analyzing the results after each iteration, it is possible to see which aspects affect the results or to limit certain aspects. By adapting uncertainties, policies or relations in step 1 or adding new uncertainties or policies, one can explore the outer limits, i.e., the strengths and weaknesses, of each option.

The scenario exploration in step 3 is also important. As mentioned, RDM is interested in the strengths and weaknesses of each option, i.e., scenarios in which a option excels or fails are more interesting than scenarios in which the option achieves mediocre results. Therefore, scenario discovery in the outer limits, i.e., the more interesting regions, is more important than in the centre [71]. In Figure 6.4, it is possible to see a trapezoid formed by the orange dots, which represent the results of Fuel B. If step 3 would have been done, it should focus on creating scenarios which will be at the border of this trapezoid, instead of the centre. The strengths and weaknesses will be established by focusing on the outer borders. This can ideally be done with the help of algorithms, as proposed by Bryant and Lempert [23], which identify scenarios of interest and pursue similar scenarios. But it could also be done by varying the parameters smartly and discover scenarios of interest. As scenarios which are in centre are avoided, the amount of scenarios needed is reduced, which makes the large amount of scenarios more manageable.

7 Parametric Design Tool

The structure of the thesis has been explained in Chapter 6, according to this structure, the first step is to develop a parametric design tool (hereinafter referred to as "the tool"), which is able to calculate all relevant properties given the required input. The tool will create different designs, which then will be assessed by means of the RDM method, i.e., the output of the tool will be the input for the RDM method. This chapter will also explain the effects that the different fuel types will have on the design of the ships, which was the third sub-question.

An overview of how the tool works can be seen in Figure 7.1. The tool has been represented in form of a flowchart, where the inputs are shown in green and individual steps in blue. In the following sections, details of all aspects will be explained: how the calculations are made and which assumptions were made.

7.1. Main Input

The tool has 3 main input variables:

- Capacity in TEUs
- Design speed in knots
- Choice of fuel

The capacity has been chosen as an input, as this primarily determines the main dimensions of the ship. It could also have been chosen to have the main dimensions, such as length, beam, and draft, as input variables, but this would result in some issues. The main dimensions of a container vessel cannot be freely chosen, because they are functions of the main dimensions of a TEU (length = 6.1 m, width = 2.44 m, height = 2.59 m). This is especially true for the beam of the ship, which is generally a multiple of the width of a TEU or slightly more. Thus, if these dimensions are not chosen accordingly it would result in a sub-optimal design.

$$P_E = R \cdot v_s \tag{7.1}$$

The installed power on a ship is mainly determined by its resistance, which is a result of the hull, and the speed at which it should sail, as can be seen from Equation 7.1[68]. The given equation is for the effective towing power (P_E), which is directly linked to the installed power through efficiencies and margins. The installed power, i.e., the engine size, affects the main dimensions of the ship and the capital expenses, which makes the design speed an important variable.

The last input variable is the choice of fuel, as the objective of the project is to make a comparison between different fuel types. The differences between the different fuels and their requirements have been discussed in Chapter 4. As can be seen from Table 4.1, the choice of fuel will also have an impact on the main dimensions of the ship as storing alternative fuels requires more space.

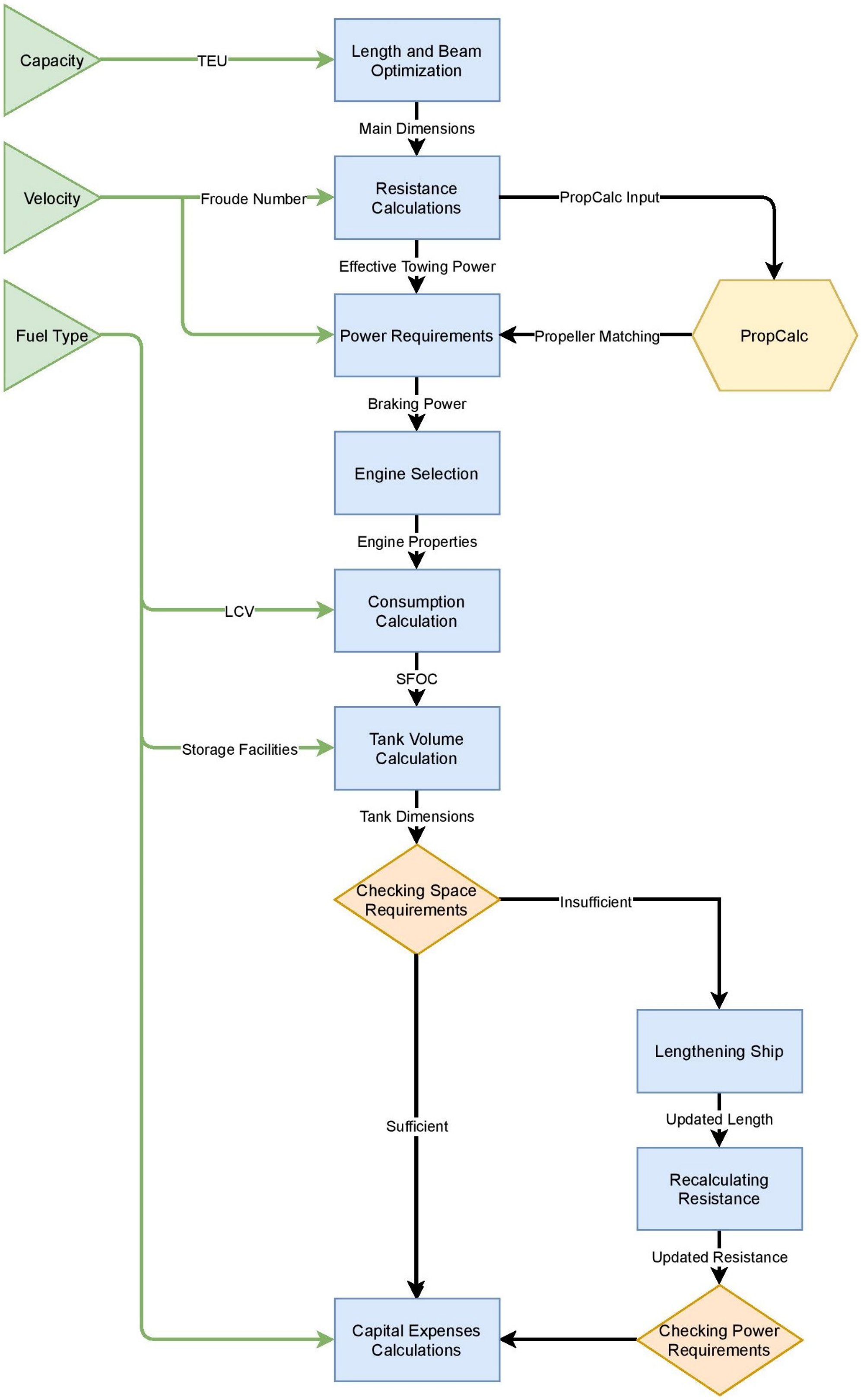


Figure 7.1: Structure of the parametric design tool

7.2. Capacity & Main Dimensions

The first step is to calculate the capacity and the main dimensions of the vessel, as they are tightly linked to each other through the number of bays (in length), rows (in width), and tiers (in height). While the capacity determines the main dimensions of the ship, the hull form determines how much containers can fit on the ship. To get a better understanding on the relationship between these 2 aspects, general arrangements, data of 263 ships from Clarksons [124] and pictures of ULCVs have been examined and the following observations were made accordingly:

Figure 7.2: General arrangement of an ULCV [8]

(i) The general arrangement of ULCVs differs from smaller container vessels. Smaller container vessels have their deckhouse at the aft, above the engine room. ULCVs, on the other hand, usually have the deckhouse at approximately 2/3 of length upfront, while the engine room is in the aft of the vessel, with the funnels also at this position. An example can be seen in Figure 7.2.

(ii) Regardless of the length of the ship, there are usually 4 bays behind the funnels.

(iii) The fifth bay from the stern, i.e., the bay in front of the funnels, is above the engine room. Thus, there is less space below deck for this bay, similarly as the last 4 bays.

(iv) The midship section of the ship is the part that gets longer as the length of the ship increases, the bow (first 4 bays) and stern sections (last 5 bays) of the ship do not change.

(v) The stack height in the first 4 bays is less due to the regulation regarding the navigation bridge visibility, which states that "The view of the sea surface from the conning position shall not be obscured by more than two ship lengths, or 500 m, whichever is the less..." [112].

(vi) Below deck there are 2 rows less than above deck, as seen in Figure 7.3.

(vii) Even though, from a regulatory perspective, the distance between the forward perpendicular and the collision bulkhead could be as short as 7 m [36], all ULCVs have a much longer bow, usually around 20-25 m.

(viii) The bays which are effected by the narrowness/form of the hull are the first 4 and last 5 bays. The bays in the midship section are not affected.

(ix) The deckhouse has a horizontal length of about 15 m.

(x) The horizontal length of the funnels vary between 6 to 15 m, depending on the size of the ship.

(xi) 87% of ULCVs, from Clarksons, have a draft of 16 ± 0.5 m.

These observations form the basis of how the capacity and main dimensions are calculated. As mentioned, the main link between capacity and main dimensions is made by the number of bays, rows, and tiers. This information is usually not directly available, but it is possible to determine them by observing pictures of ships and counting. Table 7.1 shows this relationship,

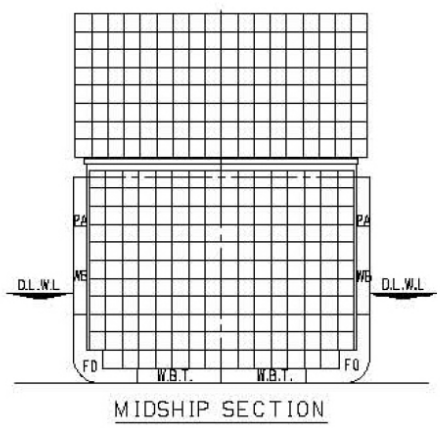


Figure 7.3: Midship section of a container ship [134]

Table 7.1: Design options for ULCVs propsed by DNV GL [119]

Bays	Rows	Tiers	TEU nominal	Draught [m]	LOA [m]	Breadth [m]
24	23	12	20332	16	400	58.6
24	24	12	21325	16	400	61.1
24	25	12	22228	16	400	63.6
26	23	12	22212	16	430	58.6
26	24	12	23301	16	430	61.1
26	25	12	24264	16	430	63.6
28	25	12	26316	16	460	63.6

as proposed as possible designs by DNV GL. For these designs, they have set the tier under the deck to 12 and above the deck to 11.

The difficulty in calculating the capacity comes from the form of the hull, as it is a curvy shape. It has been chosen to use a matrix of percentages to reflect the effect of the hull on the capacity. The values, which have been used, can be seen in Table 7.2. Only the last 5 and first 4 bays are affected by the hull shape. The midship section is not affected, but, as seen in Figure 7.3, at the bottom tier there are 2 rows less due to the structure of the ship, which has been implemented. The percentage for the other sections are based on observations made from pictures and plans such as the in Figure 7.2. It has also been implemented that there are 2 rows less under deck than above, according to the observation that was made. The tiers have been set to 12 below deck and 11 above. Bays 1-4 have less tiers above deck, as seen in Table 7.2. The validation of this matrix has been done and will be explained in Section 7.9. It should be pointed out that this matrix should change with the block coefficient, which is linked to the design speed, as a fuller hull has more space for cargo. This effect has been neglected.

Table 7.2: Matrix used to calculate the capacity

	Last 5 Bays	Midship	Bays 3 & 4	Bays 1 & 2
Tiers Above Deck	11	11	10	9
Above Deck	100%	100%	100%	100%
Below Deck	40%	100%	80%	60%

As capacity is one of the main inputs, the tool has to find an optimal combination of bays and rows, such that the calculated capacity is closest but not less than the target. This means that the following optimization has to be made:

$$Minimize \quad Z = f(x_b, x_r) - Target \tag{7.2}$$

subject to:

$$\begin{aligned} 6.5 \quad \leq \quad & \frac{L_{est}}{B_{est}} \quad \leq \quad 7.5 \\ 9 \quad \leq \quad & x_b \quad \leq \quad 28 \quad , \quad x_b \in \mathbf{N} \\ 0 \quad \leq \quad & x_r \quad \leq \quad 25 \quad , \quad x_r \in \mathbf{N} \end{aligned}$$

The lower limit for the number of bays comes from Table 7.2, while the upper limit is based on the data from 7.1. Increasing this number would result in very long vessels, which would require an additional feasibility analysis in the structures of such vessels. The upper limit for the number of rows is also based on Table 7.1, but also on the fact that the outreach of conventional ship to shore (STS) gantry cranes at port are limited to approximately 73 m [79]. The length is estimated based on the data from Table 7.1, as seen in Equation 7.3. The beam is calculated according to the number of rows as shown in Equation 7.4, which can also be confirmed with Figure 7.3. The L/B ratio is usually 7 for container vessels [114][155], but data from Clarksons has shown that this can vary between 6.5 and 7.5, which has been implemented.

$$L_{est} = 1.36 \cdot x_b \cdot (2 \cdot l_{TEU}) \tag{7.3}$$

$$B_{est} = x_r \cdot w_{TEU} \tag{7.4}$$

The number of bays and rows are given as integers, which means that to solve this optimization problem non-linear integer programming is required. A tool called *GEKKO* has been utilized, which is an open source optimization software for mixed-integer and differential algebraic equations. *GEKKO* allows users to define optimization models and automatically solves the said model for a given objective function. It is built on a selection of different non-linear solvers such as APOPT, BPOPT, IPOPT, MINOS, SNOPT which perform the actual optimization [10]. In this case, APOPT was used to find the optimal combination of bays and rows, such that the total amount of TEUs is closest to the set target, but not less than it.

Before determining the main dimensions, one aspect should not be forgotten: the limitations of the route. In Section 5.4, it had been stated that the route between China and Northern Europe will be focused on. This means that ships sailing on this route have to sail through 2 important channels: the Malacca Strait and the Suez Canal. The limitations of these channels have to be taken into account. The Malacca Strait has only a limitation for the draft, as it has an average depth of 27 m [22]. Due to the trapezoidal cross-section of the Suez Canal, the limitation of draft is in accordance with the beam of the ship, e.g., a ship with a draft of 16 m may have a beam of 62.2 m [143]. As the upper limit for the rows, in the tool, is 25, this means that the maximum for any ship beam would be 61 m. Considering this and the observation made on the drafts, it has been chosen to fix the draft at 16 m. Usually the maximum length for the Suez Canal is stated as 400 m, but the canal authority states that longer ships can pass through "with special arrangements" [143]. Therefore, it has been assumed that ships longer than 400 m should not be a problem for this route.

$$GT = 9.5072729 \cdot n_{TEU} + 12372.92 \tag{7.5}$$

Taking all of this into consideration, the main dimensions are calculated. The draft, as said, is always 16 m. The length and beam are calculated with the Equations 7.3 and 7.4, respectively. The gross tonnage (GT) is estimated according to Equation 7.5, which has been determined through data from Clarksons with a R^2 value of 0.9408. These are used as first estimations and are updated, if necessary, further on.

7.3. Resistance

The calculations for the resistance were done according to the Holtrop & Mennen Method [55]. This statistical method calculates the resistance and subsequently the required power, according to the main dimensions of the ship. It is presented as a method for the initial design stage of a ship, as the objective of the tool is not a highly precise design, the precision of the results is deemed sufficient. This section will not go into the details of the method, but the most relevant and important assumptions and choices that were made to make the calculations and the reasoning behind them.

The length estimated in the previous section is the length overall (LOA), but for the calculations the waterline length or length between perpendiculars (L_{pp}) is required. Clarksons data shows that Equation 7.6 is an accurate way of determining this length.

$$L_{pp} = 0.95 \cdot L_{oa} \tag{7.6}$$

This can then be used to calculate the block coefficient (C_B). The block coefficient usually depends on the hull shape, but as the tool does not create a detailed hull shape, the block coefficient has to be approximated. For this Equation 7.7 by Katsoulis has been used [155]. The midship section coefficient (C_M) has been assumed to be 0.98, as this is an accurate approximation, as can be seen from Figure 7.3. The waterplane area coefficient (C_{WP}) has been determined according to Equation 7.8 as proposed by Lamb [73].

$$C_B = 0.8217 \cdot L_{pp}^{0.42} \cdot B^{0.3072} \cdot T^{0.1721} \cdot v_s^{-0.6135} \tag{7.7}$$

$$C_{WP} = 0.95 \cdot C_P + 0.17 \cdot (1 - C_P)^{1/3} \tag{7.8}$$

Another parameter which is required is the longitudinal centre of buoyancy (lcb), which depends on the underwater shape of the hull. Papanikolaou [114] provides a graph with a range of optimal positions of the lcb depending on the Froude number (F_n) of the ship. Following this information, Equation 7.9 has been proposed, as means of approximating lcb, which gives the lcb as a percentage of L_{pp} relative to the midship.

$$lcb = 50 \cdot F_n - 10.5 \tag{7.9}$$

The design of the bulbous bow has also an effect on the resistance of the vessel. Especially the transverse sectional area of the bulb (A_{BT}) and the height of the centre of the transverse area (h_B) are necessary for this method. A_{BT} is in relation with the midship sectional area (A_{MS}) as seen in Equation 7.10 [70]. The cross-section parameter (C_{ABT}) has been set to 0.09, as this has been deemed to be a plausible value for ULCVs. Similarly, h_B has been set to 45% of the draft of the ship.

$$A_{BT} = C_{ABT} \cdot A_{MS} \tag{7.10}$$

The different appendages should also be accounted for, when calculating the resistance of a vessel. For this calculation, it has been chosen to only consider the rudder, as this has a larger effect compared to other appendages which can be neglected at this level of accuracy. The rudder area (A_R) has been calculated according to Equation 7.11 [82].

$$A_R = 0.001 \cdot \left(1 + 50 \cdot C_B^2 \cdot \left(\frac{B}{L_{pp}}\right)^2\right) \tag{7.11}$$

This information is sufficient to calculate the resistance according to the Holtrop & Mennen Method. The method also provides equations for the wake factor (w) and thrust deduction (t), which are necessary for the propeller matching. Matching the propeller to the hull is an important step and forms the link between the hull and the engine. The propeller matching will be discussed in the next section.

7.4. Power

The step after calculating the resistance is to calculate the required power. Equation 7.1 described the relation between the resistance and P_E, which is not the same as the power that the engine has to deliver, i.e., the brake power (P_B). Equation 7.12 shows the relation between the 2 powers with the different efficiencies [68].

$$P_B = \frac{P_E}{\eta_H \cdot \eta_O \cdot \eta_R \cdot \eta_S} \tag{7.12}$$

The hull efficiency (η_H) can be calculated according to Equation 7.13 [68]. The relative rotative efficiency (η_R) is usually around 1 to 1.07 for single screw ships, while the shaft efficiency (η_S) is usually around 0.99 [87]. In the tool, 1.03 and 0.99 have been implemented for η_R and η_S, respectively.

$$\eta_H = \frac{1-t}{1-w} \tag{7.13}$$

The open water efficiency (η_O), on the other hand, depends on the design of the propeller and its interaction with the hull, which means that it cannot be calculated easily. There are methods of matching a propeller, but as implementing these in the tool would require too much time, it has been decided to use PropCalc. PropCalc is a software which determines the optimal propeller given certain input and using the Wageningen B-series. The main input required by PropCalc is the design speed, thrust and revolutions of the propeller. PropCalc can then calculate η_O and the propeller diameter.

At this stage the tool will give all necessary input for PropCalc. The design speed is already defined by the user, the thrust is calculated by the tool, and the revolutions have been set to 80 rpm. The reason why it has been set to 80 rpm, is based on the properties of the engine, details will be discussed in the next section. The user is asked to use PropCalc to calculate the values for a 4-bladed fixed pitch propeller and enter the values for η_O and the propeller diameter. With this information, P_B can be calculated and the engine selection can be done.

7.5. Engine Selection

The brake power determines the installed power on the vessel, i.e., the main propulsion engine. The properties of this engine, such as the main dimensions and fuel consumption are important parameters and affect also other properties of the ship.

In the previous section, the brake power was calculated according to the different efficiencies. This would be the maximum power that the engine should deliver in ideal conditions, but the ship should also be able to sail in heavy weather conditions. Therefore, a sea margin is added, which is usually 15% but for large container vessels around 20-30% [87]. Besides this also an engine margin is added, as an operational margin, which is usually 10-15% [87]. Initially, a sea margin of 25% and an engine margin of 10% were considered, but at the end it was decided to implement a sea margin of 15% and an engine margin of 10% in the tool. The reason for this decision will be discussed in Section 7.9 in detail.

In order to determine the main properties of the engine, the MAN B&W G95ME-C9.5-GI-TII series have been chosen, due to the fact that MAN is one of the main engine manufacturers, which produces 2-stroke diesel engines which are used by ULCVs, and as it had a lot of publicly available information. Additionally, these engines can also operate with dual fuel, i.e., alternative fuels. MAN produces this series with up to 12 cylinders, which can deliver 82440 kW [89]. This enforces an upper limit on the design speed for the larger vessels, as the required power gets too high. This could restrict the design of the larger vessels. To avoid this, it has been assumed that producing bigger engines is possible by creating engines with more cylinders.

The data for engines with 5 to 12 cylinders was used to find the relation between the different main properties and the number of cylinders. These engines supply 6870 kW per cylinder. which was also used for the larger engines. The relation for length and height can be seen in Figure 7.4. The R^2 value of the height might seem a bit low, but it should be realized that the values are in millimeters. Furthermore, this level of precision is acceptable as there is sufficient height in the engine room. The width of these engines is always 6240 mm.

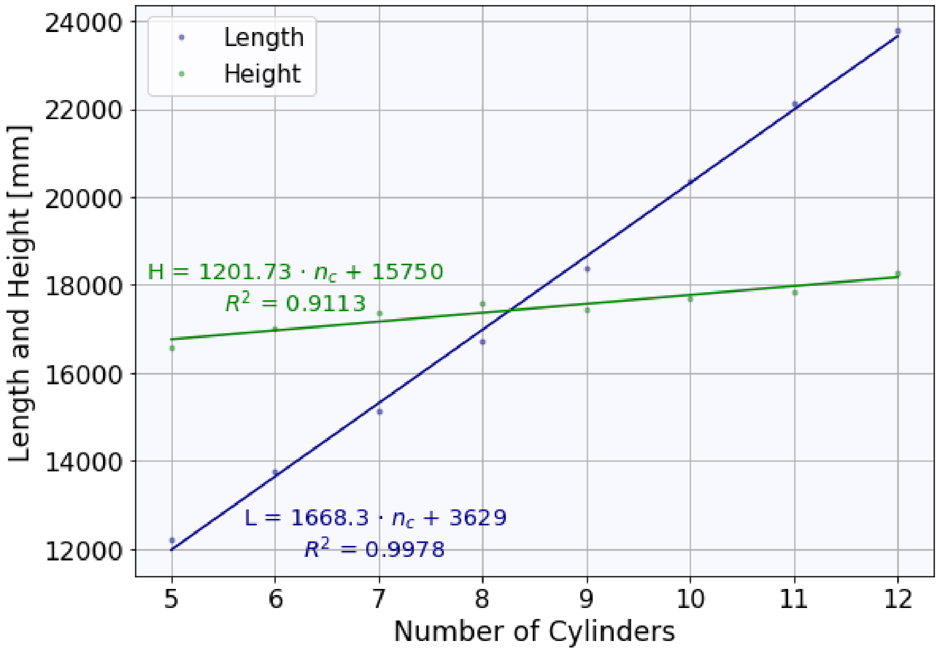


Figure 7.4: Relations between number of cylinders and length and height

In Section 7.4 it was mentioned that the revolutions were set to 80 rpm. The reason for this is that 80 rpm is the maximum engine speed. The designer has the choice to either fix the revolutions and adjust the propeller diameter or the opposite. If the diameter is fixed, usually the revolutions are just a little bit smaller or higher than 80 rpm, depending on the ship speed. This would mean that for a small difference a gearbox would be required, which would be more costly and less efficient. To avoid this, it has been decided to use the maximum engine speed and adjust the propeller diameter accordingly. This can result, depending on the ship speed and size, in a propeller diameter up to 11.5 m. Ordinarily, ship propellers are preferred around 10.5 m as manufacturing larger propellers can be problematic, but propellers up to 12 m are feasible [87]. Therefore, it should be noted that these big propellers are exceptional but are feasible options.

Figure 7.5: Notification message when a non-off-the-shelf engine is used

The data of these engines have been implemented into the tool. The tool finds the engine which meets the power requirements of the ship, i.e., the engine which has the closest power to the required power but not smaller. If this engine should be a not "off-the-shelf" engine, i.e., has more than 12 cylinders, it is brought to the attention of the user by a notification as seen in Figure 7.5.

7.6. Fuel Consumption

The specific fuel oil consumption (SFOC) of the engines can be calculated for the whole operating envelope with a tool provided by MAN [90]. This tool provides data over the SFOC for a selected design point and the rest of the propeller load. This data can be seen in Figure 7.6. Equation 7.14 gives the formula for the trend line seen in the same figure.

$$SFOC = -6.392 \cdot 10^{-5} \cdot SCMR^3 + 0.017 \cdot SMCR^2 - 1.396 \cdot SMCR + 187.175 \tag{7.14}$$

This tool also provides information about the use of dual fuel, for methane, ethane, methanol, and LPG. The SFOC is converted to specific pilot oil consumption (SPOC) and specific gas consumption (SGC) by multiplying it with the relevant percentages [89]. The SFOC is almost the same for all engines, i.e., the difference between larger and smaller engine is negligible.

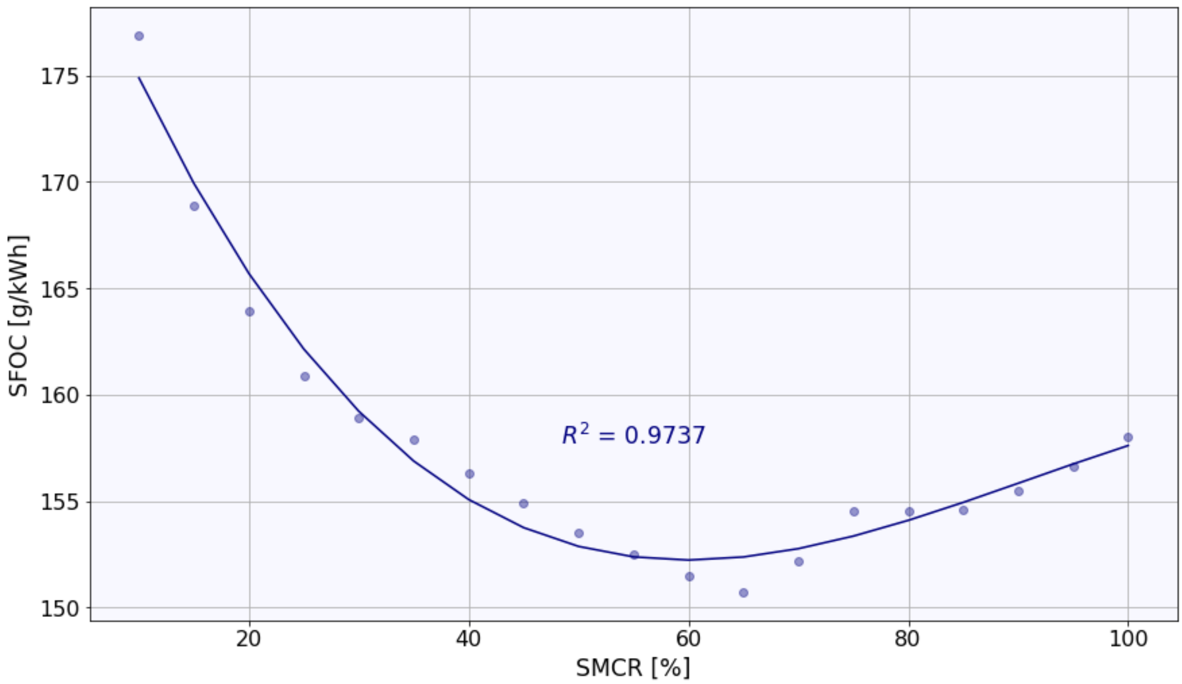


Figure 7.6: Specific fuel oil consumption as a function of specified maximum continuous rating

The fuel types seen in Table 7.3 have been implemented in the tool. As mentioned above, different fuels require a different amount of pilot fuel. As seen in Table 7.3, for some fuel types the data was available. MAN states that 1.5% pilot fuel is required when methane is used, as 85 to 95% of LNG is methane [37], it has been chosen to use the same value. Ammonia has nearly the same lower calorific value (LCV) as methanol, therefore it has been assumed that the same value should be feasible. Hydrogen has a much higher LCV, but no additional information regarding the use of pilot fuels could have been found. Therefore, it has been chosen to use 3% of pilot fuel when using hydrogen.

The conversion of SFOC to SPOC and SGC is being done in relation to the LCV of each fuel type, as has been described by MAN [89]. This conversion is done according to the choice of fuel that the user gives as an input to the tool. The consumption directly determines the amount of fuel which is required to be stored on the ship, which will be discussed in the following section.

Table 7.3: Properties of the different fuel types

Fuel Type	Lower Calorific Value [kJ/kg]	Required Pilot Fuel	Required Volume Compared to HFO	Specific CO_2 Emissions [kg CO_2 / kg fuel]
HFO	42700[89]	0.0%	1	3.11[149]
LNG	48600[148]	1.5%	3.5	2.75[149]
LPG	46000[89]	3.0%[90]	3	3.01[149]
Methanol	19900[89]	5.0%[90]	2.5	1.37[149]
Hydrogen (Liquefied)	120000[148]	3.0%	4.5	0
Hydrogen (Compressed)	120000[148]	3.0%	12.5	0
Ammonia	18600[28]	5.0%	2.5	0

7.7. Tank Volume

The consumption affects the volume of the tank, but there are also other factor which have impact. One of these is the range that the vessel should be able to sail with one full tank. It had been specified that the focus of this project is on the route between Northern Europa and China. Therefore, the distance between Shanghai and Rotterdam (via the Suez Canal) has been looked at, which is 10525 nm. This means that the range should be a multiple of this distance, as the vessel should travel only on this line.

Usually the range of a vessel is a choice of the ship owner and is a matter of business strategy. Fuel prices can change from port to port and buying the cheapest fuel can make huge savings, as the amount is considerably big. Considering this and the fact that alternative fuels require more volume than conventional fuels, it has been decided to keep the range at the lower end. The vessels should be able to sail 2.5 times the distance between Shanghai and Rotterdam. This should provide the flexibility in buying fuel at better prices and also having more fuel, in case the ship should sail in bad weather conditions.

For the tank volume of the different fuel types it is not sufficient to only consider the volume of the fuel alone. All mentioned fuels, besides HFO and methanol, require special storage facilities as they need to be cooled down and kept under pressure for storage. These facilities form a substantial part of the whole system and must be considered for a fair comparison. It should also be noted, that these storage systems have specific forms (i.e., cylindrical tanks, etc.), which would result in even bigger volumes, as the specified space cannot be used as efficiently. But this effect will be neglected for simplicity's sake and due to the lack of accessible information about the properties of these systems. It will be assumed that these storage facilities can take any form and use the assigned space completely. In Table 4.1 the required volume compared to HFO for the same amount of energy were stated, but some fuel types had a range. These values were adjusted in Table 7.3 and implemented in the tool for the tank volume calculations.

When Table 7.3 is observed, one fuel type strikes the attention of the reader. The required volume for compressed hydrogen is significantly higher than the other fuel types. This will result in a very large fuel tank. It has been implemented in the tool, but feasibility of this type of hydrogen is questionable. The other alternative fuel types will also result in larger fuel tanks. Therefore, it must be checked if these tanks have enough space on the ship.

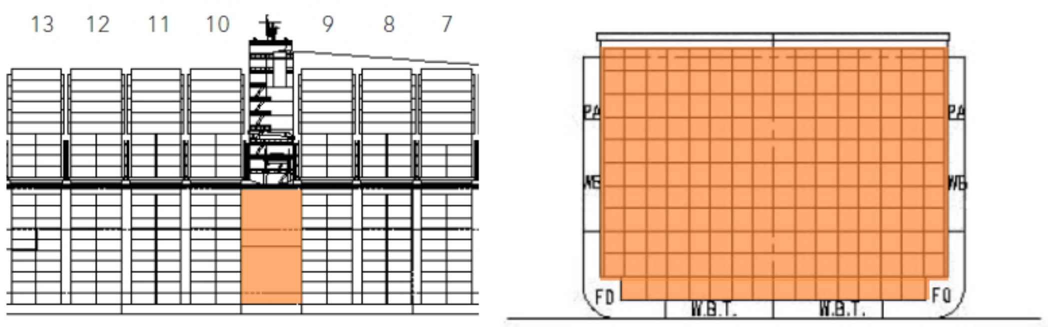
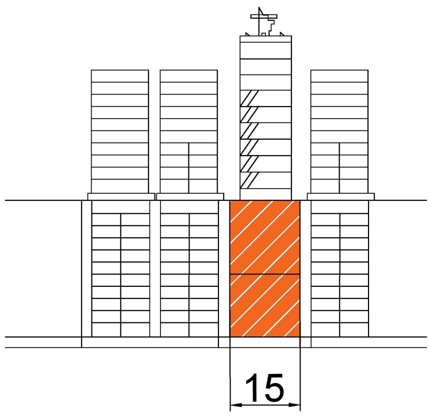


Figure 7.7: Representation of the assigned space for the fuel tank

The space assigned for the fuel tank is beneath the deckhouse, seen in orange in Figure 7.7. The tool calculates the available area of the midship section, as seen in Figure 7.7, and divides the required volume by this area. This gives the required length of the fuel tank. According to the difference between the length of the fuel tank (L_{tank}) and the length of the deckhouse (L_{dh}), which is 15 m, the ship is lengthened. One might wonder why the length is changed rather than the beam or the draft. The reason for this is the fact that these dimensions are more limited. There is a maximal beam due to the STS gantry cranes and there is a maximal draft due to the Suez Canal and the port basins. Furthermore, increasing the draft is not an option as the 12 tiers below deck and 11 above are the stack limits for both cases. Additionally, adding 1 row has a bigger impact than adding 1 bay as it changes the whole shape of the ship. Therefore, the only viable option is to lengthen the ship. The following options are applied depending on the calculated length of the fuel tank:

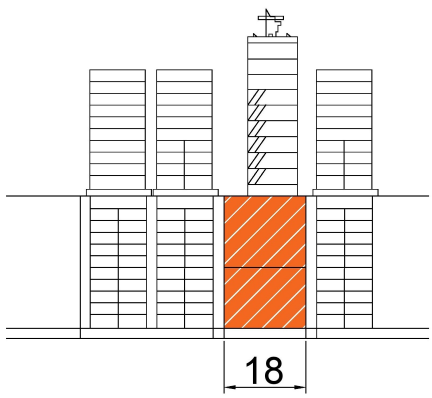
(i) If $L_{tank} - L_{dh} \leq 0$:

No adjustments are required. The fuel tank is seen in orange.



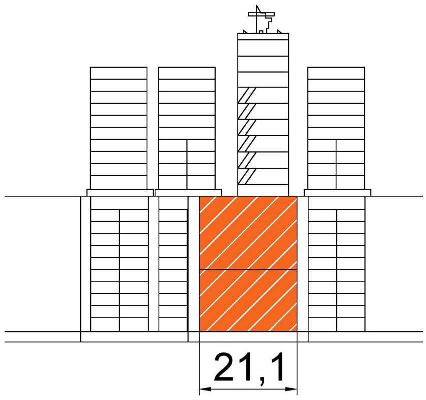
(ii) If $0 < L_{tank} - L_{dh} \leq 3$:

The ship is made 3 m longer to accommodate the necessary volume. The fuel tank is seen in orange. Gross tonnage is adjusted using Equation 7.5.



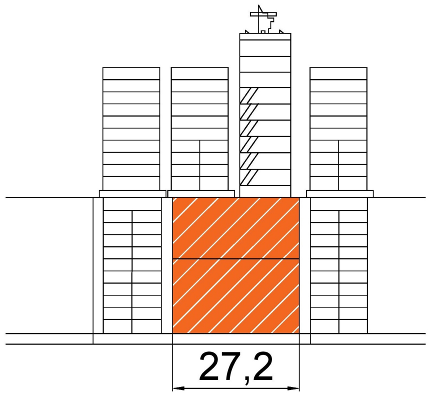
(iii) If $3 < L_{tank} - L_{dh} \leq 6.1$:

Half of a bay under the deck is added to the fuel tank. This results in a loss in TEUs, e.g., in case of a ship with 24 rows 262 TEUs are lost. The fuel tank is seen in orange.



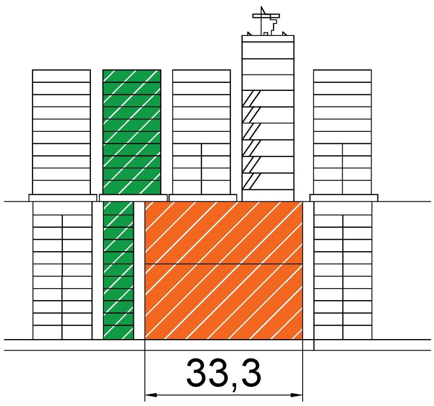
(iv) If $6.1 < L_{tank} - L_{dh} \leq 12.2$:

A whole bay under the deck is added to the fuel tank. This results in a loss in TEUs, e.g., in case of a ship with 24 rows 524 TEUs are lost. The fuel tank is seen in orange.



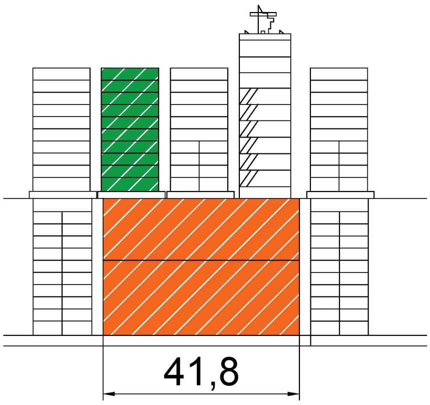
(v) If $12.2 < L_{tank} - L_{dh} \leq 18.3$:

The ship is lengthened by 1 bay, i.e., 14.6 m (including the additional bulkhead), and 1.5 bays under the deck are added to the fuel tank. This results in additional TEUs, e.g., in case of a ship with 24 rows there are 266 additional TEUs. The fuel tank is seen in orange and the added containers in green. Gross tonnage is adjusted using Equation 7.5.



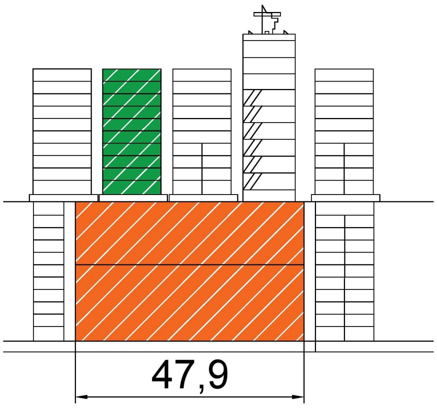
(vi) If $18.3 < L_{tank} - L_{dh} \leq 26.8$:

The ship is lengthened by 1 bay, i.e., 14.6 m (including the additional bulkhead), and 2 bays under the deck and a bulkhead are added to the fuel tank. This results in a small change in TEUs, e.g., in case of a ship with 24 rows there are 4 additional TEUs. The fuel tank is seen in orange and the added containers in green. Gross tonnage is adjusted using Equation 7.5.



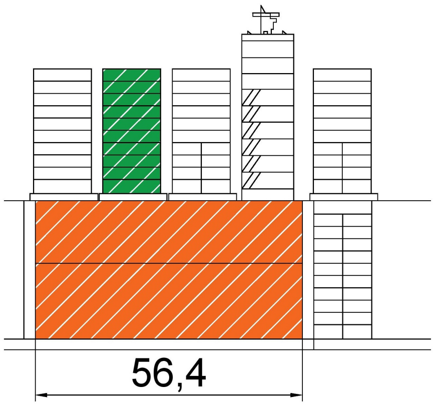
(vii) If $26.8 < L_{tank} - L_{dh} \leq 32.9$:

The ship is lengthened by 1 bay, i.e., 14.6 m (including the additional bulkhead), and 2.5 bays under the deck and a bulkhead are added to the fuel tank. This results in a loss in TEUs, e.g., in case of a ship with 24 rows 258 TEUs are lost. The fuel tank is seen in orange and the added containers in green. Gross tonnage is adjusted using Equation 7.5.



(viii) If $32.9 < L_{tank} - L_{dh} \leq 41.4$:

The ship is lengthened by 1 bay, i.e., 14.6 m (including the additional bulkhead), and 3 bays under the deck and 2 bulkheads are added to the fuel tank. This results in a loss in TEUs, e.g., in case of a ship with 24 rows 520 TEUs are lost. The fuel tank is seen in orange and the added containers in green. Gross tonnage is adjusted using Equation 7.5.



This procedure ensures that there is enough volume for the fuel. The change in TEUs is not problematic, as the tool can never achieve a 100% accuracy of the target capacity. In some cases it will be off by a small difference, in some by as large as 200-300 TEUs. Therefore, 500 TEUs less or more, due to the lengthening of the ship, should be still in the acceptable range for the capacity. But the change in length will have an effect on the resistance. Thus, it should be checked.

The first estimation of the length in Section 7.2 was based on data from Clarksons. At this stage, more information is available. Consequently, the length can be calculated more accurately with Equation 7.15, where L_{bh} is the horizontal length of the bulkhead, L_{funnel} is the horizontal length of the funnels, and L_{fs} the length of the foreship section.

$$L_{oa} = \left(l_{TEU} \cdot 2 \cdot x_b\right) + \left(L_{bh} \cdot x_b\right) + L_{funnel} + L_{dh} + L_{fs} \tag{7.15}$$

The length of the deckhouse is 15 m, unless the ship is lengthened by 3 m according to the steps above. In that case it would be 18 m. The length of the foreship section has been set to 20 m, according to the observation made in Section 7.2. In Section 7.2 it was also observed that the engine room is partially underneath the funnels and 1 bay. It was also observed that the horizontal length of the funnels varies between 6 and 15 m. Therefore, the length of the funnel should not be shorter than 6 m, but in case of a long engine room, due to a large engine, the length of the funnels should be larger. Which means that the portion of the engine room which does not fit underneath the bay should fit underneath the funnels and the length of the funnels should be accordingly, as can be seen from Equation 7.16.

$$L_{funnel} = max\{6, \quad 1.2 \cdot L_{engine} - (2 \cdot l_{TEU} + L_{bh})\} \tag{7.16}$$

Once the length is adjusted, the calculations for resistance and power are redone and the values are updated. A second iteration for PropCalc is not necessary as the change in these values are negligible. From tests it has been observed that an increase in length causes half of that increase in resistance and power. The tool also checks if the selected engine is still meeting the power requirements. Generally, the updated power does not exceed the power of the selected engine. In some cases, it was observed that it did but never exceeding 2% which is negligible as there are already 35% of sea and engine margins. If it should exceed 5% the user is notified and he has to make the required adjustments.

It should be noted that removing cargo space in the bottom of the ship and replacing it with fuel tanks will increase the centre of gravity of the ship. This could lead to problems with the stability of the ship, which is also a common problem with conventional container ships. This problem is usually solved by increasing ballast [73]. As the tool is not calculating the weights of the different parts of the ship, such as the machinery, hull, superstructure, etc., it is not possible to come to a conclusion whether this will be a severe problem or not. This is an aspect, which should be looked at in future works.

7.8. Capital Expenses

The tool also makes an estimation for capital expenses (CAPEX) of the designed ships. For this purpose, a relation between the number of TEUs and CAPEX has been looked at. Data of built and ordered ships from Clarksons were used for this. Some ships were removed from the data-set as they were outliers, because they were either forerunners or had different propulsion systems. The data, which is from conventional HFO using ships, can be seen in green in Figure 7.8.

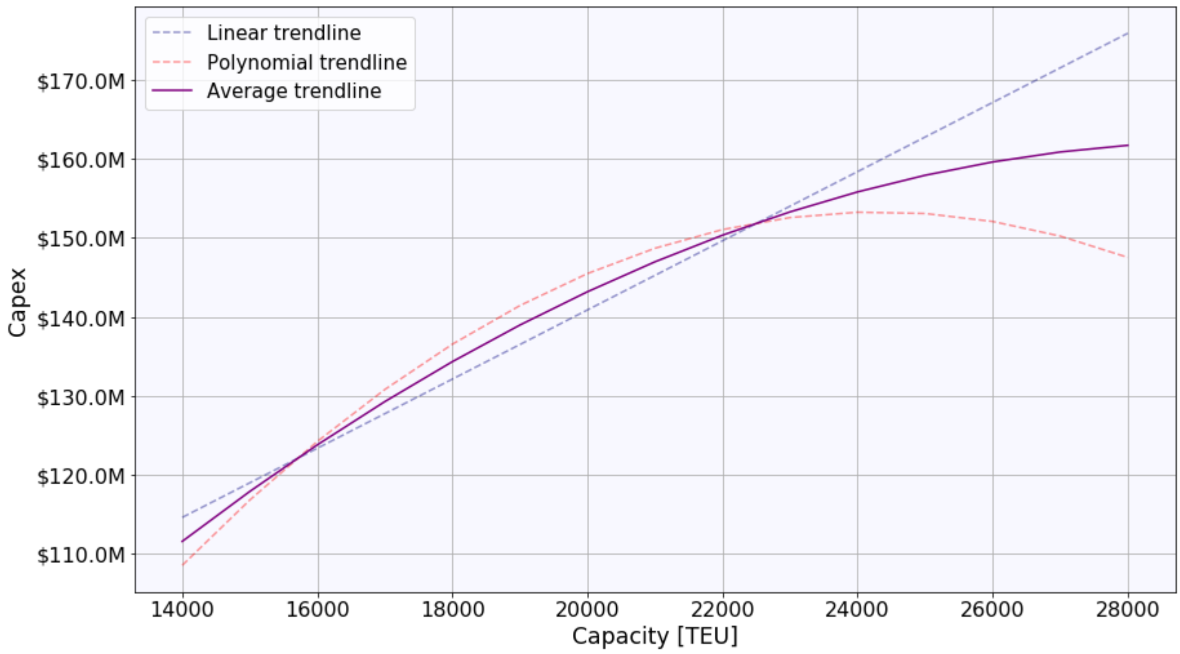


Figure 7.8: Data regarding capital expenses

To this data a linear and a second degree polynomial trend were fitted, seen in red and blue, respectively. It can be seen that a linear trend does not take the economies of scale into account, while a second degree polynomial makes larger ships cheaper than smaller ships. As both trends were not logical, it has been decided to use the average of both trends, which can be seen in purple. Equation 7.17 describes this trend, which has a R^2 of 0.8354. It has to be acknowledged that also this trend will estimate larger ships cheaper after a given capacity, but for the range for which the tool is valid it is a good estimation. It should also be noted that this estimation is only accurate for conventional ships and not for ships which use alternative fuels. As a good estimation for ships with alternative fuels has not been found, the same estimation is also used for them as a base but, naturally, they are more expensive than conventional ships.

$$Capex = -2.108 \cdot 10^{-7} \cdot n_{TEU}^2 + 12.436 \cdot 10^{-3} \cdot n_{TEU} - 21.203 \tag{7.17}$$

7.9. Verification & Validation

Every model is a mere representation of the reality or aims to be one. The reality of subjects is usually complex and many factors have impacts on different aspects, which makes it necessary to make assumptions and simplifications when modelling a subject. In the previous sections, the assumptions and simplifications that were made were explained and justified. It is critical to make sure that these assumptions did not affect the outcome at such an extent that the model is not representing the reality anymore. Therefore, it is necessary that the model is verified and validated.

During the development of the tool, at every stage and step of it, verification tests were performed. These were logical tests, checking if the tool would give a certain output with a certain input. For example, it was expected that the a longer or wider ship should have a higher resistance than a small one, which was confirmed by the tool. Similarly, it was expected that a ship which uses an alternative fuel should be longer than a ship which uses HFO, which was also confirmed. It was also assured that small increases or decreases of certain parameters would result in proportional changes in subsequent values. Doing many more tests like these, at every stage of the development, helped finding errors and debugging the tool. They also verified that the tool was working as it was intended to do.

For the validation, data from Clarksons of existing ships were used. The validation could only be done for ships which use HFO as fuel, as ULCVs which use alternative fuel could not been found. For the purpose of validation 17 ships were chosen randomly, with the intention of covering the range of 24,000 to 14,000 TEUs. These ships are usually part of a family of ships, therefore they are a representation of more ships. Their capacity and speed were used to create similar ships with the tool. Subsequently, their length, beam, draft, and power were compared using the Clarksons data. Bay and row number were also compared, but this information was determined by observing pictures of the ships as Clarksons did not have this data. The difference in percentage between the tool's result and the selected ships have been visualized as box plots, as seen in Figure 7.9.

It can be seen that the capacity is always very close to the capacity of the real ships as this is one of the main inputs. It is usually slightly off, but this was expected as the tool cannot achieve the set goal for capacity but optimizes for a the closest value it can achieve.

There are bigger differences for the bay and length, which are directly related. The tool creates designs with less bays and thus shorter ships. Out of the 17 ships, 13 have 24 bays and a length of approximately 400 m, even though the capacity varies from 24,000 to 16,000 TEUs. On closer inspection it can be seen that 152 ships out of 263 ships, i.e., 57.8%, have a length of about 400 m, while the rest have a length of 360-370 m. It seems that there are some tendencies to keep the ships length in certain ranges, but the reasons for this are unknown and would require additional inquiries. The tool tends to generate shorter vessels, i.e., usually 2 bays less, which is roughly 8% shorter.

The rows and the beam, which are directly linked, show a similar behavior. Here, the tool generally creates designs with 1 row less, which results in a roughly 5% narrower ship. The reason for both the smaller length and beam is, most likely, an assumption that was made. In Section 7.2 it was said that, in accordance with the information from DNV GL, it was chosen to set the tier below deck to 12 and above deck to 11, in all cases. This assumption was made due to the lack of information. On closer inspection of various ships it can be said that the 11 tiers above deck is not always the case, some ships have less. Analyzing the situation below deck is more difficult, as general arrangement plans are not accessible and it also cannot be observed from pictures. But as 87% of the ships have a draft of about 16 m, the assumption for below deck should be accurate. Closer inspection of the data also shows that there are ships of the same main dimensions, but there can be differences of up to 3,000 TEUs in capacity. Further investigations show that these differences are usually between

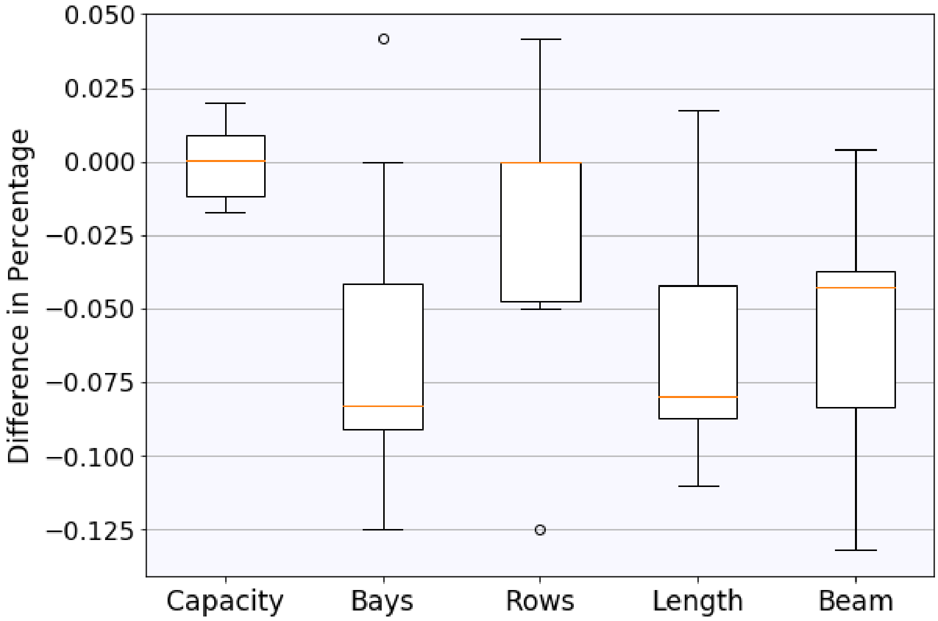


Figure 7.9: Box plots of the differences of some parameters

old and new ships, where new ships of the same main dimensions have larger capacities. Considering this, it has been assumed that better general arrangements and designs can lead to smaller designs, i.e., the fact that the tool generates smaller ships is not problematic and can be considered as optimal designs.

$$P_E = c \cdot v_s^3 \tag{7.18}$$

Another parameter which was checked was the installed power. The power is related to the main dimensions, but as can be seen from Equation 7.18 [68], speed has a higher impact on it. Thus, the design speed is an important factor for determining the installed power.

The installed power showed some irregularities. As mentioned above, initially the total margins were 35%. When compared with data it showed that the tool was assigning much bigger engines than comparable ships. This was interesting, because one would have expected that it would assign smaller engines as the tool was also tending to create smaller vessels. In a "classical" validation process, this would be highly problematic. But in this specific case following a "classical" validation would not be fair. As Pedersen et al. [117] points out, in some cases where there is a lack of information or in a new field it is not possible to follow classical methods. They propose "The Validation Square" as an alternative method, which was used to explain why the tool is valid.

If the structure of the tool is observed, it is possible to say that nothing "new" has ben actually created. Different methods, data and observations are brought together to form this tool. The first step in the tool is the estimation of the main dimensions, which is based on data and observations that have been made. When these are compared with existing ships, it can be seen that they are quite accurate. The tool has a tendency of creating smaller ships, but that is related to the assumption that every ship has 12 tiers below and 11 above deck.

The next step in the tool is to calculate the resistance, which is done with the Holtrop & Mennen Method. A method which is well-known by naval engineers and accepted. For the propeller matching PropCalc is used, which is also a well-known software and based on the publications of Maritime Research Institute Netherlands (MARIN). For the engines standard engines of MAN are used, which is one of the main engine manufacturers. But somehow the tool installs bigger engines than what seems to be the norm.

There is only one aspect where an assumption is made, regarding the engine size. It had been chosen to implement an engine and sea margin (10% and 25%, respectively), as has been advised by literature. This is roughly 35% in total. The differences between the installed power calculated by the tool and the data set can be seen in Figure 7.10. In the same figure, the results for when the total margins are decreased to 25% can also be seen.

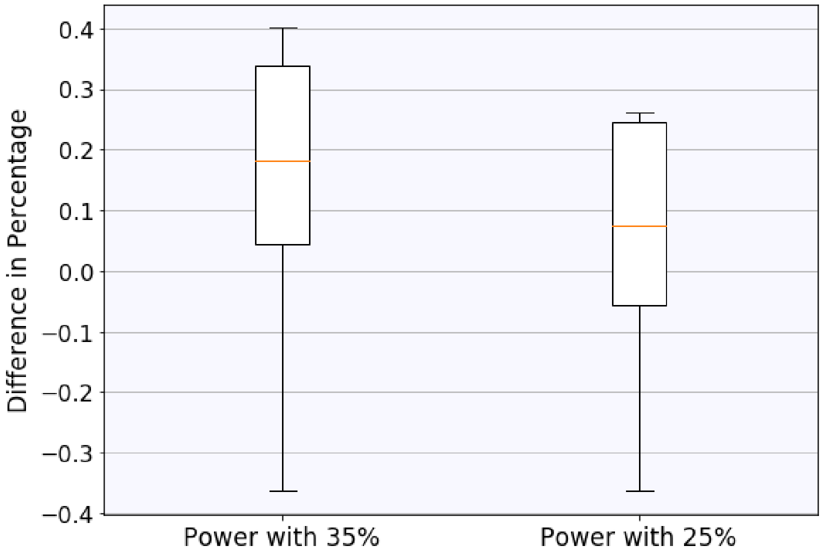


Figure 7.10: Box plot of the differences in power

To get a better understanding, the results have been analyzed in more detail. The brake power which has been calculated (without the margins) and the installed power on the ships (from data) have been compared. The calculated brake power might not be exactly correct, but it should be in an acceptable range. If these values are compared, the margins chosen by the companies should reveal themselves. Some ships did have a difference of 35% and some 25%. While lowering the margins from 35% to 25% did improve the results for some, it worsened it for others. The other ships had a difference as small as 5 to 10%.

These margins are there for security and are choices made by the ship owner. Information regarding the choice of margins are not available to this project. Literature advises 15% for engine margin and 20-30% for sea margin for container ships. Compared to this, 25-35% of margins are already low, but data shows that some of these ships have these margins. On the other hand, although it seems to be very low, some companies go even lower and have margins as low as 5-10%.

Considering these aspects, the conclusion that the tool is valid has been made. The difference is related to the choices that are made by the ship owners regarding the margins. The engine margin has been set as 10% and the sea margin to 15%, as this improves the overall results. This change lowers the median from 18% to 7.5%.

7.10. Conclusion

The ULCVs belong to a new and upcoming class in a fierce market, such as the international shipping market. The information regarding the design of these ships is limited. Based on this limited information, available data, methods, and softwares a parametric design tool for ULCVs has been developed. The tool requires capacity, speed and fuel choice as input and generates the optimal design accordingly. The biggest impact of the choice of fuel is on the consumption and consequently on the storage of the fuel. All alternative fuels require more tank volume, compared to the conventional fuel: HFO. It has been shown that the most convenient way of accommodating this extra volume is by converting some cargo space, elongating the ship or a combination of these. These fuels also require additional facilities, which would increase the building costs, i.e., the Capex, of the ships. Due to a lack of information, it has been chosen not to implement this difference. Statements regarding these additional costs will be made through the analysis of the results of the following chapter.

7.10.1. Future Work

There are a couple of aspects, which could be improved and would make the tool more precise. It has been mentioned that the effect of the block coefficient on the capacity of the ship has been neglected. If there should be a trend of slower container ships and speed is influencing the block coefficient, it would be interesting to see the effect of larger block coefficients on the design of container ships. This would mean that the hulls of container ships would look like the hulls of tanker, which would make it possible to carry more containers. Such a change would require a detailed study about the weight and buoyancy of this type of ships and other aspects.

Another improvement that would make the tool more user-friendly, would be integrating the propeller matching process in the tool. At the moment, the user has to enter values from the tool in PropCalc and then enter the obtained results in the tool. The calculations for the matching are not necessarily difficult, but the implementation would require a lot of time, which was the reason why it was not done.

It was also noted that as the weight of the different parts of the ship were not calculated, it was not possible to make a statement about the centre of gravity and consequently about the stability of the ship. Implementing weight calculations would improve the reliability of the tool. This knowledge could also be used for improving the estimation of CAPEX. Instead of estimating CAPEX through TEU, it could be calculated with the price of steel, engine, etc. This would also require a detailed research about the different elements of the ship. Furthermore, by researching the different required facilities for the alternative fuels, it would be possible to also estimate CAPEX for ships using alternative fuels. This would be a valuable addition to the existing tool.

8
Robust Decision Making

In Chapter 6, the RDM process has been explained and a summary can be seen in Figure 8.1. RDM will help in assessing and comparing the different fuel types performances, while taking different uncertainties and possible policies into account. This chapter will firstly explain XLMR framework which has been implemented to build the basis of the RDM process and then describe the subsequent steps of this process.

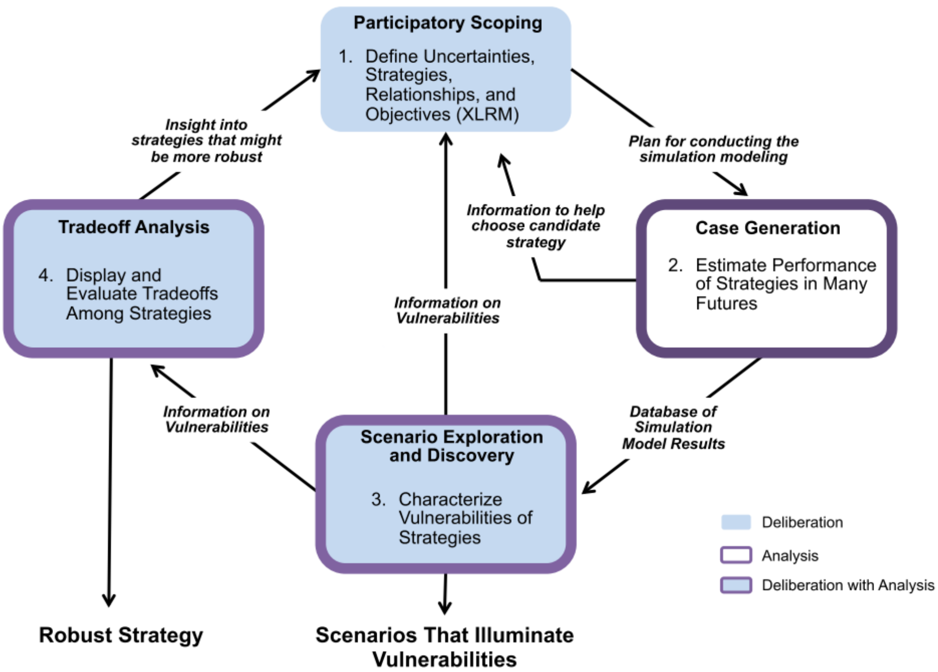


Figure 8.1: Steps of Robust Decision Making [77]

8.1. XLMR Framework

The first step of RDM is defining the exogenous uncertainties (X), the policy levers (L), metrics/objectives (M), and relationships (R). This provides the basis for the scenarios and the simulation.

It is in the interest of RDM to consider a vast number of different scenarios. Every added uncertainty or policy option may add value, but these additions have to be made wisely as the more variables there are the more scenarios there will be. This could result in an explosion of scenarios, which could be difficult to handle and interpret. Therefore, 3 exogenous uncertainties, 2 policies with 2 variables, 2 metrics and a simple economic model have been proposed, which will be explained in the following parts.

8.1.1. Exogenous Uncertainties (X)

As mentioned above, there are 3 uncertainties, which will be used for this process. They are the following:

- **Fuel Prices**

  As a comparison between different fuel types is targeted, the price of each fuel type is of utmost importance, as this will have a big effect on the profitability. Fuel prices (P_{fuel}) usually fluctuate and might have a rising or falling trend over a longer period. Some fuels have similar trends as their production is integral. These trends and fluctuations are important, but when comparing fuel types not necessarily crucial. The difference between the fuel prices is more important for a comparison. Therefore, fluctuations and trends will be neglected and constant prices for the lifetime of the ships will be applied. This is a simplification of reality.

  A baseline for the price of each fuel will be set and the prices will be varied depending on this. As the year 2020 is an unusual period, the prices of 30 August 2019 have been taken to form the baseline. The prices for HFO (more specifically very low sulphur fuel oil VLSFO), LNG, LPG and methanol can be seen in Table 8.1. The reason why VLSFO has been chosen is the fact that ships either have to use this or install scrubbers, such that they meet the regulations regarding SO_x emissions. Prices in Euros were converted with the exchange rate (of the day) of 1.1 to USD [83], this rate will be used throughout this thesis.

  Table 8.1: Base prices for fuel types

Fuel Type	**Price**
HFO (VLSFO)	500.5 $/tonne [24]
LNG	253.3 $/tonne [58]
LPG	362.8 $/tonne [141]
Methanol	346.5 $/tonne [97]

  HFO, LNG, LPG, and methanol have established and open markets, this is why the prices above can be given. The situation for hydrogen and ammonia is slightly different. Ammonia is mainly used for agriculture or pharmaceutical purposes (currently). Consequently, it is not part of the fuel market. The price of ammonia, as a fertilizer, in 2019 was 235 USD per tonne [95], which will also be used as a base price. This is supported by Afman et al. [4], which puts the price of ammonia as a fuel in range of roughly 155-360 USD per tonne, depending on different scenarios.

  Hydrogen, on the other hand, does not have a transparent market. It is usually produced on-site or as a byproduct and is sold through bilateral contracts, which makes it a non-transparent market. The price of hydrogen depends on the method of production. It can be produced from natural gas or through electrolysis. If the price of LNG is 20 €/MWh the price for hydrogen would be 1.5 €/kg. If it is produced with electrolysis and the price of electricity is 40 €/MWh the price would be 2.5 €/kg [101]. As the main method of production is through natural gas, the price of 1.5 €/kg, i.e., 1650 USD per tonne, will be used.

- **Fullness**

  Container ships generally do not sail with full capacity [42]. They carry a fraction of the maximal capacity; this fraction has been named fullness δ for simplicity. The fullness of the ship depends on macroeconomical aspects, which are beyond the scope of this project. Information regarding this variable is difficult to get, but it can be said that 80% of fullness is a high value for ULCVs [131]. The value for fullness will be taken as a baseline and will be varied for values below this baseline.

- **Freight Rate**

  Freight rate r_f is the price a customer pays the shipping company for transporting 1 TEU from one port to another. This changes from route to route and is also connected to macroeconomical aspects, by which it should also be related to the fullness of the ships. But, as mentioned above, this is beyond the scope of this project.

  The Shanghai Containerized Freight Index (SCFI) can be used to determine the freight rate between Rotterdam and Shanghai. In August 2019 the SCFI for Europe was at about 800 USD per TEU [104], which will be used as a baseline for the scenario generation.

8.1.2. Policy Levers (L)

For the policies there will be variables: the magnitude and the time when they will be introduced. This time could be in 2, 5, etc. years from the start of the simulation. The implemented policies are the following:

- **Carbon Tax**

  Carbon tax is a taxing scheme where an amount of tax is payed for every tonne of CO_2 produced. Different countries have different taxing schemes and prices, but the currently discussed price in the European Union is 25 €/CO_2tonne, which could be raised to 55-65 in the future [30]. Values between 25 and 65 will be implemented.

- **Speed Limit**

  The second policy option which will be looked at is a speed limit, which would limit the maximum speed at which ships can sail. These limits could be varied between the speed of 15-20 knots.

8.1.3. Metrics (M)

The metrics on which the performances of the ships are going to be judged should be about the profitability of the ships and their emissions. There are a couple of methods to determine which project is more profitable, such as the net present value (NPV), internal rate of return (IRR) or looking at the payback period. Usually, NPV is considered to be the most reliable indicator [13], which is why it will also be used. Equation 8.1 indicates how it is calculated, where t_{life} is the lifetime of the ship, i.e., 25 years [31], $Cashflow_i$ the cash flow in year i, and r the interest rate. The interest rates, at the moment, are very low, but the average of the last 10 years (for the USA) is 2.405% [106]. Considering both information, it has been decided to use an interest rate of 2% , but it can be noted that this could be considered as an additional uncertainty for future works. It should be noted that in year 0 there is a negative cash flow for the acquisition of the vessel, which is equal to the CAPEX, and in the last year, the vessel is sold at scrap value, additional to the normal cash flow. The scrap value is usually based on the lightweight of a ship. As the parametric design tool does not calculate the lightweight of the ship, a relation between the scrap value and the CAPEX was tried to be determined. Due to the limited amount of information, it was not possible to find such a relation. Based on this limited information, it was assumed that the scrap value is 10% of the CAPEX.

$$NPV = \sum_{i=0}^{t_{life}} \frac{Cashflow_i}{(1+r)^i} \tag{8.1}$$

For the emissions a couple of aspects must be considered. Taking only the produced amount of CO_2 would not be a fair approach, as it does not look at how much work has been done in terms of transported cargo. Therefore, using the Energy Efficiency Operational Index (EEOI) as proposed by IMO [59] is fairer. The EEOI indicates the produced CO_2 relative to the carried cargo and traveled distance. The equation of the EEOI is Equation 2.2, but it can be rewritten as in Equation 8.2.

$$EEOI = \frac{\sum_i m_{CO_2,i}}{\sum_i (m_{cargo,i} \cdot D_i)} \tag{8.2}$$

8.1.4. Relationships (R)

The relationships explain how each of the above mentioned variables connect to each other and influence the outcome of the scenarios. For this purpose a simple economic model has been developed. The model simulates the operations that a ship makes during its lifetime. This model should also incorporate the above mentioned uncertainties and policies, additionally to other aspects which have influence on the performance of a ship.

The main assumption of the economic model is that the ship operators' main goal is to maximize annual profits. Annual profits π are a function of ship speed v and number of trips made in a year z, as seen in Equation 8.3, where c_{fuel} is fuel costs, f_{port} is port fees, f_{canal} is canal fees for the Suez Canal, f_{cargo} is cargo handling fees, and c_{fix} is fixed costs.

$$\pi(v,z) = Income(z) - c_{fuel}(v,z) - z \cdot \left(f_{port} + f_{canal} + f_{cargo}\right) - c_{fix} \tag{8.3}$$

Income is a function of number of trips and depends on the freight rate r_f, fullness δ, and the ship's capacity n_{TEU} as seen in Equation 8.4.

$$Income(z) = z \cdot r_f \cdot \delta \cdot n_{TEU} \tag{8.4}$$

It should be pointed out that the fullness of ships traveling from China to Europe is not equal to ships traveling in the opposite direction. Ships bring more cargo to Europe than to China. This can also be seen from the trade balance (in goods) between China and the European Union (EU). In 2019 the trade deficit of the EU was 164 billion Euros [41]. As the trade goods are mainly transported via container ships, this data can also be used to make a comparison between the fullness of ships traveling in each direction. The exports of the EU to China are roughly 55% of their imports (based on the data of 2019) [41]. This relation has been adapted as the relation between the fullness of each direction. Implementing 2 values for fullness, which change depending on the direction the ship travels, seems easy but requires complex programming, as the objective function for the optimization is changing depending on the parity of the number of trips. To circumvent this, the average of the fullness in both directions has been implemented as δ, as seen in Equation 8.5. δ_r in this equation is the referred fullness in Section 8.1, which is the fullness of the ships traveling from China to Europe.

$$\delta = \frac{1+0.55}{2} \cdot \delta_r \tag{8.5}$$

The cost associated with the fuel consumption are being calculated as in Equation 8.6, where P_{fuel} is the fuel price, P_{pilot} the price of the pilot fuel, D the traveled distance (i.e., the distance between Shanghai and Rotterdam), $P(v)$ the power as a function of speed, and $cons(v)$ the fuel consumption as a function of speed.

$$c_{fuel}(v,z) = z \cdot \left(\left(P_{fuel} \cdot cons_{fuel}(v) + P_{pilot} \cdot cons_{pilot}(v) \right) \cdot \frac{D}{v} \cdot P(v) \right) \tag{8.6}$$

The power as a function of speed is calculated with the relevant efficiencies and c_1 as proposed by Klein Woud and Stapersma [68], see Equation 8.7 and 8.8, respectively.

$$P(v) = \frac{c_1 \cdot v^3}{\eta_H \cdot \eta_R \cdot \eta_S \cdot \eta_O} \tag{8.7}$$

$$c1 = \frac{R}{v_s^2} \tag{8.8}$$

The port fees are estimated based on the manual provided by the Port of Rotterdam [108] and it has been assumed that the fees in the Port of Shanghai are the same. The port fees are calculated in Euro as seen in Equation 8.9 and converted to USD.

$$f_{port} = 0.247 \cdot GT + 0.493 \cdot (\delta \cdot n_{TEU}) \tag{8.9}$$

As the ships which sail from Shanghai to Rotterdam pass the Suez Canal, they have to pay canal fees for the passage. The Suez Canal Authority has a distinctive and intricate price scheme, which is based on the net tonnage (NT) calculated according to the Moorsom System, which is in accordance with the Commission of Constantinople of the year 1873 [143]. As this method is not straightforward, a simplification has been made. Using data from Clarksons, it has been determined that the Suez NT of a ship is approximately 90.67% of its GT (with a R^2 value of 0.9914). Then the canal fees for ships in the range of 140,000 to 300,000 GT have been estimated [156]. For simplicity, it has been assumed that there is no price difference between northbound and southbound ships. Using this data, the canal fees (in USD) as a function of GT has been determined, as seen in Equation 8.10.

$$f_{canal} = 2.88 \cdot GT + 165135 \tag{8.10}$$

Port fees do not include cargo handling fees, which are payed to the terminal based on the cargo handling rate r_{thc} per TEU. The r_{thc} in Shanghai is approximately 130 USD [111], while it is about 225 USD in Rotterdam [51]. For simplicity the average, i.e., 177.5 USD per TEU, has been taken and assumed that it is the same in both ports. Cargo handling fees are calculated as shown in Equation 8.11.

$$f_{cargo} = r_{thc} \cdot \delta \cdot n_{TEU} \tag{8.11}$$

The fixed costs are determined by the costs made for the crew, the administration, insurance and the rest (i.e., stores, repairs, maintenance, etc.). Information regarding these costs are not widely available. Watson

[154] gives detailed estimation methods, but as his work is from 1998 the information must be handled carefully. For the costs regarding the crew, i.e., the salaries, supplements, travel expenses, etc., it is proposed to calculate 40,000 USD per officer and 18,000 USD per rating. As these values are from the year 1998, it has been decided to correct them with the inflation which occurred between then and 2019, which is 56.8%. Based on the information of the manning of some ships, it has been assumed that the ULCVs have 10 officers and 20 ratings [125][126][127], regardless the size.

The cost regarding insurance can be divided into 2, the insurance based on the value of the ship and the P&I insurance, which is based on the GT of the ship. Watson [154] suggests that the insurance premium is 1% of the value of the ship, i.e., CAPEX. Naturally, the value of the ship decreases over its lifetime, but the cost to insure an older ship also increases. Therefore, in order to keep it simple, it has been decided to fix the insurance fee at 1% of the initial CAPEX. For the P&I insurance 7 USD per GT is suggested, which when corrected for inflation makes 12.3 USD.

For administration, Watson [154] estimates 230,000 USD per year, but for a smaller ship compared to ULCVs. This value could be adjusted for inflation, but besides the change in the value of money there was also a change in technology, which should be considered. A lot of jobs which had to be done manually 20 years ago, can be done by computers, which means that the same job can be done with less people. While the salaries rose with inflation the number of employees fell. Considering this, it has been assumed that administration cost are 300,000 USD per year. Similarly, the rest cost has been assumed to be 500,000 USD. These values might not be an exact representation of reality, but as all the ships within the simulation are subject to them, it should not affect the end comparison. It should also be noted that there are other costs due to demurrage, detention, transshipment, etc., all of which have been neglected in order to keep the model simple.

As this model is based on a route between 2 ports, it is possible to talk about liner shipping. Under normal circumstances this would mean that there would be a number of vessels forming a fleet, depending on the schedule the shipping company wants to achieve. Implementing this would require introducing another variable and would make the model more complex. It has been chosen to avoid this and it has been assumed that 1 ship is sailing between two ports, independent of a fixed schedule. Other aspects, such as alliances between shipping companies, have also been neglected for simplicity.

Optimization It has been mentioned that one of the main assumptions is the assumption that the only goal of the operator is to maximize profits. Therefore, the function as seen in Equation 8.3 will be maximized on a yearly basis. The speed at which the ship sails and the number of trips made in a year will be determined this way. The optimization can be written as follows with the following constraints:

$$Maximize \quad \pi(v,z)$$

subject to:

$$\begin{aligned} 5 \leq\ & v \leq v_{max}, \quad v \in \mathbf{R} \\ & z \geq 0, \quad z \in \mathbf{N} \\ & z \leq \frac{t_{year}}{t_{trip}(v)} \end{aligned}$$

The lower bound of speed is 5 knots, because the power required for speeds less than 5 knots are too small and and result in powers that are less than 10% of the SMCR, which is the lower bound of the operational envelope [89][90]. The upper bound is the maximum speed, which can be achieved with the installed engine. The number of trips z is an integer, this makes the computation easier as the time in a year t_{year} is used fully and unused time does not have to be accounted for. This is not very realistic, but is a useful simplification. This way the cash flow for 1 year, which is required for the NPV calculation, can be calculated easier. Changing this would also require of implementing a more advanced accounting side of the model. t_{trip} is the time required for completing one trip and is calculated as seen in Equation 8.12, where t_{berth} is the time for berthing the ship, λ_{sts} the productivity of a STS crane, and n_{sts} the number of STS cranes (un)loading the ship.

$$t_{trip}(v) = \frac{1}{24} \cdot \left(\frac{D}{v} + 2 \cdot t_{berth} + 2 \cdot \frac{\delta \cdot n_{TEU}}{\lambda_{sts} \cdot n_{sts}} \right) \tag{8.12}$$

The berthing time for ULCVs is 21 hours on average [115]. STS cranes have a productivity of 25 moves per hour on average [81], which is important for calculating the time required for (un)loading the ship. Considering the length of ULCVs and the dimensions of STS cranes it has been assumed that 6 cranes would be available to the ships at all time. It should be noted that waiting and queuing time at ports and the Suez Canal have been neglected for the purpose of simplicity. It has been assumed that t_{year}, i.e., the working days of ship in a year, are equal to 300 days. This would account for the time lost for maintenance and other aspects.

One can also notice that as the variables do not change over the lifetime of the ship, it is not necessary to optimize the speed and number of trips for each year. Doing more than 1 optimization is only necessary if there is a change in conditions, such as the introduction of a new policy. If there is no change, the EEOI and NPV for the lifetime of the ship can be calculated by using the results of the optimization for one year.

Introducing Policies The only changes during the lifetime of a ship, as assumed, will be the implemented policies. When a policy is introduced a new optimization must be done, as the circumstances have changed. This means that for the years before the policy was introduced, the result of the optimization, as explained above, would be used. For the years after the changes are applied and a second optimization is done.

If a carbon tax policy is introduced, the profit function is altered. The term below, which represents the extra cost due to the tax, will be added to the function. P_{CO_2} is the price per tonne CO_2 and m_{CO_2} is the mass of CO_2 in tonnes.

$$-P_{CO_2} \cdot m_{CO_2}$$

In case of a speed limit, one of the constraints of the optimization is changed. The maximum speed would become the introduced limit, if it is smaller than the maximum speed that the ship can achieve. The implementation would be as follows:

$$0 \quad \leq \quad v \quad \leq \quad min(v_{max}, v_{limit}), \qquad v \in \mathbf{R}$$

8.2. Scenario Generation

The basis of the simulations with all parameters, variables and their relations has been explained in the previous sections. With this basis it is possible to create many different scenarios. It should be noted that there are 7 variables, i.e., freight rate, fullness, fuel price, price of carbon, the time when the carbon tax policy will be introduced, speed limit, and the time when the speed limit policy will be introduced. The price of the pilot fuel, which is not the same of the main fuel, could also be varied, but adding another variable would increase the number of scenarios drastically. While RDM profits from the large amount of scenarios, it should be approached carefully such that one is not overwhelmed by the sheer amount of scenarios. It has been decided not to consider the pilot fuel price as a variable, as the used amount is very small (i.e., between 1.5-5%) and thus its effect will be also negligible.

Table 8.2: Values of the variables, which are used for scenario generation

Variable	**Symbol**	**Values**	**Unit**
Freight Rate	r_f	600, 700, 800	$ / TEU
Fullness	δ	0.6, 0.7, 0.8	-
Fuel Price	P_{fuel}	80%, 100%, 120% of P_{fuel}	$ / tonne
Carbon Tax	P_{CO_2}	25, 45, 65	$ / tonne
Time for CO_2 Policy	t_{p,CO_2}	2, 5, 10	years
Speed Limit	v_{limit}	16, 18, 20	kn
Time for Speed Policy	$t_{p,v}$	2, 5, 10	years

It has been decided to vary each variable 3 times. The values can be seen in Table 8.2. The freight rate has been varied for values smaller than the baseline, which was established in Section 8.1, because annual reports of shipping companies show that 2019 was a relatively good year [52][85]. As the focus of RDM is on robustness, scenarios which are more "critical" are more interesting. For the fuel prices the variation depends on the base price, which has been determined in Section 8.1.1. This variation will give 27 scenarios, without any policies, and 243 scenarios for each policy, which is 513 scenarios in total for each ship.

There are also other sampling methods, such as Latin hypercube sampling or Monte Carlo sampling. Implementing these methods could be beneficial for the approach. But based on preliminary tests and time constraints, this type of factorial sampling was deemed acceptable.

Step 1 and 2 of RDM have been explained. The next 2 steps are more case specific. Therefore, these steps shall be looked at together in the following sections for each case.

8.3. Case I

For the first case, it was decided to look at ships with a capacity of roughly 25,000 TEU and a max. speed of 23 kn. The choice of 25,000 TEU was made on the basis that this will be, most likely, the next class of ULCVs. 23 kn was chosen for speed, because this is the most common speed amongst ULCVs [124]. Coincidentally, this speed also requires the ships of this size to have the biggest engine that MAN produces, i.e., an engine with 12 cylinders and 82,440 kW. Using the capacity and speed as the main input for the parametric design tool, which was explained in Chapter 7, ships for each fuel type has been generated. The main properties of these 6 ships can be seen in Table 8.3.

Table 8.3: Main properties of the compared ships in Case I

Fuel Type	Length [m]	Beam [m]	Draft [m]	Capacity [TEU]	GT	CAPEX [M $]	Power [kW]
HFO	414	61	16	24,900	249,104	157.75	82,440
LPG	414	61	16	24,352	249,104	156.63	82,440
LNG	429	61	16	25,450	259,543	158.75	82,440
Methanol	414	61	16	24,626	249,104	157.20	82,440
Hydrogen	429	61	16	25,176	259,543	158.27	82,440
Ammonia	414	61	16	24,626	249,104	157.20	82,440

8.3.1. Results

The performance of each ship for the 513 scenarios have been simulated in the economic model. The results of these can be seen in Figure 8.2. Two groups can be identified immediately, the non-carbons on the left (which have been highlighted) and the hydrocarbons on the right. That the non-carbons have a much lower EEOI (i.e., one order of magnitude smaller) was expected, as the only CO_2 they produce comes from the pilot fuel, which is a very low percentage of the whole consumption.

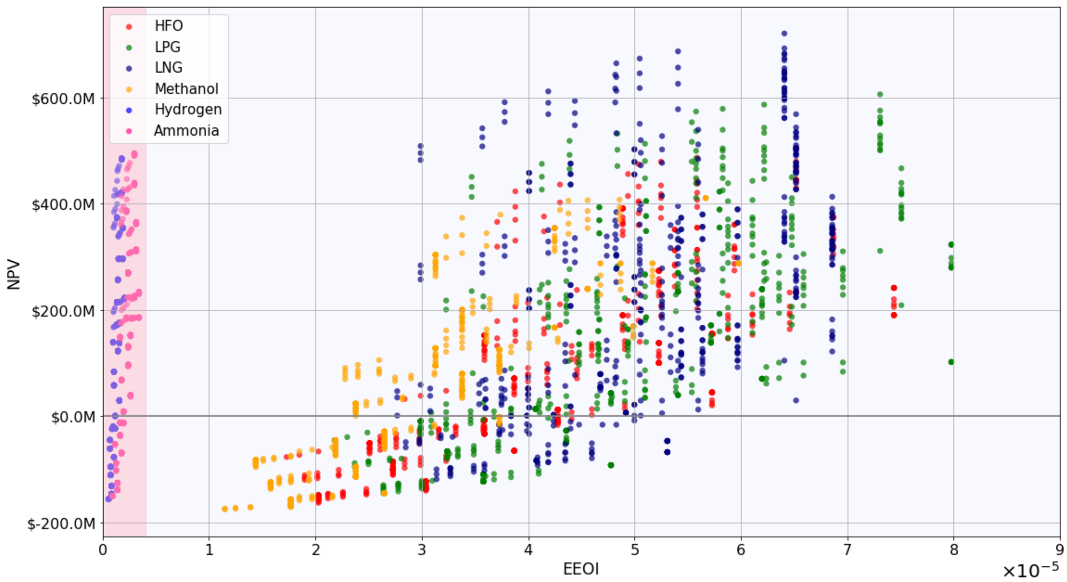


Figure 8.2: Results of all ships in Case I, non-carbon fuels have been highlighted

As the non-carbon fuel using ships have a much lower EEOI, their results cannot be seen clearly. They have been isolated in Figure 8.3, which shows the performance of hydrogen and ammonia in detail. It can be seen that while the NPVs of both hydrogen and ammonia are similar in general, hydrogen has generally a smaller EEOI compared to ammonia. It is interesting that they show similar behavior in NPV, as ammonia and hydrogen have very different properties. Hydrogen has a very high LCV compared to ammonia, which results in a lower consumption of hydrogen relative to ammonia. On the other hand, ammonia has a much lower price than hydrogen. It seems that these 2 factors equalize each other.

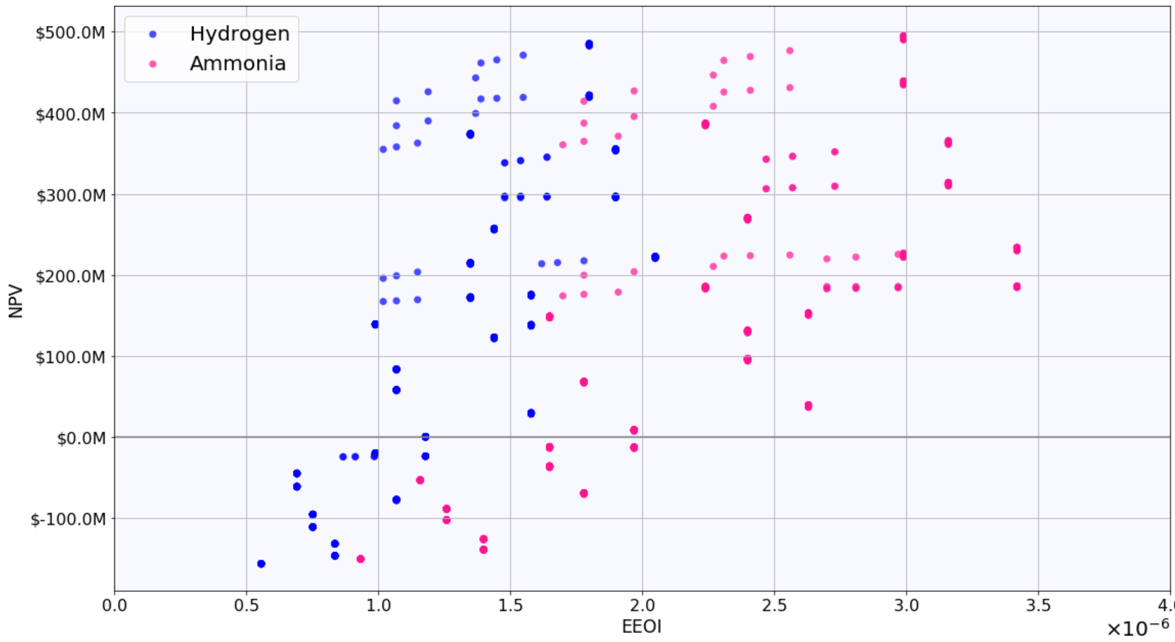


Figure 8.3: Results of ships using non-carbon fuels in Case I

The difference in EEOI between hydrogen and ammonia becomes more clear in Figure 8.4, in which the box plots of their EEOI is shown. It can be seen that hydrogen has roughly half of the EEOI of ammonia, generally speaking. This is related to the fact that hydrogen requires only 3% pilot fuel, compared to 5%.

The same box plots have also been done for hydrocarbon fuels, which can be seen in Figure 8.5. It can be seen that hydrocarbon fuels using ships have EEOI one order of magnitude higher than ships which use non-carbon fuels. It can be seen that methanol has a much lower EEOI than the rest and HFO also has lower EEOI than LPG and LNG, which are both interesting and may seem odd. Before continuing it should be emphasized that the results for each fuel type are **not the results for the same operations**. Each ship optimizes its operations to the different scenarios. Therefore, one cannot come to the conclusion that HFO is a "cleaner" fuel, because it has a smaller EEOI than LPG and LNG, by looking at this figure. To understand why HFO results in a lower EEOI, the data of the simulations must be analyzed in detail.

Data shows that the average speed for HFO is between 13-15 kn on average, while it is between 16-18 kn for LPG and 17-20 kn for LNG. It is known that at lower speeds the engines work more efficiently and thus produce less CO_2 emissions, which also results in a lower EEOI. Thus, the question that should be asked is "Why is the HFO using ship sailing at lower speeds?". VLSFO has a much higher price compared to LPG and LNG, which leads to the hypothesis that the results would be different, i.e., HFO would have a higher EEOI, if the prices for HFO would be smaller. This hypothesis can be tested by running the same simulations for a ship which uses HFO and substituting VLSFO with IFO380, which is a type of HFO but with a higher sulphur content. VLSFO has been chosen in the first place as it is the only HFO, which can be used without scrubbers under the new regulations regarding SO_x emission. IFO380 was the fuel of the conventional ships. The price of IFO380 on 30 August 2019 was 297.5 USD per tonne, while VLSFO was 500.5 USD per tonne [24]. The results of IFO380 and the other ships can be seen in Table 8.4. The results show that the ship sails at higher speeds when using IFO380 and consequently has also a higher EEOI than LPG and LNG. This also demonstrates the effect of fuel price on the operations of a ship.

Another interesting aspect that can be seen in Figure 8.5 are the results of methanol. Methanol has the lowest EEOI amongst the ships that use hydrocarbons. Data shows that this ship is also sailing at speeds between 12-13 kn, on average. This also has an effect on the NPV, which can be seen in Figure 8.6. A lower

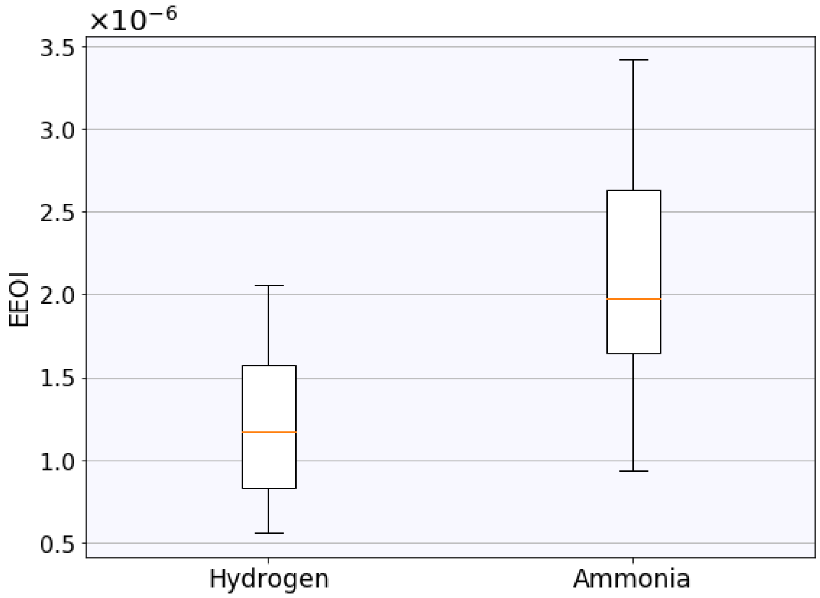


Figure 8.4: Box plots of EEOI of ships using non-carbon fuels in Case I

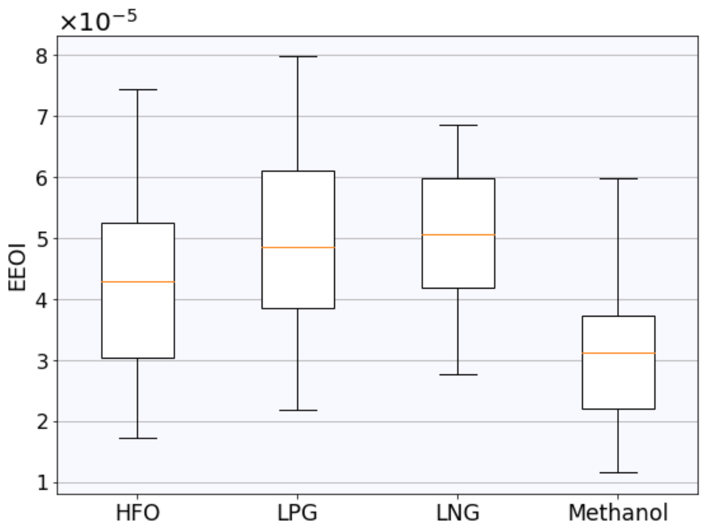


Figure 8.5: Box plots of EEOI of ships using hydrocarbon fuels in Case I

Table 8.4: Main results of Case I

Fuel Type	Condition	Parameter	Median	Average	Minimum	Maximum
VLSFO	Before Policy	Speed	14.96	14.49	8.46	19.06
		Number of Trips	8	7.52	5	9
		Annual Cash Flow	$ 12,715,191.00	$ 13,409,577.04	$ -58,283.00	$ 33,443,282.00
	After Policy	Speed	13.48	13.40	8.46	19.06
		Number of Trips	7	7.09	5	9
		Annual Cash Flow	$ 11,353,942.00	$ 12,267,380.75	$ -860,809.00	$ 33,443,282.00
	-	EEOI	4.27718E-05	4.32502E-05	1.73098E-05	7.44128E-05
	-	NPV	$ 86,571,075.00	$ 98,180,114.65	$ -163,383,421.00	$ 504,792,853.00
LPG	Before Policy	Speed	18.91	18.07	12.6	22.08
		Number of Trips	9	8.93	7	10
		Annual Cash Flow	$ 16,275,368.00	$ 16,787,065.26	$ 1,209,720.00	$ 38,567,163.00
	After Policy	Speed	15.44	15.70	10.45	22.08
		Number of Trips	8	8.06	6	10
		Annual Cash Flow	$ 14,546,399.00	$ 14,896,920.41	$ -37,991.00	$ 36,720,750.00
	-	EEOI	4.84098E-05	4.98224E-05	2.17948E-05	7.97587E-05
	-	NPV	$ 144,167,531.00	$ 155,036,622.17	$ -145,398,079.00	$ 605,885,457.00
LNG	Before Policy	Speed	21.31	20.39	15.03	22.51
		Number of Trips	10	9.67	8	10
		Annual Cash Flow	$ 21,234,685.00	$ 21,365,246.19	$ 3,339,039.00	$ 44,539,988.00
	After Policy	Speed	17.54	17.42	12.7	22.51
		Number of Trips	9	8.63	7	10
		Annual Cash Flow	$ 18,638,591.00	$ 18,518,480.84	$ 1,341,133.00	$ 41,880,654.00
	-	EEOI	5.05298E-05	5.06546E-05	2.77356E-05	6.86209E-05
	-	NPV	$ 227,049,646.00	$ 229,451,162.45	$ -119,014,050.00	$ 720,497,859.00
Methanol	Before Policy	Speed	12.62	12.48	8.45	18.98
		Number of Trips	7	6.70	5	9
		Annual Cash Flow	$ 10,040,623.00	$ 10,687,733.04	$ -986,013.00	$ 28,590,295.00
	After Policy	Speed	11.03	11.83	6.56	18.98
		Number of Trips	6	6.43	4	9
		Annual Cash Flow	$ 9,341,049.00	$ 10,040,665.14	$ -1,500,432.00	$ 28,590,295.00
	-	EEOI	3.12435E-05	2.99293E-05	1.14979E-05	5.98313E-05
	-	NPV	$ 41,512,268.00	$ 52,266,628.64	$ -175,916,943.00	$ 410,559,280.00
Hydrogen	Before Policy	Speed	13.52	14.14	8.47	19.14
		Number of Trips	7	7.37	5	9
		Annual Cash Flow	$ 11,905,475.00	$ 12,701,895.81	$ -396,653.00	$ 32,473,013.00
	After Policy	Speed	13.52	13.86	8.47	19.14
		Number of Trips	7	7.27	5	9
		Annual Cash Flow	$ 11,892,044.00	$ 12,591,873.79	$ -418,995.00	$ 32,473,013.00
	-	EEOI	1.17756E-06	1.22082E-06	5.57928E-07	2.05247E-06
	-	NPV	$ 83,813,210.00	$ 97,870,449.78	$ -156,759,665.00	$ 485,362,643.00
Ammonia	Before Policy	Speed	14.92	14.44	8.45	18.98
		Number of Trips	8	7.52	5	9
		Annual Cash Flow	$ 12,511,942.00	$ 13,178,696.22	$ -144,650.00	$ 32,899,968.00
	After Policy	Speed	13.44	14.13	8.45	18.98
		Number of Trips	7	7.40	5	9
		Annual Cash Flow	$ 12,478,143.00	$ 13,012,390.98	$ -181,217.00	$ 32,899,968.00
	-	EEOI	1.9744E-06	2.12312E-06	9.33528E-07	3.41915E-06
	-	NPV	$ 96,654,255.00	$ 107,416,883.00	$ -151,089,085.00	$ 494,698,993.00
IFO380	Before Policy	Speed	19.06	18.70	12.65	22.97
		Number of Trips	9	9.11	7	11
		Annual Cash Flow	$ 17,517,827.00	$ 18,062,297.04	$ 1,782,383.00	$ 40,537,707.00
	After Policy	Speed	15.53	15.80	10.49	22.29
		Number of Trips	8	8.06	6	10
		Annual Cash Flow	$ 15,462,235.00	$ 15,697,034.08	$ 148,470.00	$ 38,423,214.00
	-	EEOI	5.93699E-05	6.09E-05	2.75913E-05	0.000126177
	-	NPV	$ 161,019,829.00	$ 172,435,301.75	$ -142,064,618.00	$ 643,300,551.00

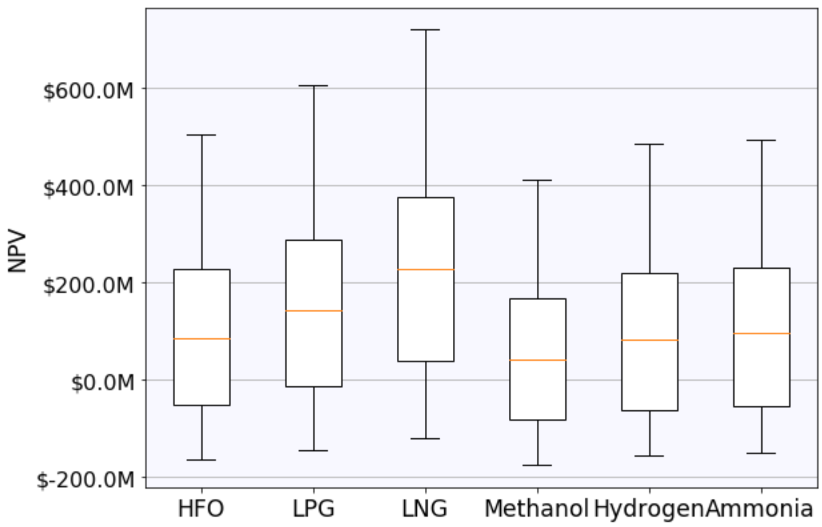


Figure 8.6: Box plots of NPV of all ships in Case I

speed results in a lower number of trips per year, which decreases the annual cash flow and consequently the NPV. As seen, methanol has the lowest NPV amongst all fuel types. It can also be seen that LPG and LNG have higher NPVs than HFO. This information should be handled carefully. In Section 7.8 the capital expenses were calculated with the same formula, regardless of the fuel type. It was also noted that as different fuel types require different installations, ships using alternative fuels would be more expensive. Looking at Figure 8.6, it is possible to say that as long as the price difference is roughly 60 million USD for LPG and 140 million USD for LNG, both can be as profitable as a ship using HFO. Methanol is slightly less profitable than HFO, but it should be pointed out that the price difference between both is minimal, as a HFO using ship can be converted to a methanol using ship with small adjustments [1]. Hydrogen and ammonia are more challenging. High CAPEX would not only make them less profitable than HFO, but also result in negative NPVs, which means that they would not be profitable investments.

Table 8.5: Comparison of overall results

Fuel Type	positive NPV
HFO	61%
LPG	72%
LNG	82%
Methanol	56%
Hydrogen	62%
Ammonia	63%

Table 8.5 shows in how many scenarios the different ships had a positive NPV. Looking at this, it can be determined which fuel type results in a more robust design qua profitability. Based on the 513 scenarios, which have been simulated, LNG is the most robust as it has a positive NPV in 82% of the scenarios.

8.3.2. Weaknesses & Strengths

By taking a closer look at the results, some weaknesses and strengths can be recognized. If the scenarios with a negative NPV are observed, it can be seen that the freight rate has a big effect on this. It would be of interest to know below which freight rate it is impossible to make profits and above which rate profit is secure. For this purpose, the freight has been varied for a wider range, from 550 to 800 USD per TEU. Table 8.6 shows the percentage of scenarios in which a negative NPV was achieved. It can be seen that 600 USD per TEU is a critical freight rate for the majority of ships. While the majority of ships have always positive NPVs for freight rates, which are greater than 700 USD per TEU. It should be noted that LNG can go below 600 USD per TEU and is already nearly always profitable with 650 USD per TEU. This indicates the strength of LNG.

It has already been mentioned above that the fuel price is a limiting factor for some of the fuels. An indicator for this is the low median speed, which is the case for HFO, methanol, hydrogen, and ammonia. The

Table 8.6: Percentage of scenarios with negative NPVs depending on the freight rate in Case I

	Freight Rate [$/TEU]										
Fuel Type	550	575	600	625	650	675	700	725	750	775	800
HFO	100%	100%	99%	80%	51%	35%	16%	1%	0%	0%	0%
LPG	100%	99%	84%	52%	30%	16%	1%	0%	0%	0%	0%
LNG	100%	87%	53%	30%	8%	0%	0%	0%	0%	0%	0%
Methanol	100%	100%	100%	94%	72%	49%	33%	15%	1%	0%	0%
Hydrogen	100%	100%	99%	77%	55%	33%	14%	0%	0%	0%	0%
Ammonia	100%	100%	99%	77%	54%	33%	11%	0%	0%	0%	0%

effect of lower fuel prices has been shown partly with HFO, where VLSFO and IFO380 were compared. The latter is 40% cheaper and Table 8.4 shows that it would have a 86% higher NPV and 39% higher EEOI (based on the medians). Similarly, for methanol, hydrogen, and ammonia additional scenarios were simulated to determine what changes lower fuel prices would induce. For this purpose, the same scenarios, but with 50%, 60%, and 70% of the base fuel prices have been simulated. The results can be seen in Figure B.1a, B.1b and B.2 in Appendix B. The ships sail faster in each case and have higher emissions and NPVs as a result. Based on the medians, the increase in EEOI for methanol is 40%, for hydrogen 43%, and for ammonia 51%. Methanol also has an increase in NPV of 167%, hydrogen 105%, and ammonia 85%. In this case the performance of methanol becomes similar to the one of VLSFO, where the EEOI is roughly the same, but the NPV is slightly higher than VLSFO; which would mean that it would outperform VLSFO if the relation between the fuel prices of VLSFO and methanol would be like this. Hydrogen and ammonia have a similar NPV to LPG, while their EEOI is still one order of magnitude smaller, which would make them a serious contender. This demonstrates the significance of fuel prices and the influence it has on the performance of ships. It can be seen that current fuel prices are a weakness of HFO, methanol, hydrogen, and ammonia.

The fullness of ships has a direct influence on profits. It has been seen that methanol is affected more by lower fullness, compared to the other ships. Methanol is not profitable for 67% of the scenarios with 60% fullness, while this number is approximately 30-40% for other ships. This is linked to the poor performance due to high fuel prices with which profits are already low and get negative as soon as profits drop. This effect is much smaller with other ships.

The policies do not pose a weakness for any ship. The only effect that they have is lowering the NPVs and the EEOIs, but not to an extent that they make some ships unprofitable. They only make ships unprofitable in scenarios in which they were already unprofitable or had a small profit without the policies. According to the results, if the ship owners had a choice between policies types, they would choose speed limits, as these policies result in a smaller reduction in NPV compared to carbon tax policies. This was also the conclusion of Psaraftis [121], who compared the effectiveness of speed limits and bunker levies.

8.3.3. Effect of Policies

The analysis, which has been done up to this point, is more from the ship owner's perspective. The analysis could also be done from the perspective of the policymaker. In this case the effects of the different policies, which have been simulated, can be analyzed. This is not directly in the scope of this thesis, but it shall be done briefly for demonstration purposes. As the policymaker's interest lies in reducing the EEOI, the focus will be on this aspect.

Table 8.7: Biggest reductions due to policies in Case I

		HFO	**LPG**	**LNG**	**Methanol**	**Hydrogen**	**Ammonia**
NPV	Reduction	43.9%	36.9%	30.7%	50.2%	6.7%	8.2%
	Policy	Carbon Tax	Carbon Tax	Carbon Tax	Carbon Tax	Speed Limit	Speed Limit
EEOI	Reduction	25.2%	30.1%	38.8%	18.2%	11.0%	12.7%
	Policy	Carbon Tax	Speed Limit	Speed Limit	Carbon Tax	Speed Limit	Speed Limit

To see the effectiveness of each policy option, the average EEOI of the scenarios without any policy has been compared to averages of the scenarios with policies, which has been done for every fuel type. Table 8.7 shows the biggest reduction in NPV and EEOI for each fuel type and shows the policy that caused this reduction. The biggest reductions are caused by the most severe policies, which are the carbon tax of 65 USD per tonne CO_2, which gets effective after 2 years and the speed limit of 16 kn, which gets effective after 2 years.

It can be seen that the effectiveness of the policies depend on the fuel type. For example, the non-carbon fuels are not affected by the carbon tax policies, as the amount that would need to pay is negligible. For these the speed limits are more effective. The biggest reduction in EEOI is gained with a speed limit of 16 kn, which gets effective after 2 years. The reduction is 11% for hydrogen and 12.6% for ammonia.

For the hydrocarbon fuels the situation is slightly different. Both policy types, i.e., speed limits and carbon taxes, are effective, but which one is more effective is based on the ship speed at which the ships sail in the scenarios without policies. For example, HFO has a 25.2% reduction with a 65 USD per tonne CO_2 carbon tax, which is implemented after 2 years, while it has 13% reduction with a speed limit of 16 kn, which is also implemented after 2 years. LNG has reductions, for the same policies, of 21% and 38.8%, respectively. The main difference occurs from the fact that the ship with LNG sails at much higher speeds in the scenarios without policies, that it is affected way more by the speed limit.

This analysis could be done more thoroughly and in more detail, but it is not the main focus of the project, as mentioned above. It can be understood, from this demonstration, that different stakeholders could use the same method and results to analyze the uncertainties and their effects on the design or to test the effectiveness of different policies.

8.3.4. Emission Reduction

The fifth sub-question of this thesis is about the reductions in emissions. Normally, one would look at the results of a reference and compare the rest of the result to this to see how they differ. If every ship was doing the exact same thing, then any comparison could be done without hesitation. In this case doing so would not be fair, as mentioned above. The ships determine their operations depending on the changing circumstances and do this with the goal of maximizing profits. This means that comparing the profitability of each ship can be done without hesitation, as it is the maximum profit for each scenario. When comparing the emissions, i.e., the EEOI, one has to be more careful. The results show that HFO can have lower EEOIs than LPG and LNG under the given circumstances. This does not necessarily mean that HFO is a "cleaner" fuel than LPG and LNG, it only performs better under these circumstances. On the other hand, VLSFO was used as the HFO option. This choice was based on the new regulations concerning SO_x emissions, which came into force recently, i.e., 1 January 2020 [61]. Therefore, a VLSFO using ship cannot be concerned as a "conventional" ship, as this change is quite recent. This leads to the question "What should be used as the reference?". The EEOI is a voluntary at the moment and therefore information regarding the EEOI of conventional ships is not publicly available. As a solution, in order to make a fair comparison, it is proposed to run the simulations for a ship that uses IFO380 and compare its EEOI to the other ships.

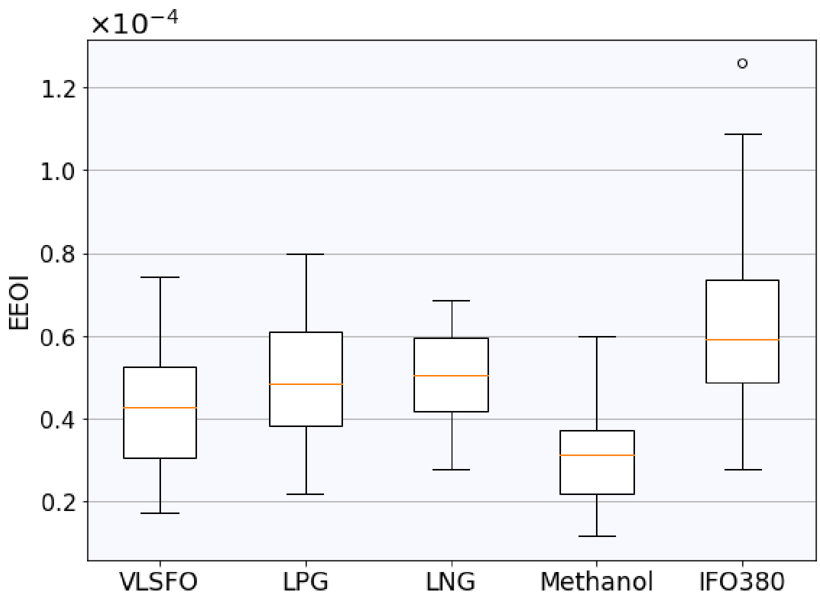


Figure 8.7: Box plots of EEOI of ships using alternative hydrocarbon fuels and IFO380 in Case I

To compare the different EEOIs of the alternative hydrocarbon fuel and IFO380, Figure 8.7 can be used. Hydrogen and ammonia have not been included in this figure as they have always a significantly lower EEOI.

If a comparison is made based on the median of each fuel type, VLSFO will have a reduction of 28%, LPG 18.5%, LNG 14.9%, methanol 47.4%, hydrogen 98%, and ammonia 96.7%. In order to determine with which certainty each fuel type would have lower EEOIs compared to IFO380, probability density functions were tried to be obtained. Histograms for each fuel type were plotted, as can be seen in Figure B.3 in Appendix B. Based on these histograms it was assumed that a normal distribution would have the best fit. In order to determine if a normal distribution was a good fit, 2 tests were performed: the Shapiro-Wilk test [135] and Anderson-Darling test [7]. The results of both tests indicated that a normal distribution was not a good fit for these datasets. The Anderson-Darling test was also used to see if other distributions such as the logistic, Gumbel, etc., would fit but a fitting distribution could not have been found.

It is also possible to fix the speed of all ships to the same value to make a comparison of their EEOIs when they perform the same operation. As all ships have the same engine, it does not matter at which speed they sail. If compared to the result of HFO, it can be seen that LPG's EEOI is 16% lower, LNG 29%, methanol 12%, hydrogen 97%, and ammonia 95%.

8.4. Case II

In the previous case, ships of the "next generation" with a speed which is common for today have been looked at. For Case II, a different perspective was taken. Ships of the same capacity, but with lower design speed were looked at. This could be a choice of a shipowner, who anticipates harsh policies and believes that having a ship with a lower design speed would be of advantage. Therefore, the parametric design tool has been used to generate ships with a capacity of roughly 25,000 TEU and a maximum speed of 18 kn. The resulting ships can be seen in Table 8.8. It must be emphasized that these ships have roughly the same CAPEX as the ships from Case I, even though they have an engine which is half as big. These ships should be cheaper, but as the parametric design tool calculates the CAPEX based on the TEUs, this change is not reflected in the costs. This fact should be kept in mind when analyzing the results.

Table 8.8: Main properties of the compared ships in Case II

Fuel Type	Length [m]	Beam [m]	Draft [m]	Capacity [TEU]	GT	CAPEX [M $]	Power [kW]
HFO	406	61	16	24900	249104	157.75	41220
LPG	409	61	16	24900	254234	157.75	41220
LNG	406	61	16	24626	249104	157.20	41220
Methanol	406	61	16	24900	249104	157.75	41220
Hydrogen	406	61	16	24352	249104	156.60	41220
Ammonia	406	61	16	24900	249104	157.75	41220

8.4.1. Results

The same 513 scenarios have been simulated also for these ships. A scatter plot of the results can be seen in Figure 8.8. Similarly to Case I, the non-carbon fuels can be seen on the left side with much lower EEOIs. A detailed scatter plot for the non-carbon fuel using ships can be seen in Figure B.4 in Appendix B.

Figure 8.8 also evidently demonstrates a phenomenon, which could also have been seen in Case I. It is possible to see that some of the points form vertical lines, as if there were some sorts of thresholds. This has a couple of reasons. The variation of some parameters, in some scenarios, is not significant enough that the ship changes its operations. For example, at the top, slightly to the left of the middle of the graph 3 dots in a line of navy points within a red circle, which represent the results of LNG, can be seen. The same can also be observed in other parts of the figure. For these points all parameters are the same, with only the fuel price varying. The fuel price has an effect on the profitability, but as the operations do not change, there is no difference in the EEOI. Policies are also a reason for these "lines", especially the speed limits. As these introduce an upper limit for speed, the operations are also limited. This results in the same operations, although the scenarios are different. The effect of this is emphasized with these ships, as they have a lower maximum speed, i.e., less flexibility. The final reason is the result of a limitation that the economic model has. In Subsection 8.1.4 the simplification, which were made for the model, were explained. One of the simplifications was that the optimization was made for 1 year and the results were used for the rest of the year, in which no changes occurred. This, in addition with the number of trips being an integer, caused the optimization to use the time in a year optimally, which was exactly what it was supposed to do, but it also meant that every year would end with a trip. This means that at the end of a year the ship cannot be on a

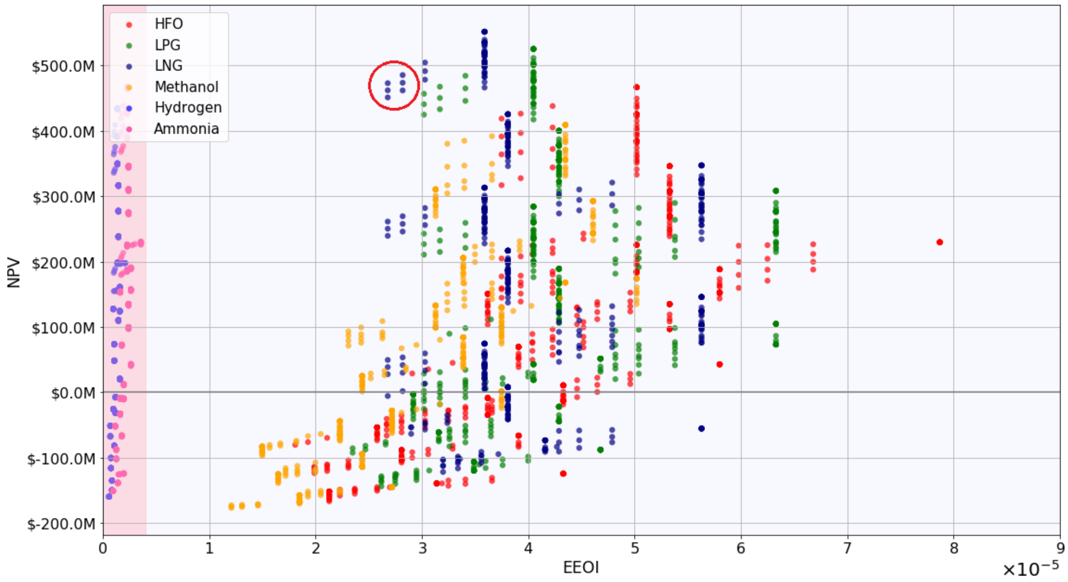


Figure 8.8: Results of all ships in Case II, non-carbon fuels have been highlighted

trip, which is not very realistic. As a result, if the actual optimal speed was, e.g., 17 kn, but it would result that there were 10 days unused, the optimizer would decrease the speed such that the whole time was used. Similarly, if the speed was a little bit too low, such that the last trip cannot be finished in time, the optimizer would increase the speed. This creates some speeds, and thus operations, which are optimal for more than one scenario. The profitability can vary as they are not the same scenarios, but the EEOI does not change as the operations are the same.

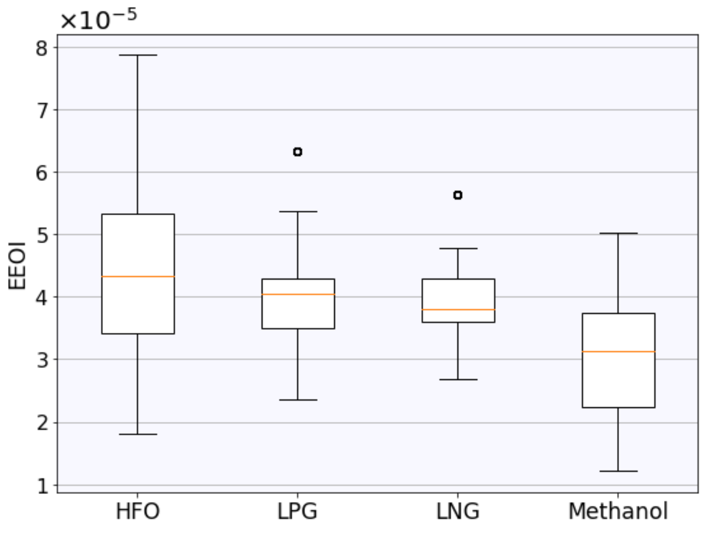


Figure 8.9: Box plots of EEOI of ships using hydrocarbon fuels in Case II

This effect can also be seen in Figure 8.9. The interquartile ranges have become much more narrow, compared to Case I. While the EEOI for LPG and LNG decreased, the EEOI of HFO increased; methanol's did not change. As a result, LPG and LNG, which had higher EEOIs than HFO in Case I, generally have EEOIs lower than HFO's. This is interesting if compared with Case I, but not shocking if one remembers that LPG and LNG have lower carbon content than HFO. If the scenarios, which result in the highest EEOIs, are compared it can be seen that the ships using HFO, LPG, and LNG sail at the same speed, which is about 17.5 kn (nearly the maximum speed), but as LPG and LNG are "cleaner" fuels their EEOI is naturally lower. Methanol, on the other hand, is still the hydrocarbon fuel with the lowest EEOI. It should be noted that the maximum speed of these ships is 18 kn, as a result they are not affected by the speed limit policies of 20 and 18 kn. Therefore, the results for many scenarios are the same, which explains why the interquartile ranges got narrower.

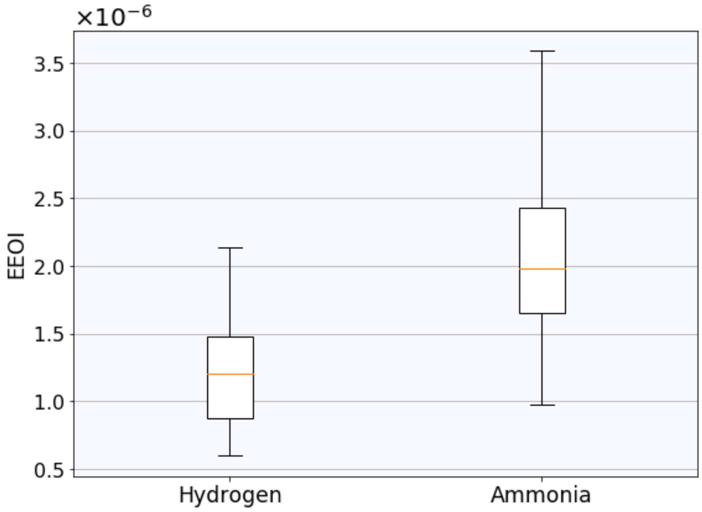


Figure 8.10: Box plots of EEOI of ships using non-carbon fuels in Case II

The picture for the non-carbon fuel has not changed much, as can be seen from Figure 8.10. The interquartile range has narrowed slightly for both fuel types, but the whiskers have gotten slightly longer.

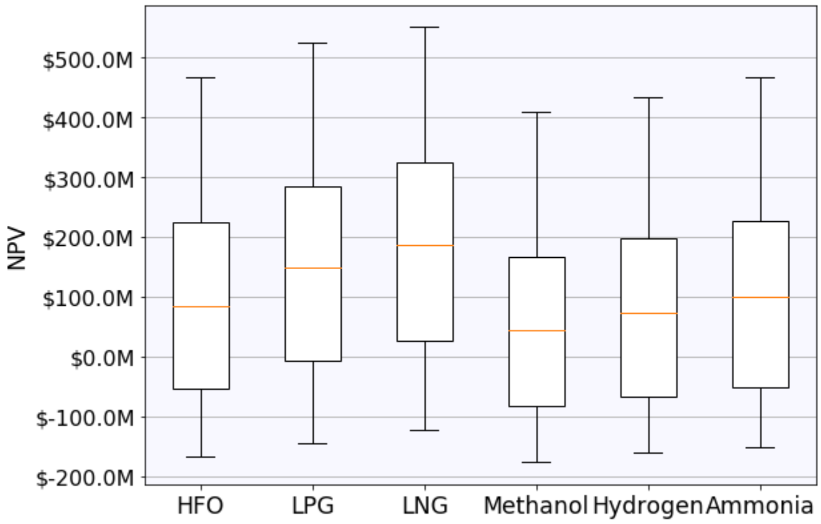


Figure 8.11: Box plots of NPV of all ships in Case II

The NPVs of the ships can be seen in Figure 8.11. It should be remembered that the alternative fuels, besides methanol, have extra costs, which lower these NPVs. When comparing these results to the ones of Case I, it should not be forgotten that as these ships have a much smaller engine they should be cheaper, which would mean that they would have a slightly higher NPV, than what is shown in the figure. The figure shows that the NPVs for LPG and LNG have decreased, when compared to Case I, while the NPV of HFO has not changed much. If the medians are taken as basis (see Table B.1 in Appendix B), it can be said that as long as the price difference between LPG and HFO is smaller than roughly 64 million USD, LPG would be as profitable as HFO. For LNG this difference should not be greater than roughly 101 million USD. This is consistent with the results of Case I. The situation for hydrogen and ammonia has also not changed. High costs for their special systems would result in negative NPVs, which would mean that they are bad investments.

8.4.2. Weaknesses & Strengths

Also in this case, it can be seen that freight rates play a big role in the profitability of the ships. 600 USD per TEU is the lower limit for freight rates, as indicated in Table 8.9. In all scenarios, which have freight rates below this, the ships will not be profitable. If this table is compared to Table 8.6, it can be said that, most likely also for this case, ships in scenarios which have a freight rate greater than 725 USD per TEU will always be profitable.

Table 8.9: Percentage of scenarios with negative NPVs depending on the freight rate in Case II

	Freight Rate [$/TEU]		
Fuel Type	600	700	800
HFO	100%	16%	0%
LPG	83%	0%	0%
LNG	61%	0%	0%
Methanol	100%	28%	0%
Hydrogen	100%	22%	0%
Ammonia	100%	11%	0%

By comparing the results of Case I and II, it can be said that the situation from the fuel price perspective is the same. LNG and LPG are less affected by the fuel prices, while the rest are more affected.

Results show that fullness is not a limiting factor, similarly to Case I. To find the value for fullness, after which it becomes impossible to have profitable ship, this factor was varied. Table 8.10 shows that ships are not profitable for a fullness of 0.4 or lower. It may seem odd that even for high values of fullness, some ships do not have a positive NPV in a third of the scenarios. The reason for this is the fact that these ships are not profitable with a freight rate of 600 USD per TEU, i.e., one third of the scenarios, as seen in Table 8.9. It should also be pointed out that LNG is still profitable in 30% of the scenarios with a fullness of 0.4 and LPG in 14%, while the rest is unprofitable. This underlines the strength of LNG and LPG.

Table 8.10: Percentage of scenarios with negative NPVs depending on fullness in Case II

	Fullness δ								
Fuel Type	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.7	0.8
HFO	100%	100%	100%	85%	67%	67%	49%	33%	33%
LPG	100%	100%	86%	67%	63%	42%	33%	33%	16%
LNG	100%	96%	70%	67%	51%	34%	33%	26%	1%
Methanol	100%	100%	100%	100%	80%	67%	61%	33%	33%
Hydrogen	100%	100%	100%	89%	67%	67%	55%	33%	33%
Ammonia	100%	100%	100%	78%	67%	67%	44%	33%	33%

The ships in this case are very robust against all policies. Nearly all ships are unaffected by the speed limits. The speed limits of 20 and 18 are ineffective, but the effect of the 16 kn speed limit is also minimal. The biggest decrease in NPV due to a speed limit was with LNG with a decrease of 10% of NPV an average. In the same case the decrease in EEOI was 15%. The biggest decrease in NPV due to a carbon tax was with a 65 USD per tonne CO_2, which was implemented after 2 years, with methanol, which had a 49% decrease. Methanol was followed by HFO with a decrease of 44%, on average. Results also show that carbon taxes are more effective in lowering the EEOI, but the differences are smaller compared to Case I. The biggest decrease was with HFO, which had a decrease of 20% in EEOI, on average. The overall changes for all ships are relatively small, therefore it can be said that these ships are robust against policies.

8.4.3. Emission Reduction

For the reasons mentioned in the previous section, the simulations were also done for IFO380. The results regarding the EEOI of IFO380 can be seen together with the rest of the alternative hydrocarbons in Figure 8.12. If a comparison is made based on the median of each fuel type, the EEOI of VLSFO will have a reduction of 13.8%, LPG 19.4%, LNG 24%, methanol 37.6%, hydrogen 97.6%, and ammonia 96.1%.

8.5. Conclusion

Case I and Case II demonstrate that ships using alternative fuels can be viable alternatives to conventional ships. All fuel types would reduce emissions and be profitable depending on the circumstances. The most

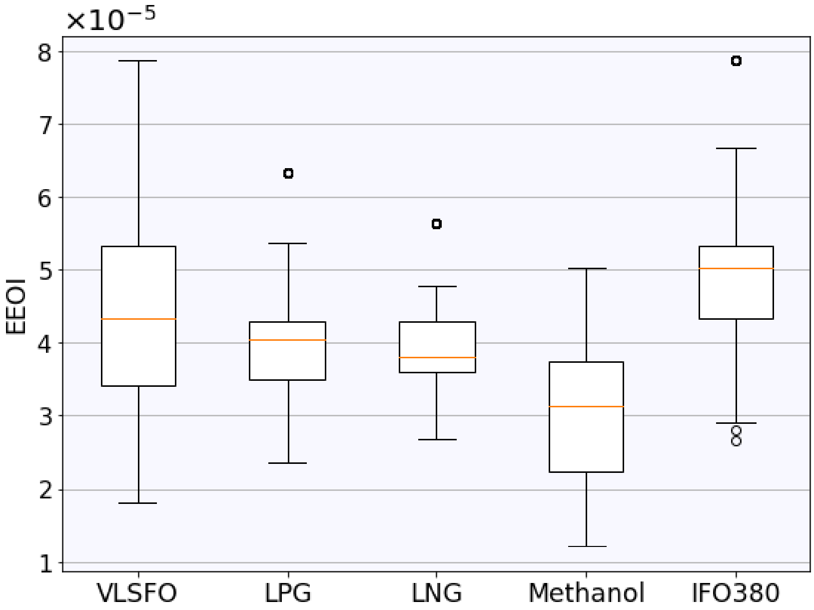


Figure 8.12: Box plots of EEOI of ships using alternative hydrocarbon fuels and IFO380 in Case II

robust alternative is LNG, followed by LPG. LNG is strong against low freight rates and fullness. It outperforms the rest of the alternatives in all aspects, except emissions. LNG would be as profitable as HFO or more as long as the cost of its facilities do not surpass roughly 100 million USD. For LPG these costs should not exceed about 60 million USD. Methanol, hydrogen, and ammonia are also feasible alternatives, but would require lower fuel prices to show their real potentials. Hydrogen and ammonia require also additional costs for their facilities, which makes it critical as they have relatively low NVPs. High additional costs would make these options not profitable for a majority of scenarios.

When it comes to reducing CO_2 emissions, the non-carbons hydrogen and ammonia are the clear winners. Both fuel types practically eliminate CO_2 emissions, regardless of the circumstances. For hydrocarbon fuels it is different. It has been seen that switching to fuel with smaller carbon content does not necessarily mean a decrease in emissions. The manner of operating has a bigger influence on emissions than the "cleanliness" of a fuel type. Certain aspects can force a ship to sail at lower speeds, which makes them more efficient and subsequently "cleaner". Even VLSFO, which is a type of HFO, can have lower EEOIs than fuels such as LPG and LNG, even though they are deemed "cleaner" fuels. Generally speaking, it can be said that using ships with VLSFO would reduce the EEOI by a range of 14-28%, LPG by 19%, LNG by 15-24%, methanol by 38-47%, hydrogen by 98% and ammonia by 97%.

Results show that there are certain limits for parameters, which when exceeded make it impossible for ships to be profitable. This is the case for freight rates of 600 USD per TEU and below. It has also been demonstrated that ships can sail with a fullness as low as 45% of their capacity and still stay profitable. For lower values it becomes impossible to stay profitable.

A conclusion regarding the policy options can also be made. The carbon tax policies were able to reduce the EEOI in all scenarios. In the majority of the scenarios, it was also more effective in reducing compared to the speed limits. The effectiveness of the speed limits depend on the properties of the ships and their preferred operations. Carbon taxes also caused bigger decreases in NPVs.

Considering these points, it can be said that the most robust fuel type option is LNG. LNG has a wide range of scenarios and parameters, under which it does not show weaknesses and is mostly profitable, if not the most profitable alternative. LPG and VLSFO are also robust options. Methanol, while being feasible has a weakness with its fuel price, which means that it is heavily impacted by it. Hydrogen and ammonia are promising options, but their feasibility depends on the additional costs for their storage facilities and fuel prices.

8.5.1. Future Work

There are a couple of points regarding the economical model, which if improved would have a positive effect on the results. It has been mentioned that as the ships sail between 2 ports, they can be considered as liner ships. These ships usually are in a fleet of sister ships, working on the same line, and have schedules. Implementing this behavior would require a better understanding of the liner shipping mechanics, but would make the model more realistic.

Furthermore, there are also alliances between big shipping companies, especially on major routes. These alliance influence the dynamics of pricing. Results show the importance of freight rate, which is why it would be beneficial to implement this type of dynamic in the economic model.

It was also assumed that certain variables do not change over the lifetime of a ship, which is not realistic. Each exogenous uncertainty is volatile in reality. This assumption results in ships making perpetually the same profits or losses. In reality this should be more volatile. This would require a method of varying these variables over the years, which would be a significant improvement to the economic model.

The information regarding the costs are based on old sources, as these were the only sources available. Updating these values with data from more recent sources would make the results more reliable and would remove some uncertainty regarding these parameters. The model was built in such away that it would be easy to update these values, for this purpose.

For the optimization it was assumed that the number of trips is an integer. This simplified the programming of the optimization, but affected the results. As explained above, in order to use the time in a year most efficiently the ship would increase or decrease its speed, such that the end of the year would coincide with the end of a trip. This effect was also visible in the results. Changing this aspect would improve the model and results, but would also require further improvements. A more sophisticated accounting method would be necessary and the introduction of new policies would require some changes.

Factorial sampling was used for scenario generation, which was a simple method. It would be an improvement to use Latin hypercube sampling and could improve results. Furthermore, it has been seen how critical fuel prices can be. These have been varied for ± 20% around the set baseline. In hindsight, it should be acknowledged that for some fuels the volatility could be higher and should be taken into account.

9 Conclusion & Discussion

The maritime sector, under the leadership of IMO, wants to reduce GHG emissions in order to tackle global warming. This will have effects on ships and how shipping is done. However, the achievability of IMO's goals regarding emission reductions for 2050 is overshadowed by uncertainties. The aim of this thesis was to contribute to the solution of this problem by answering the following research question, which deals with a small part of the grand picture:

"What is an adequate approach to assess alternative fuel types for robust ultra large container vessels in face of uncertainty, regarding the goals of IMO for the year 2050?"

To assist answering this question, 5 sub-questions were formulated. These shall be answered first.

What are the implications of the IMO goals for 2050 on container ship requirements?

IMO wants to reduce GHG emissions by 50% by 2050 and CO_2 emissions by 70% by 2050 (compared to 2008). At the moment, IMO plans to reduce emissions by forcing newly built ships to have a lower EEDI, but regulations regarding this are updated by IMO in the yearly MEPC meetings. Container ships built in recent times meet the regulations for the foreseeable future. IMO has also introduced the EEOI, which is based on the operations of the ship rather than its design. Future regulations will most likely introduce further reductions in one or both of these indexes. These will require ships to be more efficient or to have energy systems which produce less emissions.

Which uncertainties can be identified in this subject?

The uncertainties involved in this subject can be divided into 3 categories: political, technical, and economic. The magnitude of the future reductions in EEDI are unknown. Furthermore, policies enforcing speed limits or bunker levies are being discussed. These aspects can be considered as political uncertainties. Technical uncertainties concern the development of new, game-changing technologies, such as fuel cells, batteries, etc. When technological breakthroughs in these technologies, which would have big potential in reducing emissions, are going to happen is uncertain. Fuel prices, freight rates, trade demand, etc. are economic uncertainties, which affect how profitable ships are and also affect the willingness of ship owners to invest in cleaner ships.

What will be the effect of different alternative fuel types on the design of ULCVs?

The considered alternative fuels, i.e., LPG, LNG, methanol, hydrogen, and ammonia, can all be used in existing 2-stroke Diesel engines. The main change between these fuels and conventional HFO is the fact that these fuels require more tank volume for the same amount of energy. Furthermore, as LPG, LNG, hydrogen and ammonia need to be cooled down to be stored, they also require additional facilities such as cryogenic tanks and cooling systems. More details can be found in Chapter 4. The parametric design tool, which is explained in Chapter 7, has been developed to see the full effect of implementing different fuels. Through a combination of lengthening the ship and deleting cargo space, it is possible to accommodate the additional space that is required. Depending on the fuel choice, this can lead to a slightly larger ship and/or a slight change in capacity.

What will be the effects of fuel choice on the ship's performance in combination with changes in markets and regulations during the lifetime of the ship ?

The choice of fuel affects the ship's financial and environmental performance. Results show that the best performance regarding emissions is achieved by the non-carbon fuels hydrogen and ammonia. They are followed by methanol, VLSFO, LPG, and LNG. This ranking changes for the profitability. It has been shown that LNG is the most profitable and robust fuel choice, followed by LPG, VLSFO, ammonia, hydrogen, and methanol. This is true as long as the additional facilities for LNG are not more than 100 million USD and 60 million USD for LPG. If additional costs for ammonia and hydrogen are too high, they become an unviable option.

It has been determined that non-carbon fuels are not affected by carbon tax policies, as they produce a limited amount of CO_2. Hydrocarbon fuels, on the other hand, are much more susceptible to these kind of policies.

How much emission reductions will different fuel types offer and with what certainty?

If the ships using different fuel types sail under the same circumstances, it can be said that compared to HFO (based on EEOI) LPG will always have a reduction of 16%, LNG 29%, methanol 12%, hydrogen 97%, and ammonia 95%. This changes in the case when ships adapt their operations to maximize their profits. In this case, also a differentiation between VLSFO and IFO380 has to be made as the price difference between these HFOs also influences the outcome. Results show that cleaner fuels do not necessarily result in lower emissions. If compared to IFO380, VLSFO would have a decrease of 14-28% in EEOI, LPG 19%, LNG 15-24%, methanol 38-47%, hydrogen 98% and ammonia by 97%. Hydrogen and ammonia will always have lower emissions than the other fuels, but the reduction of the hydrocarbon fuels depends on the circumstances.

The answers to the sub-questions lead the way to the answer for the main research questions. If the goals that wanted to be achieved, the scope of the problem, the level of uncertainty that was handled, and the obtained results are considered as a whole, it can be said that the proposed approach is adequate. A detailed research was done to achieve a good understanding of topic. Based on this knowledge, RDM was chosen as the most suitable method. The implementation of RDM required a manner of creating different designs based on certain variables. The parametric design tool was developed for this purpose. It did not only generate designs for RDM, but also provided a better understanding of ULCV designs and the implications that the implementation of alternative fuels would have. Lastly, RDM ensured to produce the desired type of results, while managing the relatively high level of uncertainty of the subject. It showcased the strengths and weaknesses of each fuel type and made it possible to come to a conclusion regarding the robustness of each fuel type.

This approach can give a valuable insight for multiple stakeholders. Results did not only indicate the potential of different fuel types, but also revealed critical parameters for performance of the ships. It has been seen that the majority of ships can not stay positive if the freight rate goes below 600 USD per TEU or when the fullness goes below 0.4. These are valuable information for shipping companies, but it has also been demonstrated that policymakers could also benefit from this approach. The effectiveness of the policies can be tested via this method. Results showed that both carbon taxes and speed limits are effective in reducing emissions, but the effectiveness can vary from fuel type to fuel type.

Even though the results give a valuable insight to the potentials of the different fuel types, which are overshadowed by uncertainties, it should be taken with a pinch of salt. The approach tries to tackle future uncertainties, but assumptions and simplifications, which were made due to the lack of information or to make the problem at hand more manageable, introduce new uncertainties. Throughout this thesis, it was tried to be as clear as possible which assumptions and simplifications were made, for which reason, and what possible effects these could have. The parametric design tool and economic model were constructed in such a way that if more information would be available in the future, they could be updated by a change of number. Recommendations for improving the tool and model were made in the previous chapters. The most important improvement for the tool would be a better CAPEX estimation for ships, which use alternative fuels. For the economic model, changing the way the optimization is done regarding the trips made in a year, would make the model more realistic and improve the results.

All in all, it is believed that through this thesis a valuable contribution to societies endeavour for a brighter, greener future has been made. This thesis has 2 key products, which are the parametric design tool for ULCVs with a choice for fuel type and the first time adaption of Robust Decision Making for a ship design subject. The parametric design tool can give valuable insight on the preliminary design of ULCVs and the effect that the choice of fuel type will have. On the other hand, it has been demonstrated that RDM is also applicable for ship design purposes and has potential for many stakeholders in the field. This second aspect makes this thesis a novelty.

The goal of this thesis was to get a better understanding of the future of container ships, which is full of uncertainties or, as Rumsfeld said, known unknowns and unknown unknowns. Having a better understanding of this will secure better planning for the future and lead to wiser choices. This can be true for the engineer who designs the container ships, the ship owner who operates them or the policymaker who tries to create a greener maritime sector for a better future. Wiser choices and better planning will ensure that a better, greener future is achieved quicker and for certain.

References

[1] ABS. Setting the course to low carbon shipping. Technical report, American Buraeu of Shipping, 2019.

[2] Michele Acciaro. Real option analysis for environmental compliance: Lng and emission control areas. *Transportation Research Part D: Transport and Environment*, 28:41 – 50, 2014. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2013.12.007. URL `http://www.sciencedirect.com/science/article/pii/S136192091300151X`. Emission Control Areas and their Impact on Maritime Transport.

[3] Masaki Adachi, Hiroyuki Kosaka, Tetsugo Fukuda, Shota Ohashi, and Kazuyoshi Harumi. Economic analysis of trans-ocean LNG-fueled container ship. *Journal of Marine Science and Technology (Japan)*, 19(4):470–478, nov 2014. ISSN 09484280. doi: 10.1007/s00773-014-0262-5.

[4] Maarten Afman, Sebastian Hers, and Hijs Scholten. Energy and electricity price scenarios 2020-2023-2030. Technical report, CE Delft, jan 2017.

[5] Nader R. Ammar. An environmental and economic analysis of methanol fuel for a cellular container ship. *Transportation Research Part D: Transport and Environment*, 69:66–76, apr 2019. ISSN 13619209. doi: 10.1016/j.trd.2019.02.001.

[6] Karin Anderson and Carlos Marquez Salazar. Methanol as a marine fuel report. Technical report, FCBI Energy, oct 2015. URL `http://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf`.

[7] T. W. Anderson and D. A. Darling. Asymptotic theory of certain "goodness of fit" criteria based on stochastic processes. *The Annals of Mathematical Statistics*, 23(2):193–212, 1952. ISSN 00034851. URL `http://www.jstor.org/stable/2236446`.

[8] Anonymous. Development of large container ships – what are the limits? *All About Shipping*, 2014. https://www.allaboutshipping.co.uk/2014/10/28/development-of-large-container-ships-what-are-the-limits/.

[9] Paul Balcombe, James Brierley, Chester Lewis, Line Skatvedt, Jamie Speirs, Adam Hawkes, and Iain Staffell. How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Conversion and Management*, 182:72–88, feb 2019. ISSN 01968904. doi: 10.1016/j.enconman.2018.12.080.

[10] Logan Beal, Daniel Hill, R. Martin, and John Hedengren. GEKKO Optimization Suite. *Processes*, 6(8): 106, jul 2018. ISSN 2227-9717. doi: 10.3390/pr6080106. URL `http://www.mdpi.com/2227-9717/6/8/106`.

[11] Till ben Brahim, Frauke Wiese, and Marie Münster. Pathways to climate-neutral shipping: A Danish case study. *Energy*, 188:116009, dec 2019. ISSN 03605442. doi: 10.1016/j.energy.2019.116009.

[12] Yakov Ben-Haim. Info-gap decision theory (ig). In *Decision Making under Deep Uncertainty: From Theory to Practice* Marchau et al. [93], pages 93–115. doi: 10.1007/978-3-030-05252-2_5. URL `https://doi.org/10.1007/978-3-030-05252-2_5`.

[13] Jonathan Berk and Peter DeMarzo. *Corporate Finance*. Pearson Education, fourth edition, 2017. ISBN 1-292-16016-0.

[14] Yusuf Bicer and Ibrahim Dincer. Clean fuel options with hydrogen for sea transportation: A life cycle approach. *International Journal of Hydrogen Energy*, 43(2):1179–1193, jan 2018. ISSN 03603199. doi: 10.1016/j.ijhydene.2017.10.157.

[15] Yusuf Bicer and Ibrahim Dincer. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. *International Journal of Hydrogen Energy*, 43(9):4583–4596, mar 2018. ISSN 03603199. doi: 10.1016/j.ijhydene.2017.07.110.

[16] Mike Bird. 12 of the worst economic predictions ever made by highly intelligent people. *Business Insider*, may 2015. URL https://www.businessinsider.com/12-of-the-worst-predictions-about-the-global-economy-that-intelligent-people-have-ever-made-2015-5.

[17] T.J. Blasing. Recent greenhouse gas concentrations. Technical report, Carbon Dioxide information Analysis Center, U.S. Department of Energy, apr 2016.

[18] Elizabeth G Bloxam. *The Organisation , Transportation and Logistics of Hard Stone Quarrying in the Egyptian Old Kingdom : A Comparative Study*. PhD thesis, University College London, August 2003. URL https://discovery.ucl.ac.uk/id/eprint/1446697/1/U602622redacted.PDF.

[19] T.A. Boden, G. Marland, and R.J. Andres. Global, regional, and national fossil-fuel co2 emissions. Technical report, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., 2017.

[20] Edward H. Bowman and Gary T. Moskowitz. Real Options Analysis and Strategic Decision Making. *Organization Science*, 12(6):772–777, 2001. ISSN 10477039. doi: 10.1287/orsc.12.6.772.10080.

[21] Hendriks W. Brinks and Christos Chryssakis. Lpg as a marine fuel. Technical report, Det Norske Veritas - Germanischer Lloyd, 2017. URL https://www.dnvgl.com/publications/lpg-as-marine-fuel-95190.

[22] Encyclopædia Britannica. Strait of malacca. *Encyclopædia Britannica*, jun 2019. URL https://www.britannica.com/place/Strait-of-Malacca.

[23] Benjamin P Bryant and Robert J Lempert. Technological Forecasting & Social Change Thinking inside the box : A participatory , computer-assisted approach to scenario discovery. *Technological Forecasting & Social Change*, 77(1):34–49, 2010. ISSN 0040-1625. doi: 10.1016/j.techfore.2009.08.002. URL http://dx.doi.org/10.1016/j.techfore.2009.08.002.

[24] Ship & Bunker. Rotterdam bunker prices, 2020. URL https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#VLSFO.

[25] Pierre Cariou. Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? *Transportation Research Part D: Transport and Environment*, 16(3):260–264, may 2011. ISSN 13619209. doi: 10.1016/j.trd.2010.12.005.

[26] Pierre Cariou, Francesco Parola, and Theo Notteboom. Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. *International Journal of Production Economics*, 208:17–28, feb 2019. ISSN 09255273. doi: 10.1016/j.ijpe.2018.11.016.

[27] Richard de Neufville and Kim Smet. Engineering options analysis (eoa). In *Decision Making under Deep Uncertainty: From Theory to Practice* Marchau et al. [93], pages 117–132. doi: 10.1007/978-3-030-05252-2_6. URL https://doi.org/10.1007/978-3-030-05252-2_6.

[28] Niels de Vries. Safe and effective application of ammonia as a marine fuel. Master's thesis, Delft University of Technology, jun 2019. URL http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8.

[29] Cengiz Deniz and Burak Zincir. Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, 113:438–449, feb 2016. ISSN 09596526. doi: 10.1016/j.jclepro.2015.11.089.

[30] Bundesregierung der Bundesrepublik Deutschland. Foundations in place for co2 pricing, oct 2019. URL https://www.bundesregierung.de/breg-en/issues/nationaler-emissionshandel-1685054.

[31] O Dinu and A M Ilie. Maritime vessel obsolescence, life cycle cost and design service life. *IOP Conference Series: Materials Science and Engineering*, 95:012067, nov 2015. doi: 10.1088/1757-899x/95/1/012067. URL https://doi.org/10.1088%2F1757-899x%2F95%2F1%2F012067.

[32] DNV GL. A global and regional forecast of the energy transition to 2050. *Energy Transition Outlook 2017*, 2017. URL https://eto.dnvgl.com/.

[33] DNV GL. Maritime Forecast To 2050. *Energy Transition Outlook 2017*, 2017. URL https://eto.dnvgl.com/2018/maritime.

[34] DNV GL. Low carbon shipping towards 2050. Technical report, Det Norske Veritas - Germanischer Lloyd, 2017.

[35] DNV GL. Assessment of selected alternative fuels and technologies. Technical report, Det Norske Veritas - Germanischer Lloyd, 2019.

[36] DNV GL. *DNV GL rules for classification: Ships*. Det Norske Veritas - Germanischer Lloyd, 2020.

[37] DOE. Liquefied natural gas: Understanding the basic facts. Technical report, United States Department of Energy, 2013. URL https://www.energy.gov/sites/prod/files/2013/04/f0/LNG_primerupd.pdf.

[38] Norbert Doerry and Philip Koenig. Modularity and Adaptability in Future U . S . Navy Ship Designs. In *Mecon*, pages 1–9, Hamburg, Germany, November 2017.

[39] Karl H Dreborg. Essence of backcasting. *Futures*, 28(9):813 – 828, 1996. ISSN 0016-3287. doi: https://doi.org/10.1016/S0016-3287(96)00044-4. URL http://www.sciencedirect.com/science/article/pii/S0016328796000444.

[40] EPA. Draft inventory of u.s. greenhouse gas emissions and sinks: 1990-2018. Technical report, United States Environmental Protection Agency, mar 2020. URL https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018.

[41] Eurostat. China-eu trade in goods: €164 billion deficit in 2019, mar 2020. URL https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200320-1#:~:text=In%202019%20the%20trade%20deficit%20stood%20at%20%E2%82%AC164%20billion.&text=For%20both%20EU%20exports%20and,imports%20of%20goods%20from%20China.

[42] The Maritime Executive. One breaks record for highest utilization of a container ship, 2019. URL https://www.maritime-executive.com/article/one-breaks-record-for-highest-utilized-container-ship.

[43] Israel Finkelstein, Elena Zapassky, Yuval Gadot, Daniel M. Master, Lawrence E. Stager, and Itzhak Benenson. Phoenician "torpedo" amphoras and egypt: Standardization of volume based on linear dimensions. *Agypten und Levante*, 21(January):249–259, 2011. ISSN 10155104. doi: 10.1553/AEundL21s249.

[44] UK Department for Transport. Maritime 2050 - navigating the future. Great Minster House 33 Horseferry Road London SW1P 4DR, jan 2019. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872194/Maritime_2050_Report.pdf.

[45] FreightWaves. How many gallons of fuel does a container ship carry? *American Shipper*, jan 2020. URL https://www.freightwaves.com/news/how-many-gallons-of-fuel-does-a-container-ship-carry.

[46] José Luis Sánchez García and Juan María Díez Sanz. Climate change, ethics and sustainability: An innovative approach. *Journal of Innovation & Knowledge*, 3(2):70 – 75, 2018. ISSN 2444-569X. doi: https://doi.org/10.1016/j.jik.2017.12.002. URL http://www.sciencedirect.com/science/article/pii/S2444569X18300027. Poverty, Hunger and Sustainability.

[47] H. M. Gaspar, S. O. Erikstad, and A. M. Ross. Handling temporal complexity in the design of non-transport ships using Epoch-Era Analysis. *The International Journal of Maritime Engineering*, 154(PART A3):109–119, 2012. ISSN 14798751. doi: 10.3940/rina.ijme.2012.a3.230.

[48] Paul Gilbert, Conor Walsh, Michael Traut, Uchenna Kesieme, Kayvan Pazouki, and Alan Murphy. Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172:855 – 866, 2018. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2017.10.165. URL http://www.sciencedirect.com/science/article/pii/S0959652617324721.

[49] David G. Groves and Robert J. Lempert. A new analytic method for finding policy-relevant scenarios. *Global Environmental Change*, 17(1):73–85, feb 2007. ISSN 09593780. doi: 10.1016/j.gloenvcha.2006.11.006.

[50] Christian Haehl and Stefan Spinler. Technology Choice under Emission Regulation Uncertainty in International Container Shipping. *European Journal of Operational Research*, 284(1):383–396, jul 2020. ISSN 03772217. doi: 10.1016/j.ejor.2019.12.025.

[51] Hapag-Lloyd. Price announcement terminal handling charges in the netherlands, 2018. URL https://www.hapag-lloyd.com/en/news-insights/news/2018/12/terminal-handling-charges-in-the-netherlands.html.

[52] Hapag-Lloyd. Annual report 2019. Technical report, Hapag-Lloyd, mar 2020. URL https://www.hapag-lloyd.com/en/ir/publications/financial-report.html.

[53] Hercules E. Haralambides. Gigantism in container shipping, ports and global logistics: a time-lapse into the future. *Maritime Economics & Logistics*, 21(1):1–60, 2019. doi: https://doi.org/10.1057/s41278-018-00116-0.

[54] Martin B Hocking. *Handbook of Chemical Technology and Pollution Control*. Elsevier Science & Technology, San Diego, UNITED STATES, 2006. ISBN 9780080478272. URL http://ebookcentral.proquest.com/lib/delft/detail.action?docID=294163.

[55] J. Holtrop and G.G.J. Mennen. An approximate power prediction method. *International Shipbuilding Progress*, 1982. URL http://resolver.tudelft.nl/uuid:ee370fed-4b4f-4a70-af77-e14c3e692fd4.

[56] Galen Hon and Haifen Wang. The energy efficiency design index (eedi) for new ships. Technical report, International Council on Clean Transportation, oct 2011. https://theicct.org/publications/energy-efficiency-design-index-eedi-new-ships.

[57] Hongtao Hu, Jun Yuan, and Victor Nian. Development of a multi-objective decision-making method to evaluate correlated decarbonization measures under uncertainty – The example of international shipping. *Transport Policy*, 82:148–157, oct 2019. ISSN 1879310X. doi: 10.1016/j.tranpol.2018.07.010.

[58] IEA. Lng import prices in selected countries, 2010-2019. *IEA*, jul 2020. URL https://www.iea.org/data-and-statistics/charts/lng-import-prices-in-selected-countries-2010-2019.

[59] IMO. Guidelines for voluntary use of the ship energy efficiency operational indicator (eeoi), aug 2009. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Technical%20and%20Operational%20Measures/MEPC.1_Circ.684_Guidelines%20for%20Voluntary%20use%20of%20EEOI.pdf.

[60] IMO. Un agency pushes forward on shipping emissions reduction, may 2019. URL http://www.imo.org/en/MediaCentre/PressBriefings/Pages/11-MEPC-74-GHG.aspx.

[61] IMO. Sulphur 2020 – cutting sulphur oxide emissions, 2020. URL https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx.

[62] ITF. Decarbonising maritime transport - pathways to zero-carbon shipping by 2035. Technical report, International Transport Forum, mar 2018. URL https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf.

[63] Callum Jones. World's biggest container ship msc gülsün makes waves on first european visit. The Times, aug 2019. URL https://www.thetimes.co.uk/article/worlds-biggest-container-ship-msc-guelsuen-makes-waves-on-first-european-visit-3z7sfdlbq.

[64] Austin Kana, Joshua T Knight, Michael J. Sypniewski, and David J Singer. A Markov Decision Process Framework for Analyzing LNG as Fuel in the Face of Uncertainty. *International Marine Design Conference*, 2(Figure 1):297–308, 2015. doi: 10.13140/RG.2.1.2189.5525.

[65] Austin A. Kana and Brandon M. Harrison. A Monte Carlo approach to the ship-centric Markov decision process for analyzing decisions over converting a containership to LNG power. *Ocean Engineering*, 130(October 2016):40–48, 2017. ISSN 00298018. doi: 10.1016/j.oceaneng.2016.11.042. URL http://dx.doi.org/10.1016/j.oceaneng.2016.11.042.

[66] Richard Karslen, George Papachristos, and Nishatabbas Rehmatulla. An agent-based model of climate-energy policies to promote wind propulsion technology in shipping. *Environmental Innovation and Societal Transitions*, 31:33–53, jun 2019. doi: 10.1016/j.eist.2019.01.006.

[67] Joseph R. Kasprzyk, Shanthi Nataraj, Patrick M. Reed, and Robert J. Lempert. Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling and Software*, 2013. ISSN 13648152. doi: 10.1016/j.envsoft.2012.12.007.

[68] Hans Klein Woud and Douwe Stapersma. *Design of Propulsion and Electric Power Generation Systems*. IMarEST, 80 Coleman Street, London, UK, 2002.

[69] Martin Köpke, Apostolos Papanikolaou, and Stefan Harries. CONTiOPT–Holistic Optimisation of a High Efficiency and Low Emission Containership. *Friendship-Systems.Com*, 2014. URL https://www.friendship-systems.com/downloads/papers/papers2014/2014{_}tra{_}koepke.papanikolaou.harries.nikolopoulos.sames{_}contiopt-holistic-optimisation-high-efficiency-low-emission-containership.pdf.

[70] Alfred M. Kracht. Design of bolbuos bows. *SNAME Transactions*, 86:197–217, jan 1978.

[71] Jan H. Kwakkel, Willem L. Auping, and Erik Pruyt. Dynamic scenario discovery under deep uncertainty: The future of copper. *Technological Forecasting and Social Change*, 80(4):789 – 800, 2013. ISSN 0040-1625. doi: https://doi.org/10.1016/j.techfore.2012.09.012. URL http://www.sciencedirect.com/science/article/pii/S0040162512002387. Scenario Method: Current developments in theory and practice.

[72] Jan H. Kwakkel, Marjolijn Haasnoot, and Warren E. Walker. Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. *Environmental Modelling and Software*, 86:168–183, dec 2016. ISSN 13648152. doi: 10.1016/j.envsoft.2016.09.017.

[73] Thomas Lamb. *Ship Design and Construction, Volumes 1-2*. Society of Naval Architects and Marine Engineers (SNAME), 2003 - 2004. ISBN 978-0-939773-40-4 (Vol. I); 978-0-939773-41-1 (Vol. II). URL https://app.knovel.com/hotlink/toc/id:kpSDCV0001/ship-design-construction/ship-design-construction.

[74] R. J. Lempert. Robust decision making (rdm). In *Decision Making under Deep Uncertainty: From Theory to Practice* Marchau et al. [93], pages 23–51. doi: 10.1007/978-3-030-05252-2_2. URL https://doi.org/10.1007/978-3-030-05252-2_2.

[75] Robert J. Lempert, Steven W Popper, and Steven C Bankes. Implementing Robust Decisionmaking. In *Shaping the Next One Hundred Years*, pages 132–134. Rand Corporation, 2003. URL https://www.jstor.org/stable/10.7249/mr1626rpc.13{%}0AJSTOR.

[76] Robert J. Lempert, David G. Groves, Steven W. Popper, and Steve C. Bankes. A general, analytic method for generating robust strategies and narrative scenarios. *Management Science*, 52(4):514–528, 2006. ISSN 00251909. doi: 10.1287/mnsc.1050.0472.

[77] Robert J. Lempert, Nidhi Kalra, Suzanne Peyraud, Zhimin Mao, Sinh Bach Tan, Dean Cira, and Alexander Lotsch. Ensuring Robust Flood Risk Management in Ho Chi Minh City. *World Bank*, 1(May):1–63, 2013. doi: 10.1596/1813-9450-6465.

[78] Eric Levenson. Ten legitimately fascinating facts about the shipping industry. The Atlantic, aug 2013. URL https://www.theatlantic.com/international/archive/2013/08/shipping-industry-bigger-you-can-imagine/312253/.

[79] Liebherr. Technical description ship to shore gantry cranes. Technical report, Liebherr, 2020. URL https://www.liebherr.com/shared/media/maritime-cranes/downloads-and-brochures/brochures/lcc/liebherr-sts-cranes-technical-description.pdf.

[80] Granta Design limited. Ces edupack software, 2009. Cambridge, UK.

[81] Han Lingteringen. *Ports and Terminals*. Delft Academic Press, Leeghwaterstraat 42, 2628 CA Delft, The Netherlands, second edition, 2017. ISBN 97890-6562-4147.

[82] Jialun Liu and Robert Hekkenberg. Sixty years of research on ship rudders: effects of design choices on rudder performance. *Ships and Offshore Structures*, 12(4):495–512, 2017. ISSN 17445302. doi: 10.1080/17445302.2016.1178205.

[83] Pound Sterling Live. Historical rates for the eur/usd, 2020. URL https://www.poundsterlinglive.com/best-exchange-rates/euro-to-us-dollar-exchange-rate-on-2019-08-30.

[84] Lloyd's Register and UMAS. Zero-Emission Vessels: Transition Pathways. Technical report, Lloyd's Register, 2019. URL https://www.lr.org/en-gb/insights/global-marine-trends-2030/zero-emission-vessels-transition-pathways/.

[85] Maersk. Annual report 2019. Technical report, A.P. Moller - Maersk A/S, Esplanaden 50, DK-1098 Copenhagen, feb 2020. URL https://investor.maersk.com/static-files/984a2b93-0035-40d3-9cae-77161c9a36e0.

[86] Kalyeena Makortoff. Barclays sets net zero carbon target for 2050 after investor pressure. *The Guardian*, March 2020. URL https://www.theguardian.com/business/2020/mar/30/barclays-sets-net-zero-carbon-target-for-2050-after-investor-pressure-climate.

[87] MAN. Basic principles of ship propulsion. Technical report, MAN Diesel & Turbo, Teglholmsgade 41 2450 Copenhagen SV, Denmark, 2011. URL https://spain.mandieselturbo.com/docs/librariesprovider10/sistemas-propulsivos-marinos/basic-principles-of-ship-propulsion.pdf?sfvrsn=2.

[88] MAN. Propulsion trends in container vessels. Technical report, MAN Diesel & Turbo, 2016. URL https://web.archive.org/web/20120507192232/http://www.mandieselturbo.eu/files/news/filesof4672/5510-0040-01ppr_low.pdf.

[89] MAN. Man b&w g95me-c9.5. Technical report, MAN Turbo & Diesel, Teglholmsgade 41, DK-2450, Copenhagen SV, Denmark, 2018. URL https://marine.man-es.com/applications/projectguides/2stroke/content/epub/G95ME-C9_5.pdf.

[90] MAN. Ceas engine calculation, aug 2020. URL https://marine.man-es.com/two-stroke/ceas.

[91] MAN. HFO, 2020. URL https://powerplants.man-es.com/fuels/hfo.

[92] Sarah Mander. Slow steaming and a new dawn for wind propulsion: A multi-level analysis of two low carbon shipping transitions. *Marine Policy*, 75:210–216, jan 2017. ISSN 0308597X. doi: 10.1016/j.marpol.2016.03.018.

[93] Vincent A. W. J. Marchau, Warren E. Walker, Pieter J. T. Bloemen, and Steven W. Popper, editors. *Decision Making Under Deep Uncertainty*. Springer International Publishing, 2019. ISBN 9783030052515. doi: 10.1093/oxfordhb/9780190455811.013.50.

[94] Vincent A. W. J. Marchau, Warren E. Walker, Pieter J. T. M. Bloemen, and Steven W. Popper. Introduction. In *Decision Making under Deep Uncertainty: From Theory to Practice* Marchau et al. [93], pages 1–20. doi: 10.1007/978-3-030-05252-2_1. URL https://doi.org/10.1007/978-3-030-05252-2_1.

[95] IHS Markit. Ammonia fertilizer market and price analysis, 2020. URL https://agribusiness.ihsmarkit.com/sectors/fertilizers/ammonia.html.

[96] Merriam-Webster Online. Merriam-Webster Online Dictionary, 2020. URL http://www.merriam-webster.com.

[97] Methanex. Historical methanex posted price, 2020. URL https://www.methanex.com/sites/default/files/MxAvgPrice%20Sept%2030%202020.pdf.

[98] Oliver Milman, David Smith, and Damian Carrington. Donald trump confirms us will quit paris climate agreement. *The Guardian*, jun 2017. URL https://www.theguardian.com/environment/2017/jun/01/donald-trump-confirms-us-will-quit-paris-climate-deal.

[99] Enayat A. Moallemi, Sondoss Elsawah, and Michael J. Ryan. Robust decision making and Epoch–Era analysis: A comparison of two robustness frameworks for decision-making under uncertainty. *Technological Forecasting and Social Change*, 2020. ISSN 00401625. doi: 10.1016/j.techfore.2019.119797.

[100] C. W. Mohd Noor, M. M. Noor, and R. Mamat. Biodiesel as alternative fuel for marine diesel engine applications: A review. *Renewable and Sustainable Energy Reviews*, 94:127–142, oct 2018. ISSN 18790690. doi: 10.1016/j.rser.2018.05.031.

[101] Machiel Mulder, Peter Perey, and José L. Moraga. Outlook for a dutch hydrogen market. *Policy Papers*, 5, mar 2019.

[102] G. Myhre, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglesvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stepehens, T. Takemura, and H. Zhang. Anthropogenic and natural radiative forcing. In T.F. Stocker, D. Qin, G.-K Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors, *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chapter Anthropogenic and natural radiative forcing, pages 659–740. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, 2013. ISBN 9781107415324. doi: 10.1017/CBO9781107415324.018.

[103] United Nations. Kyoto protocol to the united nations framework convention on climate change, 1998. URL https://unfccc.int/resource/docs/convkp/kpeng.pdf.

[104] Container News. Shanghai containerized freight index, 2020. URL https://container-news.com/scfi/.

[105] Nathan D. Niese and David J. Singer. Strategic life cycle decision-making for the management of complex Systems subject to uncertain environmental policy. *Ocean Engineering*, 72:365–374, 2013. ISSN 00298018. doi: 10.1016/j.oceaneng.2013.07.020.

[106] OECD. Long-term interest rates (indicator), 2020. doi: 10.1787/662d712c-en.

[107] Port of Hamburg. Vessels, 2020. URL https://www.hafen-hamburg.de/en/vessels.

[108] Port of Rotterdam. General terms and conditions, 2020. URL https://www.portofrotterdam.com/sites/default/files/general-terms-and-conditions-including-port-tariffs-2020.pdf.

[109] Naya Olmer, Bryan Comer, Biswajoy Roy, Xiaoli Mao, and Dan Rutherford. Greenhouse gas emissions from global shipping, 2013–2015. Technical report, International Council on Clean Transportation, 2017. URL https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015.

[110] United Nations Framework Convention on Climate Change. Paris agreement. *United Nations Treaty Collection, Chapter XXVII 7. d*, 2015. URL https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en.

[111] OOCL. Local surcharges, 2020. URL https://www.oocl.com/china/eng/localinformation/localsurcharges/shanghai/Pages/default.aspx?site=china&lang=eng.

[112] International Maritime Organization and International Conference for the Safety of Life at Sea. *SOLAS: International Convention for the Safety of Life at Sea, 1974.* Resolutions of the 1997 SOLAS Conference Relating to Bulk Carrier Safety, London: International Maritime Organization, 1999.

[113] Jonathan Page. Flexibility in early stage design of us navy ships: An analysis of options. *Journal of Ship Production and Design*, 28, 01 2012. doi: 10.5957/JSPD.28.3.120012.

[114] Apostolos Papanikolaou. *Ship Design - Methodologies of Preliminary Design*. Springer, 09 2014. ISBN 978-94-017-8750-5. doi: 10.1007/978-94-017-8751-2.

[115] Nam Kyu Park and Sang-cheol Suh. Tendency toward mega containerships and the constraints of container terminals. *Journal of Marine Science and Engineering*, 7:131, 05 2019. doi: 10.3390/jmse7050131.

[116] Tatjana Paulauskiene, Martynas Bucas, and Airida Laukinaite. Alternative fuels for marine applications: Biomethanol-biodiesel-diesel blends. *Fuel*, 248:161–167, jul 2019. ISSN 00162361. doi: 10.1016/j.fuel.2019.03.082.

[117] Kjartan Pedersen, Jan Emblemsvåg, R. Bailey, Janet Allen, and Farrokh Mistree. The"validation square"-validating design methods. In *ASME Design Theory and Methodology Conference*, 01 2000.

[118] Alexandros Priftis, Evangelos Boulougouris, Osman Turan, and Apostolos Papanikolaou. Parametric design and multi-objective optimisation of containerships. *Ocean Engineering*, 156:347–357, may 2018. ISSN 00298018. doi: 10.1016/j.oceaneng.2018.02.062.

[119] Jan-Olaf Probst. Pump up the volume. Technical report, Det Norske Veritas - Germanischer Lloyd, 2016.

[120] Jan-Olaf Probst. Terminal challenges. Technical report, Det Norske Veritas - Germanischer Lloyd, 2018.

[121] Harilaos N Psaraftis. Speed optimization versus speed reduction: Are speed limits better than a bunker levy? *Maritime Economics & Logistics*, 21:524–542, 2019. doi: 10.1057/s41278-019-00132-8. URL `https://doi.org/10.1057/s41278-019-00132-8`.

[122] Nishatabbas Rehmatulla and Tristan Smith. Barriers to energy efficient and low carbon shipping. *Ocean Engineering*, 110:102–112, dec 2015. ISSN 00298018. doi: 10.1016/j.oceaneng.2015.09.030.

[123] Nishatabbas Rehmatulla, Sophia Parker, Tristan Smith, and Victoria Stulgis. Wind technologies: Opportunities and barriers to a low carbon shipping industry. *Marine Policy*, 75:217–226, jan 2017. ISSN 0308597X. doi: 10.1016/j.marpol.2015.12.021.

[124] Clarksons Research. World fleet register, 2020.

[125] RINA. *Significant Ships of 2014*. The Royal Institute of Naval Architects, 8-9 Northumberland Street London, WC2N 5DA, UK, 2015.

[126] RINA. *Significant Ships of 2015*. The Royal Institute of Naval Architects, 8-9 Northumberland Street London, WC2N 5DA, UK, 2016.

[127] RINA. *Significant Ships of 2016*. The Royal Institute of Naval Architects, 8-9 Northumberland Street London, WC2N 5DA, UK, 2017.

[128] Jean-Paul Rodrigue, Claude Comtois, and Brian Slack. *The geography of transport systems*. Routledge, 2016.

[129] Donald Rumsfeld. DoD News Briefing - Secretary Rumsfeld and Gen. Myers. U.S. Department of Defense, feb 2002. URL `https://archive.defense.gov/Transcripts/Transcript.aspx?TranscriptID=2636`.

[130] Dan Rutherford and Bryan Comer. The international maritime organization's initial greenhouse gas strategy. Technical report, International Council on Clean Transportation, apr 2018. URL `https://theicct.org/publications/IMO-initial-GHG-strategy`.

[131] Safety4Sea. World's largest containership achieves new record load, may 2020. URL `https://safety4sea.com/worlds-largest-containership-achieves-new-record-load/`.

[132] O. Schinas and M. Butler. Feasibility and commercial considerations of LNG-fueled ships. *Ocean Engineering*, 122:84–96, aug 2016. ISSN 00298018. doi: 10.1016/j.oceaneng.2016.04.031.

[133] Henry Schwartz, Magnus Gustafsson, and Jonas Spohr. Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? *Journal of Cleaner Production*, 254:120069, may 2020. ISSN 09596526. doi: 10.1016/j.jclepro.2020.120069.

[134] Ivo Senjanović, Nikola Vladimir, Marko Tomić, Neven Hadžić, and Šime Malenica. Global hydroelastic analysis of ultra large container ships by improved beam structural model. *International Journal of Naval Architecture and Ocean Engineering*, 6(4):1041–1063, 2014. ISSN 20926790. doi: 10.2478/IJNAOE-2013-0230.

[135] S. S. Shapiro and M. B. Wilk. An analysis of variance test for normality (complete samples). *Biometrika*, 52(3/4):591–611, 1965. ISSN 00063444. URL http://www.jstor.org/stable/2333709.

[136] Amir Sharafian, Paul Blomerus, and Walter Mérida. Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. *Energy Policy*, 131:332 – 346, 2019. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2019.05.015. URL http://www.sciencedirect.com/science/article/pii/S0301421519303118.

[137] David Sheppard, Myles McCormick, Anjli Raval, Derek Brower, and Hudson Lockett. Us oil price below zero for first time in history. *Financial Times*, apr 2020. URL https://www.ft.com/content/a5292644-958d-4065-92e8-ace55d766654.

[138] T. W. P. Smith, J. P. Jalkanen, B. A. Anderson, J. J. Corbett, J. Faber, S. Hanayama, E. O'Keeffe, S. Parker, L. Johansson, L. Aldous, C. Raucci, M. Traut, S. Ettinger, D. Nelissen, D. S. Lee, S. Ng, A. Agrawal, J. J. Winebrake, M. Hoen, S. Chesworth, and A Pandey. Third imo ghg study 2014. Technical report, International Maritime Organisation, London, UK, apr 2014.

[139] Tristan Smith, Paul Newton, Graeme Winn, and Andrea Grech La Rosa. Analysis techniques for evaluating the fuel savings associated with wind assistance. In *Low Carbon Shipping Conference*, London, sep 2013. UCL.

[140] S. Solomon, M. Manning D. Qin, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Climate change 2007: Synthesis report. Technical report, IPCC, Geneva, Switzerland, 2007. URL https://www.ipcc.ch/report/ar4/syr/.

[141] Statista. Liquefied petroleum gas (lpg) price in the netherlands from 2009 to 2019 (in euro cents per liter)*, sep 2019. URL https://www.statista.com/statistics/658367/liquefied-petroleum-gas-price-in-the-netherlands/#:~:text=Concerning%20the%20price%20of%20LPG,again%20to%20approximately%2062.6%20cents.

[142] Laurence Stevens, Christa Sys, Thierry Vanelslander, and Edwin van Hassel. Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies? *Research in Transportation Business and Management*, 17:14–25, dec 2015. ISSN 22105395. doi: 10.1016/j.rtbm.2015.10.003.

[143] *Rules of Navigation*. Suez Canal Authority, El-Shaheed Abd El-Moneim Riad Rd, Al Temsah, Al Ismailia, Ismailia Governorate, Egypt, aug 2015. URL https://www.suezcanal.gov.eg/English/Navigation/Pages/RulesOfNavigation.aspx.

[144] Robert J. Szczerba. 15 Worst Tech Predictions Of All Time. *Forbes*, jan 2015. URL https://www.forbes.com/sites/robertszczerba/2015/01/05/15-worst-tech-predictions-of-all-time/#7586fa901299.

[145] Zafer Tas. The advantages and disadvantages of ultra-large container ships, jan 2018. URL https://www.morethanshipping.com/advantages-disadvantages-ultra-large-container-ships/.

[146] T&E. Statistical analysis of the energy efficiency performance (eedi) of new ships. Technical report, Transport & Environment, oct 2017. URL https://www.transportenvironment.org/publications/statistical-analysis-energy-efficiency-performance-eedi-new-ships.

[147] Helen Thanopoulou and Siri Pettersen Strandenes. A theoretical framework for analysing long-term uncertainty in shipping. *Case Studies on Transport Policy*, 5(2):325–331, jun 2017. ISSN 22136258. doi: 10.1016/j.cstp.2017.03.008.

[148] Engineering ToolBox. Fuels - higher and lower calorific values, 2003. URL https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html.

[149] Engineering ToolBox. Combustion of fuels - carbon dioxide emission, 2009. URL https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html.

[150] Tien Anh Tran. Calculation and Assessing the EEDI Index in the Field of Ship Energy for M/V Jules Garnier. *Marine Science : Research & Development*, 6(212), 2016. doi: 10.4172/2155-9910.1000.

[151] UNFCCC. What is the United Nations Framework Convention on Climate Change?, 2020. URL https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change.

[152] Seb van den Berg. Low carbon shipping: A decision support tool for the implementation of co2 reducing measures. Master's thesis, TU Delft, nov 2018. URL http://resolver.tudelft.nl/uuid:b758d9f7-63a0-4ba0-ba97-d7345f46a38e.

[153] Zheng Wan, Abdel el Makhloufi, Yang Chen, and Jiayuan Tang. Decarbonizing the international shipping industry: Solutions and policy recommendations. *Marine Pollution Bulletin*, 126:428–435, jan 2018. ISSN 18793363. doi: 10.1016/j.marpolbul.2017.11.064.

[154] David G.M. Watson. Chapter 19 operational economics. In *Practical Ship Design*, volume 1 of *Elsevier Ocean Engineering Series*, pages 491 – 510. Elsevier, 1998. doi: https://doi.org/10.1016/S1571-9952(98)80021-4. URL http://www.sciencedirect.com/science/article/pii/S1571995298800214.

[155] David G.M. Watson. Chapter 3: The design equations. In *Practical Ship Design*, volume 1 of *Elsevier Ocean Engineering Series*, pages 55 – 79. Elsevier, 1998. doi: https://doi.org/10.1016/S1571-9952(98)80005-6. URL http://www.sciencedirect.com/science/article/pii/S1571995298800056.

[156] Wilhelmsen. Suez toll calculator, 2020. URL https://www.wilhelmsen.com/tollcalculators/suez-toll-calculator/.

[157] Allan H. Willet. *The Economic Theory of Risk and Insurance*. The Columbia University Press, New York, 1901. URL https://lccn.loc.gov/04002585.

[158] WLPGA. Lpg bunkering - guide for lpg marine fuel supply. Technical report, World LPG Association, 2019. URL https://www.wlpga.org/wp-content/uploads/2019/10/LPG-Bunkering-2019.pdf.

A
General

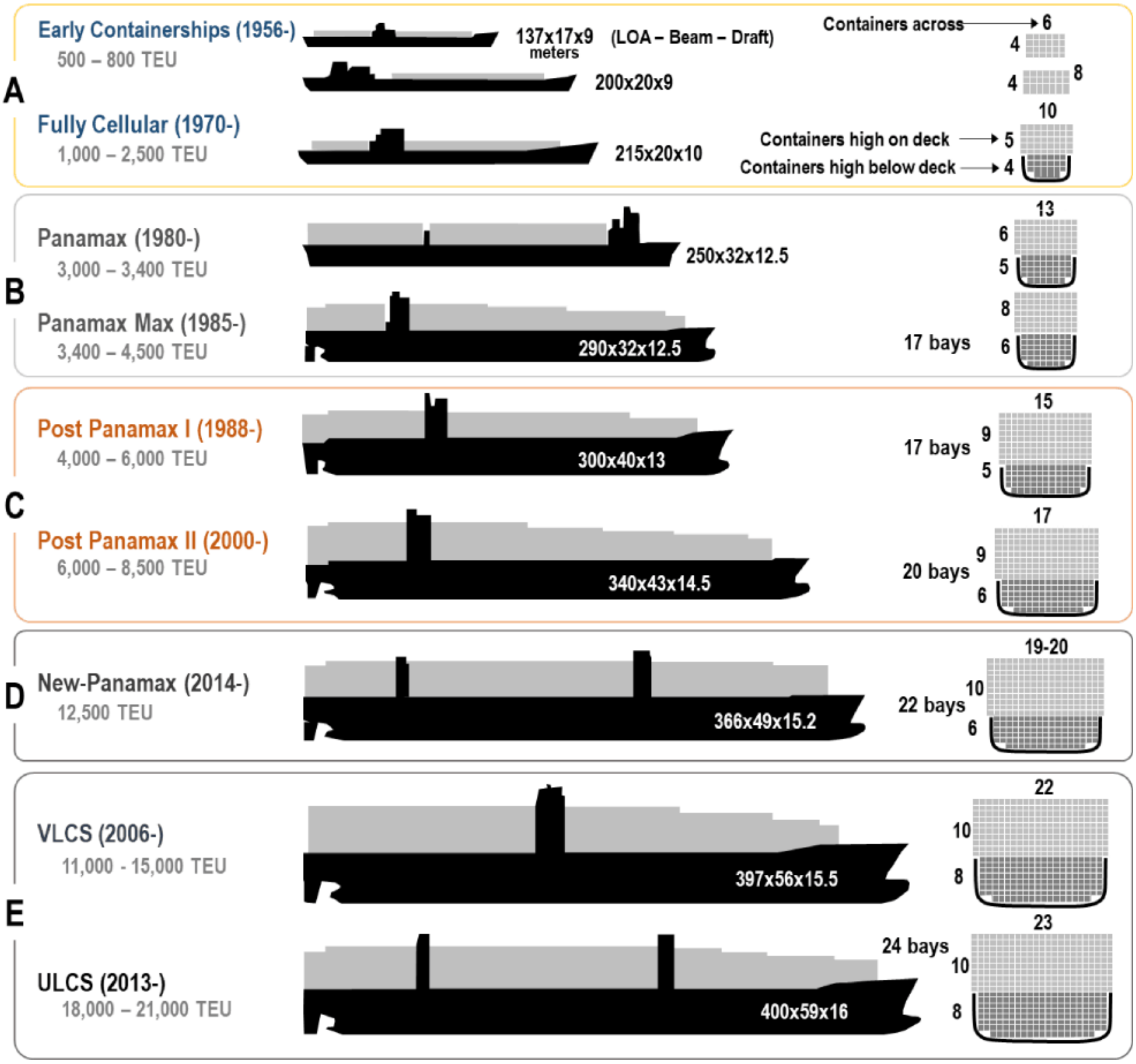


Figure A.1: Evolution of container ships [128]

Table A.1: A selection of ULCVs [107]

Ship Name	DWT [t]	TEU	Engine Power [kW]
CMA CGM Jean Mermoz	199855	20954	67430
Manchester Maersk	190300	20568	62000
Ever Goods	218000	20388	59250
MOL Tribute	197106	20170	75570
Tihama	199744	19870	61000
MSC Tina	198700	19437	75570
COSCO Shipping Scorpio	197500	19273	67100
MSC Maya	199272	19224	62500
CSCL Indian Ocean	184000	18980	56800
Mathilde Maersk	196000	18340	65360
Mette Maersk	194829	18270	52620
CMA CGM Zheng He	185000	17859	63910
MSC Diana	202036	17590	75570
CMA CGM Vasco De Gama	184700	16872	63910
MSC Istanbul	186700	16652	53250
Ebba Maersk	158200	15500	80800
CMA CGM Mexico	147966	15128	68640
Al Jasrah	149360	15000	54900
Salahuddin	150000	14993	54900
COSCO Himalayas	153811	14568	49000
Triton	153520	14354	63910
CSCL Star	165300	14074	72240
ONE Columba	139500	14052	58040
MSC Alexandra	165300	14000	72240
CSCL Venus	165300	14000	73181
APL Raffles	150100	14000	63910
Madrid Bridge	146778	14000	48900
Average	176995	16967	63796
Median	184700	16872	63910

Table A.2: Results of Fuel A

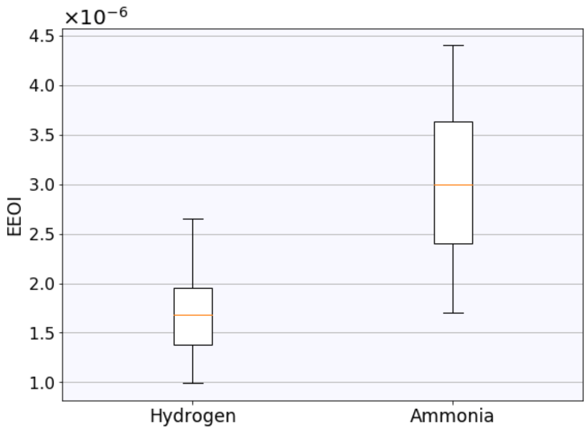
Trips	20				15				10			
Fuel Price [USD/uE]	140	150	160	170	140	150	160	170	140	150	160	170
Cargo Capacity [TEU]	21000	21000	21000	21000	21000	21000	21000	21000	21000	21000	21000	21000
Fuel Consumption [uE]	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
Freight Rate [USD/TEU]	80	80	80	80	80	80	80	80	80	80	80	80
OPEX [USD]	28000000	30000000	32000000	34000000	21000000	22500000	24000000	25500000	14000000	15000000	16000000	17000000
Income [USD]	33600000	33600000	33600000	33600000	25200000	25200000	25200000	25200000	16800000	16800000	16800000	16800000
Profit [USD]	5600000	3600000	1600000	-400000	4200000	2700000	1200000	-300000	2800000	1800000	800000	-200000
Emission rate [uM/uE]	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total Emissions [uM]	140000	140000	140000	140000	105000	105000	105000	105000	70000	70000	70000	70000

Table A.3: Results of Fuel B

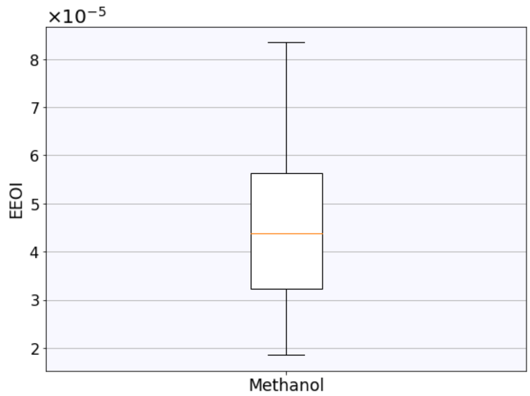
Trips	20				15				10			
Fuel Price [USD/uE]	110	120	130	140	110	120	130	140	110	120	130	140
Cargo Capacity [TEU]	17000	17000	17000	17000	17000	17000	17000	17000	17000	17000	17000	17000
Fuel Consumption [uE]	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
Freight Rate [USD/TEU]	80	80	80	80	80	80	80	80	80	80	80	80
OPEX [USD]	22000000	24000000	26000000	28000000	16500000	18000000	19500000	21000000	11000000	12000000	13000000	14000000
Income [USD]	27200000	27200000	27200000	27200000	20400000	20400000	20400000	20400000	13600000	13600000	13600000	13600000
Profit [USD]	5200000	3200000	1200000	-800000	3900000	2400000	900000	-600000	2600000	1600000	600000	-400000
Emission rate [uM/uE]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total Emissions [uM]	100000	100000	100000	100000	75000	75000	75000	75000	50000	50000	50000	50000

B

Results of the Cases



(a) Box plot of EEOI for hydrogen and ammonia



(b) Box plot of EEOI for methanol

Figure B.1: EEOI of methanol, hydrogen, and ammonia in Case 1 with 50%, 60%, and 70% fuel prices

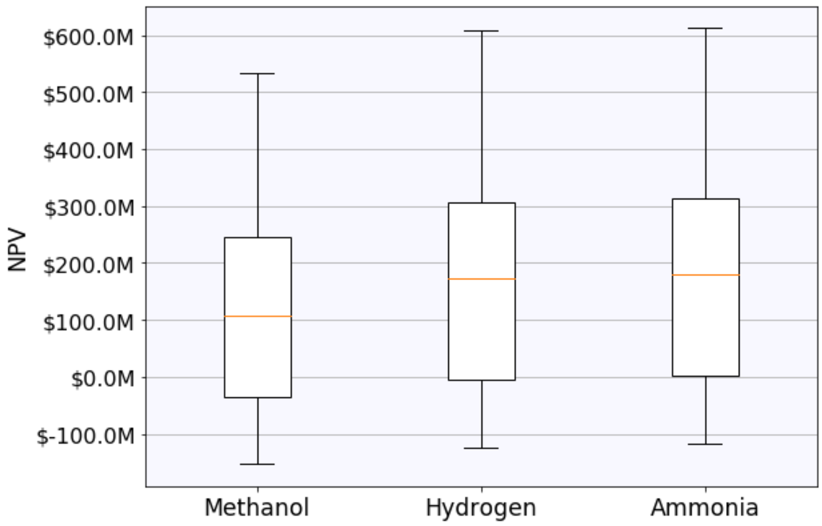
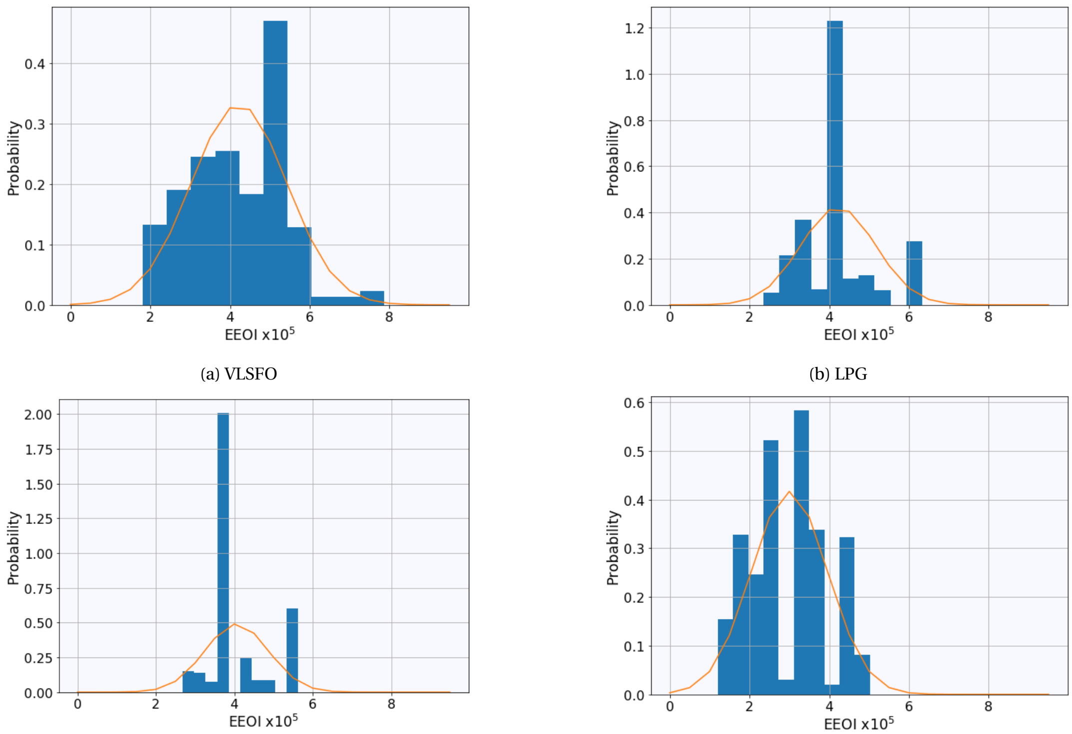


Figure B.2: NPV of methanol, hydrogen, and ammonia in Case 1 with 50%, 60%, and 70% fuel prices



(a) VLSFO

(b) LPG

(c) LNG

(d) Methanol

Figure B.3: Histograms of the hydro-carbon fuels with fitted normal distributions

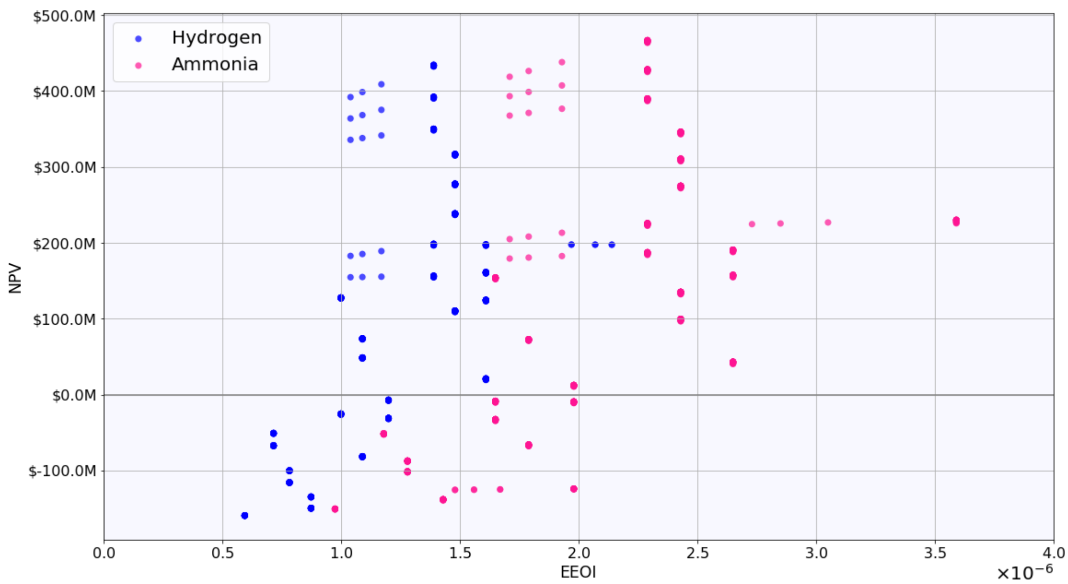


Figure B.4: Results of all ships using non-carbon fuels in Case II

Table B.1: Main results of Case II

Fuel Type	Condition	Parameter	Median	Average	Minimum	Maximum
VLSFO	Before Policy	Speed [kn]	14.96	13.95	8.46	17.44
		Number of Trips	8	7.33	5	9
		Annual Cashflow	$ 12,546,169.00	$ 13,092,910.56	$ -185,174.00	$ 31,482,911.00
	After Policy	Speed [kn]	13.48	13.19	8.46	17.44
		Number of Trips	7	7.01	5	9
		Annual Cashflow	$ 11,282,024.50	$ 12,085,027.94	$ -1,030,407.00	$ 31,482,911.00
	-	EEOI	4.32857E-05	4.2266E-05	1.81104E-05	7.86778E-05
	-	NPV	$ 84,844,929.00	$ 93,818,676.77	$ -166,611,642.00	$ 466,519,635.00
LPG	Before Policy	Speed [kn]	15.53	15.64	12.65	17.44
		Number of Trips	8	8.04	7	9
		Annual Cashflow	$ 16,125,182.00	$ 16,299,292.41	$ 1,449,953.00	$ 34,482,722.00
	After Policy	Speed [kn]	15.53	14.96	10.49	17.44
		Number of Trips	8	7.76	6	9
		Annual Cashflow	$ 14,987,146.00	$ 15,111,838.39	$ 83,886.00	$ 34,482,722.00
	-	EEOI	4.04531E-05	4.22517E-05	2.35127E-05	6.32828E-05
	-	NPV	$ 148,602,823.00	$ 153,983,755.44	$ -143,845,560.00	$ 525,086,315.00
LNG	Before Policy	Speed [kn]	16.08	16.13	14.92	17.39
		Number of Trips	8	8.26	8	9
		Annual Cashflow	$ 17,876,763.00	$ 18,212,611.07	$ 3,074,340.00	$ 35,802,436.00
	After Policy	Speed [kn]	15.48	15.63	12.62	17.39
		Number of Trips	8	8.06	7	9
		Annual Cashflow	$ 17,101,428.00	$ 16,957,764.08	$ 1,129,620.00	$ 35,802,436.00
	-	EEOI	3.81489E-05	4.06179E-05	2.68425E-05	5.63385E-05
	-	NPV	$ 186,256,885.00	$ 190,938,161.82	$ -121,792,221.00	$ 551,365,201.00
Methanol	Before Policy	Speed [kn]	12.65	12.30	8.46	16.14
		Number of Trips	7	6.63	5	8
		Annual Cashflow	$ 10,272,939.00	$ 10,832,992.89	$ -1,014,944.00	$ 28,531,615.00
	After Policy	Speed [kn]	12.65	11.83	6.56	16.14
		Number of Trips	7	6.43	4	8
		Annual Cashflow	$ 9,563,605.00	$ 10,186,759.59	$ -1,514,700.00	$ 28,531,615.00
	-	EEOI	3.13291E-05	3.00082E-05	1.2136E-05	5.01931E-05
	-	NPV	$ 45,438,208.00	$ 54,600,411.03	$ -176,737,480.00	$ 408,900,136.00
Hydrogen	Before Policy	Speed [kn]	13.4	13.53	8.44	16.03
		Number of Trips	7	7.19	5	8
		Annual Cashflow	$ 11,319,274.00	$ 11,911,479.00	$ -628,550.00	$ 29,777,042.00
	After Policy	Speed [kn]	13.4	13.48	8.44	17.34
		Number of Trips	7	7.17	5	9
		Annual Cashflow	$ 11,306,043.00	$ 11,847,535.04	$ -651,609.00	$ 29,777,042.00
	-	EEOI	1.2046E-06	1.19332E-06	5.95319E-07	2.13624E-06
	-	NPV	$ 73,912,483.00	$ 84,607,437.17	$ -159,755,760.00	$ 434,271,913.00
Ammonia	Before Policy	Speed [kn]	14.96	13.95	8.46	17.44
		Number of Trips	8	7.33	5	9
		Annual Cashflow	$ 12,691,955.00	$ 13,197,757.07	$ -126,793.00	$ 31,503,996.00
	After Policy	Speed [kn]	13.48	13.83	8.46	17.44
		Number of Trips	7	7.28	5	9
		Annual Cashflow	$ 12,657,370.50	$ 13,098,730.12	$ -165,392.00	$ 31,503,996.00
	-	EEOI	1.97675E-06	2.0429E-06	9.74599E-07	3.59301E-06
	-	NPV	$ 99,655,224.00	$ 108,187,649.27	$ -151,289,689.00	$ 466,931,287.00
IFO380	Before Policy	Speed [kn]	15.53	15.64	12.65	17.44
		Number of Trips	8	8.04	7	9
		Annual Cashflow	$ 16,500,786.00	$ 16,681,049.04	$ 1,732,064.00	$ 34,891,682.00
	After Policy	Speed [kn]	15.53	14.87	10.49	17.44
		Number of Trips	8	7.72	6	9
		Annual Cashflow	$ 15,341,674.00	$ 15,243,115.02	$ 21,592.00	$ 34,891,682.00
	-	EEOI	5.02191E-05	5.20379E-05	2.67281E-05	7.86778E-05
	-	NPV	$ 151,386,897.00	$ 158,041,028.04	$ -144,393,071.00	$ 533,070,627.00