Decision Support Tool for Maritime Decarbonisation

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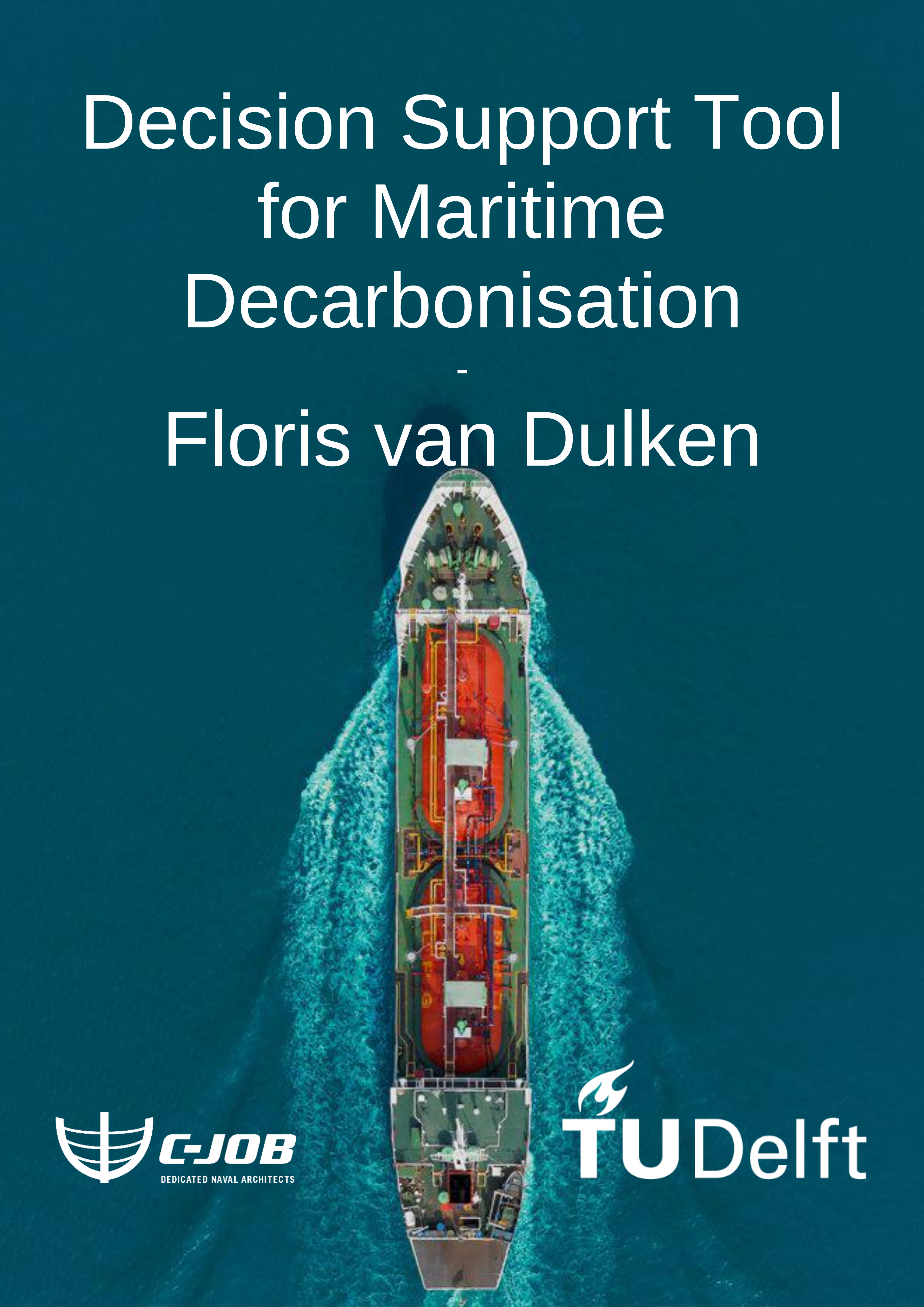

Decision Support Tool for Maritime Decarbonisation

By

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Preface

When I started in 2015 with a bachelor of Maritime Technology in Delft, I did not have much interest in sustainability. However, over the years of my study, I learned the effect of climate change and the share that my discipline contributes to problems. So, when I got the chance to do my final research on a subject to counter the emissions of greenhouse gasses, I was immediately enthusiastic. I firmly believe that the shipping industry can become carbon-neutral before the effects of climate change are catastrophic. I hope that, even in the slightest way possible, the study will contribute to a cleaner and better world in the years to come.

I want to thank my supervisor, Edwin. Your support throughout the process and the insights and help you gave during our meetings always got me back on track when I was stuck. All my colleagues at C-Job also deserve a big thanks for the support, help and coffee throughout the year. I especially want to thank Jelle for the weekly meetings where I could always bounce my ideas off you. I want to thank all the friends I have made during my almost eight years in Delft; you all made my time here unforgettable. A special thanks to my roommates, who were always there for advice during my thesis, asked and unasked. Lastly, I want to thank my parents for always supporting and believing in me, which has brought me to this point.

Floris van Dulken
Delft, January 2023

Abstract

With the current focus on climate change, the shipping industry is forced to decarbonise its fleet. The need for decarbonisation is not only fuelled by the aspirations of the sector but also by laws and regulations from countries and organisations. As these laws are gradually tightening and there is not one clear technical or operational solution, there is a need for a strategy to combine multiple operational and technical solutions. These solutions, as well as other aspects, are associated with risks and uncertainties, such as fuel prices, technical aspects and cost. To help the decision makers in this field, this research aims to present a method that can be used as the basis for a decision making tool. The method will mainly focus on finding the lowest total cost per tonne mile but will also consider other aspects that are found to be necessary, such as safety and technological readiness. The difficulty in the decision is the number of factors that could influence the decarbonisation of the vessel and how these aspects influence each other. The addition of CRSs (Carbon Reduction Systems) will affect the operation profile of the vessel and, with that, the fuel use of the vessel. With fuel being one of the main expenses of ships, fuel use will affect the total cost of the vessel. The method will combine several different analyses to consider all aspects and risks. The strategy will be created by adding CRSs every time the vessel does not comply with the regulations anymore, affecting the vessel's operational profile and fuel use. The cost of fuel use, and other OPEX, will be evaluated with an NPC (Net Present Cost) analysis to compare costs in time. These costs will then be entered into an MCA (Multi Criteria Analysis) and combined with the other criteria, such as safety and technological readiness level, leading to a strategy selection. To increase the method's robustness, the whole set of calculations will also be subjected to a Monte Carlo simulation to mitigate the risks that concern future inputs. The method was translated into a model where a case study was carried out to validate the method and to find some early insights. From this came the result that the method creates valid answers and that there is one method that is the most cost-effective manner to comply with the regulations. This is plainly sailing slower; it has almost no expense and significantly reduces the cost of shipping.

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Nomenclature

AHP	Analytic Hierarchy Process
CBA	Cost-Benefit Analysis
CCD	Carbon Capturing Device
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CII	Carbon Intensity Indicator
CRS	Carbon Reduction Solutions
CRS	Carbon Reduction System
DCS	Data Collection System
DWT	Deadweight Tonnage
ECA	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEIO	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EIV	Estimated Index Value
EPL	Engine Power Limitation
ESD	Energy Saving Devices
ETS	European Trading System
EU	European Union
FAME	Fatty Acid Methyl Ester
FR	Flettner Rotor
GHG	Green House Gasses
GT	Gross Tonnage
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
ICS	International Council of Shipping
IMO	International Maritime Organisation
IRR	Internal Rate of Return
LBG	Liquid Bio Gas

LNG	Liquid Natural Gas
MCA	Multi Criteria Analysis
MCDM	Multi Criteria Decision Making
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MRV	Monitor, Report & Verify
NPC	Net Present Cost
NPV	Net Present Value
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SWOT	Strengths, Weaknesses, Opportunities & Threats
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
VLSFO	Very Low Sulphur Fuel Oil
WASP	Wind Assisted Ship Propulsion
WPM	Weighted Product Model
WSM	Weighted Sum Model

Chapter 1

Introduction

Carbon emissions are one of the significant problems of this time due to their negative impact on the climate, and reducing carbon emissions is becoming increasingly important in the world. Because the shipping industry still heavily relies on carbon-based fuels, it is an industry where there is still a lot of room for improvement. The industry is now responsible for 3% of the annual global greenhouse gas emissions in terms of CO_2. [77] Fortunately, governments and organisations, such as the IMO, are already implementing rules that force ships to reduce their carbon emissions. These rules include the EEXI, EEDI and CII, and voluntary measures such as the SEEMP. These rules force the owners, builders, managers and charterers to implement different solutions to monitor and reduce their carbon emissions. These solutions will require investments, of which the stakeholders are unclear about what investments have the desired impact on the fleet. Decarbonisation investments can range from methods that increase the ship's efficiency and different operational profile to alternative fuels, vessel scrapping, and new building. Combining or implementing other solutions on various fleet vessels is possible. Therefore, a method must be created that helps the stakeholders to choose from all the solutions available and make a clear plan for future investments.

At this point, the IMO aims for a 50% reduction in 2050 relative to 2008 [72], and it can be expected that, due to new rules, this point will be sooner in the future. In the long run, it can also be expected that shipping ultimately should have a (near) 0% emission of carbon. The decarbonisation of the shipping industry is associated with a lot of uncertainties. These uncertainties are not only limited to rules and regulations in the far future but also rules and regulations in a short time. This is the case for the CII and EEXI, which are planned to come into effect in 2023, but at this point, some precise details of these regulations are still unknown. This leads to the other problem for the stakeholders: some uncertainty about the rules to come. This means uncertainty about which strategy to choose and, thus, which investments to make.

There are already several CRSs (Carbon Reduction Systems) available that can roughly be divided into two groups, CRSs that reduce carbon emission by reducing the demand for energy per freight unit or CRS that reduce the emission by eliminating the use of carbon (based fuels). However, there are also possibilities to combine these CRSs because, at this point, almost all the carbon-free fuels, and fuels that act carbon-free, still produce carbon somewhere in their supply chain. It is also important to mention that the CRSs can interact, be complementary, opposing or interchangeable. This leads to a further in-depth analysis of different technical CRS' impacts and interactions between those technical CRS. All these technicalities and impacts of (future) laws and regulations make it hard to get a clear economic view, which is cost-efficient and future-proof, of the desired investments to comply with those laws and regulations.

1.1 Goal

The main goal of this research is to create and get insight into a method which can help make decisions about the decarbonisation of ships. The method will be designed to help stakeholders make decisions on how to decarbonise vessels with low extra costs or even with CRSs that pay back their CAPEX by decreasing the OPEX of the vessel. The stakeholders that require this information will mainly be shipowners, who ultimately make the decisions concerning the vessels. However, builders and designers could also benefit from this tool when designing, building and retrofitting new and existing ships.

To create the method, this research aims to find a clear view of what sorts of CRSs can be used to decarbonise the emission of vessels. This is to see how they impact the vessel and, thus, how they should be implemented in the method. To use the insights found in this literature research, a method shall be developed to help the stakeholder make an informed decision about what CRSs should be implemented and when and in what order they should be implemented. This could help design aspects of the vessel to implement the CRSs more efficiently when the time comes to add a specific CRS. The CRSs will only be added when the ship does not comply with the regulations anymore, so these will fall together with years when the regulations will tighten. The regulations are legal restrictions that must be adhered to. To comply with these regulations, there is a need for CRSs, so for this to happen, it should become clear what CRS would be ideally used.

It should also become clear what regulations there are and which are expected to come into effect shortly. What regulations may be expected in the future should also be taken into account, which applies to other variables, such as technical developments, and oil prices, that also have to be predicted. So the known knowns, unknown knowns, known unknowns and unknown unknowns should be found. The associated risks of faults due to these uncertainties should be mitigated. At this point, there is still a lot unknown about the coming regulations, the working and effectiveness of the CRSs and other (financial) aspects. So, the research must present the risks and uncertainties associated with CRSs and regulations. The risk associated with the CRSs is primarily the cost and the effectiveness. Risks related to the regulations are tightening existing and new regulations, which may not even impact the decarbonisation aspect but could limit the CRSs and operations in other elements. These risks concerning the regulations can mostly be seen as known unknowns.

There are also already some methods that are translated into a tool to help with decision making. This method should be more complete, and from that, a tool should be developed to test, get insight, and validate the proposed method. That tool will focus on complying with the regulations as cost-effective as possible. The tool will help the decision-making process and should reflect that in the inputs and outputs. So, the tool will not give a definitive answer but will be used as a decision support tool.

1.2 Research Question

The main research question is as follows:

'What method can be used to support deciding the most cost-effective strategy for a vessel to comply with decarbonisation regulations whilst including more requirements than existing methods'

To answer this question, there are several sub-questions:

- *'What are the relevant regulations concerning the decarbonisation of vessels?'*
- *'What are the relevant decarbonisation solutions, how do they affect the vessel's operations, and with what cost are they associated?'*
- *'What decision support methods are there, and what addition would the proposed method bring?'*

1.3 Structure

The structure of the report follows the form of the research. First, the study into the relevant regulations and CRSs were performed, and then the methods to perform the necessary analysis and the existing methods and tools. Then the model's design will be explained, and what analyses are part of the model. After that, the essential data is collected, preliminary analyses are carried out, followed by the creation of the model and the simulations of the case study. This report follows that same structure, and it will begin in chapter 2 with the relevant regulations, the CRSs and the analysis methods. This will be followed by the scope and research gap in chapter 3, which is followed by chapter 4, in which the model is presented. After that is chapter 5 with the SWOT analysis of the CRSs, and then the used data for the case study is presented in chapter 6. The results of the case study simulations are discussed in chapter 7, followed by the conclusions in chapter 8. Lastly, the report is fished with discussion and recommendations.

Chapter 2

Literature & Background

This chapter will cover the literature study of this research and the background for the research that follows. It will first discuss the regulations concerning decarbonisation, the regulations already in effect and the ones yet to come. Then it will select what regulations are relevant for this research and will be used in the method. Next, this chapter will discuss the CRSs (Carbon Reduction Systems) that could be used to decarbonise vessels. It will discuss how they work and how they could be used. Here the report will present what CRSs have been chosen to be included in the model. This will be followed by the methods that could be used for the analysis that will have to be carried out in this research. It will also show the methods chosen to be included in the model. Lastly, this chapter presents what tools and methods are already available.

2.1 Laws & Regulations for Decarbonisation

Several regulations aim to reduce carbon emissions in the shipping industry. The IMO (International Maritime Organisation) introduced most of these regulations. There are already some regulations in effect, the EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan), and some will come into effect shortly, [36] EEXI (Energy Efficiency Existing Ship Index) and CII (Carbon Intensity Indicator). These regulations have different ways to ensure that the total amount of carbon produced by shipping will decrease. The IMO also has regulations concerning the emission of NO_x and SO_x, such as the ECA (Emission Control Area). These regulations impact what fuel vessels use and thus the emission of CO_2. The Marine Environment Protection Committee (MEPC) developed the regulations concerning reducing carbon emissions. They are additions to the MARPOL (International Convention for the Prevention of Pollution from Ships) convention. The IMO is not the only institute that is implementing regulations. As a sizeable regulatory body, the EU has also introduced some regulations. At this moment, there is the MRV, and other regulations are expected to follow soon. This section aims to present the relevant regulations that will be used for this method. The order of regulations is, firstly, the regulations set by the IMO that are already in effect or will come into effect soon. Then the EU regulations are discussed, which will go into effect soon or can come into effect shortly. Lastly, other regulations that could be interesting will be presented.

2.1.1 EEDI - Energy Efficiency Design Index

The EEDI is a theoretical calculation that uses the design aspects of the vessel; it does not use the operational aspects of the vessel. The IMO introduced the EEDI in 2011 [99] to reduce climate change in the shipping industry. The EEDI focuses on promoting less polluting engines and machinery on vessels. The EEDI is mandatory for new build vessels with over 400 GT [9], or vessel that undergo significant rebuild and requires a minimum energy efficiency level per capacity mile. For each type of ship, there is a specific reference line that decreases every five years; that line is the specific required EEDI for that vessel. This started with a 10% in reduction from 2015 to 2019 and will rise to a decrease of 30% in 2025 and onwards.

The specific calculations require different information about the vessel, such as design speed, fuel type, installed power and more variables. [101, 103, 104] Formula 2.1 shows how the EEDI for a specific ship is calculated, and table 2.1 shows the definitions. The C_F is the conversion factor between the fuel consumption and the CO_2 emission, for which the values can be found in appendix A in table A.1. V_{ref} is the ship speed for normal conditions for the defined total power of the main engines. The capacity is the DWT of the vessel, except for passenger vessels, where it is the GT. P_{ME} is the power of the main engine, P_{PTO} and P_{PTI} are the power of the power take-off and power take-in, respectively. P_{AE} is the power used for the auxiliary engines and P_{AEeff} is the reduction achieved on these engines. The P_{eff} is the output of innovative mechanical energy-efficient technology, such as propulsion power supplied by WASP technology.

The f symbols are all factors used for specific situations or vessels. f_j is a factor for specific ships and could be a factor for ice class, shuttle tankers, ro-ro vessels or general cargo. The f_w factor is used for the speed reduction at sea due to weather. In contrast, the f_i factor is the capacity factor, which could be used for ice-classed ships and vessels with a specific voluntary structural enhancement. The cubic capacity factor f_c is mainly used for chemical tankers and gas carriers. f_l is the factor for general cargo vessels' cranes and other cargo-related gear. $f_{eff(i)}$ is the availability factor of energy efficient solutions, which is 1.0 for solutions that can be used the whole time, like waste heat recovery, and lower than 1.0 for solutions that cannot be used the whole time, like WASP. [71] Lastly is f_m which is a factor for ice-classed ships.

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

Symbol	Definition
C_F	Conversion factor
V_{ref}	Ship speed
Capacity	Cargo capacity (DWT or GT, depends on ship type)
P_{ME}	Power of main engines
P_{PTO}	Power Take Off
P_{PTI}	Power Take In
P_{eff}	Output of innovative mechanical energy efficient technology
P_{AEeff}	Auxiliary power reduction
P_{AE}	Power of auxiliary engines
SFC	Specific fuel consumption
f_j	Correction factor for ship-specific design elements
f_w	Weather factor
f_i	Capacity factor
f_c	Cubic capacity correction factor
f_{eff}	Availability factor of innovative energy
f_m	Ice class factor
f_l	Factor for general cargo vessels

Table 2.1: Definitions of symbols in the EEDI Formula

The result of the formula 2.1 is the "Attained EEDI", which should be lower than the "Required EEDI", which is shown in formula 2.2 [99], in which X is the reduction factor. The reduction factor is a value that increases over time, which ensures that vessels emit less carbon over time. The reduction factor can be found in the appendix A in table A.3. The reference line is calculated with formula 2.3 [99], where a and c are values specific for the ship type and b is the DWT of the ship. The values for the reverence line can be found in appendix A in table A.2.

$$\text{Attained EEDI } \leqq \text{ Required EEDI } = (1 - X/100) \times \text{ Reference line value} \tag{2.2}$$

$$\text{Reference line value} = a \cdot b^{-c} \tag{2.3}$$

The variables from table 2.1 can be determined with data from the vessel and formulas from the MEPC. For example, the $P_{ME(i)}$ that is used in the EEDI equations is defined as 75% of the MCR for one engine. [103] However, some data to calculate the EEDI can only be measured with sea trials, so the EIV (Estimated Index Value) was introduced, as seen in formula 2.4. [51, 100] The EIV is higher on average than the EEDI, so this means that the vessels are, in general, more efficient than the EIV shows.

$$\text{Estimated Index Value } = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{\text{Capacity } \cdot V_{ref}} \tag{2.4}$$

To simplify the EEDI in the model, the EIV could be used. The EEDI would be closer to reality, but the EIV would be easier to calculate, which would decrease the complexity of the model and reduce the run time.

2.1.2 EEXI - Energy Efficiency Existing Ship Index

The EEXI is an Energy Efficiency Index for existing ships and is based on the EEDI. It can be calculated in the same way, with formula 2.1, 2.2 and 2.3, as the EEDI. The EEXI can be seen as the sister of the EEDI, where the EEDI is for new vessels the EEXI is for existing vessels. This means that vessels that did not fall under the EEDI regulations have to comply with the EEXI. Vessels only must comply once in their lifetime with the EEXI or the EEDI. [36] The EEXI will come into effect in 2023 and thus practically all vessels will have to comply with these regulations from then on. [79] Because the restrictions on carbon emissions have become stricter, it is estimated that most of the older vessels do not comply, and Simpson Spence Young even estimates that less than 25% of the bulk carriers and tankers comply with the EEXI. [146] The values for the reduction factor for the EEXI are slightly different from the ones from the EEDI and are shown in appendix A in table A.4. The EEXI is can be seen as an energy cap and will thus be suitable to use in the research as the energy cap.

2.1.3 CII - Carbon Intensity Indicator

The CII is the Carbon Intensity Indicator, which calculates the amount of carbon emitted in terms of transport. In contrast with the EEDI and the EEXI, the CII is calculated with operational data and gives an insight into the carbon emissions in an operational profile. These will result in a score from A to E, where A is the highest, C is average and E is the lowest score. When a vessel scores an E one year or a D three years in a row, it is required to turn in a plan to score at least a C. The IMO aims with the CII for an annual reduction of carbon of 1% from 2018 till 2023, 2% from 2023 till 2026 and an open amount till 2030. [169] The CII is mandatory for vessels of a GT higher than 5000 GT. [9]
The attained CII can be calculated with the formula 2.5. Where the definitions of M and W are presented in formula 2.6 and 2.7, respectively. [105]

$$attained\, CII_{ship} = \frac{M}{W} \tag{2.5}$$

$$M = FC_j \times C_{Fj} \tag{2.6}$$

$$W_s = C \times D_t \tag{2.7}$$

In these equations the definitions are for M: j is the fuel type, and FC_j is the total mass (in grams) of consumed fuel oil of type j in the calendar year. C_{F_j} is the fuel mass to CO_2 mass conversion factor for fuel type j, this has to be in line with resolution MEPC.308(73). [103] For W_s the definitions are as follows: C represents the capacity and D_t the distance travelled in nm. C should be the DWT for bulk carriers, tankers, container ships, gas carriers, LNG carriers, ro-ro cargo ships, general cargo vessels, reefer vessels and combination carriers. For passenger vessels and ro-ro passenger vessels, the GT should be used.
As with the EEDI/EEXI, the CII has a reference line, of which the formula is presented in equation 2.8, which is the reference line for 2019. [106] The values for the reference line can be found in appendix A in table A.6.

$$CII_{ref} = a \cdot Capacity^{-c} \tag{2.8}$$

The capacity is the same value as used in formula 2.7, and a and c are values specific to the ship type. As with the EEDI/EEXI, the reference line decreases yearly, which can be seen in equation 2.9. The CII_{ref} is the same as in equation 2.8 and is thus gradually reduced with the help of the reduction factor Z. In 2023 Z will be 5% and will increase with 2% till 11% in 2026; values later than 2026 are still being developed by the MEPC. [107]

$$Required\, annual\, operational\, CII = (1 - Z/100) \cdot CII_{ref} \tag{2.9}$$

In contrast with the EEDI/EEXI, the CII reference line is not a hard constraint. The CII is built up of levels A to E, which means that the reference line is in the middle of the C level. To determine the boundaries between the levels, the MEPC has introduced the following formulas in 2.10. The values d_1, d_2, d_3 and d_4 are specific per ship type. [108] The values for the d vectors can be found in appendix A in table A.5.

$$
\begin{aligned}
\text{superior boundary} &= \exp(d_1) \cdot required\, CII \\
\text{lower boundary} &= \exp(d_2) \cdot required\, CII \\
\text{upper boundary} &= \exp(d_3) \cdot required\, CII \\
\text{inferior boundary} &= \exp(d_4) \cdot required\, CII
\end{aligned} \tag{2.10}
$$

It should be noted that according to the MEPC, vessels may achieve an E score one year and a D score three years in a row. This means that the one-year E or three-year D scores are the boundaries created by the CII in the model.
Early in 2022 there were some details of the CII still being developed and discussed within MEPC 78 in June 2022 and have come into effect in November 2022. [74] The formula to calculate the attained CII will change from the combination of equation 2.5, 2.6 and 2.7, to equation 2.11. [9, 144] The definitions of the symbols are shown in table 2.2. The symbols associated with voyage adjustment, $FC_{voyage,j}$ and D_x, are exceptions on the CII. These exceptions will be applied when the safety of the crew and vessel are endangered or when the vessel sails in ice conditions, but only if the vessel is ice classed. The TF_j is associated with ship-to-ship and shuttle transfers. The fuel consumption exclusions are related to the fuel used for operations such as cargo cooling, cargo heating, transfer pump generators and other fuel used for the vessel operation. The f factors are the same as those used by the EEDI/EEXI. These details to the CII are presented by the American Bureau of Shipping and Lloyd's Register. Because these are two highly regarded classification bureaus involved in drafting the regulations, these details will be used to calculate the CII in the model. The CII is, in essence, a cap on the total use of carbon per freight unit, which makes it suitable to represent the carbon cap regulations in the model.

$$
\frac{\sum_j C_{Fj} \cdot \{FC_j - (FC_{voyage,j} + TF_j + (0.75 - 0.03y_i) \cdot (FC_{electrical,j} + FC_{boiler,j} + FC_{others,j}))\}}{f_i \cdot f_m \cdot f_c \cdot f_{iVSE} \cdot \text{ Capacity } \cdot (D_t - D_x) \cdot AF_{PT}} \tag{2.11}
$$

Table 2.2: Definitions of symbols in the new CII Formula

Symbol	**Definition**
C_{Fj}	C_{F_j} is the fuel mass to CO_2 mass conversion factor
FC_j	Total mass of fuel consumption
$FC_{voyage,j}$	Voyage Exclusions
TF_j	ST and STS Tankers Correction Factors
y_i	Year
$FC_{electrical,j}$	Fuel Consumption Exclusions (electric)
$FC_{boiler,j}$	Fuel Consumption Exclusions (boiler)
$FC_{others,j}$	Fuel Consumption Exclusions (other)
f_i	Capacity factor
f_m	Ice class factor
f_c	Cubic correction factor for chemical tankers
f_{iVSE}	Voluntary Structure Enhancement factor
$Capacity$	Cargo capacity (DWT or GT, depends on ship type)
D_t	Distance traveled
D_x	Voyage Exclusions
AF_{PT}	Port Time Correction Factor for Cruise Passenger Ships

2.1.4 SEEMP - Ship Energy Efficiency Management Plan

The SEEMP (Ship Energy Efficiency Management Plan) is used to get more insight into the energy use of the ship. This can be used to reduce the energy needed on the vessel, which then would lead to a decrease in the emission of GHG. The SEEMP is a plan of which measures can be taken with little cost that reduces energy use. It is mandatory to have a SEEMP on board; however, there is no requirement for it to be used. [99] Part of the SEEMP is the EEOI (Energy Efficiency Operational Indicator), which can be used to document the energy use of the vessel during a certain time. [69] The idea is that this insight will help the users of the vessel to reduce their energy use. The CII is also considered part of the CII; however, the vessel has no obligation to use the rest of the measures presented in the SEEMP. So, the SEEMP, excluding the CII, will not be used further in this research, as there is no obligation, the measures are ship specific and are thus difficult to implement in a tool and it is expected that other regulations also reduce the energy use.

2.1.5 EU Regulations

Whereas the IMO issues regulations that are used around the globe, the EU also issues laws and regulations concerning decarbonisation. These regulations are only applicable to vessels that enter the EU. However, the share of global vessels that enter the EU is significant. The regulations also have a significant impact on the global shipping market. In 2019 36.4% of the global DWT was registered to EU owners, [48] with the assumption that most of these vessels enter the EU at some time in their lifetime and that also vessels from non-EU owners enter the EU, it can be seen that EU regulations have a significant impact on the world fleet. At this point in time, only the MRV system is in effect in the EU. However, in the Fit for 55 proposal from the European Committee several other measures were presented. The Fit for 55 proposal is the plan of the EU to reduce the emissions of GHG by 55% in 2030. [38] So, this section will discuss the MRV and other regulations that can be expected in the future from the EU.

MRV - Monitor Report & Verification

The MRV system is called the first step towards the decarbonisation of the shipping industry by the EU. [49] The system requires vessels that sail between harbours inside the union or trips that start or end in the union to monitor their carbon emissions by fuel consumption. [47] It is mandatory for vessels with a GT over 5000 to use the MRV, submit it yearly to a verifier and then submit the verified version to the flagstate and the Commission. The MRV system has been in effect since 2018. [125] The idea is, comparable with the SEEMP, that shipowners get an insight into their fuel use and will take that as an insight to reduce their fuel use. The IMO has a comparable method that falls under the SEEMP, which is called the DCS, which stands for Data Collection System. [102] However, both these regulations are only required to monitor the operation of the vessel and do not, mandatory, influence the operations, so these will not be used in the method.

Regulations in the future

The European Union is working on implementing more regulations concerning the decarbonisation of the maritime industry, and Fit for 55 has presented some measures. The most important proposals include the European Trading System Directive (ETS) and the FuelEU Maritime Regulation. [38] Also, other regulations are presented in the Fit for 55 proposal, but they are less focused on individual ships. One example is the Alternative Fuels Infrastructure Regulation, which focuses on improving the infrastructure for alternative fuels but has less impact on individual vessels.

ETS - European Trading System Directive The European Trading System is already used on land in the European Union. The ETS uses allowances for the right to emit GHG in the EU, which are given or auctioned to companies. When companies have more of these allowances than they need, they can sell these to other companies that have too little. The total amount of allowances decreases, and the prices of the allowances rise every year, which gives the incentive to the industry to produce less harmful gasses. The maritime industry is, at this point, not part of the ETS, whereas heavy industry and electricity producers on land are. [17] One of the proposals in the Fit for 55 package is an introduction of the ETS in the maritime sector. [47] This would mean that shipping companies should have to pay for their emissions of harmful gasses. However, because there is a market for the allowances, the price that must be paid for these emissions is not fixed. This could, in turn lead to more risks for the owner in terms of cost. When this would be a carbon tax, it would mean that it is clear what the cost of emission is. The carbon tax will be discussed in section 2.1.6. When it is introduced, it will most likely focus on the Tank-to-Wake emissions and will start the earliest in 2023. [144]

The FuelEU Maritime Regulation The FuelEU maritime regulation is an initiative that proposes a regulatory framework to increase the use of fuels that are low, or free, of carbon and renewable. This should happen in an integrated way so that no unnecessary barriers are in play for the market. It is designed to keep the playing field level for all the users, and it is fully integrated with the other measures presented in Fit for 55 and the MRV. [46] For the FuelEU Maritime regulations, it is expected that 2025 will be the earliest year for it to come into effect. [144]

2.1.6 Carbon Tax

Already shortly mentioned in section 2.1.5 is a carbon tax. The idea of a carbon tax is to discourage the use of carbon-based fuels and to bridge the gap between these fuels and more 'green' fuels. [135] The carbon tax has not yet been implemented, and although mentioned several times around IMO and EU meetings, no significant plans are made yet. However, it is likely that one of these regulatory bodies will introduce the carbon tax. The EU is already close with indications that it will include the maritime sector into the ETS, even though it is not a fixed price per emission it still creates costs to produce CO_2. Also, the ICS (International Council of Shipping) has suggested a carbon levy. [70] The carbon tax will most likely be introduced as a tax per tonne CO_2 emitted or as a tax on fuel. The prices that are predicted that will be used for the carbon tax range from 25$ per tonne CO_2 to 200$ per tonne CO_2, where just under the 200$ is seen as the minimum to achieve the goal of a 50% reduction in 2050. [128, 129]
Because it is not yet clear at this moment how the carbon tax will be implemented, two options will be provided. The one option is that there comes an (extra) tax on fuel, which will be added to the model as an increase in fuel price. The other option is to tax the amount of carbon emitted, but it is unclear what calculation method should be used for this. The calculation method of the CII for the amount of carbon emitted, as seen in formula 2.6, which presents the mass of carbon emitted per capacity times distance, could be used for this. The chance of a carbon tax, such as the ETS, in the future, is high so it will be included in the model.

2.1.7 Conclusion

There are several regulations that aim to reduce the total emission of carbon in the maritime industry. There are roughly two sorts of regulations, on the one hand, there are regulations that try to make the vessel more efficient, such as the EEDI and EEXI. On the other hand, are regulations that just look at carbon emission, like the CII. The model will include these regulations and regulations that are expected to come into effect. The expected regulations include the extension and thus, the tightening of the existing and new regulations. These regulations will be simplified to a carbon tax, carbon cap and an energy cap. The EEXI/EEDI can be seen as the energy cap and the CII as the carbon cap, so these will be used as the method to implement these regulations in the model. This means that the SEEMP and MRV will be excluded from the research. The dates and percentages will be implemented as inputs that the user could alter. The carbon tax can also be added to the model by the user, which can be done as a tax on fuel or a tax on the amount of carbon emitted.

2.2 Carbon Reduction Systems (CRS)

There are several methods to decarbonise vessels, which all work in their own way. In this research, they will be called CRS, Carbon Reduction Systems. There are roughly two ways to reduce the amount of carbon emitted by the ship. There are methods that reduce the amount of fuel needed to sail the vessel and methods that reduce or eliminate the carbon in the fuel or exhaust. The amount of fuel used can be reduced by reducing the friction of the vessel, sail with a lower speed or more cargo or even using clean propulsion power. The methods that reduce the carbon in the fuel and exhaust are mainly alternative fuels with less or no carbon, such as ammonia or H_2, by capturing the CO_2 exhaust or using electric propulsion. There are also some other methods to reduce or eliminate the emission of CO_2, such as the capturing of carbon and the use of electricity from the grid in port. This section is used to provide information about relevant decarbonisation solutions and to present which ones will be considered in the model.

2.2.1 Energy Efficient Solutions

There are many solutions to make a vessel more energy efficient, from small additions to the hull to complete wind-assisted propulsion systems. However, solutions that have a significant impact are scarce. Potential solutions are, among other things, WASP (Wind Assisted Propulsion Systems), the reduction of speed, the increase of loading and air lubrication. Other options also include solar energy and waste heat recovery, and this section aims to present energy-efficient relevant solutions.

WASP - Wind Assisted Ship Propulsion

Before engines with carbon-based fuels became dominant in the shipping industry, the wind was the main method of propulsion. [30] In current times, the wind is becoming increasingly interesting again. The wind is clean and can be found everywhere on earth and is thus ideal to use for propulsion purposes. However, the wind is not constant and is thus less dependable, where reliability is necessary for the shipping industry. So, for the most viable options at this point, the wind will be used to reduce the need for propulsion power via other mediums and can provide auxiliary power. The different WASP technologies all have different advantages and disadvantages, such as the use of deck space, amount of energy provided and height. This section discusses the different sorts of WASPs and their use.

Flettner Rotor The Flettner rotor (FR), or rotor sail, was introduced in the 1920s by German engineer Anton Flettner and first used on a vessel in 1925. [98] Flettner rotors are large vertical rotating cylinders with an end plate on top. The cylinders are powered by electric engines in the base of the rotor, so the rotors can use the Magnus effect to create lift, which helps with ship propulsion. [96] Due to the Magnus effect, the Flettner rotors work best with a side wind, as shown in figure 2.1. The advantage is that the Flettner rotors can provide lift by a wide range of wind directions, which makes them less dependent on geographical locations and weather conditions. [30] This is important for ship owners because it makes the vessel more flexible in which routes to sail. There are also reports that Flettner rotors can increase the stability of vessels. [96] The Flettner rotors are relatively high and usually higher than the superstructure. This means that the vessel will be restricted in the movement by more bridges or other obstacles, and it will restrict the movements of cranes by loading and unloading. However, Flettner rotors are already developed that can tilt so that the rotor can move to the deck of the ship, which minimises the obstacles presented by the rotor. [170] The Flettner rotor has a high potential to be an energy-saving device that will be used on vessels and will thus be included in the model.

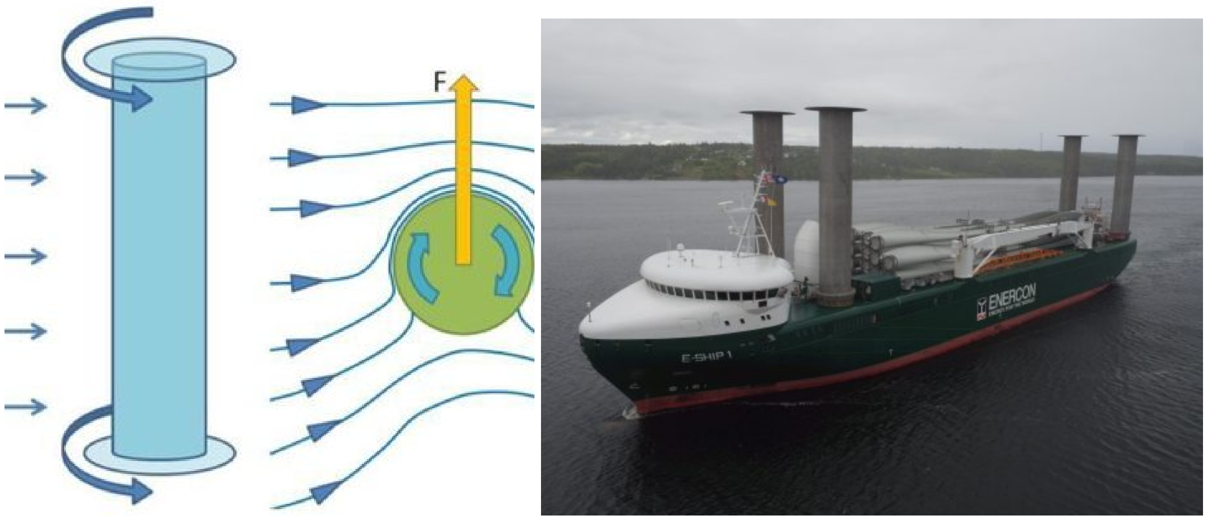

Figure 2.1: Magnus effect by Flettner Rotor (l) [130]
Flettner Rotor on a vessel (r) [55]

Towing Kite Towing kites are large kite sails that fly from the bow of the vessel. [30] The system consists of the kite, connected through a towing rope onto a telescopic mast that is connected to the vessel. The kite is connected with the cable to a system that flies a kite in the most optimal pattern, which is 8 shaped. [5] The kite performs most optimally on courses downwind, and the kite flies high in the air to use the higher wind speeds there. [91] The advantages of the towing kite are the minimal deck space that it uses, only the system that flies a kite is mounted on the deck, and the fact that the kite is relatively easy to put away, so it does not limit the vertical clearance of the vessel flying a kite. At this point, the kites are mostly made by market leader SkySails, but it has recently stopped and now focuses on creating kites for energy generation. [150] A schematic view of how a towing kite works and how it is connected to the vessel is shown in figure 2.2. The ease of use and the high potential of the towing kite makes it ideal to be included in the model.

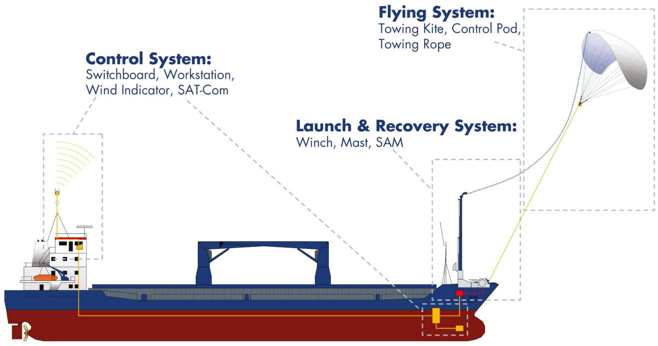

Figure 2.2: Schematic overview Towing Kite [149]

Soft Sails Soft sails are the sails that have been used for years as the main method to propel the vessels. As the wind is not always constant and thus less dependable, the soft sails were quickly replaced by steam engines and later ICEs. Nowadays, soft sails are becoming interesting again, with DynaRig as one of the leading methods being used. The DynaRig rigging looks like the rigging of the 19th century but with curved yards. The sails are integrated into the yards and can be automatically operated. [170] However, these are primarily used on yachts at this time. They could also be of use on cargo vessels. [30] At this point in time, soft sails are not used on cargo vessels, only yachts and cruise vessels. However, the French company Neoline has placed an order for a sail-powered ro-ro vessel, which is planned to be launched in 2024. [118] This is however the only cargo vessel on this day that is sailing or planned to be built. So, the low interest in soft sails as WASPs makes that they will be excluded from the model.

Rigid Sails Rigid sails are sails made from a stiff material and thus have different properties than soft sails. The rigid sails can be divided into three groups; normal rigid sails, which have the same shape as soft sails; wing sails, which are sails that use the same concept as aeroplane wings and turbo sails, which use a boundary layer suction.

Normal rigid sails Rigid sails are sails not made from a soft material but are made from a stiff material which is more robust. Although they were already installed on a number of vessels in the 1980s, after the drop in fuel prices, these were already removed, so at this point in time, they are not widely used anymore. [12] However, due to the increased attention to WASPs, the idea of rigid sails are coming back. The sails were able to achieve a significant drop in fuel use. The sails were also reported to increase stability and could sail the ship independently from the engines for low speeds. This meant that they could also function as a safety propulsion system when the normal propulsion failed. [21] The design of the sail can be seen in figure 2.3. Normal rigid sails are, however, somewhat outdated and will thus be excluded from the model.

Figure 2.3: JAMDA (rigid) sail on a ship [12]

Wing Sails Wing sails are already widely used in fast-racing sailboats and are making the step to larger cargo ships. An artist's impression of these sails is shown in figure 2.4. The principle of a Wing Sail is based on the same principle as aeroplane wings. Because they are also made from an inflexible material, they can also be scaled under rigid sails. [93] At this point, there are no vessels sailing with wing sails, but there is one planned, the Conopée project. This vessel is being developed by Zéphyr & Borée, Jifmar Offshore Services and Bureau Veritas. The vessel will be used to ship rocket parts from Europe to French Guyana. [27] Despite the fact that there is no vessel sailing at this point with a wing sail, research is being conducted for this subject, mostly CFD simulations, for instance, by Viola et al. and Ouchi et al. [123, 167] Wing sails could be an interesting CRS to include in the model, however, the comparable turbo sails from the next paragraph are expected to have more potential, so these will be used.

Figure 2.4: An artist impression of wing sails [167]

Turbo Sails The turbo sails are suction aerofoils and were first developed in the 1980s. Currently, the VentiFoils are being developed by Enconowind and are used on vessels. [22] The turbo sail is based on the same principle of other sails, by creating high pressure on one side and low pressure, where the pressure difference leads to lift; the lift is then used to propel the ship forward. The turbo sail has a different appearance than a normal sail. It looks like an aerofoil but is relatively thick and with a movable fin. Normally, a thick profile would create a significant adverse pressure gradient in the boundary layer. This would reduce the speed of the air in the boundary layer and would thus reduce the lift. The turbo sail counters this by using suction on the leeward side, which removes the slow-moving air. So, there is still a lift being created which can provide thrust for the vessel. [61] The fact that turbo sails are already installed on vessels makes that they have potential and will thus be included in the model.

Figure 2.5: The VentiFoil from Enconowind [40]

Solar Sails Solar sails are a combination of two clean energy methods, solar and wind energy. The idea is as follows, solar cells are placed on a rigid sail, so the surface of the sails is used 'double'. The idea has yet to be implemented, and research is still in the early phases. The University of Tokyo has created a concept of a vessel with solar sails till 2015 [172], but there have been no new relevant developments at this time. The idea of using rigid sails with solar cells has a promising outlook, but the absence of relevant research makes that it cannot be included in this research.

Solar Energy

One of the main renewable fuels, next to wind energy, is solar energy. As ships sail on open water, there is a lot of potential energy to be used on vessels. Solar energy can be harvested by solar panels and used on the ship. Solar energy is most appealing for vessels with large open deck spaces, like tankers, where there is lots of room for the panels. This means that it is less attractive for vessels will little free deck space, like container vessels. Nowadays, however, it is not possible to power a whole vessel with solar energy. [65] So, solar energy can mainly be used as auxiliary power. [180] The energy provided with the solar panels can be used for propulsion when the vessel sails in a diesel-electric set-up or when combined with batteries. For the use of solar panels as an energy source, the free surface on deck is most important, but also the region where the vessel sails have a large impact on the energy generation. The difference in the region can make a difference of up to 50%. [126] The fact that solar panels will be relatively easy to use and provide clean energy makes that they will be included in the model.

Change in Ship Characteristics

The decarbonisation of vessels can also be achieved by changing (operational) characteristics of the vessel by reducing the speed, for example. Other modifications can be to increase the loading of the vessel. This can be done by increasing the detentions of the vessel or by using the space of a vessel in a different way.

Slow Steaming When decreasing the cruising speed of a vessel, which is called slow steaming, the amount of fuel needed decreases significantly. This is because ship speed and resistance are exponentially related. [81] So, by reducing the ship's speed, the amount of fuel used decreases, and thus the amount of carbon that is emitted is also reduced. So, a small reduction in speed can create a large decrease in carbon emissions. The problem with this method is that clients must wait longer on their products, and if ships are longer in transit, the whole fleet should be increased to ship the same amount of cargo. This means that in times of overcapacity in the world shipping market, there is more incentive to do this due to the lower cargo hauling prices. [176]

To achieve slow steaming in line with the regulations, the Engine Power Limitation (EPL) is used. Here the maximum engine power is limited, so the vessel is normally unable to sail with more power. To keep the vessels safe in dangerous situations, the EPL can manually be switched off, so the vessel can have more power. [171] This is normally done when retrofitting a vessel. For new vessels, owners are more likely to install lighter, cheaper engines, which is not desirable for the vessel's safety. [14, 33]

What also could be considered slow steaming is using the just-in-time principle. Vessels spend a significant part of their lifetime waiting on the anchor for a place in the harbour. [113] This means that the vessels sailed faster than needed in the trip prior to anchoring. So, when it becomes clear earlier when the vessel could enter the harbour, the vessel could reduce speed and arrive just in time. The just-in-time principle can deliver significant fuel and thus a CO_2 reduction. However, this is dependent on the port call method of the harbour and difficult to put in the model. So, it will not be included in the research, but it can be a helpful method for the ship owner to decrease the CII of the vessel. However, slow steaming itself has a high impact for low investment and will thus be included in the model.

Increase of loading Increasing vessel loading could lead to the cargo being shipped more efficiently. When the increase of propulsion power is not proportionally higher than the increase of cargo, the cargo is shipped more efficiently. This can be achieved by making sure the vessel uses its capacity more efficiently or by ship lengthening. By making the vessel longer, the vessel can carry more cargo. This will not lead to a significant increase in energy needed to propel the ship. So, the amount of fuel used per cargo unit decreases. [45] This is substantiated in figure 2.6, which shows that increasing vessel size decreases fuel use per freight unit. In general, when lengthening a ship, the wetted surface increases, and so the frictional resistance increases; however, the wave resistance relatively decreases, leading to less resistance for more loading. [2, 83]

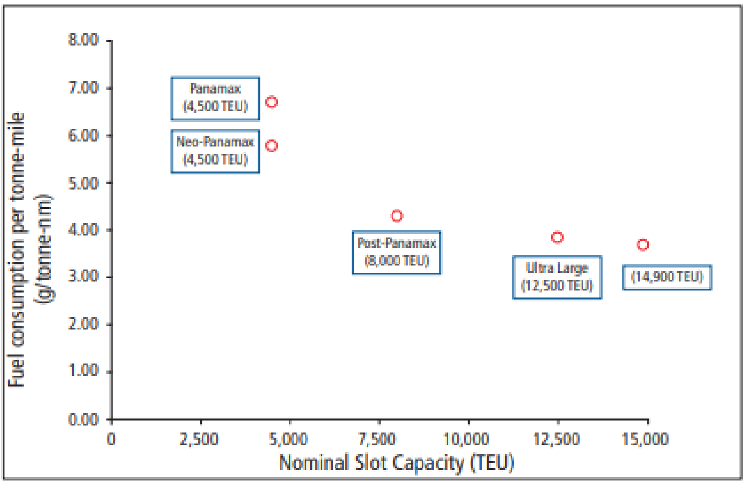

Figure 2.6: Fuel use per vessel size [2]

The lengthening of the vessel requires an investment in terms of material and installation, but it also requires the vessel dock. The docked vessel will still have costs but cannot be used to generate revenue. However, it is still a method that is used already by shipping companies to increase the revenue that a vessel can generate with a relatively low investment. [37] So, the fact that it is already an economically viable option without the coming carbon restrictions makes this a valuable option to reduce CO_2 emissions. Ship lengthening, however, cannot be done indefinitely because the forces on the vessel will become too large.

More efficient use of loading can be achieved by making sure the vessel always sails as fully as possible. This is something that shipowners always aim to do, where it is always an economic consideration of planning. However, when the CII is implemented, it can be that useful for the owner to sail as fully as possible because otherwise, the CII is not met. Although this could be the case in the future, the impact and probability are too low to introduce this in the model.

Air Lubrication

Air Lubrication is when a layer of air is introduced under the hull of the vessel, which reduces the drag of the ship. [43] This decrease in frictional resistance can lead to significantly less engine power and, thus, less carbon emission. [136] The air lubrication is mostly applied on vessels that have a flat bottom, which ensures that the bubbles stay under the hull as much as possible, which is shown in figure 2.7. Air lubrication has different forms, air cavity, micro bubble drag reduction and air film. For air cavities, the hull is shaped so that large 'flat' air bubbles can form under the ship. This fill of air reduces the drag of the vessel. Another form of air lubrication is microbubbles. Microbubbles are, as the name says, small bubbles that are pumped under high pressure under the vessel. These bubbles create a field of air under the vessel, which, as the other air lubrication, reduces drag. The last one is the air film, which is generated by injecting air onto a super water-repellent coating that is placed on the hull of the vessel. This creates a small film of air under the vessel that reduces the drag resistance. [158]

The air lubrication reduces the drag resistance of the vessel, which means that it is a net effective power reduction if combined with other energy-saving solutions if they do not also reduce drag. The main disadvantage of air lubrication is that the effectiveness reduces by increased wave height, currents and other effects that affect the ability to keep the air trapped under the vessel. [158] This is not only a disadvantage for the energy reduction of the vessel, but this should also be addressed in the model in which the air lubrication will be used.

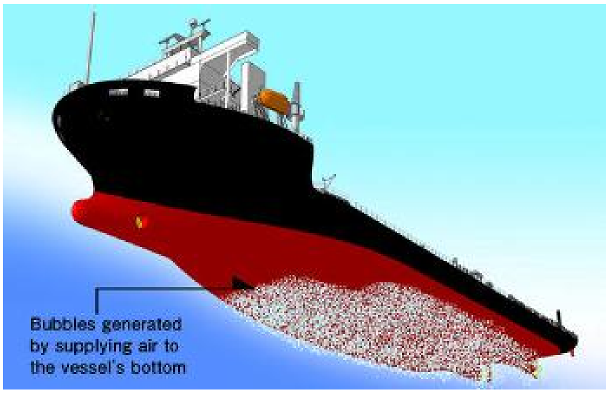

Figure 2.7: Air lubrication [80]

Waste Heat Recovery

Around 50% of energy in the fuel is discharged as waste heat by a vessel, in the exhaust gas or cooling water. A schematic overview of the heat flows in a marine engine can be seen in figure 2.8. It also shows what happens with the flow if a waste heat recovery system is installed. Waste heat recovery systems aim to use a part of this waste energy and turn it into electrical or mechanical energy. [147] This is a difficult task because the quality of this energy is low due to its low temperature and limited use for energy production. The waste heat can be turned into usable energy using the Rankine cycle, the Kalina cycle, the exhaust gas turbine system or thermoelectric generation. The Rankine cycle is a thermodynamic cycle which converts heat energy into mechanical work, whereas the Kalina cycle is a thermodynamic power cycle with an ammonia and water mixture. [122]

The exhaust gas turbine system uses a turbocharger to put the exhaust gas through a power turbine, which can then produce usable energy. The thermoelectric generation is based on the Seebeck Effect. It uses two dissimilar conductors or semiconductors where the temperature difference between those creates a voltage difference. The waste heat recovery systems used at this time can significantly increase the efficiency of fuel use on a vessel. It is also expected that waste heat recovery systems will become even more efficient in the future, so they are ideal for including in the model.

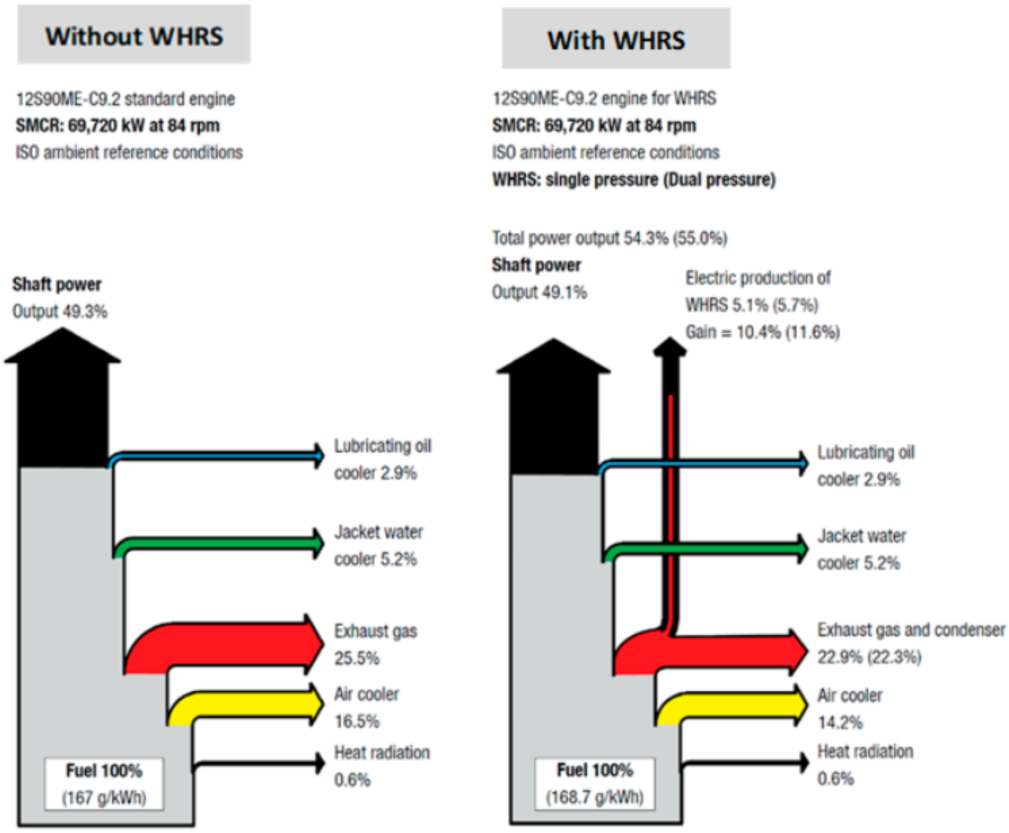

Figure 2.8: Increased efficiency through waste heat recovery [97]

Other

There are lots more methods to make the ship more efficient, but with negligible effect compared with other solutions presented. From solutions that decrease the use of auxiliary power to tweaks to the propeller. [82] These are of little influence on the total fuel use, or they are so specific to certain ships that nothing meaningful can be said about it on a larger scale that they will be placed out of scope. Other solutions will also be placed out of scope because they are expected to be done already by the owner as a normal business decision. These include, among other things, the use of more fuel-efficient engines and better planning of trips. Also included are energy-saving devices (ESD) that are more ship specific. Such include ducts, rudder configurations and design and redesign of the bulbous bow, as these are also ship-specific and have a relatively small impact. [178] It is also expected that some of these are easy to install and that shipowners already use these to reduce fuel costs.

Conclusion

The presented energy-efficient solutions all differ in how they make the ship more energy efficient. The WASP technologies provide extra propulsion power, which reduces the amount of energy that the main engines must supply. This could lead to a substantial reduction of energy needed, especially when combined with slow steaming. Slow steaming is one of the methods that can have a high impact since the resistance is quadratically connected with the speed of the vessel. So, slow steaming is a remarkably interesting method to reduce carbon emissions and can be used as an addition to get the last part of carbon reduction to comply with the regulations. Solar energy will not be able to sail the vessel. Still, it can be used to supply auxiliary energy, as well as some propulsion power, if the vessel has a (partly) electric propulsion power train. Air lubrication and the increase of loading, so ship lengthening, both decrease the amount of energy needed for a certain amount of loading. However, air lubrication decreases the amount of energy needed to propel the vessel, whereas ship lengthening increases the energy needed to propel the vessel. The vessel can then carry more cargo than before, which leads to more energy-efficient shipping.

2.2.2 Alternative Fuels

Currently, there is a lot of ongoing research into alternative fuels for the shipping industry, and there are several contenders to become the next dominant fuel, as HFO is at this moment. [10] The fuels that are being researched are ammonia, hydrogen, LNG, methanol, bio-fuels and E-fuels. Bio-fuels and E-fuels are collective names for fuels that are synthetically produced in a biological or electric way, respectively. Not all these fuels are carbon-free, and the ones that are carbon-free could have a supply chain that is not, at this point in time, free of carbon admissions. Nuclear material is also used at a small scale for the propulsion of vessels, but due to the hazardous nature of the materials, it is not expected that this will be used on a large scale. This section aims to present the advantages and disadvantages of the main contenders to become the fuels of the near future, as well as the fuels that can be used further in the future.

LNG

LNG (Liquid Natural Gas) is a fuel that must be stored and transported cooled and/or under pressure. LNG is already used to propel vessels at this time and is one of the most available alternative fuels presented in this research. However, it is mostly used by LNG carriers as they already have the storage infrastructure on board. Because of the needed storage infrastructure, there are limited non-LNG carriers that use LNG these days. [16] LNG carriers can use LNG fairly easily because they do not require much extra specialised equipment to store en transport the fuel. However, vessels that will only require LNG on board to be used as fuel will need specialised storage equipment to use LNG. LNG is mostly methane which still contains carbon, so the fuel is not carbon-free. It could be made in the future in a synthetic or biological way, but at this point in time, it is still a fossil fuel. It is estimated that a significant drop in greenhouse gases (GHG) could be achieved compared to HFO and MDO. However, this drop is around 20 % [89], which would only make the vessel comply quickly when the regulations will rapidly tighten. As the IMO presented that the shipping industry should be carbon neutral in 2050, which is almost a 4% reduction per year till then, so a 20 % reduction would only be enough for approximately 5 years. What also should be added is that methane is not always completely burned, leading to a 'methane slip', which is methane that is expelled into the air. Methane is a much more harmful GHG than CO_2, which will also present some difficulties. [163] These negative impacts make that LNG will be excluded from the model.

Ammonia

Ammonia is a nitrogen-based substance which can be used as a fuel in vessels, with a formula of NH_3. Because ammonia consists of nitrogen and hydrogen, it is free of carbon emissions when used as a fuel. [58] At this point in time, ammonia is mostly still produced and transported with fossil fuels, but this can change in the future. Ammonia does have a volumetric energy density that is about one-third lower than MDO. [77] One of the advantages of ammonia is that it can be used for ICE and fuel cells, next to the advantage that ammonia is already created on a large scale at this point in time, although mainly for the production of fertilizer. One of the negative effects is that it is toxic for humans and nature and therefore needs more attention than MDO or HFO. [174, 159] The high potential of ammonia makes it suitable to be included in the model.

Methanol

Methanol is an alcohol that can be used as fuel for ships. It has a formula of CH_3OH, so it still contains carbon and thus produces GHG. Yet, the CO_2 conversion factor is around one-third of that of MDO and HFO. Also worth noting is that methanol can be produced syntactically, and it can also be produced from waste CO_2; this means that no carbon is emitted. The technology for methanol engines is already proven [77], but it still has the disadvantage of having a volumetric energy density that is about one-half lower than MGO. [95] One of the main advantages of methanol is that it is liquid under normal circumstances, which means that it can be stored in the same sort of tanks as MDO or HFO. The other main advantage is that it can be used in normal ICEs [87], which would require fewer investments. The fact that methanol can be used as a drop-in fuel makes it ideal for the model.

Hydrogen

Hydrogen has the potential to be the ideal fuel of the future. Hydrogen, combined in a fuel cell with oxygen, can produce electricity, leaving only water as a waste product. So, when using it to power a vessel, no GHG is emitted, and the water can be discharged easily. At this point, most of the hydrogen is still produced by using natural gas, but hydrogen can also be produced with water and electrolysis. [155] To store and transport hydrogen in an effective manner, the hydrogen should be cooled or pressurised to reduce the volume. This leads to large tanks and energy use, which makes it less practical in comparison with HFO or MDO. Although it is not ready yet to be used on a large scale, there is enough potential to include hydrogen in the model.

Bio-fuels

Bio-fuels are the collective name for fuels made from biological materials, so these fuels can be considered carbon neutral. The biomass used for this captured CO_2 out of the air when the organic material grew. However, when these fuels are burned, the carbon is emitted into the air once again, but because the carbon is extracted from the air, no 'new' carbon is added to the environment, which makes it carbon neutral. There is, however, some discussion about how carbon natural bio-fuels should be considered. Lippke et al., for instance, argues that the potential reduction in carbon emissions, as compared with fossil fuels can be between 60 and 100%. [94] However, by the IMO they are considered carbon neutral. The fuels can be gas-made liquid, like liquid biogas (LBG), or diesel-like fuels, like FAME (Fatty Acid Methyl Ester). [157] Bio-fuel that will be used in this research is bio-diesel, which could be an almost one-on-one substitute for the MDO used in the research right now. The renewability of biofuel makes it interesting to include it in the model.

E-fuels

E-fuels are much like bio-fuels but created not from biological material but only electricity, water and carbon dioxide or nitrogen. When CO_2 is a waste product or taken from the air, it presents a carbon-neutral fuel. When nitrogen is used, no carbon is emitted. [166] Examples of E-fuels are E-methanol, E-diesel and E-LNG. When the E-Fuel has the same characteristics as its non-renewable counterpart, it can substitute that fuel, so it does not need an investment to prepare the vessel for a different fuel. As with the bio-fuels, the most logical E-fuel to use for this research would be E-diesel, which can be used as a substitute MDO or HFO. The potential of E-fuels is high and will thus be included in the model. For E-Fuels, it is, as with bio-fuels, the question how much reduction can be calculated.

Nuclear

Nuclear power as a power source is already used on land and on the sea. On land, there are large nuclear reactors that supply power to the power grid. At sea, it is only used on naval vessels, mainly submarines and aircraft carriers. [68] The only non-military vessels that use nuclear powers are Russian icebreakers. [60] Nuclear energy is mainly used because there is a very small amount of fuel needed for a long amount of time, which makes it ideal for long trips or submerged operations. The main disadvantages that prevent it from being used on a large scale are the safety issues and the political sensitivity surrounding nuclear power. [139] The raw materials used as nuclear fuel are subjected to a large array of trade barriers and sanctions and the knowledge associated with nuclear power. The safety issues and societal impact makes nuclear energy, for now, excluded from the model.

Conclusion

Most of the alternative fuels presented in this section have promising aspects of becoming a fuel for the future. Although not all the proposed fuels are available to be used for fuels, their potential makes they are included in the research. Still, all the fuels have advantages and disadvantages, which makes it difficult to predict what the new dominant fuel for the future will be and, thus, which fuels to use in the model. However, based on the information presented in this section, two fuels will be excluded. Firstly, LNG will require new and complex storage for a fuel that only provides a 20% drop in CO_2 emissions. When biological or synthetic alternatives are produced, it can be expected that they will also be created for more manageable fuels such as diesel. The other fuel that will be excluded is nuclear power. This is because of safety issues, but mainly about the (geo-) political issues surrounding this subject, which would limit the availability of fuel and research about the fuel.

2.2.3 Others

There are a few other solutions that cannot really be placed in the other groups of decarbonisation solutions, carbon capturing devices and cold ironing. These are both solutions that help to decarbonise vessels, but they are not making the ship more efficient and are not other, less full of carbon fuels. With carbon capturing, the CO_2 from the exhaust is filtered and stored, and cold ironing is the name for using shore electricity as auxiliary power when in port.

Carbon Capturing Device

Carbon capturing devices differ from the decarbonisation solutions presented in section 2.2.1 and 2.2.2. While these solutions try to reduce the amount of carbon that enters the vessel and thus reduce the output, the Carbon Capturing Devices aim to control where the carbon ends up. This means that the carbon that is stored in the fuels is captured and stored on board the vessel during the voyage. This carbon can then be transported to land and then stored or used. CCDs are not expected to be the end of decarbonisation, but they can play a significant role in the intermediate area between now and the carbon-free shipping industry. [24] The CCD will cost energy, so the vessel becomes less energy efficient. This means that the energy efficiency per loading decreases, but carbon emission per loading decreases too. [179]

The carbon that is captured on board a vessel needs to be stored on board the vessel before it can be discharged on land. CO_2 can be stored in phases on board a ship, solid or liquid. As a solid, it has reacted with another material. [53] CO_2 that is stored as a liquid must be pressurised and possibly cooled. When cooled, the CO_2 requires less pressure to stay liquid. [141] To reduce the space the carbon capturing device uses, it would be helpful if the captured carbon could be stored in empty fuel tanks, mainly LNG tanks. This idea was brought up by Garcia et al. [53]. However, Bruima et al. concluded that this was not possible. [24] The CO_2 that is captured and stored is still harmful when it is emitted into the atmosphere elsewhere. So, even if it is captured and sold, it is important to keep clear where the CO_2 ends up. The first part here is the storage on board the vessel, and if the CO_2 leaks away from the storage then the whole capturing has failed. Also, irresponsible use of carbon on land can lead to CO_2 ending up in the atmosphere. However, only the risk of carbon being emitted into the sea will be considered a risk of this solution. The research will consider carbon delivered to land non-emitted carbon. Although it will not be the solution, in the long run, it will still be interesting to include this in the model.

Cold Ironing

Cold ironing, also known as Alternative Marine Power (AMP) and Onshore Power Supply (OPS), means that a vessel uses shore power when staying in a harbour instead of using the auxiliary engines to supply energy to the vessel. The idea is that the energy on the grid is cleaner than the energy provided by auxiliary engines. Ports in Europe are required to have cold ironing capabilities by the end of 2025 [181], and in 2030 all container and passenger vessels staying longer than 2 hours are expected to use it. [38] The advantage of cold ironing is that the vessel does not emit carbon in the harbour for its energy supply. The energy comes from the grid, so the way that that electricity has been generated determines the carbon emission of the energy. It is estimated that around 16% of the carbon emission of ships is generated at berth or anchorage. [34] This could mean that if the energy is supplied to the vessel with green electricity, a significant reduction of GHG is possible. Because the EEXI and the EEDI are non-operational measures, cold ironing does not influence them. However, the CII is an operational measure and is measured over the carbon emission per year. By reducing the need for energy supplied by the auxiliary engines, the CII can also be reduced. When the prices of energy from the grid are lower than the cost of fuel used to provide auxiliary power, it can also be an economic advantage to use cold ironing. [57] The payback time from a purely economic view is dependent on the cost of the instalment of the cold ironing infrastructure on the vessel and the difference between the price of the shore-based energy supply and the price of the fuel used to create energy. The ease of use makes cold ironing suitable for the model.

2.2.4 Compatibility

Most CRSs will not be able to decarbonise the vessel alone or could, economic-wise, benefit from the combination of CRSs. However, not all CRSs are compatible with each other or are impracticable to combine. An easy example of incompatibility is combining carbon-capturing devices with hydrogen as a fuel due to the lack of carbon in hydrogen. The capabilities between the CRSs can be seen in table 2.3, where a Y stands for yes, an N stands for no and a D for depends. The yes means that two CRSs can be combined without problems. They impact other aspects of the vessel or complement each other. The no means that the options are, in essence, not compatible. However, it could be that in special circumstances or in the future, the two options will become compatible but will not be used that way in this research. An example of this is ammonia, which can be used as a hydrogen carrier for fuel cells, so, it could be that pure hydrogen and hydrogen from ammonia can be used as 'dual' fuel and thus combined. The dependent options are options that are unclear or will reduce the effectiveness of each other. Towing kites and Flettner rotors, for example, both use wind for propulsion, but more sail area does not lead to a linear increased towing power. [13] So, these two can be combined, but their effectiveness will decrease. There is also the case of carbon-capturing devices and carbon-based carbon-neutral fuels, such as bio-fuels and E-fuels. They could be combined because the carbon from these fuels can be captured, but there is no need for it. Then different fuels can be combined as drop-in fuels for each other, but this is not yet presented as an option for marine fuels.

So, to keep the model structured, the alternative fuels will not be combined with each other and will also not be combined with carbon-capturing devices. The Flettner rotors and turbo sails will also not be combined because these could be interchangeable in space; it will not help the clarity of the model. These two, Flettner rotors and turbo sails, on the one hand, and towing kites, on the other hand, can be combined but will be reduced in their effectiveness.

Table 2.3: Compatibility CRS

	Turbo sails	**Flettner rotor**	**Cold ironing**	**Towing kite**	**Solar energy**	**Ship lengthening**	**Air lubrication**
Turbo sails	-	N	Y	D	Y	Y	Y
Flettner rotor	N	-	Y	D	Y	Y	Y
Cold ironing	Y	Y	-	Y	Y	Y	Y
Towing kite	D	D	Y	-	Y	Y	Y
Solar energy	Y	Y	Y	Y	-	Y	Y
Ship lengthening	Y	Y	Y	Y	Y	-	Y
Air lubrication	Y	Y	Y	Y	Y	Y	-
Waste heat recovery	Y	Y	Y	Y	Y	Y	Y
Carbon capturing device	Y	Y	Y	Y	Y	Y	Y
Ammonia	Y	Y	Y	Y	Y	Y	Y
H2 Liquid	Y	Y	Y	Y	Y	Y	Y
H2 Gas	Y	Y	Y	Y	Y	Y	Y
Methanol	Y	Y	Y	Y	Y	Y	Y
Bio-fuel	Y	Y	Y	Y	Y	Y	Y
E-fuel	Y	Y	Y	Y	Y	Y	Y

	Waste heat recovery	**Carbon capturing device**	**Ammonia**	**H2 Liquid**	**H2 Gas**	**Methanol**	**Bio-fuel**	**E-fuel**
Turbo sails	Y	Y	Y	Y	Y	Y	Y	Y
Flettner rotor	Y	Y	Y	Y	Y	Y	Y	Y
Cold ironing	Y	Y	Y	Y	Y	Y	Y	Y
Towing kite	Y	Y	Y	Y	Y	Y	Y	Y
Solar energy	Y	Y	Y	Y	Y	Y	Y	Y
Ship lengthening	Y	Y	Y	Y	Y	Y	Y	Y
Air lubrication	Y	Y	Y	Y	Y	Y	Y	Y
Waste heat recovery	-	Y	Y	N	N	Y	Y	Y
Carbon capturing device	Y	-	N	N	N	D	D	D
Ammonia	Y	N	-	N	N	N	D	D
H2 Liquid	N	N	N	-	N	N	N	N
H2 Gas	N	N	N	N	-	N	N	N
Methanol	Y	D	N	N	N	-	D	D
Bio-fuel	Y	D	D	N	N	D	-	D
E-fuel	Y	D	D	N	N	D	D	-

- = Inapplicable **N** = No **Y** = Yes **D** = Depends

2.2.5 Conclusion

There is a large scale of solutions that can decarbonise a vessel. However, to what extent they are effective, cost-effective, available, or even developed differs. The model, however, should be used for many vessel types. This means that the model will work broadly and not go into too many details. So, solutions that are more ship specific or generally have a negligible effect will be placed out of scope. Also, solutions that are not yet proven or are dependent on future infrastructure are excluded. This leads to a model that will focus on: WASP, solar, cold ironing, slow steaming, air lubrication, carbon capturing and ship lengthening. It will also include some alternative fuels; ammonia, hydrogen, methanol, bio-fuel and E-fuel.

2.3 Methods for Analysis

An important part of the model, and thus the research, are the methods with which the CRSs for the decarbonisation strategy are selected. The methods to decarbonise vessels are different in many aspects, such as the impact on the operational profile, the cost, the risks, and the readiness of the technology. It is important that the scoring method can compare different CRSs in a quantitative way. This means that data that does not exist of measured or calculated numbers can be compared with data that is calculated or measured, so how can safety be compared with costs? There are some methods to compare different criteria, one of which is a multi-criteria analysis. This way, more subjective criteria, which often represent risks, can be compared with more objective criteria. What is also of interest is how these criteria will be processed. For example, the cost of the CRSs has to be calculated for the different strategies. So, for the different criteria that have to be compared, different analysis tools or models are needed. It could be that the different CRSs influence or enhance each other, or it could even be that they cannot go together. This should also be addressed with a tool or model. The model will also have to consider the uncertainty in data or data that is not as precise as possible. This could be achieved with a probability analysis, like a Monte Carlo simulation. This section aims to present what methods will be used to calculate, compare and use the effect of the CRSs on the vessel.

2.3.1 CBA - Cost-Benefit Analysis

A Cost-Benefit Analysis is a method where the inputs (cost) and the outputs (benefits) are compared. The basis of a CBA is that the benefits should outweigh the cost, and the benefits should outweigh the benefits of the next best thing. [88] A CBA can be as simple as the resale of an item. If the cost to buy it is lower than the price when selling it (benefits), then the CBA is positive. The CBA can also be used for larger problems and can even be used for non-monetary values. The other values, such as social impact, can be monetized and then compared with the cost. Due to the complexity of the inputs and outputs of the model, it seems that a CBA is not the right tool. Although different methods can, in essence, also be seen as CBAs, this research will treat the other methods as separate analysis models. So, the CBA will be considered the simple method of comparing costs and benefits in a monetized way, which is considered to be an unfit tool for the preferred model.

2.3.2 SWOT Analysis

SWOT stands for Strengths, Weaknesses, Opportunities and Threats and is a method to identify important aspects of plans and can be used for strategic business planning. The model shows the relations between the internal and external factors that influence an investment. The SWOT analysis uses two internal factors, namely Strengths and Weaknesses. The other factors are external factors, and these are Opportunities and Threats. [115] The strengths are the advantages that the project has over other similar projects, whereas weaknesses are the opposite. The opportunities are the possible external effects that could help the project, and threats are the elements that could negatively impact the project. By systematically scoring projects or business decisions this way, the user gets a clearer view of important factors, which helps better decision-making. SWOT analysis can also be combined with MCA, presented in section 2.3.3, methods where both can complement each other. [18] There are several different MCA methods that are combined with a SWOT analysis, but the AHP is mostly mentioned as a combination. [66] However, it is expected that the SWOT can also be combined with the WPM or the WSM, where the SWOT analysis can help to get values for the WPM/WSM, which are all further discussed in section 2.3.3. In this research, the SWOT analysis can be used to identify the positive and negative aspects of the CRSs, which could then be used to substantiate the scores of the strategies used in the MCA.

2.3.3 Multi Criteria Analysis

Multi Criteria Analysis is used to make decisions when several distinct aspects of the possible alternatives should be weighted. Given that the instinct of the decision maker is not always rational, it helps to use a tool that gives a clearer insight into the various aspects. Several different methods can help decision-makers choose from several alternatives. One of the easiest methods is ranking the alternatives for the different criteria and then choosing the one with the best scores overall. With a somewhat more accurate method, the criteria are weighted, and the alternatives scored, which then multiplied and added yields an overall score. When going further, there are the methods like AHP that use pairwise comparisons to create scores. For the model in this research, the MCA will be used to choose the best possible option to decarbonise a vessel. This section will discuss the relevant Multi Criteria Decision Making (MCDM) techniques that are used for the MCA and will show which will be best to use.

Weighted Methods

The most simple MCDM techniques are the weighed methods, namely the WSM (Weighed Sum Model) and the WPM (Weighed Product Method). These are weighted methods because they assign a weight of importance to different decision criteria. In almost all cases, these methods make use of normalisation of the data, in which there is a difference that should be mentioned. There is also a method where the WSM and the WSP are combined, called the WASPAS. This section will discuss these three methods.

WSM - Weighted Sum Model The WSM is one of the simplest MCDMs there is, and it scores all the alternatives for different criteria. Scores can be chosen, but are typical 1-5, 1-10 or 1-100 scores. The criteria all have a weight of importance, the weight of each criterion is multiplied by the score of the criteria, and all these are summed for the same alternative. The formula for the WSM can be seen in equation 2.12. In this formula, WSM stands for the WSM score for one alternative. i is the index and n the number of features, whereas v_i is the score for criteria i and w_i the weight of the criteria.

$$WSM = \sum_{i=1}^{n} v_i w_i \tag{2.12}$$

According to the WSM, the alternative with the highest score is considered the 'best' alternative. [84] In table 4.1 shows an example of a WSM matrix. It can be seen that alternative A_1 scores high marks on criteria with a higher weight and thus has the highest score.

		Criteria				
		C_1	C_2	C_3	**Score**	**Rank**
Alternative	**Weight**	4	1	6		
	A_1	7,00	3,00	8,00	79,00	1
	A_2	4,00	9,00	2,00	37,00	3
	A_3	5,00	7,00	6,00	63,00	2

Table 2.4: Example of WSM Table

		Criteria				
		C_1	C_2	C_3	**Score**	**Rank**
Alternative	**Weight**	4	1	6		
	A_1	1,00	0,33	1,00	10,33	1
	A_2	0,57	1,00	0,25	4,79	3
	A_3	0,71	0,78	0,75	8,13	2

Table 2.5: WSM table normalised

The WSM is a simple tool where, when used as a more subjective MCDM, the DM (decision maker) has a considerable influence. It could occur that an alternative gets the highest score but still has a low score on especially important criteria that has a high weight. Although the WSM is simple and seems straightforward, there are some alternatives to how the tool is used that could give different outcomes. This is mainly in the way how and if the scoring matrix is normalized. The normalization is done because the data that is used is not always in the same order of magnitude, like when fuel use, cost and the number of crew members must be compared. So, the normalisation of the values is required to compare the scores. This could be done by different methods, which all have different results. The most used methods are:

- Linear: Max
- Linear: Max-Min
- Linear: Sum
- Vector normalization
- Logarithmic normalization
- Fuzzification trapezoidal function

However, according to Vafaei et al., the max, sum and vector methods are recommended as the best methods. The formulas for these normalisations are shown in equation 2.13, 2.14 and 2.15, where r_{ij} is the score, r_{max} the max score for that criteria and n_{ij} the normalisation. [164]

$$\begin{array}{lrl} \text{Linear: Max} & \text{Benefit criteria} & n_{ij} = \frac{r_{ij}}{r_{\max}} \\ & \text{Cost criteria} & n_{ij} = 1 - \frac{r_{ij}}{r_{\max}} \end{array} \tag{2.13}$$

$$\begin{array}{lrl} \text{Linear: Sum} & \text{Benefit criteria} & n_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \\ & \text{Cost criteria} & n_{ij} = \frac{1/r_{ij}}{\sum_{i=1}^{m} 1/r_{ij}} \end{array} \tag{2.14}$$

$$\begin{array}{lrl} \text{Vector normalization} & \text{Benefit criteria} & n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \\ & \text{Cost criteria} & n_{ij} = 1 - \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}} \end{array} \tag{2.15}$$

The presented model will have a large number of alternatives that all need to be scored on a criterion with thus will have the need for normalisation. The linear max normalisation uses only the highest score as a reference and will thus be more suitable because it reduces the number of calculations and will therefore be used in the model.

WPM - Weighted Product Method The WPM works with the same principle as the WSM. However, the scores that alternatives score per criteria are not multiplied by the weight, but the score is raised to the power of the weight. Then all the scores are multiplied, which gives the weighted product model. The equation of the WPM can be seen in formula 2.16.

$$WPM = \prod_{i=1}^{n} (v_i)^{w_i} \tag{2.16}$$

In this formula, WPM stands for the WPM score for one alternative. i is the index and n the number of features, whereas v_i is the score for criteria i and w_i the weight of the criteria, which is the same as for the WSM. As for the WSM, the WPM matrix can be normalized to create a clearer overview. [173]

A major weakness of the WPM is that it overestimates the extremes, which could lead to undesired results. This is because it significantly favours/disfavors the alternatives that are far from the average in one criterion, and this is not the case with WSM. [28]

In table 4.3, it is clear that when the matrix is not normalized, the scores can get incomprehensible because of the difference in the order of magnitude.

		Criteria				
		C_1	C_2	C_3	**Score**	**Rank**
Alternative	**Weight**	4	1	6		
	A_1	7,00	3,00	8,00	1.888.223.232	1
	A_2	4,00	9,00	2,00	147.456	3
	A_3	5,00	7,00	6,00	204.120.000	2

Table 2.6: Example of WPM table

		Criteria				
		C_1	C_2	C_3	**Score**	**Rank**
Alternative	**Weight**	4	1	6		
	A_1	1,00	0,33	1,00	0,33	1
	A_2	0,57	1,00	0,25	0,00	3
	A_3	0,71	0,78	0,75	0,04	2

Table 2.7: WPM table normalised

WASPAS - Combination The WASPAS is a combination of the WSM and the WPM, where the scores of both are combined to create a score that reflects the concerns of both methods. The simplest form of the WASPAS is the fifty-fifty average of the scores from the WSM and WPM. There are also methods where the weight between the two differs, so seventy thirty, for example, which makes one part more important than the other. [29]

For this research, the WSM is the most suitable due to the influence of the decision maker and the lesser impact of the extremes as with the WPM. This is because of the randomisation of the Monte Carlo simulation. It could be that some extreme scenario would be presented and thus a larger impact from this scenario.

AHP - Analytic Hierarchy Process

The AHP compares different alternatives to get to a certain goal. It compares all the alternatives one on one and assigns a number to it, which mostly ranges from 1-9 for positive and 1-$\frac{1}{9}$ for negative. By comparing all the data of the different alternatives, one of the alternatives should get the highest score and is thus the "best", according to the AHP. One of the biggest benefits of the AHP is that it can be checked for inconsistencies in the decision maker. This is due to the fact that the alternatives are scored against each other and can be easily mathematically checked; when A > B and B > C, then A > C. So when this is mathematically not consistent, it becomes clear that the decision maker has not been consistent and the data has to be changed. The AHP is mostly used for group decision making and has some shortcomings. Because all the alternatives are scored one on one with each other, it is possible that a miss match occurs when comparing more alternatives. [8] AHP also requires that all alternatives are scored against all other alternatives for all criteria. Which makes it less practical when adding a new CRS to the model in the future. So, the AHP will not be used in the model.

Others

Multi Criteria Decision Making has many different approaches, and there are many different techniques. Most models have a specific area for which they are designed, such as engineering, business, design, health, etc. The models also have a lot of different levels of complexity and to what extent the decision maker checked in his consistency of choices. Models that are also widely used are, among other things, TOPSIS, ELECTRE, PROMETHEE, MACBETH and MAUT. The model has a clear view of the inputs and will mostly be influenced by the economic input in the MCA, so these more complex models are not used in the model.

Conclusion

The MCA is, with the use of the financial analysis, the body of the decision making tool. The main criterion that will enter the MCA is the cost that is associated with the decarbonisation of the vessel. So, it will be logical that the cost has a large weight in the model. Also, the fact that CRSs that do not fit the vessel type or CRSs that are incompatible are already filtered out by the decision tree makes the other criteria than the cost less important. This leads to a tool that mainly has to compare the cost, where the other criteria will mainly be used to choose between strategies where the cost are nearly the same. So, this does not require a complicated tool. Thus, ultimately the WSM or WPM is chosen because of the simplicity of the method. What weight and scores will be used for the MCA will be found in section 6.3.

2.3.4 Decision Tree

As shown in section 2.2.4 there are some restrictions and influences between the different CRSs. There are space restrictions, such as the case when soft sails are installed; there is no room anymore for hard sails. Other space-related restrictions are, among other things, the combination of solar panels and Flettner rotors. When placing the rotors, there is less space for solar panels, so the model should then use fewer solar panels. There are also CRSs that have a combined effect, but that effect is measured in other calculations. For instance, a WASP provides propulsion power, and air lubrication reduces resistance; together, they reduce fuel use. This combination will result in a change in the power train calculations and thus will not need a special method to incorporate these in the model. To visualise the restrictions and changes associated with the CRSs in the model, a block-like method will be used. Figure 2.9 shows a simplified example of what a model could look like when there are only restrictions between the CRSs that exclude some combinations.

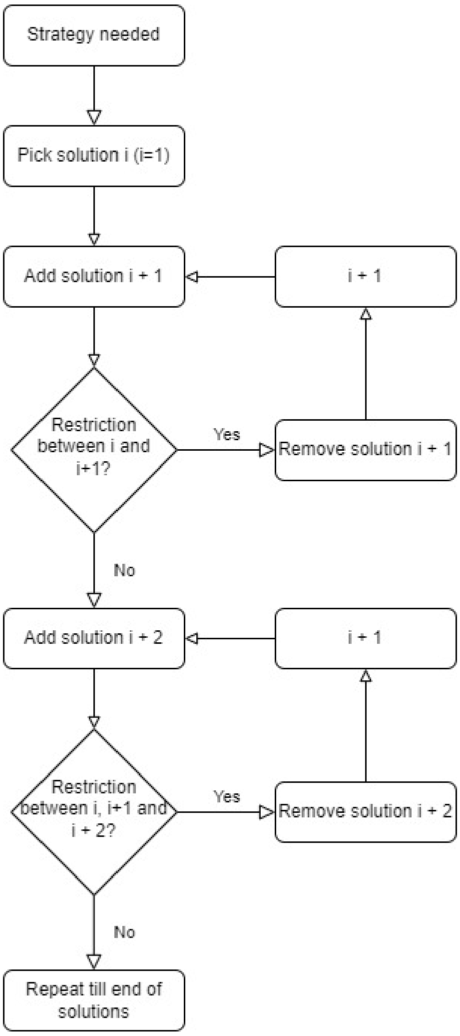

Figure 2.9: Simplified model decision tree

This tool will be used to build the different strategies of combinations of decarbonisation CRSs. Using this method will reduce the number of strategies created by the model and will thus reduce the run time of the model.

2.3.5 Financial Analysis

The financial analysis is, in essence, also a cost-benefit analysis. However, as the world normally experiences inflation every year and loans can be used for investments, so costs and benefits cannot normally be added and subtracted. To compare costs and revenues in time, both the NPV and the IRR are important tools to do so. The NPV, Net Present Value, is used to convert costs and benefits in the future to the current equivalent. When the NPV is positive, it means that value is created for the company. When it is zero, the company breaks even, and with a negative NPV, it loses value on the investment. [54] The formula with which the NPV is calculated is seen in formula 2.17. [20] Here C_t is the cashflow annually, k the discount factor, C_0 the initial investment and t the year. The discount factor is a factor that the company itself uses for their own yearly minimum acceptable return on investment. When using it in the model, the value for the discount factor should be derived from a comparable vessel as the vessel used in the case study. This should lead to a realistic comparison.

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{C_t}{(1+k)^t} - C_0 \tag{2.17}$$

The IRR, Internal Rate of Return, works based on the same principle as the NPV, but the IRR is the discount factor when the NPV is 0. So, the IRR presents the annual return on the investment for the lifetime of the project. The IRR is presented in the formula 2.18. [20]

$$\sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0 = 0 \tag{2.18}$$

When the future revenues are missing or if they are too unsure of predicting, the NPV can be changed into the NPC, the Net Present Cost. The NPC works with the same formula. However, there is now no cash flow, only cost. What also differs is that the NPV can assume values that are positive and negative, which determines if the investment is 'good' or 'bad'. The NPC, however, is only cost and thus only a positive value, where the lowest value, less cost, is considered 'best'.

The NPV, IRR and NPC can all be used to determine how "good" an investment is. However, the goal of the research is to make a tool that helps shipowners to determine which strategy to choose, and after the strategy, there is still research to be done. This means that further, in-depth research into the strategy and, thus, the finances should be done, which means the calculated NPV, IRR, or NPC is not that important. So, the NPV, IRR or NPC will be used in the model to determine which strategies are presented that are economically viable and will be presented to the user for an indication. Because the model will only use cost, the only choice is to use the NPC calculations, as the NPV and IRR also use income as a factor.

2.3.6 Monte Carlo Simulation

The proposed method uses large amounts of data, where several crucial parameters are notoriously unpredictable. So, it is important to see if there is a significant effect when there is a change in the variables. This can be carried out by a Monte Carlo simulation, which runs multiple calculations with different starting values. The basis of Monte Carlo simulations was already presented in the 18th century and has been used since the 19th century to confirm theories. [59] Using Monte Carlo simulations means that some values are not inserted as a constant but as a range in which the constant should fall. For every run of the model, the value is then chosen at random in the range presented and then the model is calculated with those values. If this happens often, more reliable data can be produced that better reflects the effect of the uncertainties than a single simulation. The proposed method has values, such as fuel prices, that are hard to predict in the future and for which price volatility should be considered. These values do include not only prices but also the properties of the CRS and the innovations for these CRS. When several simulations are carried out, the model could show which strategy and which CRS perform the best. This could lead to a clearer view of the future for the user and will mitigate some of the risks associated with predictions for the future.

Several aspects impact the results of Monte Carlo simulations; the number of iterations, the inputs subjected to the randomisation and the distribution of the randomisation The amount of iterations is important to find the reliability of the results. The more iterations, the more reliable the results. This is because the fault margin decreases, a difference of one is more significant for ten iterations than for ten thousand. So, when analysing data from a Monte Carlo simulation, it is important to evaluate the difference between the answers and adapt the amount of iteration on the outcomes. For instance, when 10 iterations all yield the same answer, it is not necessary to run more iterations, but when they all yield another result, an increase in iterations is recommended.

The inputs that are subjected to the randomisation of the Monte Carlo simulation also have to be chosen carefully. Not every input value could or should be used for this part of the simulation. It is important only to include values that have a high uncertainty or range. The distribution of the randomisation in the Monte Carlo simulations has two impacts, the range for the distribution and the sort of distribution. The range depends on the uncertainty of the corresponding input. The more accurate the input is, the less range is needed to deal with the uncertainty. For the distribution of the random numbers, there are several mathematical standards, such as the normal distribution or the uniform distribution, which can both be seen in figure 2.10. The Normal distribution is better suited to reflect values where the likelihood of the value decreases when it gets further from the centre. The Uniform distribution, on the other hand, is better used when the probability is equal for all parts. For this research, it is hard to predict most of the values for the future, so the centre of the range is also hard to predict. This is the reason that a Uniform distribution, with an equal chance for all values, is to be used in the research for all ranges.

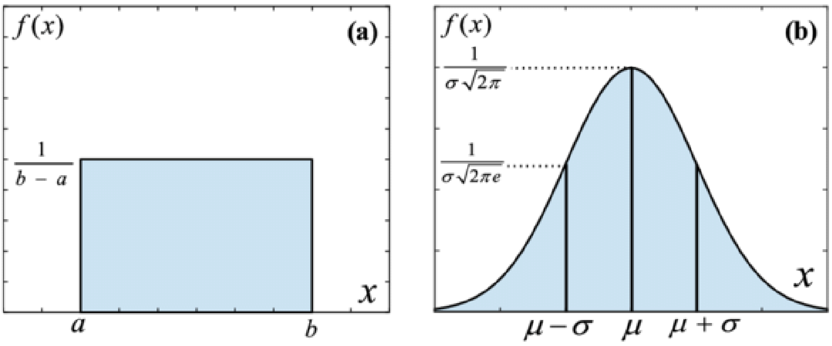

Figure 2.10: Difference between Uniform (a) and Normal (b) distribution [1]

2.3.7 Conclusion

The decision-making tool will be a hybrid form consisting of a multi criteria analysis, a financial analysis, and a carbon emission analysis, which in turn will be subjected to a Monte Carlo simulation. The carbon emission analysis is a coalition of the carbon emissions to see if the strategy complies with the regulation. For these strategies that comply with the regulations and the mutual restrictions, a financial analysis will be carried out. This financial analysis shall be an NPC calculation. The values from the financial analysis can be combined with the input data of the multi criteria analysis in a WSM model. The input of the MCA can be substantiated through a SWOT analysis. This all will be subjected to a Monte Carlo simulation that will reduce some of the problems associated with uncertain values.

2.4 Existing Decision Support Tools

The methods for analysis discussed in section 2.3 are the basis for decision support tools. These analysis methods are for the calculations, and the tools bring the inputs and outputs, as well as the interface. These decision support tools are mostly developed for one aspect of an investment decision. Such as a method presented by Metzger and Schinas [114], which focuses on calculating the overall NPV of the decarbonisation solutions. There are already some decision support tools that can help make decisions concerning decarbonisation or maritime investments. This section will discuss existing tools that concern alternative fuels, maritime investments, decarbonisation solutions, regulations calculators and combinations of those.

2.4.1 Alternative energy source

Several tools can help make decisions concerning the choice of alternative fuels. One of those is the tool for assessing bio-fuels by Perimenis et al. [132]. This tool uses an MCA to asses bio-fuels from different biomasses, such as oil, sugar and starch biomass. It assesses it on different criteria, such as production transport and end-use, with the AHP method. Another paper that discusses the use of MCA for choosing a different energy carrier is presented by Ahmed et al. [4], which uses a WSM MCA to find a suitable energy source, such as biomass or solar. These are good methods to compare similar alternatives, such as comparable fuels but are less suitable for larger differences, such as the different CRSs used in this research.

2.4.2 MCA for Regulations

There are also some decision support tools that are made to make decisions concerning regulations in engineering. One that is comparable with the direction of this research is the tool from Bui et al. [23]. This tool uses a fuzzy MCDM approach to find which alternative fuel is most suitable to comply with regulations such as EEDI and SEEMP. The method of analysis it uses is AHP and TOPSIS. There is also the tool by Beşikçi et al. that uses Fuzzy-AHP as its approach for the MCDM to comply with the SEEMP. The alternatives that are used in this research to comply with the SEEMP are all operational or operation measures. [19] There are not only tools to reduce CO_2 emissions but also NO_x and SO_x emissions, for instance, the tool proposed by Yang et al. [175], which makes use of TOPSIS to find which technology is best suited to reduce those emissions. These tools are, in essence, only MCDM tools that only use fixed values, which are found by surveys and are not, in terms of fuel use, calculated for the specific ship. These tools do not calculate the values of the regulations but rather choose options that will make the vessel comply with the regulations and then do the MCA that will fit the best.

2.4.3 Regulations Calculators

There are also some companies that have created calculators with which ship users can calculate their score for regulations such as EEXI and CII. These have been developed, for example, by DNV [36]. These tools calculate the scores of regulations and compare that with the required scores of those regulations in time. This makes sure that the user can see at what point in time the vessel does not comply with the regulations and, thus, at what time a CRS should be implemented. These are relatively simple tools that calculate the achieved score and then plot that against time. These tools could come in handy for the first assessment of the need for decarbonisation for a ship. However, they do not achieve much more than showing when the first measure should be implemented.

2.4.4 Advanced tools

The method that is presented by Hu et al. [63] is already somewhat more advanced. It ranks several different CRSs for their cost and potential, but it also ranks combinations of CRSs. So, this can be seen as a first start of a decarbonisation strategy in which a combination of CRSs is evaluated. Another somewhat advanced tool is presented by Ren and Lützen [134], which is an MCDM method that uses fuzzy-AHP to evaluate different CRSs on several aspects, such as cost but also the social-political impact. There are also some tools that are more advanced and combine several aspects of other tools. One of the main tools that can be used for the decarbonisation of vessels is the EE Appraisal Tool from the Green Voyage 2050 project.[76] This tool calculates the effect on cost and regulations of certain CRSs on a vessel. It calculates what the new EEDI and EEOI would be and what the payback period would be of a certain measure. This tool could be very helpful for ship owners, but it still lacks some aspects. The tool only works with groups of vessel sizes and not the specifics of a certain ship. This means that the effects of the CRSs are not calculated for the specific ship but are merely an indication. The EE Appraisal Tool does take into account some uncertainties but does that by altering the estimations of the effect of the CRSs and does not combine several risks.

2.4.5 Conclusion

The conclusion that can be drawn is that several different methods can help make decisions concerning decarbonisation. However, these tools are all focused on certain aspects of decarbonisation. There are MCDM tools that are used to find the most suitable CRS, methods that calculate costs, methods that calculate the effect of the CRSs on the emissions and the cost and methods that calculate regulations. All the tools presented can be helpful, but are, because they do not evaluate all aspects, less suitable to make a totally informed decision.

2.5 Conclusion

To draw a short conclusion from the literature, this section will summarise what CRSs, regulations and analysis will be used in the research. The research will focus on: WASPs, solar energy, cold ironing, slow steaming, air lubrication, carbon capturing, ship lengthening and alternative fuels. The WASPs are towing kite, Flettner rotor and turbo sail, and the alternative fuels are ammonia, hydrogen, methanol, bio-fuel and E-fuel. These have been chosen because of their impact and availability now or prospects for the future. The regulations that will be used in the research are the EEXI as an energy cap, the CII as the carbon cap and a CO_2 tax. These will be sufficient to present the current and coming regulations. The model will use several aspects of the tools presented in section 2.4, which also uses methods presented in section 2.3. These include an NPC calculation for the financial analysis and a WSM for the MCA. Lastly, there will be made use of a Monte Carlo simulation to deal with the uncertainties.

Chapter 3

Scope and Research Gap

Following the information provided in chapter 2, this chapter aims to present the scope of this research, and the research gap. The scope will present what will be included and what the model will focus on. The research gap will explain what is already researched and where the blind spot is of prior research.

3.1 Scope

The overall goal of the thesis is a decision support tool that helps stakeholders choose a strategy for decarbonising their fleet. There are, however, a significant amount of aspects and areas that can influence the decarbonisation strategy of the vessel. So, the scope will be used to delimit the goals and aspects of the research so that representative research can be carried out and the method can be validated. Further research could add aspects that have been placed out of scope, or even other aspects not mentioned here. The main aspects of the scope are as followed;

- The method should be applicable to deep sea monohull transport vessels.
- The focus will only be on regulations concerning CO_2 emissions and no other GHG emissions.
- The considered CRSs are; WASPs, solar energy, cold ironing, slow steaming, air lubrication, carbon capturing, ship lengthening and alternative fuels.
- The vessels are expected to operate in the whole world and be able to enter US and EU ports, and the method will not consider regional differences.
- The used regulations will be used as a hard target, so the method will be prohibited from exceeding the limits set by the regulations.
- The financial component will be limited to the cost generated by the vessel, and revenues will be placed out of scope.

The choice to only use deep sea monohull transport vessels for this research is because these vessels produce the most carbon in the maritime industry, with more than 55 000 ocean-going transport vessels. [78] What strengthened the choice for these vessels is that most of the regulations presented in section 2.1 are only applicable to those vessels.

The scoping decision to focus only on decarbonisation rather than including the reduction of NO_x, SO_x and other pollution in the scope of the research. The choice for decarbonisation has been based on the relevance of CO_2 as opposed to NO_x and SO_x. The relevance is the impact of the emissions. Although NO_x and SO_x are also greenhouse gasses, they have significantly less influence on climate change than CO_2, as almost 80% of the impact from GHG comes from carbon dioxide. [44] However, these emissions are also subject to rules and regulations; thus, CRSs that would not comply with those rules and regulations will not be presented.

The chosen CRSs are; WASPs, solar energy, cold ironing, slow steaming, air lubrication, carbon capturing, ship lengthening and alternative fuels. These CRSs have been chosen to get a representative display of CRSs, that considers multiple aspects. It is a mix of CRSs in use or earlier or later stages of development. It is also a mix of different technical and operational aspects: energy carriers, ways to provide towing power, and ways to operate the vessel.

Although the regulations shall differ for different regions and countries in the future, this research has chosen not to include regional differences in this model. This has two reasons: firstly, to simplify the model, and secondly, it is assumed that the model user will include the strictest regulations of the regions the vessel will enter. That is why the vessel should be able to enter EU or US ports, as it is assumed that those entities will have the most strict regulations. The regional differences will also not be included in terms of the yield of solar power or wind energy; the method will include averages for these values. This is for the same simplification reasons.

Setting the used regulations as a hard limitation has two arguments. Most importantly, deliberately not complying with regulations and thereby emitting more GHG than allowed cannot be considered responsible business management and engineering. The second is that when the choice has been made not to comply with the regulations from a financial point of view, the risk fine would be less than the cost that has to be made to comply. As it is unclear at this point how high those fines would be, they cannot reasonably be included in the research.

It has been chosen to only use cost in the method and not revenue. This has been done to remove some uncertainties. The model will be developed to deal with uncertainties; however, these are mostly connected. The cargo-hauling prices that determine the revenues are primarily independent of all other factors and determined by external factors. A relative payback time for CRSs can be derived from the fuel it saves, so there is no need to complexify the method.

3.2 Research Gap

The research gap is that there is no integrated method to support investment decision-making concerning decarbonisation in an uncertain future. The existing methods that have been turned into tools have been discussed in section 2.4, where it was found that several different tools are created for a specific part of the decision making. Existing tools work with percentages and do not precisely calculate the impact of the CRSs, in cost and emissions, for the used vessel. There is a need for a tool that computes the effects of the CRSs, in all combinations possible. Another part of the research gap is that there is a large array of tools, but they all focus on other aspects of decision making, and there is no integrated tool yet that combines all needs. There are existing MCDM tools for investments in decarbonisation, but they are not coupled with a regulations calculator that finds when the investments are needed. The current tools do not include a method to asses risks and consider future changes and developments. So, the major research gap is the lack of a tool that combines decision support with calculations of regulations in time, an assessment of risks and the calculations of the effect of the CRSs on cost and emissions.

Chapter 4

Model

This chapter shows what method will be used and how it is translated into a model which can be used for the case study. The schematic overview of the model can be found in figure 4.1. The selection process of the decarbonisation strategy is explained based on the criteria used as input for the several analysis. The chapter will then continue with the model approach, which will present what methods are used for the design and how they are coupled together. That section will also present the design of the model in MATLAB and the deliverables that will be the model's output.

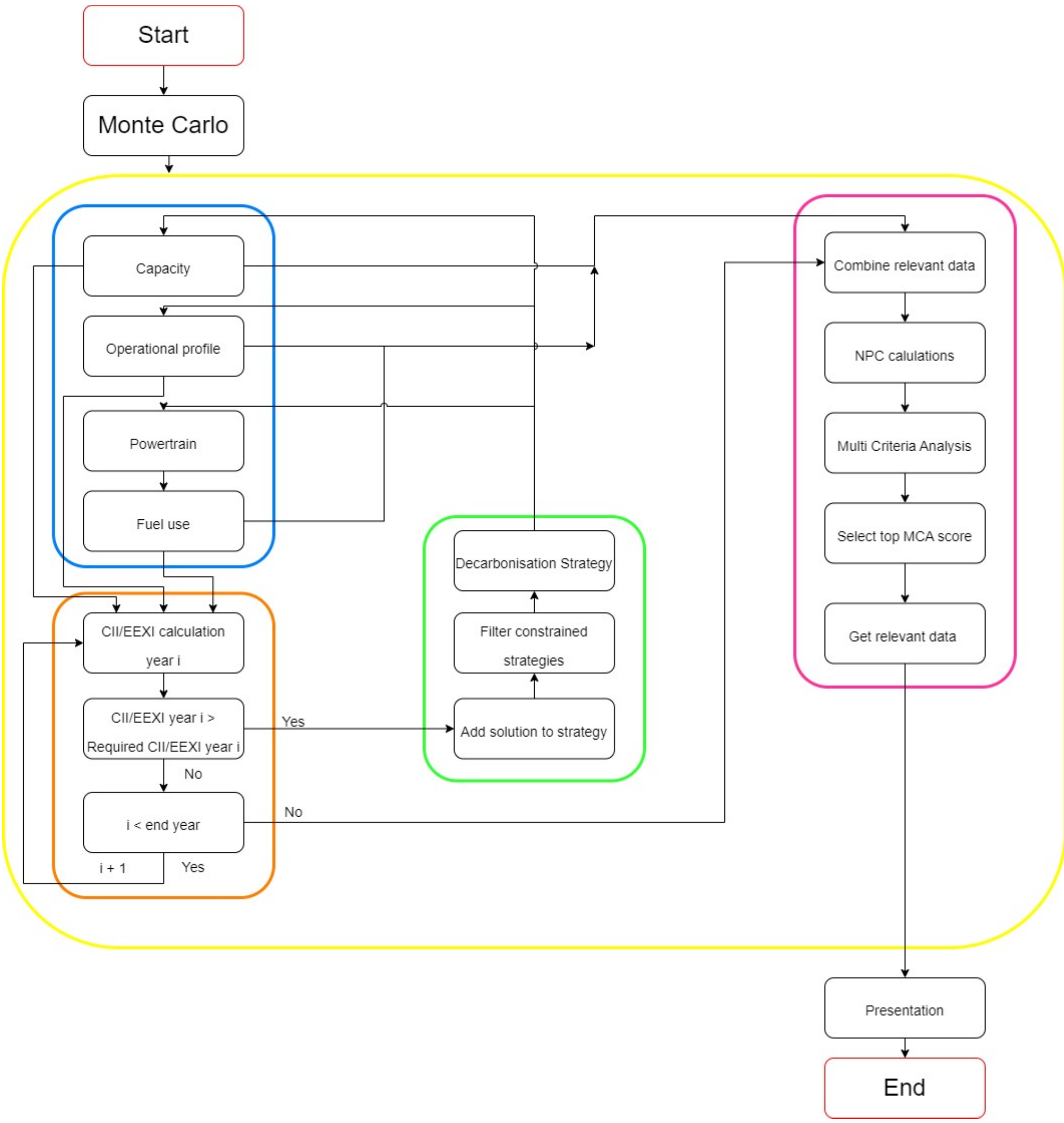

Figure 4.1: Schematic overview method

4.1 Schematic overview of the method

The method that will be the basis of the model is schematically presented in figure 4.1. It will start at the block 'start', which will start the calculation; firstly, it will begin with the Monte Carlo simulation, which is the yellow box. Then it will advance with the ship characteristics, which is the blue box. It will use the operational profile and the power train info to calculate the fuel use. Then it will advance to the regulations calculations, the orange part, where it checks when the vessel does not comply with the regulations anymore. This will trigger the entering of the strategy creation, the green part, where a CRSs is added to the vessel and will go back to the calculations where the impact of the CRSs is translated to the vessel characteristics again. This will continue till, for every strategy that will be compliant, the end of the time frame used. The data on fuel use and other expenses will be combined with the operational profile and capacity to create, with the NPC, a present cost per tonne mile. This will be combined with other CRS data for the MCA and will be entered into the MCA. The highest-scoring strategy will then be presented with the relevant data.

4.2 Selection Process

This section will show which criteria will be used for the selection of the strategy for the decarbonisation of the vessel. The criteria for the financial analysis, MCA and the carbon reduction criteria. It will set out why these criteria are used and how they will be used as input in the methods. Some criteria can be used for both the Multi Criteria Analysis and the financial analysis, but they are split as much as possible. The data used for these criteria in the case study can be found in chapter 6.

4.2.1 Financial Criteria

There are only two financial criteria; cost and revenue. However, this research will focus on the cost associated with the decarbonisation of the vessel, so the income will not be discussed in this report. The cost is divided into the operational cost (OPEX) and the capital cost (CAPEX). The criteria can be further divided into the coming parts:

- **OPEX**
  - Fuel cost
  - Crew cost
  - Maintenance cost
  - CO_2 tax
  - Others
- **CAPEX**
  - Training for crew
  - Installation
  - Equipment
  - Others

OPEX

The OPEX are the vessel's operating expenses, which means that all the costs are regularly made to keep the ship in service. This means crew wages, fuel costs, maintenance, stores for the crew, etc. These costs can be volatile and thus hard to predict. In the model, these costs will be subjected to the Monte Carlo simulation to simulate the volatility of those prices. However, these are also criteria for choosing a CRS. The CRS can provide extra propulsion power, which leads to the use of less fuel, and, thus, lower fuel cost. Some CRSs can lead to increased fuel costs, such as carbon capturing devices. [179] The costs can also increase if new CRSs need more maintenance, which could not only result in more costly but also more downtime, so less income. If a carbon tax were introduced, then that would also be OPEX, which would be presented in the model the same as the other OPEX. Other OPEX includes port charges, canal charges and additional administrative costs.

CAPEX

For this research are the investments in the innovative CRSs considered CAPEX. The CAPEX is the capital expense; these are investments in fixed assets. The CAPEX consists of several costs, mainly the cost of the equipment and the cost of installation. These are higher costs that the vessel's owner should do at specific points in time. New techniques on board could lead to training for the crew members, which is also a cost for the shipowner; these costs are also considered CAPEX. Planning these costs in the strategy is essential, so the owner has time to realise the required capital.

4.2.2 Multi Criteria Analysis

The criteria here are mostly the more subjective criteria that are nonetheless important for the shipowner to consider. These criteria consist of aspects of the CRSs that could provide risks or opportunities for the shipowner. These could be a capital risk on the CRSs itself but also risks in safety and the vessel's operational profile. Opportunities could be reduced cost and increased efficiency. The main criteria in the MCA will be the cost, which will be modelled in the financial analysis as discussed in section 2.3.5.

- Cost
- Technological readiness
- Safety
- Implementability
- Hindrance in operations
- Manoeuvrability
- Future proof

Cost

The cost associated with operating the vessel is a significantly important criterion. The costs implemented in the MCA are all the OPEX and CAPEX for the vessel's lifetime. How these costs are calculated is shown in section 2.3.5. To compare different conditions, the cost will be calculated as cost per tonne mile. So, how much does it cost to ship one tonne of freight for one mile?

Technological readiness

This criterion is about how far the technology is developed at this point. Some CRSs are currently hardly used, so there is a more significant chance that the CRS does not work as planned than by CRSs already widely used. It is how much it is used and how mature the technology is. For example, although cold ironing is not used as much yet, the theory and hardware needed are not that advanced, so the effect is more accurately predictable than the effect of rigid sails on the vessel.

Safety

The safety criteria show the new CRS's impact on the vessel. Of course, no technology will be presented that is objectively dangerous, but the innovative CRS could provide some safety risks. An example of a safety risk associated with slow steaming is the lack of reserve power. When a smaller engine is installed, or the MCR is taken back, less power can be used in an emergency with extreme weather impact, as discussed in section 2.2.1. There are also essential safety risks concerning alternative fuels, such as toxicity, explosiveness and storage under pressure.

Implementability

The implementability is the criterion of the ease with which this CRS can be installed and used on a vessel. It could be that the time between ordering and installing the CRS is exceptionally long. In that case, it could be that it cannot be used in the chosen strategy. These criteria will also consider the time it costs for the crew to get familiar with the CRS and how to use it optimally.

Hindrance in operations

The CRS could be a hindrance during the operations of a vessel; such a case is when Flettner rotors are on board a ship that is loaded by cranes, the cranes then must consider the oversized rotors on deck. The hindrance could also be that the CRS reduces the deck space where usually the crew could work. An example is when a crude carrier's whole deck is filled with solar panels. This not only reduces the amount of cargo that can be carried, but it could reduce the workability of the vessel for the crew. This could all result in an increased risk of incidents on the ship, which could damage or delay the vessel. The impact on the seakeeping should also be noted in this criterion; when the seakeeping is negatively impacted, it makes the operations harder on the ship and crew.

Manoeuvrability

The CRS can impact the vessel's manoeuvrability, which is the case when sails are installed on the vessel; it then becomes higher than before. This means that certain places become unreachable or are more challenging to reach. It could also be that the CRS impacts the ease with which the vessel makes manoeuvres, such as sails. This also means that the vessel is less flexible in unforeseen circumstances, for example, the change of route, change of destination or the change in weather.

Future proof

The future proof of CRS refers to the ability of the CRS to be relevant in the future. It could be that some CRS are not accepted anymore in the future as being "green". It could also be that other CRSs are less likely to be installed on the ship due to a CRS. This means that it could be that when a CRS is installed, another one cannot be installed anymore. This criterion also considers the ability of the CRS to be upgraded or improved, meaning that if the technology improves, it can be quickly brought up to the new standard.

Custom criteria

The criteria chosen here will be considered the base criteria, but that does not mean that all users of the method will have to use (only) these. It could be that users will want to combine criteria, such as hindrance in operation and manoeuvrability. It could also be that criteria are preferred split, one example of which could be to split safety into safety on board the vessel and safety for the environment and surroundings. The cost part is indispensable; otherwise, the model would become only an MCA.

4.2.3 Carbon Reduction Criteria

The carbon reduction criteria are the regulations that concern the emission of carbon. As discussed in section 2.1.7, the regulations that are in use come down to a carbon cap (CII), an energy cap (EEXI/EEDI) and a carbon tax. The carbon tax is considered a financial criterion, but the carbon cap and energy cap are carbon reduction criteria. In the model, they will be calculated and used, at first, with the formulas from the CII and EEXI/EEDI. In a later stadium, this could be changed to other formulas or values, but that will be considered further research. What should also be noted is that shipowners could require stricter decarbonisation than what is ordered by the regulations. This could be because the owner wants to promote itself as a company with concern for the environment. So, the model should be able to add more strict rules for decarbonisation.

4.3 Modelling Approach

The modelling approach section will show how the different methods that will be used in this research are combined and will show how the model is built. First, it will explain how the different analyses are combined and what the method will be. Then it will show the schematic of the design of the model and how that is translated into a MATLAB model. Firstly the design of the model is discussed and then how the Monte Carlo simulation is carried out for the model. The section will end with the deliverables the model is going to present.

4.3.1 Working of Model

The model is built up from different segments to create a complete model where all aspects are associated with the decarbonisation process. The parts of the model can roughly be divided into the following segment:

- Initial ship characteristics
- Carbon Emissions and Regulations
- Effect of decarbonisation solutions on the vessel
- Strategy creation
- Financial analysis
- Multi criteria analysis
- Monte Carlo simulation

The initial ship characteristic contains calculations concerning the basis needed for calculations; this includes trip lengths, fuel use and engine power. These calculations can further be used to calculate the effect of the decarbonisation solutions on the vessel. The CII/EEXI calculations will be carried out for the initial vessel, and the required and attained CII and EEXI will both be calculated; this will also include a calculation to find the total mass of the CO_2 emitted that can be used for the carbon tax calculations. Later in the model, they will be calculated per time step to find if the vessel still complies with the regulations. The next segment works in combination with strategy creation; the decarbonisation effect is the calculations on how they affect the vessel. With the strategy creation, it also calculates the result when combined with other decarbonisation solutions. After all feasible strategies are created, they undergo a financial calculation, resulting in a cost per tonne mile. This is then inserted in the next segment, the multi criteria analysis. The whole model is then subjected to a Monte Carlo simulation.

4.3.2 Initial calculations

The initial calculations on the vessel are mainly focused on finding the fuel use of the vessel because these determine the EEXI/CII scores and, thus, the decree of decarbonisation required. To do this, the most standard route of the vessel is used. Using the ship's design speed, the distance between harbours and the average time spent to load/loss the sailing time can be calculated. To find the normal fuel use, the design resistance is used to find the used engine power, which, together with the auxiliary power needed, can be used to find the fuel use. Therefore the ratio of different fuels being used, in the case of dual-fuel engines, is required, which leads to the initial fuel use.

These calculations can also find the fuel used when the vessel will sail slower, slow steaming. The formulas from Klein Woud and Stapersma can be used for these calculations. [81] This mostly includes formula 4.1, 4.2 and 4.3. Where R_d is the design resistance, c_1 constant one, V_s the ship's speed, P_p the propulsion power, P_e the engine power, η_{TRM} the transmission efficiency and η_D the propulsion efficiency.

$$R_d = c_1 * V_s^2 \tag{4.1}$$

$$P_p = c_1 * V_s^3 \tag{4.2}$$

$$P_e = \eta_{TRM} * \eta_D * P_p \tag{4.3}$$

It is known that reducing the energy use of a vessel does not reduce the fuel use one on one. This has to do with the design of the engines which are made to run optimally for a certain output. However, it has been chosen to use a constant SFC for every fuel and this has a few reasons. On of these reasons is that small changes in the output of the engine do not influence the SFC significantly. This could also happen when a combination of CRSs is implemented that creates energy demand that stays the same. Another case could be that there was already a plan to install a new (more efficient) engine, which could then be replaced by a smaller unit. These reasons, and for some simplification of the model, make the SFC is taken constant

4.3.3 Carbon Emissions and Regulations

To find the required EEXI and CII the calculations from section 2.1.2 and 2.1.3 are used. However, the calculations that calculate the attained EEXI and CII are somewhat elaborate and need to be simplified. This has been done because several values are specific for individual vessels and simplify the model. So the calculations for the CII and EEXI are transformed into equations 4.4 and 4.5.

$$CII_{attained} = \frac{\sum_j C_{Fj} \cdot FC_j}{Capacity \cdot D_t} \tag{4.4}$$

$$EEXI_{attained} = \frac{\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)} + P_{AE} \cdot C_{FAE} \cdot SFC_{AE}}{Capacity \cdot V_{ref}} \tag{4.5}$$

To calculate the weight of carbon emitted to use in the carbon tax calculations, formula 4.6 is used. This formula calculates the total weight in tonnes emitted by the vessel, which could be used to calculate the total cost of the carbon tax for the vessel.

$$Weight\,Carbon = \sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)} + P_{AE} \cdot C_{FAE} \cdot SFC_{AE} \tag{4.6}$$

4.3.4 Financial Analysis

The financial analysis is used to compare the economic impact of the CRS on the vessel and, thus, the company that owns the vessel. It is made up of different parts; fuel cost, maintenance cost, crew cost, carbon tax, port costs and CAPEX of CRS. As described in section 2.3.5, this is done using the NPC and the expected increase or decrease of prices. This would mean that the OPEX for the vessel should be calculated for every time step of the model so that it could be translated to the discounted cost of today. However, to minimise the number of calculations in the model, the calculations are grouped in parts where there is no change in specifics in the vessel. These are combined with the average discount rate, the number of years to get the discounted cost for all these years and the yearly increase/decrease of the prices. The sum of all these costs leads to one number that represents all the costs made for the vessel's lifetime, discounted to current days.

So per year, the NPC is calculated according to equation 4.7 and then divided over the tonne miles of that year to end in an ultimate Net Present Cost per Tonne Mile (NPCTM). This leads to the formula 4.8, where the C_t values stand for specific cost in year t and D_t is distance sailed in year t. Looking at formula 4.8 it can be seen that not only are operational costs discounted back to the current cost, but also the CAPEX associated with the CRSs.

$$\text{NPC} = \sum_{t=1}^{n} \frac{C_t}{(1+k)^t} \tag{4.7}$$

$$\text{NPCTM} = \sum_{t=1}^{n} \frac{C_{t_{CAPEX}} + C_{t_{Fuel1}} + C_{t_{Fuel2}} + C_{t_{Maintenance}} + C_{t_{Crew}} + C_{t_{CO_2}} + C_{t_{Port}}}{(1+k)^t * D_t * Capacity_t} \tag{4.8}$$

4.3.5 Design of the Model in MATLAB

The model is designed in MATLAB for the calculations, and the interface is made in MS Excel. This section explains how the model is programmed and how the different sections connect. Figure 4.3 is a schematic overview of the model, which is somewhat different than the schematic of figure 4.1. This is because figure 4.3 shows how the model is programmed. The biggest difference is that slow steaming is integrated differently into the model than the other CRSs.

The green, blue and red dotted boxes stand out, which show the parts that are calculated multiple times for different inputs. The blue box shows the various strategies so that part of the model is calculated for all the different combinations of CRS. This means that the impact of all the sets of combinations of CRS, except slow steaming, are calculated, and their effect on the finances of the vessel; is done for all combinations of strategies as indicated with the arrow back to the check CRS block. The red box is calculated for different speed steps, essentially the CRS slow steaming. Every run of the red part starts after the financial analysis for every speed step. The green box covers the Monte Carlo simulation, which does the sensitivity analysis for different scenarios. It can be seen that when all output data is gathered, it will start with the next iteration for other Monte Carlo values. Figure 4.2 shows the main script of the MATLAB model, where the other scripts that represent the various analyses are called. This section will further explain how the different parts of the model are connected.

```
%% Variables form excel
Variables_from_excel
%% Monte Carlo loop
Monte_Carlo_values

for i_MC = 1:Amount_of_monte_carlo
%% Compute new variables with MC values
MC_Variables
%% Variables created in matlab
Variables_creation_matlab
%% Set base line
Base_script
%% Total run

for j1 = 0:Amount_of_speed_steps-1
V_s_current_model = Speed_steps_matrix(j1+1,2);
% Run of initial variables of vessel
Initial_calculations
% Run data for different solutions
Check_solutions_and_change_variables
% Run the model through
Run_part_further
% Financial Analyisis
Financial_analysis
end

%% Multi criteria analyis first part
MCA
%% Rewrite date
Data_change_1
%% Multi criteria analyses
MCA2;
%% Output
Output
end

%% End and presentation
Presentation_and_plots
```

Figure 4.2: Main script in MATLAB

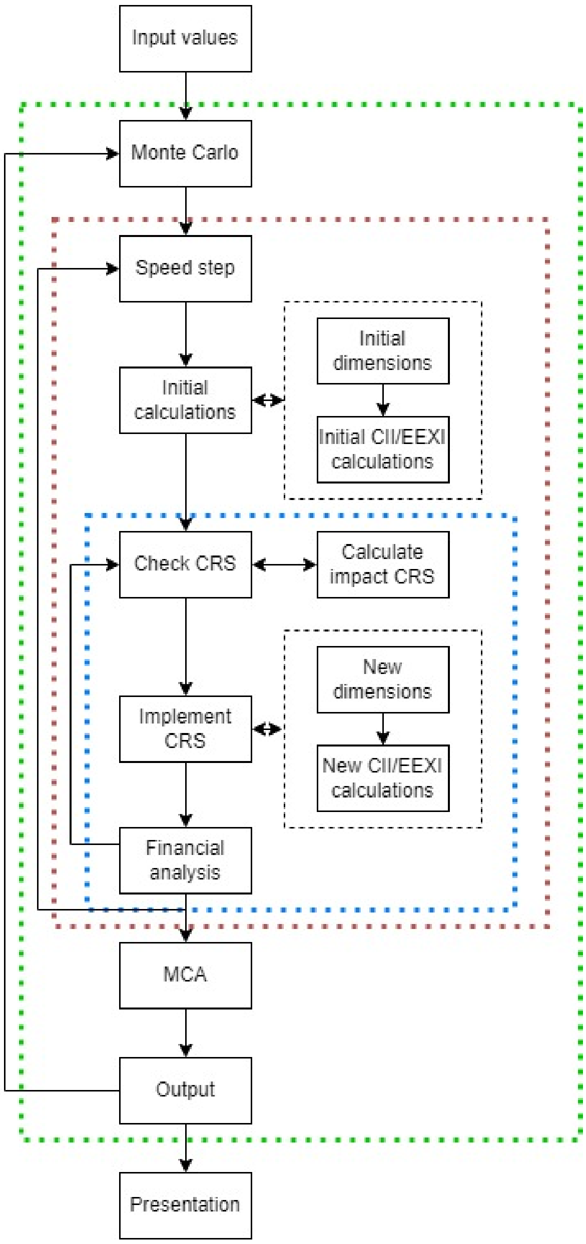

Figure 4.3: Design of model

Input values

The input values are a combination of the MATLAB and MS Excel parts. The Excel file acts as an interface where there is a clear overview of the inputs and how they should be used. There are six colour codes in the excel, which can be seen in figure 4.4. The fixed inputs are inputs that should, in normal circumstances, not be changed; these include, among other things, the values concerning the regulations already in effect. The green inputs are considered fixed per ship, so when the tool is used for a particular vessel, these are also not meant to be changed. Next are the fixed operational inputs; these can be seen as similar to the ship fixed inputs; however these concern operational inputs, such as average trip length and loading/unloading time. Of the last three, the 'open' inputs are the most important, which can be used to inspect the effect of different scenarios on the vessel's future. These include, among other things, the values for the upcoming, unknown regulations, the time frame of the model and the cost of the fuels. Other vital inputs include the ranges for the Monte Carlo simulation and the selection of CRS used in the model. The group inapplicable are older parts that are not used anymore or parts that become inapplicable due to choices of the 'open' inputs. For instance, when the CO_2 tax is selected to be calculated with a price for the different fuels, the cost of CO_2 tax per tonne CO_2 becomes grey. The last, yellow, inputs are the inputs that are not yet used but can be implemented in the future when the tool is extended to become more complex. The Excel part also includes, on different sheets, the values concerning the MCA and the CRS. These are considered fixed for this research but could be adjusted by a user.

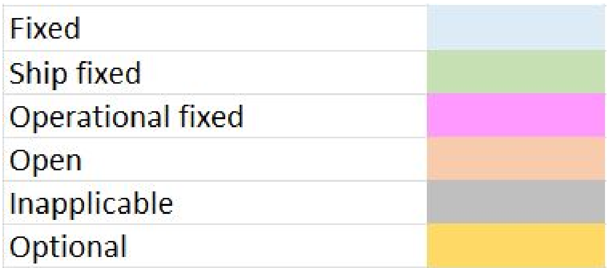

Figure 4.4: Color codes excel

All this data is imported by MATLAB from Excel and used to assign values to the variables of MATLAB, which happens in the 'Variables_from_excel' script in figure 4.2. The next step in the model is to create data that are the preconditions to use the model. This mainly includes the creation of the Monte Carlo simulation values. MATLAB creates these values randomly in the range set in the Excel file. These values impact many other values that are used, and this will be explained in section 4.3.5.

Monte Carlo simulation values

The Monte Carlo simulation will run the model a certain amount of times, an input from the Excel file, and will run all these simulations with different data. In figure 4.3, the green block shows what part will run several times for each Monte Carlo iteration. This part of the model will make sure that the model runs the designated amount of simulations and will use the Monte Carlo values to create the data used for each run. This is also the point that includes the creation of tables with lookup data that can be used further in the model. One example of these tables with lookup data is tables with the fuel cost per certain year, but also tables with all the different combinations of CRS. The part that is run for each Monte Carlo simulation covers the whole model, from the initial calculations to the output values created by the model. In figure 4.2 the script 'Monte_Carlo_Values' creates the random numbers and the for-loop below it starts the iterations. In these iterations, there are some more values that are created that have different values for each iteration. It also creates some data and other tables needed to run the model. These are the 'MC_Variables', 'Variables_creation_matlab' and 'Base_script' parts.

Speed step

For every iteration of the Monte Carlo simulation, the model will run for all the speed steps selected. This is shown in figure 4.3 in the red dotted area. This part includes the initial calculations that are carried out for the vessel without the addition of any CRS, except slow steaming, and the calculations for all the different strategies. In the MATLAB model, the speed steps are created in the second for-loop, as seen in figure 4.2.

Initial calculations

The initial calculations consist of the initial dimensions and the initial CII/EEXI calculations. In the MATLAB model, this is the 'Initial_calculations' script as seen in figure 4.2. The initial dimensions calculations part calculates the total fuel use for the starting conditions. This is achieved by calculating how much time the engines run annually and on what fuel. With the help of the total fuel use of the vessel per year, the CII and EEXI can be calculated. That is the second part of the initial calculations. This part calculates the CII and EEXI score for the vessel without using CRS and calculates the required CII and EEXI for the whole time frame under normal conditions. The model carries on to the 'Check CRS' part with this information.

Check CRS

The 'Check CRS' part starts the blue block from figure 4.3 and the 'Check_solutions_and_change_variables' block in figure 4.2. Firstly it checks if the vessel needs to have CRS added. This is the case when the initial calculations indicate non-compliance with regulations before the end of the time frame. In that case, the model will run for all possible combinations of CRS, up to five CRS per strategy, and this will be carried out in the 'Calculate impact CRS' part of the model. The possible combinations, however, have some limitations. Such a case is the combination of Flettner rotors and turbo sails or the restriction to use more than one alternative fuel. The model calculates what change the CRS would impact on the vessel or the combined impact on the vessel. The next part of the calculations will be done in the sub-part of 'check CRS', the calculate impact CRS' part, as seen in figure 4.3. These parts calculate the effect of the CRS on affected parameters of the vessel, such as the increase or decrease of engine power, change in loading or change in auxiliary power. It also takes into account the effect that the other CRS have on the vessel. For instance, when a Flettner rotor is installed, the area for solar panels decreases. The values that are impacted in this part are required auxiliary power (onshore and offshore), resistance, deck space, capacity, change in engine power, the carbon conversion factor of the fuel, sort of fuel and the ratio of fuels. This part of the model shows what the impact would be but not when the CRS is implemented; that is the next part of the model.

Implement CRS

The section 'implement CRS' starts when the vessel does not comply with the regulations and will calculate the vessel's dimensions with one or more CRS implemented. This section is called the 'Run_part_further' in figure 4.2. For all the sets of CRS created in the 'Check CRS' part, this part of the model implements the CRS. So, firstly, the dimensions of the vessel are recalculated with the first CRS of the strategy in the 'new dimensions' part of the model, which means that the change of dimensions from the 'check CRS' part is implemented on the original dimensions. This can be used to calculate the fuel use of the vessel, which can be used in the next part, which are the regulations calculations. This is the 'new CII/EEXI' block from figure 4.3, which will check if the vessel now complies with the regulations. When that is the case, the model keeps reviewing the calculated CII/EEXI against the required CII/EEXI until the vessel does not comply or the end of the model's time frame is reached. When the ship is no longer in check with the rules, the model implements another CRS in combination with the one already implemented, and this part starts over again. This will continue till the end of the time frame of the model. At this point, it is clear how much and which fuel will be used each year, and this can be used in the next part of the model.

Financial analysis

The financial analysis part will calculate the total cost made for the vessel's entire lifetime, so the model's whole time frame. Together with the capacity of the vessel, which could change due to the CRS, the operational data, such as percentage ballast trips and sailed miles, will lead to the total cost per tonne mile. The financial analysis calculates all costs for every set of years that there is no change in ship characteristics in the same instance, concerning the increase or decrease of costs over time and discounted to the cost value for the model's first year. The cost is calculated for; CAPEX, fuel use, maintenance, crew cost, CO_2 tax and port costs. The cost per tonne mile is the input for the next part of the model, the MCA.

MCA

The financial analysis yields a cost per tonne mile for all the strategies and speed steps. The MCA uses these costs combined with the scores for the different CRS, as presented in section 6.3.2. The used method is, as presented in section 2.3.3, the Weighted Sum Model (WSM). The MCA scores of the different CRS used in a strategy, except the score for costs, are averaged, and all the scores, including cost, are then normalised for all the strategies presented. Then, using the weighted sum model from section 2.3.3, the total MCA scores are calculated and then in terms placed on a scale of 0-100 where 0 is the lowest possible score and 100 is the maximum score achievable. In the MATLAB script of figure 4.2, it is presented by two scripts, 'MCA' and 'MCA2', where the script between them changes some of the data in a more usable format.

Output

The output part of the model selects the highest-scoring strategy and saves this strategy, combined with the corresponding MCA score and cost per tonne mile. This is done for all Monte Carlo iterations and will thus lead to a list of the highest-scoring strategies for the amount of Monte Carlo simulations run. This can be used in the presentation part of the model. It is also called 'Output' in the MATLAB model, as shown in figure 4.2.

Presentation

The presentation part of the model mainly shows the effect of the Monte Carlo simulations and will thus show how sensitive the model is. The primary importance of the model is to show which strategy is most common and which CRS is advised the most. This is done by counting how many times a CRS is presented in the strategies, it could be that a CRS is most common but is not included in the most common strategy, and these are presented in a bar plot for the corresponding speeds. The model also offers two scatter plots in which the MCA score or cost per tonne mile is plotted against the strategies.

4.3.6 Monte Carlo simulation

As discussed in section 2.3.6, the Monte Carlo simulations have three aspects: the number of iterations, the values that are randomised and the distribution of randomisation. After testing the model, it became clear that 100 iterations were enough to find a clear answer to which strategy was most likely to be chosen. Sometimes, when the hypothesis was that the model would only yield one strategy, it was first tested for 25 iterations to reduce the computing time. When that did non clearly shows one strategy, it would still be run with 100 iterations. The model was also tested with 1000 iterations to find if the model was stable and, thus, if 100 iterations were enough to get relevant data. There were slight differences between the 100 and 1000 iterations simulations, but the randomisation can explain these from the Monte Carlo simulation. For instance, in table 4.1, the top-scoring strategies for the no EEXI scenario for two different results of 100 iterations and one set of results for 1000 iterations are shown. It can be seen that there is not a lot of difference in the selection percentage. The most significant difference between the two options is that for the 1000 iterations option, there are a lot more strategies selected at some point, but these are strategies that are chosen around 2% or less. The Comparison finds that the sum of the percentages of the first ten highest-scoring strategies is comparable between 75% and 73% for the 100 iterations to 70% for 1000 iterations. What also should be noted is that the model selects the best scoring strategy from every run, so there is a high chance that strategies with almost comparable scores are not selected. That is why the amount of times a CRSs is scored should also be compared. As can be seen in table 4.2, these are also comparable, which shows that 100 iterations are similar to 1000 iterations.

Table 4.1: Comparison between the number of iterations

1000 runs		**100 runs (1)**		**100 runs (2)**	
Strategy	**Percent**	**Strategy**	**Percent**	**Strategy**	**Percent**
12-3-5-4-6-8.5	20	12-3-5-4-6-8.5	23	12-3-5-4-6-8.5	17
12-8.5-0-0-0-0	14.6	12-8.5-0-0-0-0	17	12-8.5-0-0-0-0	16
12-3-5-4-8.5-0	8.9	12-3-4-8.5-0-0	6	12-3-5-1.2-6-8.5	9
12-3-5-1.2-6-8.5	6.4	12-3-5-1.2-6-8.5	6	12-3-5-4-8.5-0	8
12-3-5-6-8.5-0	4.3	12-3-5-4-8.5-0	6	12-3-5-6-8.5-0	6
12-3-5-1.2-4-8.5	3.6	12-4-1.2-3-8.5-0	4	12-3-5-8.5-0-0	5

Table 4.2: Comparision CRSs selection

	1000	100 (1)	100 (2)
Turbo Sails	4.8	2	1
Flettner rotor	35.7	37	41
Cold ironing	0.3	0	0
Towing Kite	82.3	82	80
Solar energy	61.3	63	55
Ship lengthening	71.6	60	65
Air Lubrication	54.2	51	53
Waste Heat Recovery	0	1	0
Carbon capturing device	5.9	4	5
Ammonia	0	0	0
H2 Liquid	0	0	0
H2 Gas	0	0	0
Methanol	94	95	95
Bio Fuel	0	0	0
E-fuel	0	0	0

It was essential to choose which values would be subjected to the Monte Carlo simulation and find which inputs would have high uncertainty. These include the prices for fuels and shore power in the future, the CAPEX of the CRSs in the future, other OPEX and the effectiveness of the CRSs in the future. The regulations are also unsure, but these values' effect is better presented by changing the reduction percentage in different scenarios. Most prices can vary in two aspects, the base prices and the increase/decrease over time. So, there is a range for the starting price and the percentage of change in the future per year. For all the increases and starting values, it has been decided that the distribution should be a uniform distribution. This was chosen because these values are hard to predict, and the effect of change in range would become more apparent. The standard range has been set from 0.75 to 1.25 from the base of 1, so 25 % more or less than the base value. However, to see the effects of developments in the future, the model can be run in different scenarios with different ranges.

4.3.7 Order of model

The model includes several different analyses that are coupled the create the proposed method. This section sets aims to present the choice for the proposed order. Some choices are logical and impossible in any other order; for example, when costs are an input in the MCA, the finical analysis will always have to be carried out first. There are several restrictions; namely, the calculations of the effect of the CRSs on fuel use have to be carried out prior to the regulations and financial calculations. This is because both are influenced by fuel use; the regulations concern carbon or energy, both dependent on the fuel use, so these calculations have to be prior. The financial analysis also depends on the fuel cost and, thus, the fuel use. The proposed method has placed the regulations calculations before the financial analysis. This has been done because the regulations are a hard limitation and, therefore, easier to use to eliminate a large part of the unusable data. This is opposed to the financial analysis, where it is less clear when a strategy is unsuitable. The Monte Carlo simulation has been placed to include uncertainties in all analyses. This has been chosen because, in all analyses, there are uncertainties. However, when the method is required to produce a faster-running model or when some uncertainties have been made certain or mitigated, the method could reduce the parts that are subjected to the Monte Carlo simulation. An example of this could be only to include the financial analysis in the Monte Carlo simulation.

The most interesting choice that has been made is the choice to use cost as an MCA input and, therefore putting the selection of CRSs after the financial analysis. This requires a pre-selection of CRSs that are considered suitable for the project. The other option would be to put the MCA before the financial analysis. The user would then set a minimum score that the strategies should achieve to advance to the financial analysis. Both options have their merits; the proposed option of MCA after finances uses the MCA as a tie-breaker when strategies have almost the same cost per tonne mile. Whereas the other option, with MCA before finances, uses financial analysis to choose the cheapest option from all suitable options.

The reason why the method uses the proposed option to put the MCA after the financial analysis is that there is a large chance that the cost difference between two or more strategies is negligibly small. In such a case, it is more desirable to use other criteria to make the ultimate decision, so in that case, the MCA acts as a tiebreaker. When this would be the other way around, the MCA would select all suitable deemed strategies; however, after that decision, the MCA score would not be used anymore. That could lead to a case where two strategies have almost the same cost per tonne mile, but one is a negligible amount cheaper. That strategy would then be selected by the method even if that strategy would have a significantly lower MCA score than the other. The effect of this is shown in table 4.3, which shows the top 10 strategies with the lowest cost per tonne mile. The difference is the most visible between the strategies in places 3 and 4. The fourth strategy cost 0.001482 % more than the third, whereas the difference in MCA is 1.223 % in favour of the fourth strategy. This means that according to the MCA, the fourth strategy is much more favourable for the user on other aspects than the small difference in cost, especially because the cost is a large input in the MCA. So, to prevent that negligible difference in cost from preventing the model from choosing a more suitable strategy according to the MCA, it has been decided to put the MCA after the financial analysis.

Table 4.3: Use of MCA as a tiebreaker

Place	Strategy code	Normalised cost per tonne mile	Normalised MCA score
1	12-1.1-5-4-6-8.5	1	93.32583
2	12-1.1-4-6-8.5-0	0.999216229	92.46303
3	12-1.1-2-4-6-8.5	0.999216229	92.42751
4	12-1.1-3-4-6-8.5	0.999201417	93.55776
5	12-1.1-4-6-7-8.5	0.999183512	92.19996
6	12-1.1-6-8.5-0-0	0.998895017	91.78729
7	12-1.1-2-6-8.5-0	0.998895017	91.87475
8	12-1.1-3-6-8.5-0	0.998891144	93.23215
9	12-1.1-2-3-6-8.5	0.998891144	93.06417
10	12-1.1-6-7-8.5-0	0.998862113	91.60219

4.3.8 Deliverable of the Model

The key deliverable of the model is to show that the method presented in this research is sound and what impact specific input changes have on the model's output. The model aims to show which set of CRSs is the best to decarbonise the vessel, so every Monte Carlo iteration selects the best scoring strategy. These will be presented, but it will also be checked how many times a CRS is part of a strategy for all the Monte Carlo simulations to compare if the most selected CRS is also in the best scoring strategy. To visualise this, the MCA scores and cost per tonne mile can be plotted in two different scatter plots against the strategies to show which strategies are mostly chosen and with what values. The model can also create a bar plot to show how often a strategy presents a CRS. The percentage of times a strategy contains a specific CRS is plotted in this plot. The bars are associated with the different speeds used in the method to show how slow steaming impacts the division. However, the bar plot is only interesting if more than one speed is selected. Another plot that the model will be able to present is a line plot that shows in which order the CRSs are mainly selected. It shows for every step that a new CRS can be installed and what percentage of the Monte Carlo iterations have a strategy with the CRS in it. This could show if some CRS are faster chosen than others or if some CRS are more effective over time.

A code will present the strategies to reduce the lengths of the labels, where every number represents a CRS, as seen in table 4.4. The code for the strategy is built from 6 numbers, where the first number indicates the speed (so if slow steaming was implemented or not) and the rest the CRSs, in order of how they are added to the vessel. An example can be seen in equation 4.9, where the code means a ship speed of 12 knots, with then solar energy installed, followed by ship lengthening, turbo sails and bio-fuels. The 0 indicates that no more solutions were needed to comply with the regulations in the time frame. The CRS that have the same number before the decimal point are options that cannot be combined: the group of sails (number 1) and the group of alternative fuels (number 8). The sail group does not include the towing kite because it could work together with the other sails, as discussed in section 6.2. Carbon capturing is included in group 8 because combining carbon capturing and alternative fuels is not logical.

$$12 - 4 - 5 - 1.1 - 8.6 - 0 \tag{4.9}$$

Due to the Monte Carlo simulation, some data is difficult to present in a well-organised manner, of which the most important is the time when a CRSs is implemented in the research. When the model is run once, it is evident in what years the ship does not comply with the regulations and, thus, in which year the certain CRSs are implemented. However, when the model is run many times, these dates will have some distribution. This is because will the small changes introduced by the Monte Carlo simulation, the years in which a CRS is implemented will differ. So, because it is unwanted to include a year in the strategy code, it has been decided only to show the code and, thus, the order in which the CRSs have been implemented. However, this data is created, so it can be found in the output data sets and could be presented clearly in a further version of the model. This could be with an average, median, mode or range.

Table 4.4: Numbers associated with respective CRSs

Number	**CRS**
0	No CRS
1.1	Turbo sails
1.2	Flettner rotor
2	Cold ironing
3	Towing kite
4	Solar energy
5	Ship lengthening
6	Air lubrication
7	Waste heat recovery
8.1	Carbon capturing device
8.2	Ammonia
8.3	H2 Liquid
8.4	H2 Gas
8.5	Methanol
8.6	Bio-fuel
8.7	E-fuel

The Monte Carlo aspect of the model will show the distribution of best scoring strategies for different sets of inputs and, thus, other circumstances for the future. When the distribution shows a large scatter of strategies, there is no clear view of what strategy will be considered the best under changing circumstances. If the Monte Carlo simulation distribution is smaller and one or few strategies are mainly selected, these are still considered best under varying circumstances. So, the most common strategy should be regarded as the best option; however, there are some exceptions. This is the case when two or more different options are selected (almost) the same amount of times as the best scoring strategy; then, there is less clear which the best strategy is. Of course, there is also some difference in these, for example, that two almost equal strategies are selected. This could be the case when two strategies only differ in one CRS or if one CRS is added or removed in contrast with another. Then it could be concluded that the main part of the best strategy is clear, but there is a difference in the details.

4.4 Conclusion

The conclusion drawn from this chapter is mainly the design of the method and how it will be placed in a model that can be used for the case study. The model will use calculations that impact the power train to calculate fuel use and other expenses. The model will use the regulations as boundaries and optimise to the highest score for the strategy in the MCA. The model will also be subjected to a Monte Carlo simulation of 100 runs to counter some of the uncertainties and risks. This will all lead to outputs, which will be plots that show the distribution of the chosen strategies to the MCA score and the cost. It will also show in what order the CRSs are primarily selected in the strategies, and it will show what CRSs are mostly chosen.

Chapter 5

SWOT Analysis

The SWOT analysis is used in this model to identify the (possible) positive or negative impacts of the different CRSs. The description of how these SWOT analysis work are discussed in section 2.3.2. This chapter describes, per CRS, the strengths, weaknesses, opportunities and threats which can be used for the MCA scores in section 6.3.2. The negative points, threats and weaknesses can be used to substantiate why the CRSs score low on specific criteria. An example is a low score for the technological readiness level when one of the weaknesses of the CRSs is that it has not been brought to market yet. On the other hand, the positive points, strengths and opportunities can be used to explain the higher scores in the MCA. For instance, the implementability score can be increased if the strength of a CRS is that it is easy to install.

5.1 Turbo Sails

Strength

One of the strengths of a turbo sail is the wide angle of attack, which is more than a conventional sail due to the suction on the leeward side. This means the vessel could use the turbo sail as a method of propulsion for more headings. The renewability of the energy that the turbo sail primarily uses is a considerable strength; the wind will always blow. However, this does not only mean that it will always be able to provide propulsion power; it also increases the redundancy of the vessel because it can deliver propulsion power, even if the engines fail. The engine also concerns one of the strengths of the turbo sail; it does not need to be replaced to make the vessel use less carbon. The last strength of the turbo sail is that it is available in the form of a container, which means that it does not take up a lot of deck space and can be easily placed and removed, which can be used to place newer versions or remove them together when something else proves to be more effective.

Weakness

The main weakness of the turbo sail is the dependency on the wind; when the wind does not blow or blows from the wrong direction, the turbo sail could be useless or even reduce the vessel's efficiency. It also needs an electric engine, which requires a power supply, which is more complex than conventional sails. The high of the turbo sail will restrict the vessel from entering certain waters and can reduce the line of sight from the bridge. The turbo sails are also not, or less, suitable for every ship type or not suitable in large amounts for such vessels as geared general cargo vessels.

Opportunities

The development is not yet at an advanced stage; therefore, there is still significant room for improvement. It could mean that the turbo sails become cheaper and more efficient and will, even in a business-as-usual scenario, lead to reduced cost.

Threats

It is not the only CRS being developed and the only WASP; the Flettner rotor and soft and rigid sails compete on the same level. This competition could lead to the turbo sail's downfall as the future's primary WASP. The turbo sail still needs other propulsion methods, so it could be that the propulsion power delivered by the turbo sail is not cost-effective enough. The turbo sail would become absolute when a carbon-free medium provides additional propulsion power. The absence of turbo sail on many ships at this point can also be seen as a threat because there is little data available to know the working and effectiveness of the sail.

5.2 Flettner Rotor

Strength

The Flettner rotor is effective for a wide range of wind directions, which makes it less dependent on the wind and takes more advantage of the wind than conventional sails. The other strengths have significant similarities with the strengths of the turbo sails, such as the renewability of the energy, the redundancy it provides, and the engine does not have to be replaced. The Flettner rotor is said to create a large amount of lift and, thus, a significant drop in fuel use. The Flettner rotor is also more than 100 years old, so the technique is long-proven, and the rotors can also improve stability.

Weakness

The weaknesses also have a lot in common with the turbo sail, such as the dependency on the wind, the need for electric engines and the height. The Flettner rotor is also unsuitable for every ship type and takes up a deck space, which can be a weakness for specific ship types.

Opportunities

The opportunities associated with the Flettner rotor are new developments; it is expected that the rotors can become larger and more effective. The number of rotors that could be installed on a vessel could also increase, which could all lead to a significant increase in propulsion power from the Flettner rotor.

Threats

The threats of the Flettner rotor are also similar to those of the turbo sail. There is also the risk that it will not become the primary WASP of the future. The developments of existing or future developed WASPs are hard to predict. When a WASP becomes more dominant, it will probably be developed more, and this will be an even more dominant position. That could lead to (maintenance) infrastructure that is more suitable for the dominant CRSs and a CRSs that is probably more cost-efficient. This would make it a threat to a WASP, such as a Flettner rotor that has no future perspective. The Flettner rotor also needs other propulsion methods, and there is still little information available. However, more Flettner rotors are installed now, so the threat is less for the Flettner rotor than for the turbo sail.

5.3 Cold Ironing

Strength

The technique behind cold ironing is pretty straightforward, using the grid power to power the ship when in port. When the shore power is generated with renewable sources, it emits no carbon, but even if there is a mix of fossil and renewable sources, it likely emits less carbon than the auxiliary engines. The auxiliary engines would also have to run less, resulting in a longer lifetime and less maintenance. There is also less pollution in the harbour from other harmful particles in the fuel and less noise when in port.

Weakness

There is no standard yet, so there is no plug-and-play yet. There is also a difference in voltage and frequency in the world. Different vessels also have various power supplies, so it could be that different cables or plugs are needed for different ship types. All these will be a weakness for the availability. Another weakness is that the auxiliary engines are still needed, so it does not relieve the vessel of a part that uses fossil fuels until the auxiliary engines run with renewable energy sources. Lastly, comparing the energy cost from the grid against burning fuel in the auxiliary engines, it is more costly to use grid energy, which can be seen in section 4.3.4.

Opportunities

One of the main opportunities is that the prices of renewable energy from the grid will most likely decrease in the future, as renewable energy is significantly cheaper in the long run than fossil fuels. When cold ironing gets bigger, it is expected that (some) standardisation will take place. Lastly, it could be that the cold ironing system could also be used in the future to transport power between vessels in case of emergency or other uses.

Threats

The slow growth of power grids could be a threat to cold ironing; the power grids in the Netherlands, for example, are full in some regions of the country now. [120] It can be expected that that will or is happening in other countries, and in the future, it could be even more pressing because whole countries are trying to stop using fossil fuels and use electric energy instead. Another threat on the other side could be that less developed countries will not have the infrastructure for a long time, so that cold ironing would be useless there.

5.4 Towing Kite

Strength

The strength of the towing kite is the small area needed for the installation, which means there is less hindrance. The kite also flies at great heights with more wind than the heights where the turbo sails and Flettner rotors get their wind. The energy source is renewable, and the installation has a relatively low weight, which are both strengths and, just like the turbo sails and Flettner rotors, it does not need an engine change. The great strength over the Flettner rotor and turbo sails is the fact that the kite can be hauled in, which decreases hindrance by the kite.

Weakness

The main weaknesses of the towing kite are the same as the turbo sail or Flettner rotor; not suitable for all wind headings, is still in development and is dependent on the strength of the wind. Also in line with the other two WASPs is the need for other propulsion powers combined with the towing kite.

Opportunities

The opportunities for the towing kite are in the new developments; it can be expected that the kites will get better and bigger. This will, combined, lead to increased effectiveness and, thus, more towing power.

Threats

The leading company developing the towing kites, SkySails, has stopped developing towing kites for ships and is only developing them for energy generation on the land. So, the threat is that no other company will develop the towing kite or that the development will be halted for a long time. Another threat is the same as for the turbo sail and Flettner rotor, which is only auxiliary propulsion power, and there is still a need for another power source.

5.5 Solar Energy

Strength

The strength of solar panels is that the source is renewable and will mostly be placed on unused parts of the deck, which leads to more optimal use of the vessel. The panels do not hinder the ship's operations, and there is no need to change the engines, only less or no, use of auxiliary engines.

Weakness

The panels will not deliver enough power to propel the ship and will thus only be used for auxiliary power. However, the panels will not work at night, so there must be an alternative power source at night. Clouds could also impact effectiveness, just as the part of the earth and the season are limiting. The use of deck space also makes less room for the crew to operate.

Opportunities

The solar panels could be combined with other solutions that use electrical energy. When the vessel uses a (partly) electrical drive, it could be used as part of the propulsion power. There are also floating solar fields being developed [156], which could lead to improved solar panels for offshore operations.

Threats

Solar panels are a highly researched subject, and the threat that goes hand in hand with that is the possible limited growth in effectiveness. So, if the panels do not significantly increase, it could be that the cost-benefit is too low on vessels.

5.6 Ship Lengthening

Strength

The main strength of ship lengthening is the ability to create significantly more cargo space without the significant investments associated with a vessel's new build. It also increases the capacity of a ship with a relatively low increase of resistance, which reduces the fuel use, and thus CO_2 emissions per tonne mile.

Weakness

The mean weakness is that the ship was not designed initially for that length, which could lead to unexpected technical problems or safety risks. The primary example of this is the elongating of the vessel, which could lead to more stress on the vessel and, thus, more chance of fatigue. The increase in resistance would lead to a reduced speed for the same MCR, or a new engine should be installed. The last weakness is that adding a new section to the vessel would require significant time in the dock.

Opportunities

As docking can be seen as a weakness, it also creates an opportunity. That time can also be used to upgrade other aspects of the vessel or add other CRSs, and the time could also be used for crew training to use the new CRSs. Also, the combination with slow steaming could mean no need for a new engine.

Threats

A large project such as ship lengthening would require extensive planning, so there are a lot of risks that something could go wrong. The associated threat is that the vessel is more extended out of business than acceptable, which could heavily impact the revenue of the vessel.

5.7 Air Lubrication

Strength

The air lubrication significantly impacts the resistance for a relatively small amount of energy. So, the total energy use decreases, which leads to a reduced fuel needed, which means less carbon and cost.

Weakness

Air lubrication works best for vessels with a flat bottom to trap the air under the vessel. There are even some forms of air lubrication that need a particular hull form to keep the bubbles trapped under the vessel. The air lubrication is also impacted by weather; when the waves get too high, the air does not provide enough lubrication anymore to be effective.

Opportunities

The opportunities lay in the developments that will be achieved in the future with increased effectiveness. That could be new and improved hull forms that trap the air better and will thus need less power to provide air under the vessel. Another option is that the air is blown under the vessel more effectively and will reduce energy use that way.

Threats

As with other CRS, air lubrication only reduces the amount of power needed; it still needs another clear power source in the future. So, there is still the danger that it is not cost-effective enough to be placed or stay on the vessels.

5.8 Waste Heat Recovery

Strength

The central aspect of waste heat recovery is the main strength, the increased efficiency of the fuel. So, more energy from the fuel could be used, which is still an advantage when used with bio- or E-fuels. It will also reduce the need for large auxiliary engines or even reduce the need for auxiliary engines in combination with cold ironing or systems. When combined with a PTI, it can also be used for propulsion, which could extend the vessel's range for the same amount of fuel.

Weakness

The main weakness is the increased complexity of piping and cables to accommodate the waste heat recovery system. When the waste heat recovery is build-in or planned when the vessel is a new build, this is less of a problem. However, when the waste heat recovery is a retrofit, installing the waste heat recovery system will be complex.

Opportunities

As with most CRSs, there is the option that the waste heat recovery becomes more effective in future, which would lead to an even more significant decrease in fuel use. It could also not only be used to provide electric energy but also as a heat source for the vessel.

Threats

When the waste heat recovery is combined with a fuel that uses a fuel cell, it could be that the waste heat recovery does not work anymore or is less effective. For example, when a waste heat recovery gets the energy from the exhaust gasses and the fuel cell does not provide them. It could also be that the fuel cells operate at low temperatures that there is not even hot enough waste heat to recover.

5.9 Carbon Capturing Device

Strength

Carbon capturing devices have the strength to reduce CO_2 emissions even if the fuel is fossil-based significantly. So, when still using the widely used fuel that will be used for some time, it can keep the vessel compliant with the regulations without the need for another CRS. Another strength of carbon capturing is that the CO_2 can be sold again for another use, such as a gas in greenhouses to grow plants.

Weakness

The carbon capturing main weakness is carbon storage, which could take up a lot of space. The carbon must be stored under pressure, which will also create safety risks and specialised storage equipment.

Opportunities

When fossil fuels are no longer standard, carbon capturing can still be used in combination with bio- or E-fuels. This would still lead to captured carbon that can be used for other products. They are also still being developed to be more effective in the future.

Threats

The prices of CO_2 could drop, making the carbon capturing device less cost-effective. It could also be that the method will not be as effective as needed, or it could be that it does not capture enough carbon to be effective for the regulations. A possible carbon tax also influences cost efficiency, so a low carbon tax could also be considered a threat.

5.10 Ammonia

Strength

The strength of ammonia is that it is already widely produced, so that it could be used as a fuel quite fast. Although it is now mainly produced with fossil fuels, it can also be produced with renewable energy, making it even more suitable for the transition to renewable energy. The other strength is that even when it is not produced as green ammonia, it still does not have any carbon, and the grey production produces less carbon than HFO or MDO. [7] Because ammonia is quite well known worldwide, the handling and infrastructure are also well known.

Weakness

The weaknesses of ammonia are its toxicity and low energy density. The toxicity makes it have to be handled with more care and requires more complex storage and safety technologies. It will also mean that there is more chance for negative impacts in case of an emergency. The low energy density means that there is a need for more storage space or that the range of the vessel is drastically impacted. This is even more affected by the fact that it has to be specially stored, which requires even more room.

Opportunities

Ammonia can also be combined with diesel and can thus act as a drop-in fuel, which allows ammonia to be used in earlier stages and will be able to adapt for the future. The dual use of ammonia also creates opportunities for it will be made in more places, and when there is a surplus or shortage, it can be moved between the uses.

Threats

One of the threats is the NO_x emissions associated with ammonia because ammonia consists of nitrogen and hydrogen, and combustion can lead to nitrogen oxides. These nitrogen oxides also hurt flora and fauna. Another threat is the bunker capacities, as ammonia has more uses than only fuel and also has a low energy density, so it could be that in the early years there, it will not be easy to create large amounts of ammonia bunker capacities.

5.11 Methanol

Strength

The main strength of methanol is that it has similar properties as marine fuels used nowadays. Methanol can be used in ICEs which is a tremendous strength because it is not necessary to install new engines. It is also liquid at ordinary temperatures, so it can be stored in regular bunker tanks. It is also one of the fuels already being used in vessels at this point.

Weakness

Methanol's toxicity will negatively impact the vessel when it is used as a fuel. Another safety problem is that the flames of methanol are invisible, making noticing and fighting the fire extremely difficult and requiring specialised equipment. The fuel tanks may not have to be pressurised or cooled, but they will still need a coating to store the methanol.

Opportunities

The opportunities for methanol may come from its flexibility because it cannot only be used as a fuel for ICEs but also as a hydrogen carrier for a fuel cell. So, that means that if the vessel changes its engine to a fuel cell, the fuel tanks can stay the same. It could also mean that it can be combined with other fuels that can be used in fuel cells to change the primary fuel.

Threats

The threats come from the different approaches it has to take for safety. It could be that specialised FIFI equipment is needed for the vessel, which could also lead to expensive extra training for the crew.

5.12 Bio-fuel

Strength

The greatest strength of bio-fuels is that they can be a one-on-one substitution for fossil, carbon-based fuels. So, that would mean that engines, use of engines and infrastructure could all stay the same, which would significantly reduce investment costs. For the rest, it has all the advantages of regular fossil fuels, such as standard fuel tanks and modes of transport, and in the transitions phase, could also be substituted back to the 'old' fuels.

Weakness

Bio-fuel can be made from several different components, such as organic waste and crops that are uneatable for people. However, it becomes problematic if the fuel is made from eatable crops or when a large amount of farmland will be used for bio-fuel production. The other problem is that the bio-diesel used nowadays still needs some regular fuel to be used in engines because they cannot run on bio-diesel alone.

Opportunities

The bio-fuel could be used for the transition from fossil to renewable energy. When E-fuels become more attractive, it could be that the bio-fuel will be mixed with the E-fuels, and only organic waste will be used to make bio-fuels.

Threats

The main threat is that, on a large scale, forests and farmland will be destroyed to use as materials or to create new farmland to produce bio-fuels. The other threat is that the fuels will still produce NO_x and other polluting substances.

5.13 E-fuel

Strength

E-fuels' strengths are comparable with bio-fuels in terms of use, engines, infrastructure and transport. E-fuel's main strength ahead of bio-fuels is that, in the ideal circumstances, there would only be the need for green electricity, water and CO_2 from the air. That would mean clean fuel, which does not use resources needed by people.

Weakness

The weakness is that the technology is not yet proven on a large scale, and it only has a positive influence when it is created with green energy and not grey energy.

Opportunities

When only water, electricity and CO_2 are needed to create E-fuels, it could be that they can be made at a lot of places on earth and close to green energy sources. In the ideal situation, it could be that the E-fuels are created at sea, near monopiles, which could then be used to refuel ships.

Threats

The threats of E-fuel are if it will become cost-effective and if it will be efficient to use electricity to create carbon-based fuels. It could be that other renewable fuels will become more efficient or will be less expensive. Just as with bio-fuels, the fuels will still contain carbon, and the use could still lead to emissions of NO_x and other harmful particles.

5.14 Hydrogen

Strength

Hydrogen is, in essence, the cleanest fuel there is; the only product that is produced when creating energy is water. Hydrogen is non-toxic and has a high energy density, which makes it particularly suitable as a fuel. The method to create hydrogen, electrolysis, is old and relatively easy.

Weakness

The weakness of hydrogen is mostly storage and transport. It needs special tanks to pressurise or cool the hydrogen; they leak easily because hydrogen molecules are small. Hydrogen is also explosive and is not being produced on a large scale as fuel yet.

Opportunities

Hydrogen uses fuel cells to produce electricity for the vessel, and these could become more effective in the future. The waste of the fuel is water which could be used as a source of clean or grey water or could be used with residual heat for heating purposes.

Threats

Most threats are similar to other alternative fuels, and it is unclear whether they will become efficient or cost-effective. There would also probably be a need for advanced FIFI and new infrastructure, where the building of infrastructure is vague at what speed that will progress.

5.15 Slow Steaming

Strength

The main strength of slow steaming is that it is straightforward to implement and has a high effect on the carbon emissions of the vessel. The EPL can easily be installed and will thus be a fast option to reduce carbon emissions.

Weakness

There are two main weaknesses of slow steaming; the first is the operational part. Sailing slower means a lower amount of cargo that can be carried in total; it also means that the cargo hauling prices will likely be lower due to the increased time. The other weakness is when a smaller engine is installed that, there is less reserve capacity which will impact safety.

Opportunities

In the future, vessels and engines can be designed especially for slow steaming, which will increase the efficiency even more for the vessel.

Threats

When more vessels implement slow steaming, it will mean that the total relative cargo space will be reduced. This will lead to the need for more vessels to ship the same amount of cargo. This will lead to a trade-off on the fleet level for shipowners.

5.16 Conclusion

The different CRSs have their own positive and negative points, of which the main ones are presented in table 5.1. Generally, the negative points, weaknesses and threats influence alternative fuels the same. These weaknesses of alternative fuels, such as toxicity or explosiveness, could negatively influence the safety score. The same is for the threat of alternative fuels, where the uncertainty in the availability in the future could hurt the future-proof score of the alternative fuels. Positive influences of alternative fuels are mostly their cleanness or flexibility, which would positively influence their future proof or implementability score, respectively. It can be concluded that the most opportunities found in the CRSs are that these CRSs could become more efficient and less expensive, whereas, on the contrary, the most significant threats against the CRSs are that they will not become more efficient and less costly. The most common strength is the ease of installation, and the most common weakness is that there are only certain situations in which the CRSs will work optimally or their safety risks.

Table 5.1: SWOT of CRS

CRS	Strength	Weakness
Turbo sails	Wide angle of attack Redundancy Easy instalment	Wind depended Height Need of electric power
Flettner rotor	Wide angle of attack Redundancy Easy instalment	Wind depended Height Need of electric power
Towing kite	No height restrictions Redundancy Easy instalment	Need of electric power Wind depended
Solar energy	Use of unused space Smaller aux engine	Only aux power Only work with light
Ship lengthening	Decrease cost per tonne mile Decrease CO_2 per tonne mile	Chance on fatigue New engine
Air lubrication	Significant drop in resistance	Only for calm weather
Waste heat recovery	Increased efficiency Used with more fuels	Complex installation
Carbon capturing device	Carbon can be used again Can still use most available fuel	Safety concerning storage Transition solution
Cold ironing	As clean as shore power Less maintenance	No standard Still aux engines
Ammonia	Already being produced No carbon	Toxicity Low energy density
Hydrogen	Only produces water	Storage and transport leaks
Methanol	Used in ICE Normal tanks	Toxicity Invisible flames
Bio-fuel	Existing infrastructure	Not available on large scale
E-fuel	Existing infrastructure	Not proven on large scale
Slow steaming	Very cost-effective	Safety due to smaller engine

CRS	Opportunity	Threat
Turbo sails	Reduced cost More efficiency	Not main propulsion Not the best in the future
Flettner rotor	Reduced cost More efficiency	Not main propulsion Not the best in the future
Towing kite	More cost efficient More efficiency	Not main propulsion Not the best in the future
Solar energy	Power for hybrid drive More efficiency	Cost-effectiveness
Ship lengthening	Total vessel upgrade Combination with slow steaming	Ship longer out of business
Air lubrication	Increased efficiency	Cost-effectiveness
Waste heat recovery	Could provide all aux power	Not for all fuels
Carbon capturing device	Combinable with E- and Bio-fuel	Low carbon prices
Cold ironing	Clean shore power Standardisation	Full power grids Not in every port
Ammonia	Combination with diesel Dual fuel use	Bunker capacity Effect on environment
Hydrogen	Could be used as water source	Developments unclear
Methanol	Dual fuel use	Specialised FIFI
Bio-fuel	Transition fuel	NO_x emissions
E-fuel	Could be created near vessels	NO_x emissions
Slow steaming	Designed optimally for slow steaming	Reduced total cargo space

Chapter 6

Data for Case Study

In chapter 2, the regulations, CRSs and the analysis that will be used in the model were presented. This chapter will give the vessel for the case study so the model can be tested, which will also require the data for the CRSs in proportion to the ship, such as the amount and size of the Flettner rotors. It will also include all the other data needed to run the case study, such as costs, MCA scores and numbers used for the regulations. The chapter will start with the data concerning the vessel used in the case study and present the CRS data. After that come the MCA weights and scores, and then some other data are discussed. The chapter will end with a conclusion of the essential data and choices about that data.

6.1 Vessel used for Case Study

A vessel is needed to test the model and show the impacts of several different inputs. Because there was no complete data set available with all the necessary data of a vessel, the data has been combined from several different sources, which means that the vessel used is a fictive ship. The data is presented in table 6.1, and this section will present its origin. The used ship will be a crude oil tanker with a DWT of 110 000.00 and a design speed of 15 knots and is based on several ships from Significant Ships, mainly the British Delight and the FS Diligence. [52, 152] The CAPEX of such a vessel has been estimated at 150 million dollars, which was found by taking the prices of older vessels and calculating these for current prices. So, a tanker was about $30 million in 1973, with inflation of 3.75% is around 190 million $ in 2023. [26, 145]. Another source stated that a 110 000 DWT tanker was about $74 million in 2004, with inflation of 3.75% is around 145 million in 2023. [26, 161] So, the cost in 2023 for a 110 000 DWT vessel have been set at $175 million. The design resistance has been set at 1500 kN for the design speed because, using the formulas from section 4.3.2, this resistance yields an engine power of 15 587.88 kW, which is in the range of such a vessel. Vessels this size have been found to have three auxiliary engines of 660 kW each; considering reserve capacity, the auxiliary need at sea has been set at 1 600 kW and half of that, so 800 kW at land. [52, 152] The efficiencies have been found in *Design of Propulsion and Electric Power Generation Systems* and are 0.75 for η_D and 0.99 for η_{TRM}. [81] For simplification purposes, the model assumes that no PTO/PTI is installed.

Table 6.1: Properties used vessel

Design speed	15	knots
Deadweight	110 000	DWT
CAPEX	150 000 000	$
Design resistance	1 500	kN
Main engine power	15 600	kW
Auxiliary power sailing	1 600	kW
Auxiliary power at land	800	kW
η_D	0.75	-
η_{TRM}	0.99	-

6.1.1 Route

The trip length for this research has been chosen to be 7500 nm, a trip length that can be average for crude oil tankers. A trip from Rotterdam to Kuwait, for example, is around 6500 nm and a trip from New York to Saudi Arabia is 8500 nm. [140] The ballast trips are around 40% of the time, so 40% of the trips are sailed without freight, and the vessel is expected to sail the whole year under normal conditions. [151]

Used prices and cost

To create precise results for the monitored part of the case study, it is essential to use data with at least the correct order of magnitude. Shipowners could use their own and their supplier's data to get the data as much as possible from the same sources. However, this research has used several sources to find the data needed for the case study. This includes CAPEX of the vessel and CRSs, maintenance cost, crew cost, fuel cost, CO_2 tax and port cost.

CAPEX The CAPEX of the vessel can be found if section 6.1, and is 150 million dollars. The CAPEX of some of the CRSs has been based on the values from the Green Voyage 2050 appraisal tool. [76] This is true for towing kites, waste heat recovery and air lubrication. The cost of the Flettner rotor and turbo sails comes from supplier data provided by C-Job. The cost for carbon capturing devices comes from the Stena Bulk report. [153] The cost of cold ironing used from the Port Technology Journal [148] and the cost for the solar panels was found in the paper from Wang et al. and are 80 $/m^2$. [168] The CAPEX of ship lengthening has been estimated at 10% of the original CAPEX of the vessel, as will be explained in section 6.2.6, which will lead to a CAPEX of 15 million dollars.

The CAPEX of the alternative fuels required some calculations, except for bio-fuel and E-fuel. It is expected that the available engine and storage capacity are suitable for these two fuels. To do the calculations for the required amount of fuel, the required amount of energy is needed, which has been calculated for two times the trip length of 7500 nm for 15 knots, as presented in section 6.1.1, which leads to 1000 hours of sailing time. This will lead, for the main engine power of 15.6 MW and 1.6 MW auxiliary power, to an energy need of 17 200 MWh, so the total amount of energy needed can be found in formula 6.1.

$$\text{Total energy need: } 1000\,h * (15.6\,MW\,(main) + 1.6\,MW\,(aux)) = 17\,200\,MWh \tag{6.1}$$

The CAPEX for ammonia assumes that the ammonia can be used in an ICE, so there is only a need for new storage equipment. Calculating with an SFC of 400 g/kWh or 0.4 tonne/MWh [165], a storage cost of 35 $/GJ [58] and an energy density of 22.5 GJ/tonne [86], the total cost can be calculated as seen in formula 6.2 and 6.3.

$$\text{Total mass ammonia: } 0.4\,tonne/MWh * 17\,200\;MWh = 6875\;tonne \tag{6.2}$$

$$\text{Total cost ammonia: } 6875\,tonne * 35\;\$/GJ * 22.5\;GJ/tonne = \$\,5\,414\,182 \tag{6.3}$$

Methanol will, like ammonia, be used in an ICE and will thus only need new storage. With an SFC of 0.2 tonne/MWh, [90] storage cost of 45 $/GJ [160] and an energy density 22.4 GJ/tonne [92], leads to a total cost of 3 465 076 $, which can be seen in equations 6.4 and 6.5.

$$\text{Total mass methanol: } 0.2\,tonne/MWh * 17\,200\;MWh = 3438\;\;tonne \tag{6.4}$$

$$\text{Total cost methanol: } 3438\,tonne * 45\,\$/GJ * 22.4\,GJ/tonne = \$\,3\,465\,076 \tag{6.5}$$

The hydrogen options have two parts that make up the CAPEX, the storage and the fuel cells. The fuel cells are the same for liquid or gaseous hydrogen because the same amount of energy needs to deliver. With a fuel cells cost of 2 000 000.00$/MW [160], the total cost can be calculated as seen in formula 6.6.

$$\text{Total cost fuel cells: } 2\,000\,000.000\,\$/MW * 17\,200\,MW = 34\,375\,758\,\$ \tag{6.6}$$

The cost for storing both liquid and gaseous hydrogen needs 17 200 MWh and with an SFC of 90 g/kWh [116], the weight can be calculated in equation 6.7.

$$\text{Total mass hydrogen: } 0.09\,tonne/MWh * 17\,200\;MWh = 773\;\;tonne \tag{6.7}$$

For liquid hydrogen, a density of 14.1 m^3/tonne [6], and a cost for storage of 2960 $/m^3$ [124] is used, and with which the total cost can be calculated as seen in equation 6.8.

Total cost liquid hydrogen: $34\,375\,757.58\ \$ + 773\ \ tonne * 14.1\ m^3/tonne * 2960\ \$/m^3 = 98\,937\,555\ \$$ (6.8)

The storage for gaseous hydrogen is more expensive, with a storage cost of 1180 $/GJ [160] and an energy density of 120 GJ/tonne [35]; the total cost can be calculated in 6.9.

Total cost gaseous hydrogen: $34\,375\,757.58\ \$ + 773\ \ tonne * 120\ GJ/tonne * 1180\ \$/GJ = 253\,418\,085\ \$$ (6.9)

The CAPEX for slow steaming seems counter-intuitive, but that is the cost for the engine power limitation (EPL), which is 1 000 000.00 $. [56]

Table 6.2: CAPEX CRS

CRS	Cost		Source
Turbo sails	2 000 000	$	C-Job
Flettner rotor	3 480 000	$	C-Job
Towing kite	1 886 625	$	[76]
Solar energy	80	$/m^2	[168]
Ship lengthening	15 000 000	$	Estimate
Air lubrication	1 786 339	$	[76]
Waste heat recovery	8 209 247	$	[76]
Carbon capturing device	18 000 000	$	[153]
Cold ironing	400 000	$	[148]
Ammonia	5 414 182	$	[165, 58, 86]
H2 Liquid	98 937 555	$	[160, 116, 6, 124]
H2 Gas	253 418 085	$	[160, 116, 35]
Methanol	3 465 076	$	[90, 92, 160]
Bio-fuel	-	$	-
E-fuel	-	$	-
Slow steaming	1 000 000	$	[56]

Fuel cost Fuel costs are in US Dollars per tonne, and the expected increase in price per year is also added, which can be seen in table 6.3. These prices are difficult to predict for the future, so they will be an important part of the Monte Carlo simulation, which will consider the effects of changing fuel prices. To get as comparable prices as possible, the prices have mostly been found on the same day, 7 October 2022. This is only not the case for the hydrogen cost, which was found on 21 June. However, because it has such a different order of magnitude, the fault margin will impact the model's outcome less. The yearly increase of fossil fuel prices, MDO and VLSFO, is based on the average price change from UNCTAD from 1993 to 2010. [162] The historical prices from the alternative fuels were less reliable, so the inflation from the last 50 years in the US has been chosen for the base values. [26]

Table 6.3: Fuel prices used in model

Fuel	Price ($/tonne)	Expected increase per year (%)
MDO	650 [25]	10 [162]
VLSFO	650 [143]	10 [162]
Ammonia	1100 [111]	3.75 [26]
Methanol	400 [111]	3.75 [26]
Bio-fuels	2000 [111]	3.75 [26]
E-fuels	2200 [110]	3.75 [26]
Hydrogen	16000 [131]	3.75 [26]

When the CRS cold ironing is used, the cost of the energy used from the grid will also be included, which has been set at 0.35 $/kWh. [177] The increase in the price of electricity will be 3%. [50]

Crew cost The cost for the crew will be calculated with the number of crew members and the average cost per crew member per year, which has been set at 50 000.00 $/year. The average salary of a crew member is 25 000.00 $/year [117], however due to taxes and other expenses for the crew members, the cost for the owner is estimated at 50 000.00 $/year. It is expected that all the CRS will not deliver significantly more work on the vessel, so there will be no increase in crew members. The only exception is the ship lengthening, where the vessel gets considerably larger, so it is expected to need more crew. As the total deadweight of the vessel grows by 10%, the crew will also increase by 10%, which is two extra persons.

CO_2 tax The carbon tax will be calculated as $/tonne; however, since no carbon tax has been implemented yet, the price of the carbon tax is the expected price from the literature. This price has been set at 25 $/tonne, rising at 12% per year. This has been calculated by the IMF (International Monetary Fund) to be the desired amount of tax to reach the 50% decrease by 2050. [129]

Maintenance cost The maintenance cost for the vessel has been estimated to be 10% of the CAPEX of the vessel per year. [3] So because the vessel cost for the used vessel is 150 million dollars, the maintenance will lead to a cost of 15 million dollars per year. When a CRS is installed, the increased maintenance cost can be found in table 6.4. Most are based on the Green Voyage 2050 appraisal tool [76], which is valid for the turbo sails, Flettner rotor, towing kite, solar energy, air lubrication and waste heat recovery. The increase of maintenance has been set at 10 % of the CAPEX, which is the same as for the vessel itself and the value for carbon capturing is from Stena Bulk. [153] For cold ironing, there is no increase in maintenance cost because it is expected that the decrease in maintenance for the less-running auxiliary engines will counter the rise in maintenance due to the cold ironing installation. Lastly, there is no anticipated increase in maintenance for alternative fuels and slow steaming because instead of maintaining the old power train, the new power train should get maintenance. In the case of slow steaming, the power train stays the same.

Table 6.4: Increase in maintenance cost table

CRS	**$**	**Per**
Turbo sails	200 000	year
Flettner rotor	174 000	year
Towing kite	175 500	year
Solar energy	-	m^2/year
Ship lengthening	1 500 000	year
Air lubrication	10 000	year
Waste heat recovery	10 000	year
Carbon capturing device	153 000	year
Cold ironing	-	year
Ammonia	-	year
H2 Liquid	-	year
H2 Gas	-	year
Methanol	-	year
Bio-fuel	-	year
E-fuel	-	year
Slow steaming	-	year

Port cost The port cost, so the costs for tugs, pilots and the cost for the port itself will cost around $50 000 per port call. This is based on a GT of approximately 65 000 [52, 152], which leads for a crude oil tanker to around €50 000, which translates to $50 000. [133]

Inflation and price developments

The inflation used is the average American inflation of the last 50 years, which was 3.75%. [26] This has been chosen because the currency used in this research and most used in literature is the US Dollar. Because it is unclear how the prices of all aspects will develop, it has been chosen to let the prices of all aspects develop with the used inflation. The exceptions to that are the fossil fuels, CO_2 tax and shore power as discussed above.

Other financial data

Several other financial values are used in this research, such as the discount rate and the inflation rate. The discount rate has been set at 8%, which is comparable to other maritime operations and is also the amount used for the appraisal tool of Green Voyage 2050, as well as the rate used by Wang et al. [76, 168] This means that with a discount rate of 8% and inflation of 3.75% future cost will become relatively less expensive. When translating cost from euros to USD, the rate has been set at 1 to 1 because this was almost the rate on 7 October, the day the fuel prices were used. [39]

6.2 Carbon Reduction Solutions (CRS)

When CRS are introduced to a vessel, they impact the specifics of the vessel, which should also be seen in the model. The variables that the CRS could influence are; main engine power, auxiliary engine power (both offshore or in port), resistance, free deck space, DWT and carbon conversion factor values. The effect of these changes is then introduced in the calculations that ultimately calculate the fuel use of the vessel. Table 6.5 shows which characteristic of the vessel is impacted by the CRS. Some CRSs can affect each other, which could impact their effectiveness. This section aims to present the data associated with the operational impact of the CRSs.

Table 6.5: Ship characteristics impacted by CRS

	Main engine power	**Auxiliary power (in port)**	**Auxiliary power (at sea)**	**Resistance**	**Deck area**	**Capacity**	**C_f**
Turbo sails	Y	N	Y	N	Y	Y	N
Flettner rotor	Y	N	Y	N	Y	Y	N
Towing kite	Y	N	N	N	Y	Y	N
Solar energy	N	Y	Y	N	Y	Y	N
Ship lengthening	N	Y	Y	Y	Y	Y	N
Air lubrication	N	N	Y	Y	N	Y	N
Waste heat recovery	Y	N	Y	N	N	Y	N
Carbon capturing device	Y	N	Y	N	N	Y	N
Cold ironing	N	Y	N	N	N	N	N
Ammonia	N	N	N	N	N	Y	Y
H2 Liquid	N	N	N	N	N	Y	Y
H2 Gas	N	N	N	N	N	Y	Y
Methanol	N	N	N	N	N	N	Y
Bio-fuel	N	N	N	N	N	N	Y
E-fuel	N	N	N	N	N	N	Y
Slow steaming	Y	N	N	N	N	N	N

6.2.1 Turbo sails

Turbo sails impact the vessel in several ways: the main engine power. The sail provides towing power to the vessel, which reduces the need for main engine power. The average towing power delivered by the turbo sail is 800 kW for the vessel, which will require auxiliary power to run the sails at sea, which is 136 kW. [41] The deck area and capacity will also be impacted by the installation, which leads to 60 m^2, two 40-foot equivalent containers, reduced deck area and 14 tonnes less capacity.

6.2.2 Flettner rotor

However, the Flettner rotors impact the vessel the same way as the turbo sails, with other values. The choice has been made to use four Flettner rotors with a height of 35 m and a diameter of 5m. They provide 1175 kW of propulsion power; thus, less engine power is needed, and they require 400 kW of auxiliary power. The area required is 144 m^2, and the weight is 236 tonnes; this is supplier data from C-Job.

6.2.3 Cold ironing

The cold ironing will only impact the vessel's use of auxiliary power in the port. The weight of the cold ironing installation is negligible and not placed on the deck, so there is no loss in deck area. The change on the vessel results in no fuel used in the port for the engines, so there is no cost for fuel; this will be changed by shore power and, thus, the price for electricity from the grid.

6.2.4 Towing kite

The towing kite is almost similar in its impacted aspects to the Flettner rotor or turbo sail. However, the auxiliary power needed for the kite is negligible and will thus be set at 0. The propulsion power, and thus reduced engine power, is 800 kW. The area is of one TEU, and thus around 15 m^2, and the weight is 10 tonnes. [149]

6.2.5 Solar energy

Solar energy impacts the auxiliary power, on- and offshore, in the same average manner. The energy provided depends on the free area available to place solar panels, which is smaller when CRSs, such as Flettner rotors, are placed, so the power is 0.2 kW per m^2. [168] The weight is also dependent on the area, so the reduction in capacity is 0.2 tonne m^2. [168]

6.2.6 Ship lengthening

Ship lengthening impacts the resistance, which could affect the engine power, but it is calculated with increased resistance. There is not much information available on ship lengthening in terms of size and cost. So, it has been chosen to take 10% of the vessel DWT as the starting point, and this was linearly translated to 10% of the CAPEX of the vessel. The increase of resistance is 10% of the initial resistance [45], which leads to 150 kN of increase of resistance. This has been taken as it is a more conservative assumption. For instance, Crudu et al. present a 10% increase in loading and only a 6% reduction in resistance. [31] The deck area will also increase by 10%, so 50 m^2.

6.2.7 Air lubrication

Air lubrication affects the resistance, auxiliary power at sea and capacity. The installation weighs 150 tonnes, which is a capacity that is 150 tonnes less. The installation needs 390 kW of auxiliary power to reduce the resistance by 10%. This differs under the circumstances, so when there is ship lengthening, there is more resistance and, thus, a more absolute reduction in resistance by the air lubrication. [75]

6.2.8 Waste heat recovery

The waste heat recovery system uses the waste energy of the main engine for auxiliary power. However, the main engine will become somewhat less effective. An amount equal to 10% of the power of the main engine will be produced as auxiliary power. On the other hand, there is a 5% reduction in the power of the main engine. [147] The installation weight is 160 tonnes, and thus 160 tonnes less freight can be shipped. [112]

6.2.9 Carbon capturing device

The carbon capturing device needs energy to run and thus makes the main engine less effective; the effectiveness drops to around 50% when using the carbon capturing device. The effectiveness is around 90% which has been translated to a drop of carbon conversion factor value of 90%, so for HFO and MDO, the carbon conversion factor becomes 0.3114 and 0.3151 tonne-CO_2/tonne-fuel, respectively. The weight of the installation and the place to store the CO_2 is around 2500 tonnes. [153]

6.2.10 Ammonia

When ammonia is used as a fuel, it will be the only fuel used in the model's base. Ammonia only impacts the capacity and the carbon conversion factor, capacity because of the weight of the extra fuel and the carbon conversion factor because there is no CO_2 in the fuel. The factor is thus 0, and the increase in weight is 1 776.1 tonne, which is the difference between the weight of the ammonia and the weight of VLSFO/MDO for a trip as seen in formula 6.2. The weight of the tanks is based on the weight tanks, which is 0.26

tonne/m^3 [32] for the volume of the fuel. However, the weight of the existing tanks can be subtracted from that, estimated at half the weight, leading to 0.13 tonne/m^3. The calculations for the weight of the tanks and total weight increase can be found in equation 6.10 with a density for ammonia of 1.67 m^3/tonne. [15]. Using the difference between the weight of VLSFO/MDO and the weight of ammonia plus the weight of the tanks leads to $1776.1 + 747.3 = 2523.4$ tonne.

$$\text{Weight ammonia tanks: } 3437.6\, tonne * 1.67\, m^3/tonne * 0.13\, tonne/m3 = 747.3\, tonne \tag{6.10}$$

6.2.11 H_2 Liquid

As for ammonia, the vessel is only impacted by capacity and carbon conversion factors. The carbon conversion factor also goes to 0 because there is no carbon in the fuel. The same weight for the tanks has been used as by ammonia, with a density of 14.1 m^3/tonne [15]; the weight of the tanks can be found in equation 6.11. The weight for H_2 in total will be the difference between VLSFO/MDO and the weight of hydrogen plus the weight of the tanks, which is $773.45 - 1460.97 + 1422.45 = 735$ tonne.

$$\text{Weight liquid hydrogen tanks: } 773.45\, tonne * 14.1\, m^3/tonne * 0.13\, tonne/m3 = 1422.45\, tonne \tag{6.11}$$

6.2.12 H_2 Gas

The same as for the liquid H_2 is true here, a carbon conversion factor of 0. The same weight for the tanks has been used by liquid hydrogen, with a density of 23.7 m^3/tonne [15]; the weight of the tanks can be found in equation 6.12. The weight for H_2 in total will be the difference between VLSFO/MDO and the weight of hydrogen plus the weight of the tanks, which is $773.45 - 1460.97 + 2390.95 = 1703$ tonne.

$$\text{Weight compressed hydrogen tanks:} 773.45 tonne * 23.7 m^3/tonne * 0.13 tonne/m3 = 2390.95 tonne \tag{6.12}$$

6.2.13 Methanol

Methanol can be stored in the same tanks as fossil fuels and can also use an ICE. The tanks need to be covered in a coating, making them suitable for storing methanol. This means that the only change on the vessel for methanol is on the carbon conversion factor, which goes to 1.375 for the methanol. At this point, methanol is still a drop in fuel, so for the base situations of the model, still 5% of the fuel use is MDO. [42] The weight of the fuel will slightly increase with the increase of fuel needed for the same trip length as with VLSFO/MDO and which will be 257.82 tonne which is the difference between the weight of VLSFO/MDO and the weight of methanol as seen in equation 6.4.

6.2.14 Bio-fuel

Bio-fuels do not impact the vessel other than the carbon conversion factor drops, which is 0 for bio-fuels. However, due to unavailability on a large scale and the fact that bio-fuels are still used as drop-in fuels, the ratio between bio-fuel and MDO has been set at 50/50 for the base situations of the model. As discussed in section 2.2.2, it is a question of how much of carbon emissions can be calculated in the future, but in this research, the conversion factor (C_F) of 0 will be used, as proposed by the IMO. [73]

6.2.15 E-fuel

For this part, the E-fuel and bio-fuel have the same impact, with a carbon conversion factor of 0 and a 50/50 ratio between E-fuel and MDO.

6.2.16 Slow steaming

The slow steaming reduces the speed of the vessel, and thus the amount of energy provided by the main engine can be reduced. The range for slow steaming has been chosen between 12 and 15 knots, with a step of 1 knot between. 15 knots is the maximum because that is the design speed. The speed of 12 knots as a minimum has been chosen because this is the ideal ship speed for slow steaming for tankers, according to Nain and Yuan. [119]

6.2.17 Interference between CRSs

Loss in effectiveness is expected when several WASPs are combined on the vessel. The possible WASP combinations are towing kite/Flettner rotor and towing kite/turbo sail. These can be combined because they do not physically restrict each other. However, there is no research yet on how these WASPs would influence each other, so the estimation has been made that all the WASPs combined with other WASPs will lose 5% of their effectiveness.

6.3 MCA Values

For the MCA, all the CRS are scored on several criteria, presented in section 4.2.2, which are; cost, technological readiness level, safety, implementability, hindrance in operations, manoeuvrability in operations and future-proof. The scores for these, except the cost, are based on the SWOT analysis of all the CRS found in chapter 5. The scores and weight discussed in this section are the values used in this research and can be used as default or benchmark values for later research, but users could use their own input.

6.3.1 Weights

The different criteria have weights to tell how important a particular aspect is for decision making. The idea is that a user of the model can input their own weights in importance. Such a case could be that a user wants to reduce risks and thus has a favour for CRS that have a high technology readiness level. For the case study, the weights have been chosen in such a way that the effect of the cost has the most impact. This was chosen to reflect the results of the most significant part of the model, the economic analysis, in the best way possible. This score has been selected at 100, which is significantly higher than the other criteria, where the highest weight is 10. The user could drastically decrease the economic analysis's effects by reducing the cost weight and increasing the other weights.

For the case study, the highest weight after the cost is safety, with a weight of 10. This has been chosen as the second most important to reflect the effect when safety is low. It will not only impact the vessel, in terms of defects and thus repairs and downtime, but also the ethical impact. This is in line with responsible engineering to reduce the harmful effects of technology on people and nature. Although the safety will be scored from 1-10, where 1 is not safe, and 10 is safe, totally unsafe CRSs should be excluded from the model. It should also be noted that some CRSs score low on safety now, but could, with technical improvements, become safer. The next criteria, with a weight of 5, are future-proof and technical readiness level. These two criteria can be seen as how much of a risk a specific CRS is. A low future-proof score means there is a big chance that the method will become obsolete or unable to compete in the long run. The technological readiness shows how mature a CRS is, a low score could mean that there is improvement possible, but it could also mean that when it is further developed, it does not fulfil its potential. So, these criteria deserve attention and are thus weighted with a 5.

The other three criteria are more operational, one of which is hindrance in operations. This is weighted with a 3; the effects are less significant than technological readiness. When it has a low score, for example, when Flettner rotors limit the workspace of cranes which will lead to longer loading/unloading time, this, of course, impact full on the operations of the vessel but will have less impact in the long run. The same reasoning can be used for the weight of the manoeuvrability when a vessel cannot use a specific waterway because the vessel is too high. In that case, the vessel could be forced to take another route; however, it is expected that that will take less time and influence the vessel's operations less than the hindrance in operations and thus have a weight of 2. The last criterion is implementability, which scores how easily a particular CRS can be implemented. This affects how long it takes to install and how long it will take the crew to get used to it. This is also important but will have less impact than the other criteria and thus be weighted with a 2. The weights for the different criteria can be found in table 6.6.

Table 6.6: Weights used in MCA

	Weight
Cost	100
Safety	10
Technological readiness level	5
Future proof	5
Hindrance in operation	3
Manoeuvrability	2
Implementability	2

6.3.2 MCA Score

The MCA scores used in this research are generalised for the used ship type, a large crude oil tanker, for the case study. More ideal would be to determine the MCA scores for the ship-specific or sub-segments of ship types, for instance, on size and use. Ultimately the MCA scores will be added to the model in a default manner, in which the user can change the scores to their point of view. However, this report would have required more research into these ship types. It is expected that the (minor) differences in MCA scores will not impact the validation process of the model, which is the primary goal of the case study.

The MCA scores for the different CRS have been decided with the help of the SWOT analysis of section 5, and the scores can be found in table 6.7. The scores can differ from 1 to 10, where 1 has the worst influence and 10 is the best influence (or no influence when not applicable). So, for every criterion, a score can mean something different. For example, a score of 3 with safety means it is safe when used in a controlled test environment. An 8 for manoeuvrability makes the vessel's manoeuvre slightly less optimal than without that CRS. This section discusses the scores given to the individual CRS. The strategies will not all have the same amount of CRS, and the scores of the different CRS have to be combined. So, to combine the scores, it has been decided that the scores will be averaged per criteria; it is expected that this method will lead to the fairest combinations of scores. The cost score will not be averaged because the cost is calculated for the strategy as a whole. For this research, the scores are set for all bulk cargo vessels, such as dry bulk vessels and tankers. However, in further use, the scores could be altered for certain vessels or vessel types.

Table 6.7: Scores MCA

CRS	Technological readiness level	Safety	Implementability	Hinderance in operation	Manoeuvrability	Future proof
Turbo sails	5	7	5	4	5	8
Flettner rotor	6	7	5	6	5	8
Cold ironing	8	9	9	9	10	10
Towing kite	5	8	8	8	7	8
Solar energy	9	8	8	7	10	8
Ship lengthening	8	5	4	6	6	10
Air lubrication	5	6	4	6	6	9
Waste heat recovery	6	7	6	5	10	8
Carbon capturing device	3	6	4	4	10	2
Ammonia	5	3	5	7	10	8
H2 Liquid	3	4	2	6	10	8
H2 Gas	3	4	2	6	10	8
Methanol	7	6	6	7	10	6
Bio-fuel	8	10	10	10	10	5
E-fuel	6	10	10	10	10	7
Slow steaming	10	7	10	7	7	9

Turbo sail

The turbo sail is scored with a 5 for the technological readiness level, which reflects the still early stage where the technique is at this point. The score of 5 comes from the fact that it is already in use, but a lot of research is still needed to develop a mature solution that can be used on a large scale. However, the turbo sail has been around for some time, since the 1980s, but very few vessels use it now. The safety of the turbo sail has been scored at a 7 because the sails are a new addition to the vessel and there is not as much known about the safety of the turbo sail. However, research shows that sails can lead to increased stability [64], and it can be expected that this is also true for turbo sails. So, considering the prior aspects, it can be concluded that the uncertainty about safety is the primary safety concern, and thus a score of 7 is rewarded.

The implementability of the turbo sails has three main components, the ease with which the turbo sails can be installed, the availability of the turbo sails and the interaction with the crew. The instalment ease depends on the sort of turbo sail, the sails installed directly on the vessel or the sails installed as a container.

The ones installed via a container have a high ease of installation and can thus be considered to have a high implementability; however, this is lower for the sails installed on the deck. The implementability is also influenced by the availability of the turbo sails; as they are not yet widely developed, it can also be expected that these are not readily available. Lastly, the interaction with the crew also negatively influences the implementability. Although the sails are steered automatically, the crew still has to get used to the sails, which will still take time. All aspects considered make that the turbo sails can be classified as just below neutral, which translates to a score of 5. The turbo sails greatly influence the hindrance in operation. This is not only due to the height of the sails, which limits the height of the sailing routes, but it also influences the vessel's path due to the direction of the wind. These two components negatively affect the vessel's operations, leading to an unsatisfactory score of 4.

The instalment of turbo sails also impacts the manoeuvrability of the vessel. The use of wind power leads to changing propulsion power delivered by the turbo sails when changing course, which affects the vessel's manoeuvrability. The other effect is the change of the wind direction which can affect the vessel's manoeuvrability too, leading to a score of 5. The last criterion is future proof, on which the turbo sail achieves its highest score. The turbo sail operates with clean, renewable energy, namely wind. As wind will always blow across the oceans, it can be used for all future scenarios. It can also be combined with carbon-free or natural fuels to decrease the use of those vessels. The only future downside of the turbo sail, when combined with carbon-free fuels, is the lack of effectiveness. In that case, it could be that the benefits do not outweigh the cost of the turbo sail and would thus not be future-proof. So this leads to a score of 8, which means that the turbo sail can be expected to function well in the future.

Flettner rotor

The Flettner rotor has many comparisons with the turbo sail, which is also true for the technological readiness level. The Flettner rotor also has been around for a long time, even much longer, the 1920s for the Flettner rotor and 1980s for the turbo sail. However, the Flettner has seen more development in the last years and is installed already wider than the turbo sails. [121] So, the Flettner rotor scores a 6, somewhat better than the turbo sail.

The safety can also be compared with the turbo sail, although it is less clear if a Flettner rotor also develops more stability. On the other side, the Flettner rotor is further in its development than the turbo sail and can thus be expected to be somewhat safer. So, both these aspects considered, the Flettner rotor is also scored at 7 for safety.

For the implementability of the Flettner rotor, there are also several parallels between the rotor and the turbo sail. At this criteria, the development level also favours the Flettner rotor because they are more available and thus easier to implement. However, the Flettner rotor is not yet available to be installed as a container, such as a turbo sail, which could lead to better implementability. So, combining these positive and negative aspects, the score for implementability is equal to that of the turbo sail, a 5. The hindrance in operations can be less for the Flettner rotor than the turbo sail because there are Flettner rotors available that can tilt in such a way that these are flat on the deck. This will lead to reduced hindrances with loading/unloading and the height barriers on the waterways. However, not all the Flettner rotors have this feature, which could create other problems on the vessel. Flettner rotors have an advantage in operations over turbo sails regarding wind direction. The Flettner rotor is effective for more different directions of the wind and will thus have less effect on the operations. So, the Flettner rotor will score a six on hindrance in operations.

The vessel's manoeuvrability is impacted in the same way as the turbo sail and will thus have the same score, a 5. The future-proof ability of the Flettner rotor can also be taken over one-on-one from the turbo sail, which will result in a score of 8.

Cold ironing

The technological readiness level of cold ironing is high, not because it is widely used but because the technology behind it has existed for a long time. The technology itself is accessible, connecting a vessel to the energy grid. However, cold ironing in itself is not widely used yet, and in that regard, it is not yet as ready as possible. Most of the improvement can be made in infrastructure in harbours and standardisation of the connections. These seem in contrast to the effect of the cold ironing slight, and thus will, the technological readiness level is scored with an 8. Safety is not significantly impacted when using cold ironing. Safety can be increased by using cold ironing when it leads to the end of the use of auxiliary engines in port, which will lead to less harmful emissions to the crew, surrounding and nature. The negative impact can be found when the vessel moves away from the quay when the cables are still connected, which could lead to broken cables and the loss of power on the vessel. However, the likeliness of this happening is small and thus will, the safety is scored with a 9.

The implementability is also high for cold ironing, and the main disadvantage is the instalment of the equipment that will couple the vessel to the grid. However, it will not require much work for the crew to learn how to operate it when installed. Also, the equipment itself is not complicated and can be expected to be produced relatively quickly. So this leads to an implementability score of 9. The cold ironing will not impact the operations at sea; only the operations in port could be affected by cold ironing. Here the hindrance could be found in the cables from the shore to the vessel that could hinder some loading/unloading operations. This seems to have a negligible impact; thus, the score for hindrance in operation will be a 9.

The vessel's manoeuvrability will not be impacted and thus lead to a score of 10. It is expected that the future will still use electrical energy from the grid; thus, the ability for vessels to use shore power will keep existing. Even if a vessel uses renewable fuels on board, it is expected that using shore power will still be more practical than generating it on the vessel, so the future-proof score of cold ironing will be set at 10.

Towing kite

At this moment, the towing kite is still being tested on a few vessels, which can be seen as the prototype phase. The same technology is used on land as electric energy generation, and the technology is thus being improved in a broader sense. However, the towing kite is not widely commercially available and will therefore be scored with a 5. The safety of the towing kite cannot be determined in detail yet, because it is not used as much yet. However, the towing kite will only be used on the high seas and flies high above the vessel, so the safety risks associated with the towing kite are kites that break off or when the kite is brought in. Both options have low safety risks since the kite is made of soft material and won't significantly impact people and nature.

The implementability is high; the kite can be installed as a container which takes little time to install. The kite operates autonomously and only when there is a tailwind, so the crew will have little time to get used to the kite. The negative point for the implementability is the commercial availability of the kite, which is low. These factors combined lead to a score of 8 for implementability. The hindrance in operations is low for the towing kite since the kite is only flown on the high seas. Compared with a turbo sail or Flettner rotor, there is no height restriction due to the kite. When the kite is hauled, the height of the whole installation is the height of a container which creates no height restrictions. The vessel will, however, need to consider the wind and thus maybe sail different routes, which impact the vessel's operations. This leads to a mostly positive score and, therefore, an 8.

The kite impacts manoeuvres when the vessel goes to a course where the kite does not provide towing power. This means the kite must be brought in, which will take some time for the manoeuvre. Also, considering that the vessel sails are the best with a tailwind, it will have to manoeuvre in an ideal course for the kite. The towing kite does not significantly impact the rest of the vessel's operations. All this combined leads to a score of 7 due to the low total negative implications for manoeuvrability. The future-proof score has been determined at an 8, which has the same reasons as the turbo sail and Flettner rotor. They use clean energy but must be combined with other clean propulsion powers to power the whole vessel.

Solar energy

Solar panels are a mature technology already widely used on the land. The only downside is that it is not yet used on a large scale on vessels, where there could be some technical issues that have to be worked out. However, because the technology is so mature, it is decided that the score will be a 9. The safety issues of the solar panels will concentrate around the large deck area that will be filled with the panels. This is a large area where the crew cannot move or can only move in a restricted way, which would mean that in case of emergency, they are restricted, which could lead to a safety issue. The fact that solar panels are not widely used on vessels yet is also a small safety issue, which leads to a score of 8 for safety.

The implementability for solar energy can be scaled as high. The implementability is negatively impacted by the instalment time of the solar panels, which will take some time. Using solar panels will not be difficult for the crew, so this will not negatively impact the score, just like the availability of solar panels, which are largely available. This ends in a score of 8 for implementability. The hindrance in operations is mainly in the reduced deck area, which means less room for the crew to move around and less room to store equipment when doing maintenance. All in all, the reduced space will lead to a score of 7.

The vessel's manoeuvrability is in no way impacted by the solar panels and can thus be scored with a 10. The future-proof score takes into account the efficiency of solar panels. Even when that increases, it will not be likely to let large ships sail on only solar energy, so it has to be combined with other clean propulsion power. This leads to the same issue as for the WASP and will thus lead to the same score of 8.

Ship lengthening

The ship lengthening technological readiness level has some similar aspects to solar energy. The technique with ship lengthening is essentially adding a different section of a vessel together, the same way sections are put together when newbuilding a vessel. However, ship lengthening is not often done, so the technological readiness level is unclear. Although it is not carried out that much yet, the technological readiness level can be set at a score of 8. The safety of a vessel is impacted by the ship lengthening because the vessel gets a different design than when originally designed or build. This could lead to aspects of the vessel that react sub-optimal to different environments. The elongating of the vessel could also lead to increased longitudinal stresses on the vessel, which could lead to fatigue and significant safety issues. [45] So, these negative impacts on safety lead to a score of 5 for safety.

The implementability of ship lengthening is very low since the vessel has to be dry-docked. The positive point is that dry docks are widely available worldwide, but the operation to lengthen the ship will take a long time. Combined with the influenced behaviour of the vessel due to the lengthening, which leads to the crew having to get acquainted with the vessel again, it leads to an implementability score of 4. The new dimensions of the vessel influence the hindrance in operations score; the vessel will need larger quays, locks and docks, which will lead to a reduced area of operations. So, this could lead to a considerable hindrance in operation and thus a score of 6.

The lengthening of the vessel also influences the manoeuvrability; in the same way, the hindrance is influenced. The vessel gets longer and will thus have that impact on manoeuvrability. Also, if the engines are not upgraded to deliver more propulsion power, the ship will be less easy to steer. This will both influence the manoeuvrability that will thus end with a 6, it will not have the most significant influence, but it will still be harder to handle the vessel. The future-proof score has been set at 10 because an elongated vessel will still get all the other upgrades. It is also an upgrade that does not have to be removed because it does not achieve full decarbonisation.

Air lubrication

The air lubrication is still being developed and has, as of now, been installed in very few vessels. There are significant parallels between the turbo sail and the Flettner rotor. It has potential and is being tested; however, it is not being used at a large scale yet, and more research is expected to scale up this CRS soon. This leads to a comparable score for future technological readiness level as the turbo sail and Flettner rotor of 5. There are some concerns for the safety of air lubrication, mainly about stability. It is expected that the bubbles of air lubrication will impact the stability of the vessel and will thus lead to unsafe moments. [80] There is also some concern that the bubble will lead to extra cavitation around the propeller, which could lead to reduced thrust, which can lead to unsafe moments. This, combined with the fact that there is still a lot unknown about air lubrication, leads to a score of 6 for the safety criterion.

The low implementability score of 4 comes from several aspects that can also be found for the other CRSs. For instance, the ship has to be dry-docked when installing air lubrication. Air lubrication is still not widely available, and the crew will need to learn to work with the system. These combined led to a relatively low score of 4. The technique of air lubrication will also hinder the operations because air lubrication only works in relatively calm weather, so the route has to be adjusted accordingly. This could be the most significant problem for short routes in areas with notable heavy weather. So, in the end, the score of hindrance in operation is a 6.

The vessel's manoeuvrability is also severely impacted because the bubbles must stay trapped below the vessel for optimal effect. This affects how the vessel can turn effectively and thus impacts the vessel's manoeuvrability. Trapping bubbles under the vessel is a significant task affecting the vessel's manoeuvrability and is therefore set at 6. This system can still be used in the future, but when the vessel has to be carbon neutral, the air lubrication must be combined with other clean propulsion methods. However, it will still reduce the amount of energy needed, so in the future, it may not be required to become carbon neutral but will always be able to reduce the energy needed.

Waste heat recovery

The waste heat recovery is already in use in several vessels and is responsible for the efficiency, from fuel to propulsion, which increases an average of 5%. It is, however, not used as much yet, but more than the turbo sail or Flettner rotor. The situation is comparable with those two CRS, but the waste heat recovery is somewhat further and will thus have a score of 6 for technological readiness level. The vessel's safety is not influenced by its sailing abilities, but a new installation uses hot steam to create energy. This could lead to more safety issues than when the heat is discarded with exhaust gasses or cooling water. There is also a component that the waste heat recovery is not used as much yet, so to tackle some uncertainty, the score is set at 7.

The implementability is given a score of 6 because the waste heat recovery is not used as much yet, so finding one to install would take some time. The ship does not have to be docked, but installing the machine will take some time. However, the crew does not have to be trained extra that much, hence the score of 6. The hindrance in operations is scored a 5, mainly because the waste heat recovery will primarily be used to supply auxiliary power. This means that the main engine will have to be turned on the supply auxiliary power, which could lead to scenarios where it is impossible to create enough auxiliary power. This risk will lead to a score of 5 for hindrance in operation.

The waste heat recovery will not impact the vessel's manoeuvrability because the energy it uses from the main engine would otherwise not be used and thus will not reduce the amount of propulsion power delivered. Therefore, the manoeuvrability will get a score of 10. If the vessel goes over to different fuels that produce heat, it can still be helpful to equip a ship with a waste heat recovery system to increase the efficiency of the main engine. However, when other systems are installed where it is impossible or inefficient to install a waste heat recovery system, it could be that the system becomes obsolete on certain vessels. So, considering the prior, it is decided that the future-proof score is 8.

Carbon capturing device

Carbon capturing is still in the concept phase; there are various studies into the technique and companies trying to develop the technique. There are already prototypes running on land, but before they are translated to the maritime world, it will take a long time. Because it is in the concept phase, the technological readiness level is not as low as possible, but the score will not be higher than the used 2 for some time. The safety is impacted by the fact that it is not used yet, so there is still a lot unknown about the safety of carbon capturing devices. Also, the storage and techniques to capture the carbon could impose safety risks on the vessel and thus will result in a score of 5 for safety.

The implementability has been scored as a 3 for almost the same reasons as the score for the waste heat recovery. However, the carbon capturing device is not yet available, and the storage will ask for training for the crew, leading to the aforementioned score of 3. The hindrance in operations comes mainly from the carbon storage; this will take up room and limit the crew's movements or even the cranes used to load and unload the vessel. Because of the large size needed to store the carbon, the impact of the carbon capturing device on the operations is high, and the associated score has thus been set at 4.

The manoeuvrability is not impacted by the carbon capturing devices for the same reason as the waste heat recovery and is thus set on 10. Carbon capturing cannot be seen as a solution with a bright future because fossil fuels are non-renewable. So, at some point in time, it is necessary for a vessel to transit to a fuel that is renewable and thus carbon neutral. It is also expected that the carbon capturing device will not be able to capture all the carbon emitted from a vessel. So, the prior arguments taken into account leads to a score for future proof of 2.

Ammonia

Ammonia as a marine fuel is yet to be used at a large scale, but it seems promising. The main advantage of ammonia as the green fuel of the future is that it is already being created in large volumes for other purposes, which means that the technological readiness level of production is high. Although it is now mainly created using natural gas and thus not green, it could also be made using clean energy. Ammonia could be used in ICE and fuel cells, but this is still in the prototype phase. The combination of a fuel already available and the fuel user in the prototype phase sets the technological readiness level at 5. Safety is an issue nowadays with ammonia; the fuel is highly toxic for humans and can harm the environment, especially a water-based environment. In ideal situations, no NO_x is released; however, there is a significant chance that these molecules are released. Ammonia is also reported to be flammable and corrosive, impacting the safety score, so it has been set at 5.

The implementability of ammonia has been set at 5. Several aspects positively impact the implementability of ammonia; for instance, the storage does not have to be in high-pressure or cryogenic tanks. When it is used in ICE, it does not require a lot of training for the crew. The high ammonia production means bunker capacities can be created faster than other clean fuels. The negative impact is more significant when new fuel cells need to be installed, and the infrastructure needs to be built to handle the toxic aspects of the fuel; ultimately, the score is set at 5. The hindrance in operations score is 7, mainly thanks to ammonia's toxic nature. This would lead to extra caution and attention of the crew, which would impact their focus on the further operations of the vessel. Also, in the early days of ammonia as a marine fuel, it is expected that not all ports would have bunker capacities, impacting the vessel's routes.

The vessel's manoeuvrability will not be impacted if the engine power delivered stays the same, which is usually expected and will thus lead to a score of 10. The expectations of ammonia as a marine fuel in the future are high; the energy density combined with the fact that it does not emit CO_2 gives it a bright outlook. However, there is competition for other clean fuels in the future, and it could be that those fuels will become dominant. This is the negative factor of the score for future proof, which leads to a score of 8.

H_2 Liquefied

The technological readiness level of liquefied H_2 is not high for two reasons. The first problem, as with ammonia, is that the technical aspects of H_2 as a marine fuel are still in the prototype phase. It is used in some vessels to achieve data but is not widely used. In contrast with ammonia, hydrogen is not yet produced in high volumes, so the scale-up of the production has a less high technological readiness level. This leads to a lower score than ammonia for the technological readiness level, namely a 3. The safety has been scored as a 4, due the, among other things, the explosiveness of hydrogen. The hydrogen is also stored liquid and thus severely cooled, which presents a safety risk when leaked and comes in contact with humans. In small rooms, it can also lead to oxygen displacement, leading to health risks.

The implementability is very low at this point; it would require a large installation of storage, which also requires energy to keep the hydrogen cooled. The crew should be trained in dealing with the hydrogen, and the ICE should be replaced with a fuel cell. Combined with the fact that these total installations for marine use are not widely available lead to a score of 2. The operations are hindered by the extra attention the storage needs, which ties up the crew. Also, the storage takes up space, resulting in less cargo space and less room for the movement of the crew. In line with the problem that also occurs for ammonia when it is used as fuel, it will not be widely available and will lead to routes along harbours with hydrogen bunker capacities. This will ultimately lead to a score of 6.

The manoeuvrability score has the same argument as ammonia and will therefore be 10. The future-proof score can also be compared with ammonia, the green aspect of hydrogen makes it robust for the future, but it could be that it does not become the dominant fuel, and thus an 8 is rewarded.

H_2 Gas

The technological readiness level of hydrogen gas is comparable with liquefied hydrogen; in essence, only the way of storage is different, so the score of 3 is the same. The safety of hydrogen gas, in comparison, only differs on one point; with gas, there is no risk of safety issues concerning freezing. However, the gas will be stored under high pressure, creating chances of exploding tanks or other hydrogen carriers. This leads to comparable safety risk levels, and the score with thus be the same, a 4. The implementability, hindrance in operations, manoeuvrability and future-proof score, have the same argument as liquefied hydrogen and will thus have the same score; 2, 6, 10 and 8, respectively.

Methanol

Methanol is a fuel that is liquid under normal temperatures and will thus not require special storage, so that has no impact on the technological readiness level. Internal combustion engines can easily be modified to run on methanol or as a duel-fuel engine. This means the technological readiness level is relatively high; however, some infrastructure has to be altered to make it usable for methanol, leading to a score of 7. Safety is an issue with methanol, it releases more vapours than MDO or HFO, so there are more explosive risks when leaks occur. It is also toxic for people, primarily via ingestion but also via skin and inhalation on larger scales. [11] These safety risks can mostly be mitigated but are still significant and will lead to a score of 7.

The implementability of methanol is scored at 6, and it will be relatively easy to implement in terms of instalments. However, the crew needs additional (safety) training, and there should be some altercations in the storage to tackle some safety issues. So, some negative aspects lead to a score of 6. The hindrance in operations is mainly the availability, as with H_2 and ammonia. Because there will be some altercations in the storage, it could mean that some parts of the operation will become more complex, leading to a score of 7.

The manoeuvrability has the same score and argument as ammonia and H_2, so a 10. The future-proof score has been set at 6, mainly because methanol still contains carbon. When methanol is created from renewable sources, that would be less of a problem. However, in that case, it can be expected that also diesel could be made from renewable sources, and it is more logical that that becomes the dominant fuel. This is because the infrastructure is set up for diesel, which would be more logical. So, considering this would lead to a future-proof score of 6.

Bio-fuel

Bio-fuel does not need technical altercations when used as a drop-in fuel, and minor altercations are likely required to let engines run only on bio-fuels. [62] The problem is the large-scale creation of bio-fuels, which leads to a technological readiness level of 8. Because bio-fuels are comparable with fossil fuels, there is no need for real impact on safety, implementability, hindrance in operations and manoeuvrability; those will thus be scored a 10 on all aspects. To only use bio-fuels in the future would require immense areas of agricultural land to produce these fuels. The fuels also contain carbon dioxide stored in plants, which could lead to scenarios where more carbon is used than is compensated by newly growing plants. The combination of these two aspects makes the score for future proof 5.

E-Fuel

E-fuels are much less far than bio-fuels, but most of the reasoning is the same concerning the technological readiness level. Only the scale that E-fuels are created is even smaller than that of bio-fuels, and in that aspect, there is still a lot of improvement on the technical level, which in turn will lead to a technological readiness level of 6. As for bio-fuels, they are comparable with fossil fuels; the safety, implementability, hindrance in operations and manoeuvrability will score a 10. E-fuels' future is brighter than bio-fuels because, under ideal circumstances, it could be created from only CO_2 and H_2O. However, it still contains carbon, and other emission-free fuels could become the dominant fuel in the future because it is unclear which will be the most efficient; the score for future proof has been set at 7.

Slow steaming

The technological readiness level of slow steaming has been set at 10. The technique is to sail less fast, which is an easy task. To ensure that vessels comply with the regulations, there is the EPL, but these are already developed and used now. The safety issue associated with slow steaming is the lack of reserve power in case of emergency. In the case of a retrofit with EPL, it is less of an issue because then the engine can be set at the old, full power, but with vessels that have a smaller engine, it could lead to dangerous situations, so a score of 7 is awarded.

The implementability is easy; there is no need for crew training or complicated system installations. Only possibly a small installation of an EPL, but the score will be a 10. The hindrance in operations comes from the fact that the vessel is longer underway and will thus have to take into account longer sailing time; a score of 7 is associated with this aspect.

The manoeuvrability will be impacted by the smaller amount of propulsion power available, which means that the vessel will be less manoeuvrable, and this will lead to a score of 7. The technique of slow steaming is very future-proof; it can always be used, has no negative impact on other solutions, and, when possible, could be reversed. The only negative point is that when a smaller engine is installed, and the vessel gets green fuel, it cannot yet sail at the old, higher speed. This ultimately leads to a score of 9.

6.4 Other Data

The time frame chosen for the run of the model of the case study has been based on the average lifetime of an oil tanker, which is 25 years. [85] The average downtime to load and lose the vessel has been set at 3 days, a combination of waiting time and the actual time spent in port. The average time in port is around 1 day for liquid bulk vessels. [162] The average waiting time for vessels is around 2 days [127], which yields a total time of 3 days. The ratio between fuel uses in the original condition of the vessel has been set at 80% VLSFO and 20% MDO, based on the total fuel use for crude oil tankers. [138] For the fuel used in port, it is expected that the cleanest fuel should be used, which means 100% MDO. This is already mandatory in the ECA zones in the United States, and the EU [67] and can be expected in the future also in other countries.

6.5 Conclusion

The data used for this case study has come from different sources, So the case study will be carried out with only one vessel due to the lack of data, which is a 110 000 DWT oil tanker. The route is 7500 nm and is based on an average trip for a tanker. Much of the data of the CRSs is based on the Green Voyage 2050 initiative, and the costs have been collected from several different sources. The weights of the MCA have been scored to test the model as best as possible, and the MCA scores have been determined with the help of the SWOT analysis of chapter 5.

Chapter 7

Simulations & Results

This section discusses the simulations that are run and the results that follow from these simulations. These are carried out for three reasons; the first is to test the method to determine if the results are valid. The other two are to get an insight if one or more CRSs stand out above the rest and to see if the answers consistent and logical. This is carried out by running the model in different scenarios. These scenarios include; different combinations of CRSs and the strictness of regulations or ranges of values for the Monte Carlo simulations. There will be two types of scenarios; the first is scenarios that show how the model works and if the model creates credible values, such as the scenario with tightening regulations. The other scenarios will focus on the effects of specific parameters that will show the effect of the change in fossil fuel prices and regulations. The chapter will first present all the different scenarios and then continue with the results of the simulations.

7.1 Simulations

There will be one simulation for the scenario, called the base scenario, which will be the benchmark with which the other simulations can be compared. This scenario has been chosen with values that can be seen as average or plausible. There are some standards in all the simulations, one of which is the run time of 25 years, from 2023 to 2048, with a step of 1 year. Another standard is that when slow steaming is switched on, the range of the speed is always between 12 and 15 knots, with a step of 1 knot. The other standard associated with slow steaming is that it is always from the start to reduce the number of options created by the model, so for slow steaming, there is nothing sensible to say in which order it is placed in the strategy. The amount of Monte Carlo iterations has been set at 100; it was found that this gave the same distribution as more significant amounts but was faster to run. To keep the simulations comparable, only a few aspects shall be altered to test the model. These are the strictness of the regulations, the range of the base and the increase/decrease of the cost, the combination of CRSs and the ratio between alternative and fossil fuels. In the base scenario, the range surrounding cost is between 0.75 and 1.25 when 1 is the base value.

7.1.1 Benchmark base scenario

The base scenario is based on the intention of the IMO to cut the carbon emissions of the whole sector in half by 2050, which means that vessels will have to decarbonise more than 50%, assuming that the shipping market will grow. Thus more vessels are needed, and therefore more carbon reduction is required per vessel. It has been chosen to make the existing regulations stricter after the new ones have been finished. This means that the EEXI will have a 10% reduction per 5 years from 2028, and further and the CII will be reduced by 3% per year from 2026. With the existing regulations, this will lead to a 60% reduction for the EEXI and a 77% reduction for the CII in 2048.

7.1.2 Zero carbon emission in 2050 scenario

In this case, there will be fewer carbon emissions from vessels in 2050, earlier than the IMO has set. However, this could be an interesting scenario for companies that want to decarbonise faster or if the regulations will become stricter even more quickly than the IMO has set. In this case, the decrease percentage for the EEXI will be set at 16% and the CII at 4% instead of 10% and 3%, respectively. This will lead to an EEXI of 0 in 2048 and a CII of 0 in 2050.

7.1.3 Loose regulations scenario

It is also interesting to test the model when the regulations are set less strictly than in the base scenario. So, for this scenario, the EEXI will be set at 5% per 5 years and the CII at 2% per year. As this scenario will require less decarbonisation than the base scenario, it could be interesting to show which CRS has the most impact when used alone.

7.1.4 Zero carbon emission in 2050 scenario with full use of alternative fuels

In section 7.1.2, the scenario should always select ammonia because methanol, bio-fuel and E-fuel are used as drop-in fuels and still require fossil fuels. So, these fuels could not achieve the case of no carbon emission. In this scenario, everything is the same as in the scenario of section 7.1.2, except that all alternative fuels can be used on their own, with methanol having a carbon conversion factor of 1.375 and bio- and E-fuel of 0.

7.1.5 No slow steaming scenario

Slow steaming is a CRS that is easy to use but also has the highest impact on the vessel's operations and the whole transport chain. The effect comes from later freight, but sailing slower decreases the total freight that can be shipped. So, if the ship owner will not reduce the ship's speed, it is also interesting to see if and how decarbonisation is achieved without slow steaming.

7.1.6 Scenarios of changing range of parameters

This section presents the two simulations to show the effect of changing parameters. These are the change in fossil fuel prices and the change of regulations. To better display these parameters' impact, the ranges of all the other aspects have been changed from 0.75 to 1.25 to 0.95 to 1.05. For the scenario for the changing fuel prices, there will be several Monte Carlo simulations where the only change is the range for the percentage of the yearly change in VLSFO and MDO prices. These will be a range of 10% for every run, ranging from -50% till -40% to 90% till 100%. It should be noted that these extremes are not realistic in real life. To substantiate, a decrease of 50% every year for 25 years would lead to fuel prices that are practically 0. However, this is used as an enlargement to show the effects clearly. The other simulation that uses a change in parameters will change the strictness of the regulations. This means that the reduction percentage of the EEXI and CII will be changed step-by-step, from 2028 and 2026, respectively. The EEXI and CII will be altered per step; this will go with steps of 2% per 5 years for the EEXI and 0.5% per year for the CII, which will range from 0% for both to 16% per 5 years and 4% per year for the EEXI and CII respectively. This will effectively vary from no-change to zero-emission scenarios in 2050.

7.1.7 Different MCA Weights scenario

The weights used in the case study heavily favour the cost component as it cost weight 10 times more than the next criterion. To show the impact of that weight, it can be helpful to run a scenario where the weights of all criteria are 1. This will show the effect of the cost on the answer in the end. The outcome will not always be the same because the MCA scores are also subjected to the Monte Carlo simulation.

7.1.8 Other scenarios

More scenarios have been analysed to create data, but these did not deliver (more) interesting information than the scenarios presented. These include, among others, the scenario that was the same as the benchmark scenario, only with the towing kite turned off, which delivered almost the same distribution as the base scenario, only without the towing kite. Other scenarios ran were scenarios with no alternative fuels or just low prices for alternative fuels. This would lead to a significant increase in carbon capturing and a slight increase in the cheaper alternative fuel. The results of other scenarios can be found in appendix B.

7.2 Results

This section will discuss the results of the simulations presented in section 7.1. The report will be visualised for every simulation in the form of plots and tables. These results will be substantiated and discussed to see if they are plausible and why the model presents them.

7.2.1 Benchmark base scenario

The results for this scenario are presented in tables 7.1 and figure 7.1. For the results, there are several interesting aspects, firstly is that in all the strategies, there are two CRSs in common, slow steaming and the towing kite, which can be seen in the bar plot from figure 7.1. The ship lengthening option is also chosen almost every time (86%), and always one option from the alternative fuel group, which is divided almost equally between carbon capturing and methanol. From the upper right plot in figure 7.1, which shows in what order the CRSs are selected, it becomes clear that the first steps to take are implementing, outside slow steaming, a towing kite and then ship lengthening, in that order. These are the first steps for more than 60% of the presented options. After that, it is almost equal between methanol or carbon capturing, but some option to has a more significant impact on carbon emissions. It is noticeable that the first three CRSs are options that reduce fuel use and, thus, cost per freight shipped. The last option, from the alternative fuel group, creates a significant reduction in CO_2 emissions. Due to the model's working where slow steaming is always the first CRS to be introduced, it can only be concluded that the significant effect on cost reduction is the key to choosing this option. The rest could be explained by several aspects, firstly the fact that the reduction of carbon emissions is less in the beginning. So, the towing kite can bring the required small reduction with relatively low investments. Also, when looking at the MCA scores of the towing kite in table 6.7, it is seen that the towing kite has scored relatively high. This can be explained by the fact that the towing kite can be installed relatively quickly and has the size of a TEU container. So, even when it does not deliver enough power, it also does not really negatively impact the vessel. The next option that the model chooses is ship lengthening, and although it is costly, the cost and CO_2 per tonne mile decrease drastically. This can be combined with slow steaming because the extra engine power asked for the increased resistance can be reduced by the slow steaming, which together will lead to a vessel that can carry more freight for less fuel use. What is also interesting to notice is that the most selected strategy, 12-3-5-8.1-0-0, has the highest and almost the lowest MCA score, but the cost per tonne mile falls more in the middle segment. This shows that, although the cost is essential, the lowest cost does not automatically mean the highest MCA score. The extensive range for the most selected strategy can be explained by the fact that it is selected the most. Under changing circumstances, it is selected the most, so the distribution is higher, substantiating the choice for that strategy. The strategy also has carbon capturing as CRSs, which means it depends on fossil fuel prices, whereas other strategies with other alternative fuels have more chance that these high and low prices cancel each other out.

Table 7.1: Top 5 most selected strategies base scenario

Strategy	%
12 knots - Towing kite - Ship lengthening - Carbon capturing device - 0 - 0	27
12 knots - Towing kite - Ship lengthening - Solar energy - Methanol - 0	18
12 knots - Towing kite - Ship lengthening - Methanol - 0 - 0	15
12 knots - Towing kite - Carbon capturing device - 0 - 0 - 0	6
12 knots - Ship lengthening - Air lubrication - Towing kite - E-fuel - 0	6

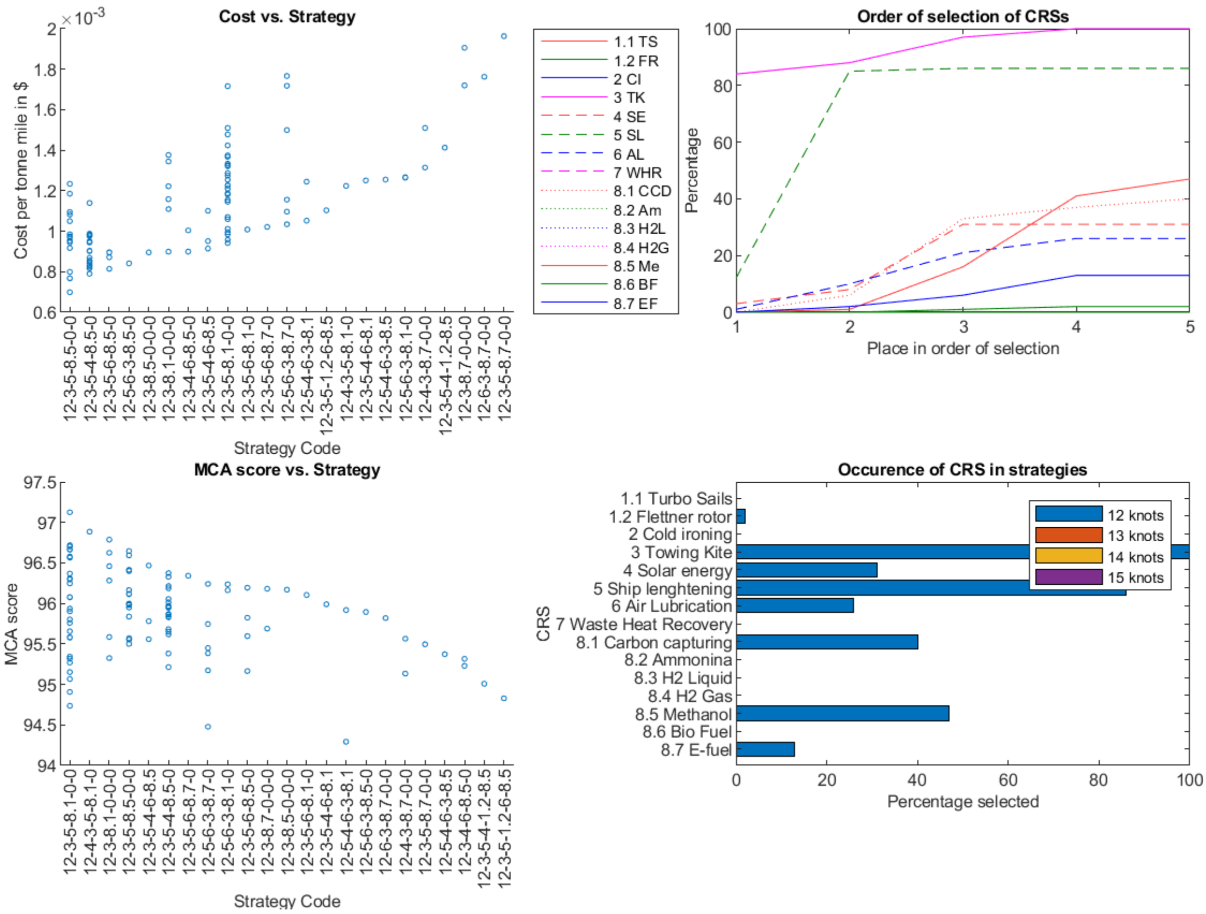

Figure 7.1: Plots Base Scenario

7.2.2 Zero carbon emission in 2050 scenario

The first thing that catches the eye is that again, in figure 7.2 and table 7.2 is that the 12-knot slow steaming is selected for all options and the fact that ammonia is also selected for all possibilities. This can be explained by the fact that ammonia has a carbon conversion factor of 0 and is not mixed with other fuels, which is only the case for the two sorts of hydrogen. The hydrogen is significantly more expensive than the ammonia option, which is logical. The towing kite is practically selected for all possibilities (99%), comparable with the base scenario, a relatively small investment for a high reward. The similarity with the base scenario can also be found in the ship lengthening, which is also selected most of the time. There are three options, Flettner rotors, air lubrication and solar energy, that are selected less, so the model shows that a combination of slow steaming, towing kite, ship lengthening, and ammonia, combined with two of the other three CRSs is the most logical option to decarbonise in this scenario. The last thing that stands out is that ammonia is always the last CRS to be chosen; this can be explained by how the model works. It optimises to the regulations, so it will not implement a CRS when the model scores lower than the regulations. Because the carbon conversion factor of zero of ammonia brings the EEXI and CII to zero, the model will not implement another CRS. This is also one of two things, the other CRSs save a significant amount of fuel and are thus an economically smart option outside the regulations, or the alternative fuel is an expensive option that should only be used when there is no alternative. The second, however, does not seem logical since methanol is selected many times in the base scenario. What is also interesting to notice from the table and the scatter plots is that there are fewer selected strategies than in the base scenario and that there is not one strategy that stands out in the number of selections. This can be explained for two reasons: the strategy will require an utterly carbon-free fuel, which could be ammonia or hydrogen, but hydrogen is too expensive. So that means that there are fewer different combinations available. The other is that the selected strategies are comparable and even the same, just in different orders, which is a' minor' detail in the whole strategy selection.

Table 7.2: Top 5 most selected strategies "0 in 2050" scenario

Strategy	**%**
12 knots - Ship lengthening - Solar energy - Flettner rotor - Towing kite - Ammonia	27
12 knots - Ship lengthening - Air lubrication - Flettner rotor - Towing kite - Ammonia	23
12 knots - Towing kite - Ship lengthening - Solar energy - Flettner rotor - Ammonia	13
12 knots - Ship lengthening - Solar energy - Air lubrication - Towing kite - Ammonia	13
12 knots - Towing kite - Ship lengthening - Solar energy - Flettner rotor - Ammonia	10

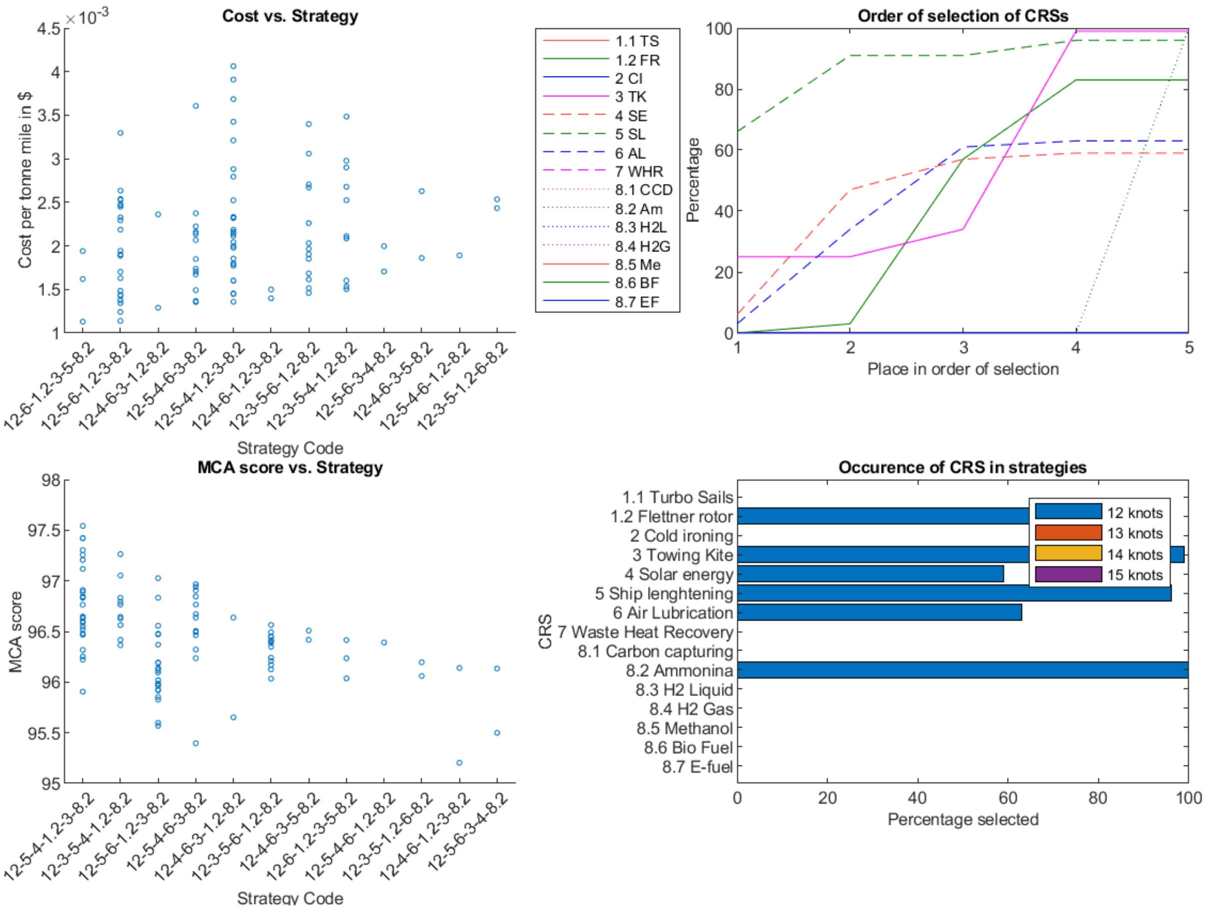

Figure 7.2: Plots 0 in 2050 Scenario

7.2.3 Loose regulations scenario

For this scenario, the selected strategy is always the same, as shown in figure 7.3 and why there is no table with the top 5 strategies. The selected strategy is only steaming at 12 knots and nothing else. This shows that slow steaming is the most cost-effective option when the need for decarbonisation is low. So, the other options will only be needed when the regulations get stricter. However, this does not need to mean that the other CRSs do not provide sufficient decarbonisation or that the other CRSs are not cost-effective. What is interesting to see from these results is the range of the cost per tonne mile, that with even the selection of the same strategy, the cost could vary more than a factor of two due to the uncertainties for the future introduced by the Monte Carlo simulation.

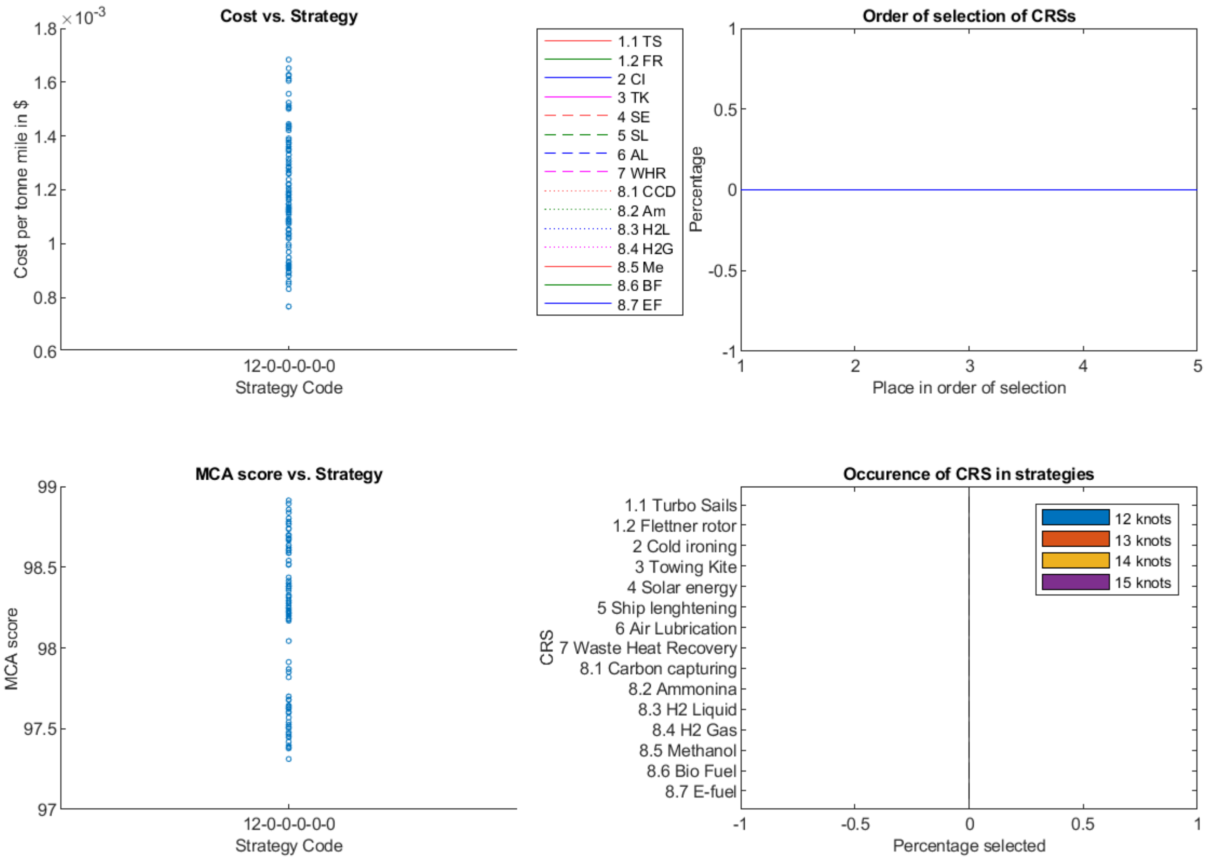

Figure 7.3: Plots non-strict rules Scenario

7.2.4 Zero carbon emission in 2050 scenario with full use of alternative fuels

What first stands out is that the top scoring strategies in table 7.3 have lower selection percentages than with the other scenarios, so the model is less sure which strategy to choose. This is also the reason for the top 6 because the fifth and sixth spots had the same percentage. This also shows up in both the scatter plots of figure 7.4, where there are more strategies, and they all have fewer points when compared with the scatters from the base scenario in figure 7.1. However, when looking at the bar plot from figure 7.4, there is more logic and unity between the outcomes. An example is that towing kites and ship lengthening almost have a score of 100%, and the model selects almost always bio- or E-fuel from the alternative fuel group. One of the differences between the base scenario and this scenario can be seen from the upper right plot of figure 7.4; whereas the towing kite is almost immediately installed for all the options in the base scenario, this scenario does it a lot more gradually, which is also true for the other CRSs. So, the order of instalments is less critical here, which also comes from the scatter plots. This could mean that the combination of these CRSs works well in this scenario. The selection of bio- and E-fuels show that the medium of liquid carbon-based fuel, such as diesel, is still ideal for vessels. This can also be compared with the choice of carbon capturing for the base scenario, which means that liquid carbon-based fuel is still used, but the carbon emissions are eliminated in another way.

Table 7.3: Top 6 most selected strategies zero emission in 2050 scenario ratio 100%

Strategy	**%**
12 knots - Ship lengthening - Solar energy - Flettner rotor - Towing kite - Bio-fuel	9
12 knots - Ship lengthening - Air lubrication - Flettner rotor - Towing kite - Bio-fuel	8
12 knots - Ship lengthening - Flettner rotor - Towing kite - Bio-fuel - 0	7
12 knots - Ship lengthening - Solar energy - Air lubrication - Towing kite - Bio-fuel	7
12 knots - Ship lengthening - Air lubrication - Flettner rotor - Towing kite - E-fuel	6
12 knots - Ship lengthening - Air lubrication - Towing kite - Bio-fuel - 0	6

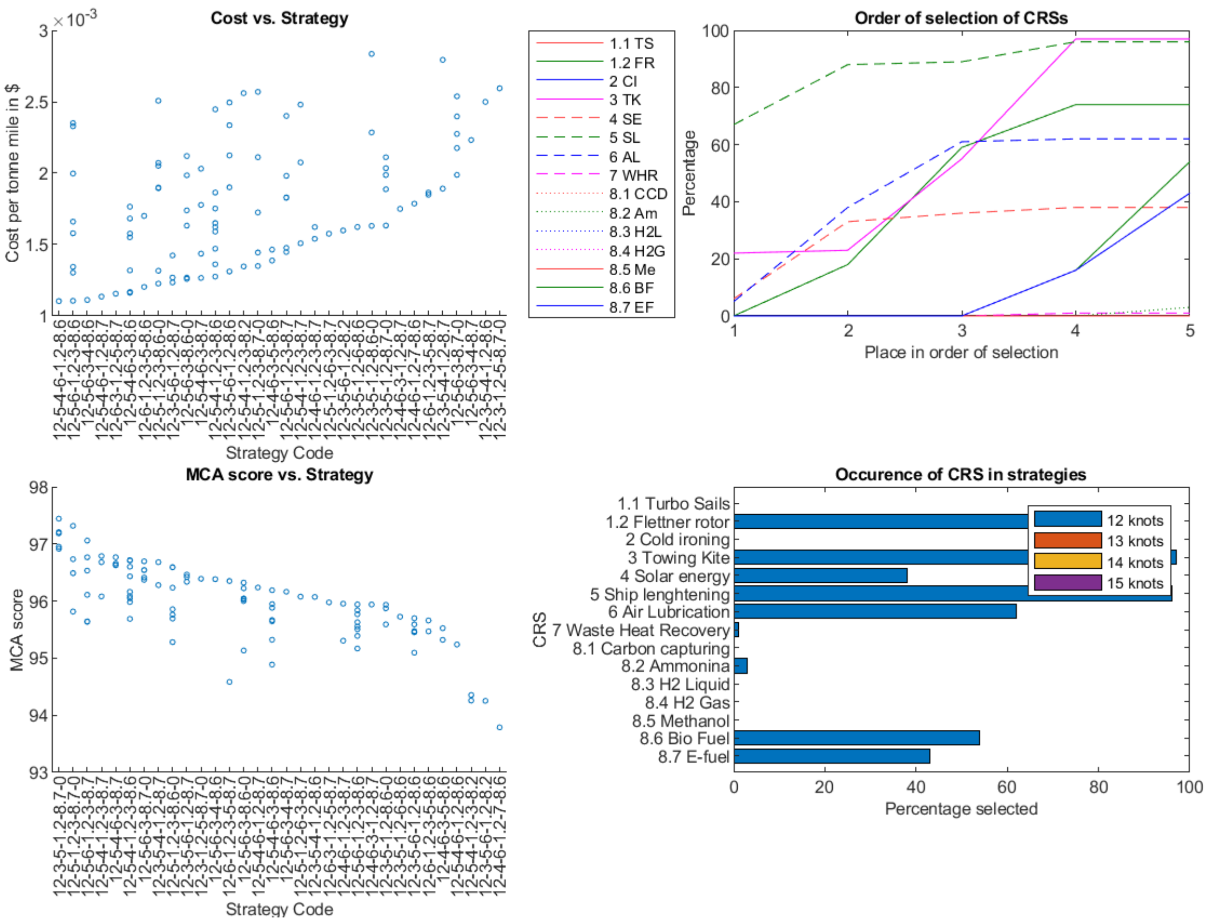

Figure 7.4: Plots 0 in 2050 with 100% ratio alternative fuels Scenario

7.2.5 No slow steaming

The first thing that stands out is the 15 knots in the strategy, opposite the 12 knots in all the strategies before, which is logical because slow steaming was turned off. What can be seen in the bar plot of figure 7.5 is that the towing kite and ship lengthening are 100% selected again. What can be concluded from table 7.4 is that the top 4 strategies, which are chosen 80% of the time, have a combination of towing kite, ship lengthening and carbon capturing.

The scatter plots of 7.5 show that the most chosen strategy also has the most range. The highest and the second lowest MCA score fall in the range of the best scoring strategy. This means that when the circumstances are as ideal as possible, when almost a score of 100 is achieved, the same strategy is selected when it is not as suitable as possible. When looking a bit further, it is seen that the range for the other three from the top four is also found to have an extensive range and relatively high MCA scores.

The difference with the benchmark scenario is mostly clear from the difference in carbon capturing and methanol use. This can be explained by the fact that the fuel use will be much higher without slow steaming, which means that the cheaper fossil fuel will be more economical in combination with the almost fixed cost of carbon capturing compared with the methanol.

Table 7.4: Top 5 most selected strategies without slow steaming

Strategy	%
15 knots - Towing kite - Ship lengthening - Carbon capturing - 0 - 0	31
15 knots - Ship lengthening - Solar energy - Air lubrication - Towing kite - Carbon capturing	22
15 knots - Ship lengthening - Air lubrication - Towing kite - Carbon capturing - 0	21
15 knots - Towing kite - Ship lengthening - Solar energy - Carbon capturing - 0	6
15 knots - Ship lengthening - Air lubrication - Air lubrication - Towing kite - Methanol	3

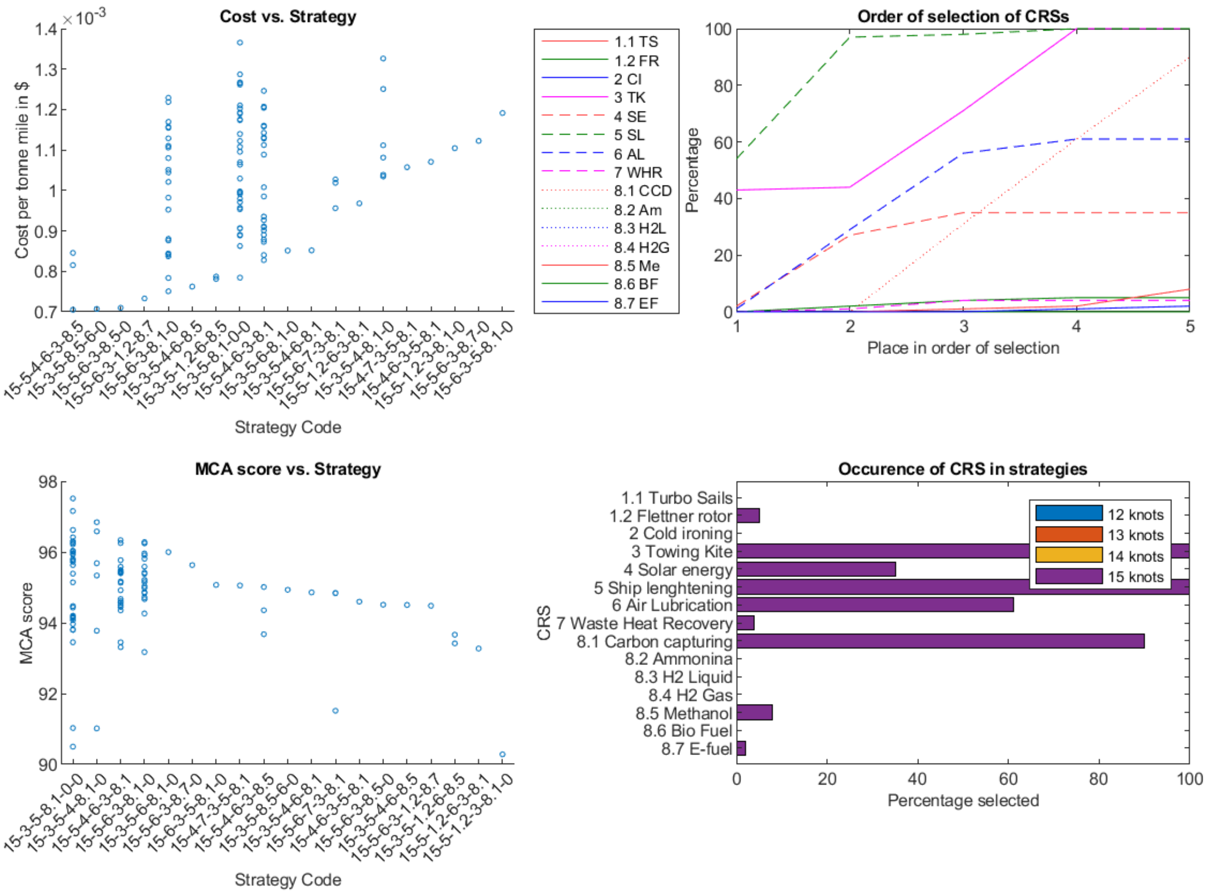

Figure 7.5: Plots no slow steaming Scenario

7.2.6 All MCA weights one

What immediately catches the eye in figure 7.6 is that for the scenario where all the weights are 1, only three different strategies are selected that also have similar traits. What also can be seen in table 7.5, is that 77% of those selections are the 12 - 3 - 8.7 - 0 - 0 - 0 strategy. The reason this model chooses this is that the combination of slow steaming and E-fuel scores the highest on MCA whilst being able to reduce the CO_2 emission to comply with the regulations. It even shows that in some cases, the significant reduction in cost from slow steaming is not necessary to be selected. This is due to the relatively small share of the cost in the MCA. However, it also gives the MCA the most influence in the choice of strategy. As proposed in section 4.3.7, the MCA should be used as a tiebreaker and not as the nominal decision maker, as we see in this case that all selected strategies in this scenario do not occur in the benchmark scenario. So, from that, it can be concluded that the results of this scenario are not the most economically sound strategies.

Table 7.5: Top 3 most selected strategies for all weights one

Strategy	%
12 knots - Towing kite - E-fuel - 0 - 0 - 0	77
12 knots - E-fuel - 0 - 0 - 0 - 0	15
15 knots - E-fuel - 0 - 0 - 0 - 0	8

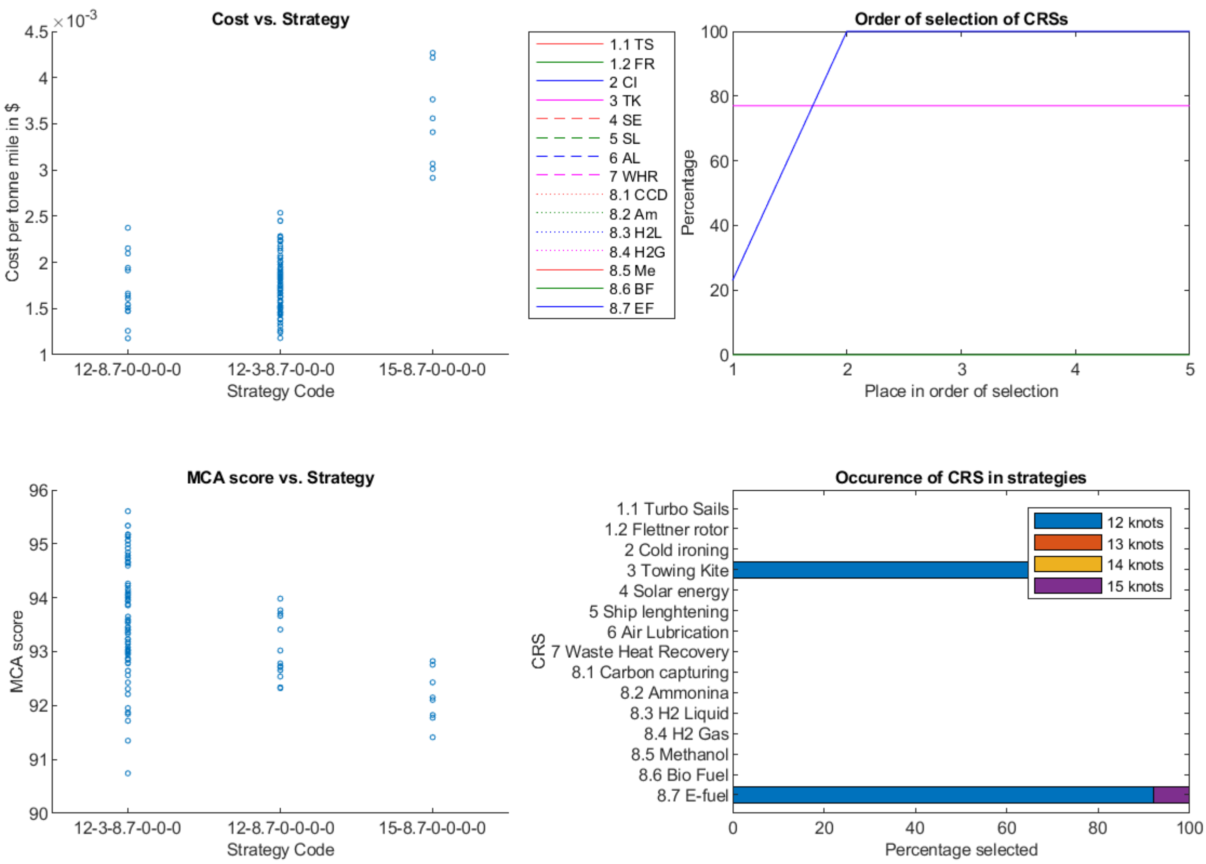

Figure 7.6: Plots all MCA weights one Scenario

7.2.7 Effect of increasing fossil fuel prices

The plot of figure 7.7 is the result of the simulations carried out by different ranges of fossil fuel prices. It is interesting to see that air lubrication becomes more used when fossil fuel prices increase, just like methanol; however, ammonia decreases. This can be explained by the fact that methanol is significantly less expensive than ammonia. So, it is more logical that with expensive fuels, the change will be made to cheaper fuel, whereas the use of ammonia is rational in the end when there is a need for CRSs that can achieve more decarbonisation. It is also interesting to see that carbon capturing has its peak by slightly decreasing prices, which is logical because that would result in a low OPEX of the CRS. The most interesting thing to conclude from this data is that, although there is some percentage change, most CRS will almost be selected the same amount of times after 25%. The explanation is that if fossil fuels become way too expensive, the model will choose an alternative fuel earlier. So, when the rest of the inputs stay the same, it is logical that the same CRSs will be selected. So, there is no clear trend after the 25%, which can be seen as the limitation of how far the change would go. It could have been interesting to zoom in on the range -5% to 25%. This is the range the model would probably operate, so those would be more interesting, and the trends there would be more applicable to the results.

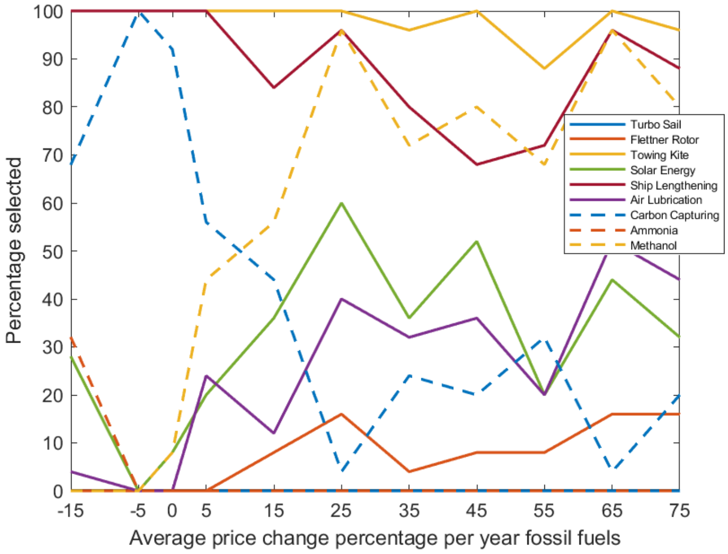

Figure 7.7: Selection of different CRSs for percentages change of fuel price per year

7.2.8 Effect of decreasing allowance of carbon emissions

Two aspects should be noted when looking at figure 7.8, one of which is that only the EEXI is shown on the x-axis; however, the CII also differs with the distribution mentioned in section 7.1.6. The other aspect that should be noted is that slow steaming is not in the plot. This is because, for all the options, slow steaming 12 knots was always chosen under these circumstances. So, it can be seen that only slow steaming is enough until an increasing percentage of 4% for the EEXI, and thus 1% for the CII. After that, there is still a step where only the addition of a towing kite is enough, except for step 8%, always a 100% selected. This shows that the towing kite has the best cost-benefit from these CRSs. As in agreement with most of the other scenarios, the ship lengthening is almost always selected as a cost-effective way to decarbonise a vessel.

The most interesting to see further is that carbon capturing is gradually more selected as the regulations get tighter; however, at total decarbonisation, it is not selected as it cannot remove all carbon from the fuel. At that point, there is a 100% choice for ammonia, as that is the only one in the model that does not contain carbon. The difference between methanol and carbon capturing is interesting; when methanol decreases, carbon capturing increases. This is because the carbon emissions are lower for carbon capturing in the model than for methanol; the conversion factor is 1.375 and 0.3 for methanol and carbon capture, respectively. So, methanol is cheaper to introduce, only not as effective; therefore, it is more suitable for lower regulations than when the required reduction is higher.

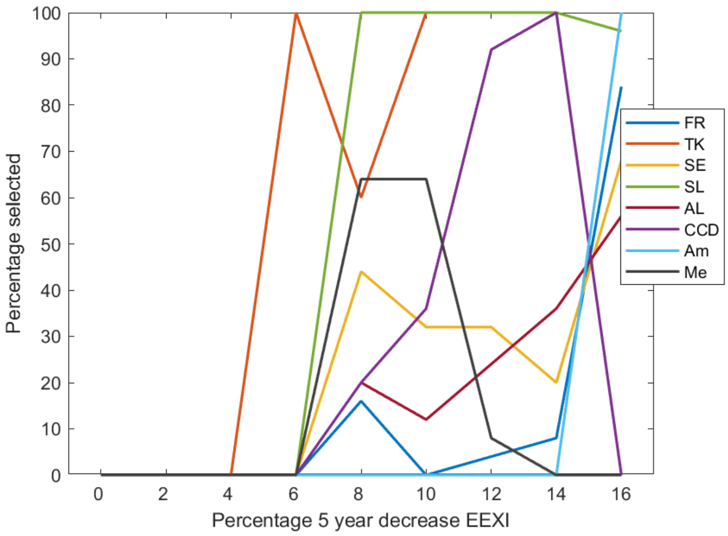

Figure 7.8: Selection of different CRSs for the strictness of regulations

7.2.9 Summary of results

This section presents a short summary of which strategy is most selected per scenario, as seen in table 7.6. The first to note is that with loose regulations, it will always be only slow steaming, while the other scenarios do not have such convincing percentages. For all, except 100% fuel use, they score around 30%. This means that these are the right scenario in 30% of the time. This does, however, not mean that the strategies are unusable in other scenarios; they could have ended up in second or third place. The 100% scenario has a low selection percentage, but section 7.2.4 shows that this scenario presents many comparable strategies. So, a low selection percentage does not directly say it is unsuitable for other scenarios.

Table 7.6: Top selected strategy per scenario

Scenario	**Strategy**	**Selection percentage**
Base	12 knots - TK - SL - CCD - 0 - 0	27
0 in 2050	12 knots - SL - SE - FR - TK - Ammonia	27
Loose regulations	12 knots - 0 - 0 - 0 - 0 - 0	100
0 in 2050, 100% fuel use	12 knots - SL - SE - FR - TK - Bio-fuel	9
No slow steaming	15 knots - TK - SL - CCD - 0 - 0	31

7.3 Comparison with existing Models

Comparing the model's outcomes with other models is interesting to show the differences. The EE Appraisal tool from the Green Voyage 2050 project is the most comparable tool. This tool calculates the impacts of the CRSs on fuel use and gives, therefore, its cost-effectiveness and impact on the EEDI. However, the input in this tool is only the vessel type and size group; the input used is a crude oil tanker of 80000-119999 DWT, comparable with the vessel from the case study. The tool does not include all the CRSs used in this model, so the model has used all the overlapping CRSs. It has to be noted that fixed/wing sails will be compared with turbo sails. The results under normal circumstances, comparable with the benchmark scenario, can be found in table 7.7. The outcome of the EE appraisal tool is a ranked list of which CRSs are most cost-effective and what the effect is on the EEDI. This is a different outcome than the strategy of the proposed method, but it can be compared with some of the results in section 7.2.1. One compassion is that towing kites perform well in both tools. Air lubrication scores highest in the Appraisal tool but is only selected around 25% of the times in the proposed method. This can be attributed to the MCA, where the towing kite scores significantly better, whereas the EEDI reduction and, thus, fuel reduction are comparable. Waste heat recovery and wing sails are both not selected in the proposed method, which can be substantiated by the results from the Appraisal tool, which shows the low impact of both, so, logically, the method does not select those into a strategy. The most interesting difference between both tools is the outcome of solar energy. The Appraisal tool shows a 0.1% fuel reduction, which would mean that it seems pointless to install, whereas it is selected more than 30% of the time by the method. What first should be noted in this comparison is that solar energy is always selected first or second by the method, so it is used for a relatively cheap slight reduction to comply with the regulations. Therefore there is no need for a large reduction in emissions. This does not explain it all, but a difference can be found in the input data. The Appraisal tool gives it a 1% reduction in the data, whereas the proposed method calculates the yield with a combination is energy produced per area and the free area on which to place the panels. So, the method offers a more realistic view of the power provided by the panels than the estimations of the Appraisal tool.

Table 7.7: Outcome EE Appraisal Tool [75]

Place	CRS	EEDI reduction
1	Air lubrication	4.1%
2	Towing kite	4.5%
3	Fixed/Wing sails	1.7%
4	Waste heat recovery	1.0%
5	Solar energy	0.1%

7.4 Verification

This section aims to present the verification for the model to check if the model is built correctly. This can be achieved by checking what happens when certain or extreme values are inserted in the model. One of the scenarios that can be used to verify the model is the '0 in 2050' scenario. In this scenario, carbon emission is not allowed at the end of the time frame. It would then be expected that the model will choose an alternative fuel that does not contain carbon or is used as a drop-in fuel. This is, therefore, the result as ammonia is selected for all strategies. To go further on the '0 in 2050' scenario is when there is full use of all alternative fuels, as seen in section 7.2.4. As bio- and E-fuels are cheaper than ammonia and have a better MCA score, it is expected that the model will shift from ammonia to bio- and E-fuel, which the model also shows. All scenarios also show that there is almost always a need for CRSs that makes the fuel (almost) carbon-free. So, when a scenario is carried out without alternative fuels, it is expected that the model will choose carbon capturing, which is the case as can be seen in the appendix in figure B.7. It is also expected that when fossil fuels become more expensive, the model will choose more alternative fuels than carbon capturing or waste heat recovery. This is also the case, as can be found in figure B.6. There is also the question if the MCA part of the model can be verified. As can be seen in section 7.2.6, when the weight of the MCA has changed results of the model also shifts. It should be logical that it shifts to high-scoring CRSs, such as bio- and E-fuel, as seen in table 6.7, which is also the case. This case can also be made for a change in MCA scores; a lower MCA score should result in CRSs being less chosen. This can be substantiated by the result of a scenario where CRSs scores are lower than before. In the appendix, in figure B.15, a scenario is shown where the towing kite, which is high scoring in most scenarios, scores two points less on all criteria. It can be seen that instead of being selected almost 100%, that percentage has dropped to around 80%, which confirms what was expected. From all these examples, it can be concluded that the model's build is verified.

7.5 Conclusion

The most crucial scenario was the benchmark, which presents the most expected scenario. From that scenario, it can be concluded, what the other scenarios substantiate, that slow steaming is the most cost-effective CRS. What can be seen from all scenarios is that ship lengthening is also very effective as it is selected for more than 80% all the time, except in the scenario where slow steaming is enough. What is also interesting to note is for the alternative fuels is that under different circumstances, different alternative fuels are suitable. Under normal circumstances, methanol is tied with carbon capturing, which means that these are the most cost-effective. However, in the 'no slow steaming' scenario, carbon capturing becomes dominant when more fuel is needed. This can be explained by the fact that carbon capturing is almost only CAPEX and with more fuel, the price of carbon-based fuels drop relatively compared to methanol. This also means, on the other hand, when fossil fuels get more expensive, the use of methanol increases. The other alternative fuels are ammonia, but only when it is the only clean fuel when it is not allowed to emit carbon; from this, it can be concluded that ammonia is not the most cost-effective. In the scenario that all fuels are used as totally carbon-free, it becomes clear that bio and E-fuel are the future, as their properties are the same as regular fossil fuel and are thus only price dependent. Another conclusion that can be drawn from all the scenarios is that the towing kite is always a cost-efficient addition to a vessel, with relatively low cost and high reward. It should also be noted that the weights used for the MCA show the working of the model better than with equal weights, which leads to heavy favour of the MCA, for which it is not intended. By testing the model on several cases and comparing the results with the expected outcome, it can also be concluded the designed model can be verified. The last thing that can be concluded from this chapter is that a low selection percentage does not mean that that is not the best possible strategy. Most of the time, they are comparable with other strategies, or it could be that the scenario ended up in a slightly lower place so that another was selected. So to conclude, the best-selected strategy is the most cost-effective in most scenarios, has large similarities with other selected strategies, and is, therefore, the most optimal strategy for the vessel.

Chapter 8

Conclusions

This chapter will conclude the research by answering the main and sub-questions. The answers to the sub-questions will be used to substantiate the answer to the main question. The answer to the main question is the final conclusion drawn from this research.

The main question of the research is:

'What method can be used to support deciding the most cost-effective strategy for a vessel to comply with decarbonisation regulations whilst including more aspects than existing methods?'

Answering the main research question is preceded by answering the sub-research question, on which basis the main question could be answered.

8.1 *'What are the relevant regulations concerning the decarbonisation of vessels?'*

This research question has mainly been answered in section 2.1, where the relevant regulations have been discussed. This section discussed that the maritime sector is a worldwide border-crossing industry subjected to many laws and regulations. Due to the variety of these regulations, the regulations used and enforced worldwide are the most relevant for this research. These are the regulations presented by the IMO and are also used as the primary regulations by many countries. In terms of relevance, the regulations that are mandatory and have an effect on the operations of the vessel are more relevant than those that are not. So this means that the mandatory regulations restricting energy or carbon use are the most relevant to this research. These regulations are the EEXI/EEDI and the CII, both mandatory in 2023. The effect of these regulations directly impacts the vessel's operations concerning fuel use, routes and loading and will require some intervention on the technical or operational level of the ship. In section 2.1, it is also noted that regulations from the EU could be relevant because of the significant portions of vessels entering the EU. However, the EU does not provide mandatory regulations restricting energy or carbon use. The regulation that the EU is planning to implement is the ETS, which can be seen as a carbon tax, and whereas there is currently no worldwide carbon tax in the maritime industry, this could happen. So, that is the reason that the ETS, and other hypothetical CO_2 taxes, are also relevant for this research. In the future, when the regulations converge to zero emissions, the relevance of what regulations are considered will become less because they will all have the same outcome in the end.

8.2 *What are the relevant decarbonisation solutions, how do they affect the vessel's operations, and with what cost are they associated?'*

The relevant decarbonisation solutions for this research are CRSs that can be used in a decarbonisation strategy created in the short term and have a significant share in the decarbonisation of the vessel. This means that (mostly) proven CRSs are required, but less proven CRSs can be helpful when they have a significant impact and will be used later. This aims mainly at alternative fuels, which are not ready yet to be used on a large scale but will be indispensable in the future. The regulations relevant to this research also need to be as generic as possible so the method can be used for different types of vessels and users. This led to sixteen different CRSs used in this research method; however, own data and additions could lead to an extended model in the future. These sixteen are the most relevant now or have high potential.

Turbo sails, Flettner rotors and towing kites were selected for this research because they all have the potential to become a positive addition to vessels. Wind energy has been the primary method of propulsion for ages, is a clean energy source, and can be available everywhere in the world. Still, it can be expected to only be an auxiliary propulsion power in the future. This also mostly applies to solar energy, which can be available everywhere in the world but has the potential only to be auxiliary power. Waste heat recovery and air lubrication are options that increase the efficiency of the vessel and can be expected to also work with alternative fuels in the future and are thus relevant for this research. Ship lengthening is relevant, not only in a decarbonisation aspect but in an economic aspect, because it decreases the fuel use per tonne mile and, thus, the cost per freight.

Alternative fuels are the most relevant CRSs because fossil fuels should be phased out to decarbonise the shipping industry. Which alternative fuel or fuels will become dominant in the future is unclear, but all the alternative fuels included in the research have the potential to be used in the future, and all have their shortcomings. That is also why LNG is not included in this study because it still contains carbon and needs special storage, so other fuels would still have more benefits when it could be created with clean energy. Carbon capturing, however, is included because it can be used in the short term as an intermediate between fossil and next-generation fuels.

The effect of the operations on the vessel differs per CRSs; however, they all impact one of the following aspects of the ship; main engine power, auxiliary engine power (both offshore or in port), resistance, free deck space, deadweight and CO_2 conversion factor. The impact on the main and auxiliary engine and the resistance are relevant because they influence fuel use and, with that, the OPEX and carbon emissions. The free deck space is relevant because it affects what other CRSs could be installed. The influence on the deadweight is relevant because it influences the total cargo that can be carried and thus influences the revenue of the vessel, but also the cost against freight shipped and the regulations for the amount of energy or carbon per freight shipped. Lastly is the carbon conversion factor that can be influenced, which impacts the regulations concerning decarbonisation and is thus relevant.

The cost associated with the CRSs exists more than the purchase costs. The CAPEX is the base of the cost the ship owner makes; however, there is also an influence on the OPEX. The OPEX can be increased by more maintenance or crew costs, which can be found in section 6.1.1, but the fuel cost can also be influenced. There are roughly two types CRSs presented in this research: those that reduce fuel use and the CRSs that remove carbon from the fuel. These all influence the total cost of the vessel in different ways. The ones that reduce fuel use, WASPS, solar energy, air lubrication, waste heat recovery, cold ironing and slow steaming will have a relative cost, depending on several aspects. The relative costs are the CAPEX and increase in maintenance cost minus the cost of the saved fuel, which means the relative cost of these could become negative in certain circumstances. Ship lengthening will increase the OPEX but decrease the cost per freight unit. The exception is carbon capturing, which could only reduce costs when the captured carbon is sold, and there is a carbon tax. The others, the alternative fuels, will have a relative cost of the CAPEX of those fuels, increased maintenance cost and the cost of the alternative fuel minus the cost of the fuel that would typically be used. So, this could, just like the CRSs that reduce fuel use, result in a negative relative cost under certain circumstances. For both these groups, the development of fossil fuel cost is the primary driver in the relative cost because of the savings on these costs.

The other two CRSs left, ship lengthening and carbon capturing, will both always increase the total cost. For ship lengthening, this is the case. However, that effect is countered by the increase in loading, and thus the cost per tonne mile will optimally decrease. The carbon capturing CRS will also always increase the cost because the engine will become less effective; the only decrease in cost it could achieve is a less high CO_2 tax. So, the total cost of the CRSs is not simply presented, and although CAPEX and maintenance costs for the CRSs can be found today, it is hard to predict the prices of this in the future. The total cost associated with the vessel due to the CRSs is even harder to present simply because many factors influence the total cost related to the vessel. It depends on the development of all the prices in the future, but mainly on the prices of the energy carriers.

8.3 *'What decision support methods are there, and what addition would the proposed method bring?'*

The other decision support methods that are currently available are discussed in section 2.4. Most decision support tools use a form of MCDM. These include tools that use MCA to support decisions for the choice of alternative fuel or, even more specifically, what sort of bio-fuel. There are also tools that use MCA to choose CRSs. There are also calculators which calculate achieved and required values for regulations, which show when a vessel does not comply with those regulations anymore. There are also tools that calculate the effect of CRSs on the regulations and the cost of the vessel. So, there are tools that concern with decision making process with an MCA, with can be used to choose suitable CRSs. There are regulations calculators that calculate which year the vessel does not comply anymore with the regulations. There are tools that calculate the effect of CRSs on fuel use, which can be used to calculate the effect on the costs or regulations of the vessel. These tools come closest to the proposed method. However, there is no method that is a one-stop for all aspects that come with decisions that have to be made for the decarbonisation of a ship, and that is what the proposed method will be adding. The tool will find the effect of the CRSs, and combinations of CRSs, on fuel use. The fuel use can be used to find the effect on the finances and the regulations. This will be combined with the decision making aspect of an MCA and analysis that deals with risks. Making this a method where all aspects of the investment decision surrounding decarbonisation are combined.

8.4 Main question: *'What method can be used to support deciding the most cost-effective strategy for a vessel to comply with decarbonisation regulations whilst including more aspects than existing methods?'*

So, using the given conclusions for the sub-questions, the main question can be answered. The method used to select the strategy will consist of a combination of methods. There are several methods to select a CRS or a set of CRSs to decarbonise a vessel, but several aspects influence the choice of a particular option. Therefore there is a need for several different analyses with their respective methods for the selection process. These analyses will be used to include all the combined aspects that are not combined in one method. The combination of CRSs needs to be analysed for the cost surrounding these systems, which also needs to consider the capital depreciation that comes over time. Because the method only considers cost in the NPC method's financial analysis, a derivative of the NPV has been chosen. With this analysis, the cost can be discounted to the present value of the cost, making it ideal for comparing the cost in the future with today's cost.

The more subjective aspects of the CRSs, such as safety and technological readiness level, also have to be considered and compared, which will be carried out by two combined methods. The MCA will compare the several aspects on which the combinations of CRSs will be scored. The method of MCA is the WSM, whose simplicity makes it suitable for a model with many options and, thus, calculations. The inputs of the MCA exist of the cost input, which will be calculated by the financial, NPC, calculations, and the other criteria, such as safety and technology readiness level. The outcomes from the SWOT analysis will determine these scores. This analysis presents the positive and negative points from the CRSs and can be used to show the scores for the MCA.

Lastly is the analysis that will tackle the uncertainties that are associated with the developments in the future. A Monte Carlo simulation is added to the method to find the optimal combination of CRSs that considers the expected ranges of specific values. This means that certain values, such as fuel prices, will be randomised in a particular range, and many calculations are carried out with different data every time. This will lead to a best-scoring strategy for every run with new data, and from that data, an estimate can be made as to which strategy has the best chance of being the most successful.

From the case study, some conclusions can be used to validate the model and as a basis to add to the method for further models. Several results from the case study stand out, but what stood out the most is that slow steaming was practically always selected and then constantly at its minimum value of 12 knots. From this can be concluded that reducing the vessel's speed will, under the presented conditions, always be the most cost-effective way to comply with decarbonisation regulations. Only in circumstances when the fossil fuel prices drop drastically is there a shift to somewhat higher velocities. What also can be concluded from the case study is that, at least for the used vessel, the towing kite is an integral part of the decarbonisation strategy. The relatively low investment cost and the relatively high fuel savings make it ideal as the first CRS in the strategy. Almost as high scoring as the towing kite is the ship lengthening. This is also a logical choice because it has long been clear that increased vessel size makes them more efficient. It can further be noted that hydrogen is still too expensive at this point and that carbon capturing becomes unfavourable when fossil fuel prices increase.

The decision support tool method will be built up of different analyses that link together to choose a strategy using several other inputs. The method will be optimised to the EEXI and CII regulations to always comply with those regulations. So, the non-compliance with the regulations will result in the addition of CRSs that will, in turn, impact fuel use and, thus, carbon emissions. This can then be translated to cost per freight distance, with the help of an NPC calculation, and used as an input in an MCA. This MCA will ensure that not only the costs are taken into account in the decision-making but also other inputs that are important for the user of the method, such as safety or technological readiness. This will ultimately lead to a method with which the built could get a clear view of what CRSs, and in what order, will match their preference the best and thus lead to decarbonisation.
With the help of the case study, this research also has concluded that even without the method, there are some universal approaches to cost-effective decarbonisation. The decision to reduce the vessel's speed would always, under the used circumstances, be the best and easiest way to decarbonise a vessel. This means when other models are developed with this method, the speed does not have to be a range as input but rather the lowest speed acceptable for the user. Another universal truth is that to decarbonise a vessel, completely different fuels will need to be used, either without carbon or created entirely from renewable sources. With the help of the case study, what can be concluded is that, on average, an effective strategy will mainly start with minor impact, high reward CRSs and CRSs that make the vessel more efficient and will generally end with an alternative fuel.

Chapter 9

Discussion, Validation & Recommendations

This chapter will present a discussion of the research results, a validation of the model and recommendations for further research. The discussion is the first part of this chapter and aims to present a critical view of the research. The validation will discuss the results of the model and will prove that these are valid. The recommendations will give indications and instructions on where the method and model can be improved and other interesting aspects to explore.

9.1 Discussion

The research has several aspects that require a critical view. This is not the only result that requires a more in-depth discussion, but also choices made during the research.

Discrepancies in data The research has taken, for the data of the case study, some estimations and used data that came from different sources. For instance, some data for one specific CRS came from different sources, so the cost came from another source than the effectiveness. This could have led to data that was not totally in line with each other and some discrepancies in the results. However, the data was compared to other inputs, which showed that they were in an acceptable range. The range of the Monte Carlo simulation should also have mitigated some risks with slightly inconsistent data. On the other hand, there are also some outliers in the results that could be attributed to the randomisation of the Monte Carlo simulation.

Drop-in fuel The choice to require a drop-in fuel setup for methanol, bio-fuel and E-fuel and not for ammonia and hydrogen is worth discussion. This has been done for several reasons, the first being that bio-fuel, E-fuel and methanol can be used immediately when used as drop-in fuel. In contrast, ammonia and hydrogen require more research and investment. So this would make it easier to implement in the research. Also, hydrogen and ammonia would require different tanks, which would not be usable for MDO. Ideally, the fuels would all be included with varying percentages of fossil fuels in the research. However, that would make that there were again several more CRSs in the research and would make the research less clear. This is also the case by choice for the amount and size of the Flettner rotors and turbo sails, which could also have been included in more setups but would, again, make the research less clear.

State hydrogen The choice for using liquid and pressurised hydrogen should be discussed. They had been split by the idea that they should have large differences; however, that was not really the case. The price of hydrogen to buy and the SFC stayed the same, so the difference is only in storage. The fact that ammonia and even methanol could also be stored in other ways makes it unnecessary and somewhat impractical to use both sorts of hydrogen in this way in the model. Better would have been to split the storage from the fuel, so ammonia and methanol could also be included. The other option would have been to make a choice beforehand on storage and only use one of the two options of hydrogen.

Mandatory cold ironing A discussion point surrounding the regulations in combination with the CRSs is the obligation to use cold ironing for all vessels in European ports from 2030. This has not been implemented in the model due to programming issues. Although this is not planned yet, to be mandatory in other countries, the assumption has been made in the whole research to take EU regulations into account, so it should make the research more accurate to include it.

Mittigated risks The question is also a point for discussion if all the risks, known knowns, unknown knowns, known unknowns and unknown unknowns are mitigated. The known are mainly the current regulations and have been included, which is also true for the known unknowns that are mainly the coming regulations, which have been tackled by running the model for different percentages of the regulations. The unknown knowns and unknown unknowns are mitigated as much as possible by the Monte Carlo simulations, where the range and randomisation of the inputs will likely take unexpected events into account. However, due to the selected range, it could be that the extreme events have not fallen into the range of the Monte Carlo simulation. So, it could be the predictions of the model are unusable after a large and fundamental event occurs in the future.

Number of ships for case study A discussion point that also influences the validation is that the model is only run with one ship. It would have been ideal for running it with different vessels, which could be the same vessel type in different sizes, other vessel types in the same size or both. This has, however, not been carried out by this research because the data for different ships were not available. This would have been better to show the effects on different ship types and would help validate the method for different ship types.

MCA scores The scores used for the MCA have now been decided with the use of a SWOT analysis. This is a substantiation of the values, but it still stays subjective values. The problem with MCA is that most times (parts of), the values are qualitative instead of quantitative because these are not easy to compare. This means that the decision maker's opinion is an integral part of the outcome of the MCA. For further use of the model, there are two different approaches to determining the MCA scores. The first is when a decision maker wants to use their own opinion; then the decision maker would simply determine the values themselves. As decision makers can be inconsistent, it could be an option to change the MCA method from WSM to AHP. This is because, as discussed in section 2.3.3, the method of AHP, where the CRSs are compared to each other, is suitable for checking inconsistencies in the answers provided by the decision maker. On the other hand, the user could want a more objective view of those scores. This could be done in multiple ways; surveying people in the industry or finding more objective points to score the criteria on. However, for the second option, it is difficult to find aspects where all CRSs can be evaluated on. So, surveying a large group of people in the industry would have the preference because it combines the opinions of a large group, which will lead to a more clear view. The same discussion about the scores can also be held about the weight of the MCA. However, the weight is much more suitable to be changed by the users than the score. The weights can be used to place emphasis on certain criteria, whereas the score should be more impartial. So, ideal for the MCA scores and weight, it would be best if the scores are determined by surveying a significant group of people from the industry, and the weight should be an user input.

Order of model There is also a discussion point about the order of the cost analysis and the MCA, which has been discussed in section 4.3.7. The model will first carry out the financial analysis, which will then be used in the MCA with a high weight for this financial criteria. This makes the MCA, in essence, a tiebreaker for strategies that score almost the same in the cost criteria. It could also be argued that the order should be reversed, which would filter unfit CRSs and strategies and then choose the most cost-effective strategy. This would make the method significantly different because of several reasons. The research now has already made a selection of CRSs deemed fit for the vessel, but the MCA combines the CRSs in a strategy which is used in the MCA. The selected CRSs comply with the lower boundary of what is acceptable for every criterion. So, when using the MCA upfront to filter lower-scoring strategies, it could be that a strategy that is scoring low would be dismissed even if it would be the best option in cost-effectiveness and not that far below the limit. What would work to use an MCA upfront is to use it to select CRSs without the pre-selection for CRSs that already comply with the lower acceptable limit and use it to do the pre-selection of acceptable CRSs.

Timeline strategy As discussed in section 4.3.8, the model only delivers as a strategy which shows the order of implementation of the CRSs and not the precise year or time frame. This is, however, something that the users will desire to get a clear view of when the investments need to take place. The problem here is that due to the Monte Carlo simulation, there are several different timelines for implementing the strategies, even with the same combination of CRSs. So, the model does create those data points but does not show them. This has been chosen to make the output of the data more structured. However, it could be argued that that is also critical information. This is indeed critical for the user but not for the research; it would not have significantly impacted the validity of the model. When users in the industry would use the model, the model could output average, mean, mode or range. This way, the user knows what timeline to follow for the investment and operations surrounding the vessel.

SFC constant As discussed in section 4.3.2, the SFC is taken constant, which means that the model does not take into account the fact that the energy output of an engine is not linear with the fuel use. Small changes in output are not a problem, but with larger changes, the model would become less accurate. This could have been countered by including the change curve, or the other option would be to add a CRSs that is a more efficient engine, which could then be chosen in a form that is as efficient as possible.

Revenue in model The choice not to include revenue in the model was ultimately a scoping decision, as discussed in section 3.1. It was a consideration between including more uncertainties in the model, but a more usable outcome, versus a model that showed the effects of different inputs better but misses a critical aspect for business decisions. When cargo hauling prices had been included, they would logically be subjected to the Monte Carlo simulations. When excluding revenue in the method, the outcomes can be compared easier as there is no effect of potential contra-developing variables. So, if CRSs would reduce costs per freight unit but increase the amount of freight that can be shipped in a year, it could be hard to show the effects when the cargo hauling prices would drastically decrease. On the other hand, it is slow steaming biased in the proposed method without revenue. This is the case because the cost per tonne mile will decrease, but the effects on the absolute profit per year are not found. When sailing slower, the cargo hauling price will logically drop, and the total amount of freight that can be shipped decreases. One option that could be used when companies use the method is that they could include one fixed cargo hauling price that they desire and see the proposed strategies for that case.

Adjusted vessel life cycle The method does not consider factors that change the vessel's life cycle. The method is built for the expected lifetime of the vessel and is thus not equipped to deal with changes therein. As the shipping market acts in cycles, there is always a chance that vessels are scrapped earlier or later than originally planned. [154] This, combined with the proposed method, could mean that according to the strategy, an investment has to take place, but the vessel will be scrapped shortly. As the model is not equipped to deal with that itself, the model should be run even after the decision for a strategy, so it could keep the strategy up-to-date and adjust for unforeseen circumstances.

Simplification of CRSs The CRSs in this model have received some simplification for ease of use in the model. Most of the simplifications concern the surrounding infrastructure of the CRSs, such as piping, wiring, electronic systems, and safety measures. Due to these simplifications, some details are not taken into account in the model. This could be small aspects; for example, when extra piping and wiring are needed, it could influence the hindrance in operations and implementability, which would mean that a different MCA score has to be used. The largest problem is that extra systems and hardware also requires additional investments. The research has used data provided by sources that should entitle the whole cost associated with the specific CRS. However, it could be that some costs have not been taken into account, for example, the cost of making the fuel tanks suitable for alternative fuels such as methanol.

9.2 Validation

The validation of the model is complex because there is no way to look into the future and check if the model predictions are true. However, there are some aspects on which the model can be checked if the answers are logical. One aspect is the cost per tonne mile; this value is for the scenarios, except the one where there is no slow steaming, between the $0.0007 and $0.0014 in present-day cost. Nowadays, these costs are around $0.0049 [137]; however, this includes the cost of capital, insurance and other business costs that are not included in this model. The added CRSs will, in the end, also reduce fuel use and, thus, some cost, so these seem to be in the normal order of magnitude. Other validation aspects are the relative constancy of the model and the choices. The model will always choose slow steaming under rational circumstances. This is logical because it requires almost no investments and greatly reduces fuel costs. The quadratics relation between the speed and resistance from formula 4.1, shows this impact. The drop from 15 knots to 12 knots means a decrease of 36% resistance and, thus, a significant drop in fuel use. This will decrease the fuel costs per tonne mile, but other costs that are time or period bound, such as crew and maintenance, will increase relatively. The selection of ship lengthening is also very logical, as the sizes of ships have always been increasing, which makes them more efficient per freight distance. What also can be used as validation is that when the regulations forbid carbon emission, the model will select an energy source with a conversion factor of zero, which shows that the model knows to choose CRSs that will comply with the regulations. The model can also be compared with other models to validate the model's outcome, as presented in section 7.3, where the model is compared with the EE Appraisal tool of the Green Voyage 2050. From that, it can be seen that the effect of CRSs on fuel use and, thus, on regulations is generally the same. With this outcome, it can be validated that the model calculates the fuel and regulations output correctly, which is a large part of the model.

9.3 Recommendations

Most of the recommendations for this research are given to make the method and model more realistic. There are, however, also some recommendations for other approaches to the model.

More realistic data To make the ways to make the model more realistic is that more aspects could be added to the simulation of the vessel, such as data on all the trips for the vessel in a normal year. This could then be expanded with the influence of environmental conditions, such as wind, current and waves. Also, a more realistic view of the different loads of the vessel could lead to a more realistic model. What also would help to make the results more realistic is to run the model with up-to-date data from a company for the operational profile. This is also the case for data from suppliers and shipyards, which have more precise data surrounding cost and time. The model that is now built was made suitable for a tanker; however, it should become usable for all cargo vessels. That would mean including also the volume aspects of the CRSs and the freight so that the impact on the number of containers is also included in the model.

Validation To increase the validation of the vessel, it could be run for a short amount of time, about 5 years, and then check the results in that time to see if the results of the model are compared with the reality. This could also be done with data from the past and checking it against current events. It could also be a good recommendation to validate the model with the industry. When using MCA, input provided by a company compared with their own calculations could be used to compare outcomes and therefore validate the model. Even when the companies yield results other than the model, it can be used to find the difference and show the advantages of the proposed method.

MCA Scores As discussed in section 9.1 the MCA scores should be found by surveying people in the industry. However, the scores could become even more suitable if these would become more dynamic, so the MCA score also differs over time. This would mean that some scores would increase and some would decrease. For example, the score for technological readiness could increase over time at a certain rate because when CRSs are being developed, their technological readiness level would also increase. This would also mean that the chance that CRSs that are not suitable for the far future would not be selected at the end of the time frame.

Extra restrictions and options The CRSs part could become more accurate when some extra restrictions and options would be added. This could mean that the method would also include options to choose a range of time for certain CRSs; one of the options that could be included would be that hydrogen could only be implemented from 2040 on. All in all, further, in-depth, research in the CRSs would be a good recommendation for the future. More details in the working and technical aspects would make the model more precise. The CRSs part could also include combinations of alternative fuels in dual-fuel configurations and differentiation for certain CRSs, for instance, the amount or size of the Flettner rotors.

Cost optimisation The method is now built to be optimised to the regulations and then cost; however, with more complex programming, it could be optimised to cost. So, it would then test for every time step of every CRSs and look if the vessel's cost would decrease with decarbonisation without the mandatory regulations. This could result in research if the CRSs are cost-effective, independent of the regulations.

Other regulations The model could also include other aspects concerning regulations, such as NO_x, SO_x and particulate emissions, and regulations regarding safety and working conditions. The model also works now with regulations that look at tank-to-wake emissions; however, for ship owners, it could also be interesting to look at well-to-wake.

Advanced programming When more and more parts and inputs will be added to the model, it could benefit from more complex programming like artificial intelligence and machine learning. This could then also be used to keep the strategy up-to-date to see what should change when the circumstances change.

Regional differences To make the model more realistic, the model could include regional differences. This is not the only difference in environmental circumstances but also regulations. So that would mean calculating the effectiveness of WASPs and solar panels according to the route the ship is sailing for the environmental impact, but it should also include wind, waves and current to calculate the fuel use more accurately. The regional differences in regulations could mean that the vessel would use less alternative fuel in areas where the regulations are less strict in areas where these are tight. However, that would reduce some of the efforts to decarbonise the industry.

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Appendix A

IMO Constants

A.1 EEDI

Table A.1: Reference values for C_F [103]

Type of fuel	**Reference**	**Lower calorific value (kJ/kg)**	**Carbon content**	C_F **(t-CO_2/t-Fuel)**
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	42,700	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
	Butane	45,700	0.8264	3.030
5 Liquefied Natural Gas (LNG)		48,000	0.7500	2.750
6 Methanol		19,900	0.3750	1.375
7 Ethanol		26,800	0.5217	1.913

Table A.2: Reduction factors (in percentage) for the EEDI relative to the EEDI reference line [109]

Ship Type	Size	Phase 0 1 Jan 2013 - 31 Dec 2014	Phase 1 1 Jan 2015 - 31 Dec 2019	Phase 2 1 Jan 2020 - 31 Mar 2022	Phase 2 1 Jan 2020 - 31 Dec 2024	Phase 3 1 Apr 2022 and onwards	Phase 3 1 Jan 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10		20		30
	10,000 and above but less than 20,000 DWT	n/a	0-10		0-20*		0-30*
Gas carrier	15,000 DWT and above	0	10	20		30	
	10,000 and above but less than 15,000 DWT	0	10		20		30
	2,000 and above but less than 10,000 DWT	n/a	0-10*		0-20*		0-30*
Tanker	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0-10*		0-20*		0-30*
Container ship	200,000 DWT and above	0	10	20		50	
	120,000 and above but less than 200,000 DWT	0	10	20		45	
	80,000 and above but less than 120,000 DWT	0	10	20		40	
	40,000 and above but less than 80,000 DWT	0	10	20		35	
	15,000 and above but less than 40,000 DWT	0	10	20		30	
	10,000 and above but less than 15,000 DWT	n/a	0-10*	0-20*		15-30*	
General Cargo ships	15,000 DWT and above	0	10	15		30	
	3,000 and above but less than 15,000 DWT	n/a	0-10*	0-15*		0-30*	
Refrigerated cargo carrier	5,000 DWT and above	0	10		15		30
	3,000 and above but less than 5,000 DWT	n/a	0-10*		0-15*		0-30*

Ship Type	Size	Phase 0 1 Jan 2013 - 31 Dec 2014	Phase 1 1 Jan 2015 - 31 Dec 2019	Phase 2 1 Jan 2020 - 31 Mar 2022	Phase 2 1 Jan 2020 - 31 Dec 2024	Phase 3 1 Apr 2022 and onwards	Phase 3 1 Jan 2025 and onwards
Combination carrier	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0-10*		0-20*		0-30*
LNG carrier***	10,000 DWT and above	n/a	10**	20		30	
Ro-ro cargo ship (vehicle carrier)***	10,000 DWT and above	n/a	5**		15		30
Ro-ro cargo ship**	2,000 DWT and above	n/a	5**		20		30
	1,000 and above but less than 2,000 DWT	n/a	0-5*,**		0-20*		0-30*
Ro-ro passenger ship**	1,000 DWT and above	n/a	5**		20		30
	250 and above but less than 1,000 DWT	n/a	0-5*,"		0-20*		0-30*
Cruise passenger ship*** having non-conventional propulsion	85,000 GT and above	n/a	5**	20		30	
	25,000 and above but less than 85,000 GT	n/a	0-5*,"	0-20*		0-30*	

Table A.3: Parameters for the determination of reference values for the different ship types [109]

Ship type	a	b	c
Bulk carrier	961.79	DWT of the ship where DWT<279,000 279,000 where DWT >279,000	0.477
Combination carrier	1,219.00	DWT of the ship	0.488
Containership	174.22	DWT of the ship	0.201
Cruise passenger ship having non-conventional propulsion	170.84	GT of the ship	0.214
Gas carrier	1,120.00	DWT of the ship	0.456
General cargo ship	107.48	DWT of the ship	0.216
LNG carrier	2,253.7	DWT of the ship	0.474
Refrigerated cargo carrier	227.01	DWT of the ship	0.244
Ro-ro cargo ship	1405.15	DWT of the ship	0.498
	1686.17*	DWT of the ship where DWT<17,000* 17,000 where DWT >17,000*	
Ro-ro cargo ship (vehicle carrier)	(DWT/GT)$^{-0.7}$ 780.36 where DWT/GT <0.3 1,812.63 where DWT/GT >0.3	DWT of the ship	0.471
Ro-ro passenger ship	752.16	DWT of the ship	0.381
	902.59*	DWT of the ship where DWT<10,000* 10,000 where DWT >10,000*	
Tanker	1,218.80	DWT of the ship	0.488

A.2 EEXI

Table A.4: Reduction factors (in percentage) for the EEXI relative to the EEDI reference line [109]

Ship type	Size	Reduction factor
Bulk carrier	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	10,000 and above but less than 20,000 DWT	0-20*
Gas carrier	15,000 DWT and above	30
	10,000 and above but less than 15,000 DWT	20
	2,000 and above but less than 10,000 DWT	0-20*
Tanker	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	4,000 and above but less than 20,000 DWT	0-20*
Containership	200,000 DWT and above	50
	120,000 and above but less than 200,000 DWT	45
	80,000 and above but less than 120,000 DWT	35
	40,000 and above but less than 80,000 DWT	30
	15,000 and above but less than 40,000 DWT	20
	10,000 and above but less than 15,000 DWT	0-20*
General cargo ship	15,000 DWT and above	30
	3,000 and above but less than 15,000 DWT	0-30*
Refrigerated cargo carrier	5,000 DWT and above	15
	3,000 and above but less than 5,000 DWT	0-15*
Combination carrier	20,000 DWT and above	20
	4,000 and above but less than 20,000 DWT	0-20*
LNG carrier	10,000 DWT and above	30
Ro-ro cargo ship (vehicle carrier)	10,000 DWT and above	15
Ro-ro cargo ship	2,000 DWT and above	5
	1,000 and above but less than 2,000 DWT	0-5*
Ro-ro passenger ship	1,000 DWT and above	5
	250 and above but less than 1,000 DWT	0-5*
Cruise passenger ship having non-conventional propulsion	85,000 GT and above	30
	25,000 and above but less than 85,000 GT	0-30*

A.3 CII

Table A.5: *dd* vectors for determining the rating boundaries of ship types [108]

Ship type		Capacity CII in calculation	*dd* vectors (after exponential transformation)			
			exp(d1)	exp(d2)	exp(d3)	exp(d4)
Bulk carrier		DWT	0.86	0.94	1.06	1.18
Gas carrier	65,000 DWT and above	DWT	0.81	0.91	1.12	1.44
	less than 65,000 DWT		0.85	0.95	1.06	1,25
Tanker		DWT	0.82	0.93	1.08	1.28
Container ship		DWT	0.83	0.94	1.07	1.19
General cargo ship		DWT	0.83	0.94	1.06	1.19
Refrigerated cargo carrier		DWT	0.78	0.91	1.07	1.20
Combination carrier		DWT	0.87	0.96	1.06	1.14
LNG carrier	100,000 DWT and above	DWT	0.89	0.98	1.06	1.13
	less than 100,000 DWT		0,78	0.92	1.10	1.37
Ro-ro cargo ship (vehicle carrier)		GT	0.86	0.94	1.06	1.16
Ro-ro cargo ship		DWT	0.66	0.90	1.11	1.37
Ro-ro passenger ship		GT	0.72	0.90	1.12	1.41
Cruise passenger ship		GT	0.87	0.95	1.06	1.16

Table A.6: Parameters for determining the 2019 ship type specific reference lines [106]

Ship type		Capacity	a	c
Bulk carrier	279,000 DWT and above	279,000	4745	0.622
	less than 279,000 DWT	DWT	4745	0.622
Gas carrier	65,000 and above	DWT	14405E7	2.071
	less than 65,000 DWT	DWT	8104	0.639
Tanker		DWT	5247	0.61
Container ship		DWT	1984	0.489
General cargo ship	20,000 DWT and above	DWT	31948	0.792
	less than 20,000 DWT	DWT	588	0.3885
Refrigerated cargo carrier		DWT	4600	0.557
Combination carrier		DWT	40853	0.812
LNG carrier	100,000 DWT and above	DWT	9.827	0
	65,000 DWT and above, but less than 100,000 DWT	DWT	14479E10	2.673
	less than 65,000 DWT	65,000	14479E10	2.673
Ro-ro cargo ship (vehicle carrier)		GT	5739	0.631
Ro-ro cargo ship		DWT	10952	0.637
Ro-ro passenger ship		GT	7540	0.587
Cruise passenger ship		GT	930	0.383

Appendix B

Results from other scenarios

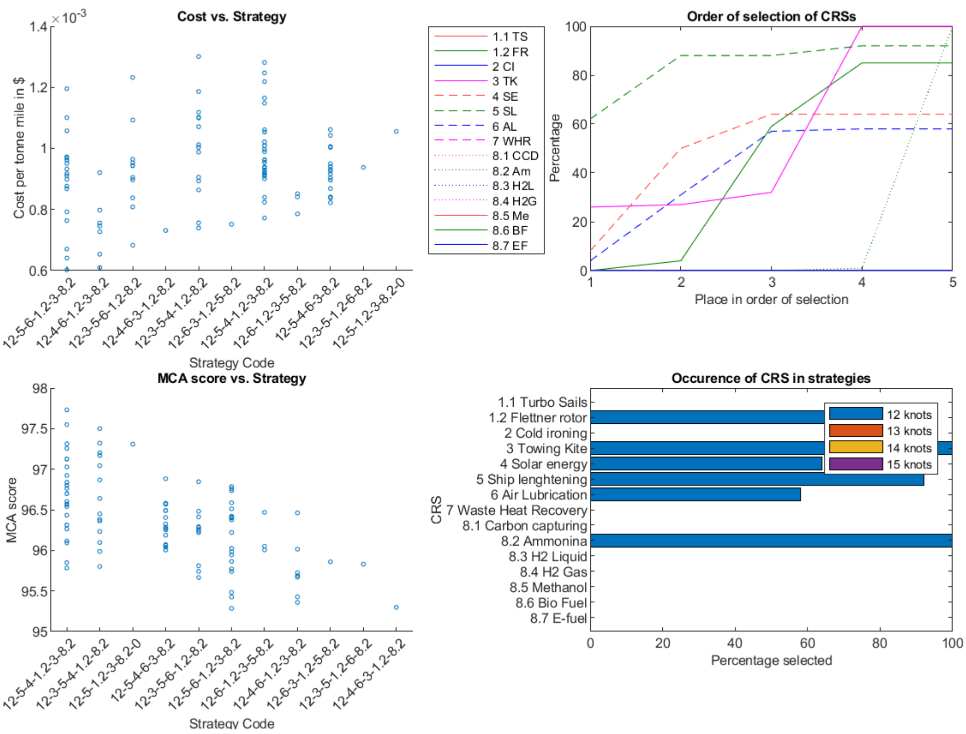

Figure B.1: 0 in 2050 scenario; all price changes in line with inflation (3.75%)

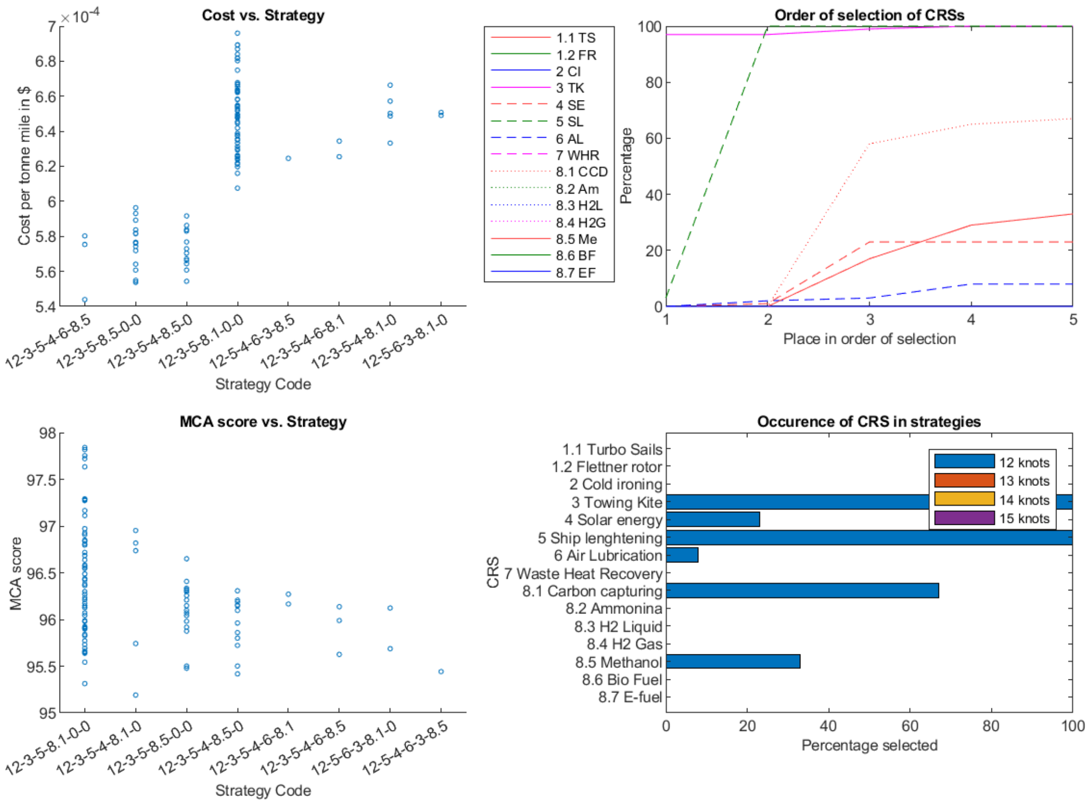

Figure B.2: All price changes in line with inflation (3.75%)

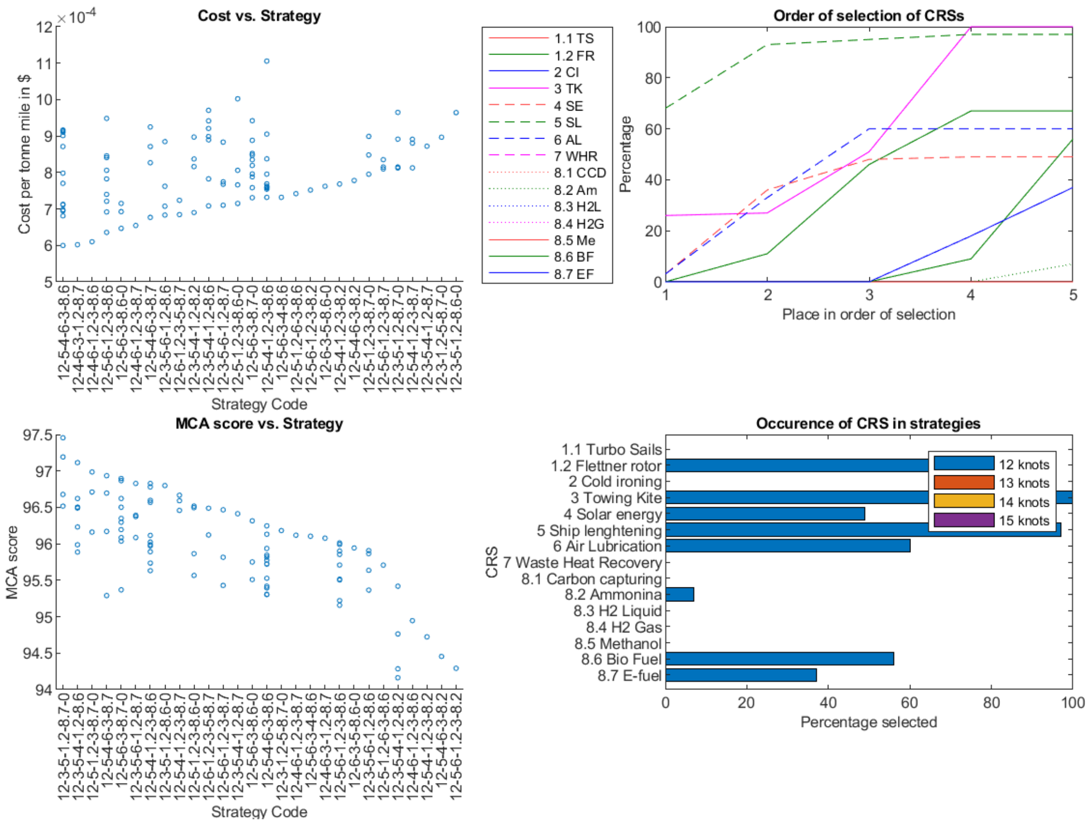

Figure B.3: All price changes in line with inflation (3.75%); full use of alternative fuels

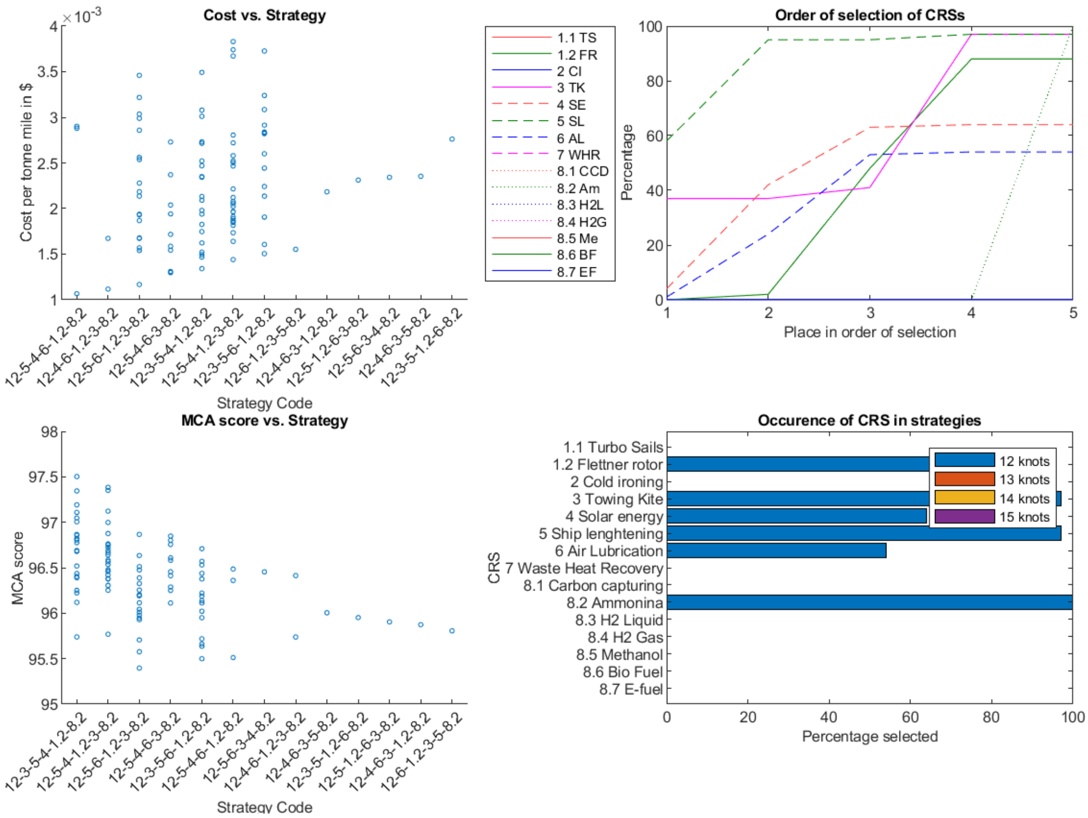

Figure B.4: 0 in 2050 scenario; decreasing ammonia prices (-1%)

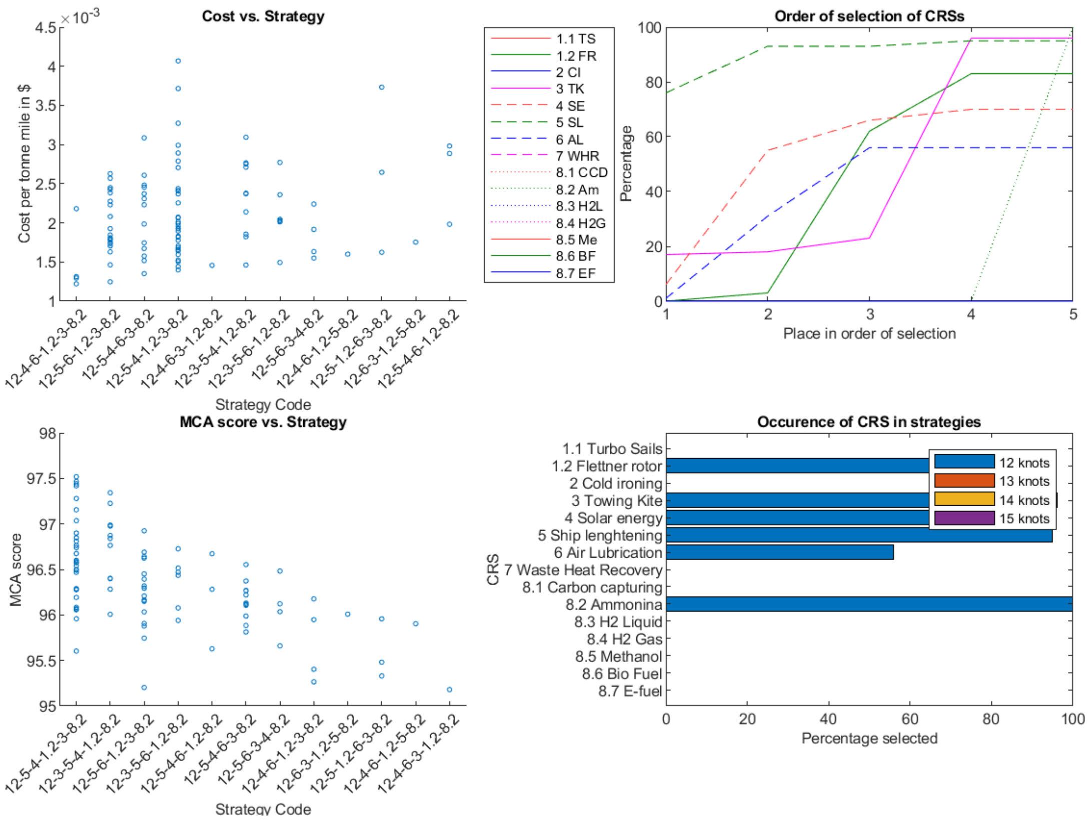

Figure B.5: 0 in 2050 scenario; decreasing methanol prices (-1%)

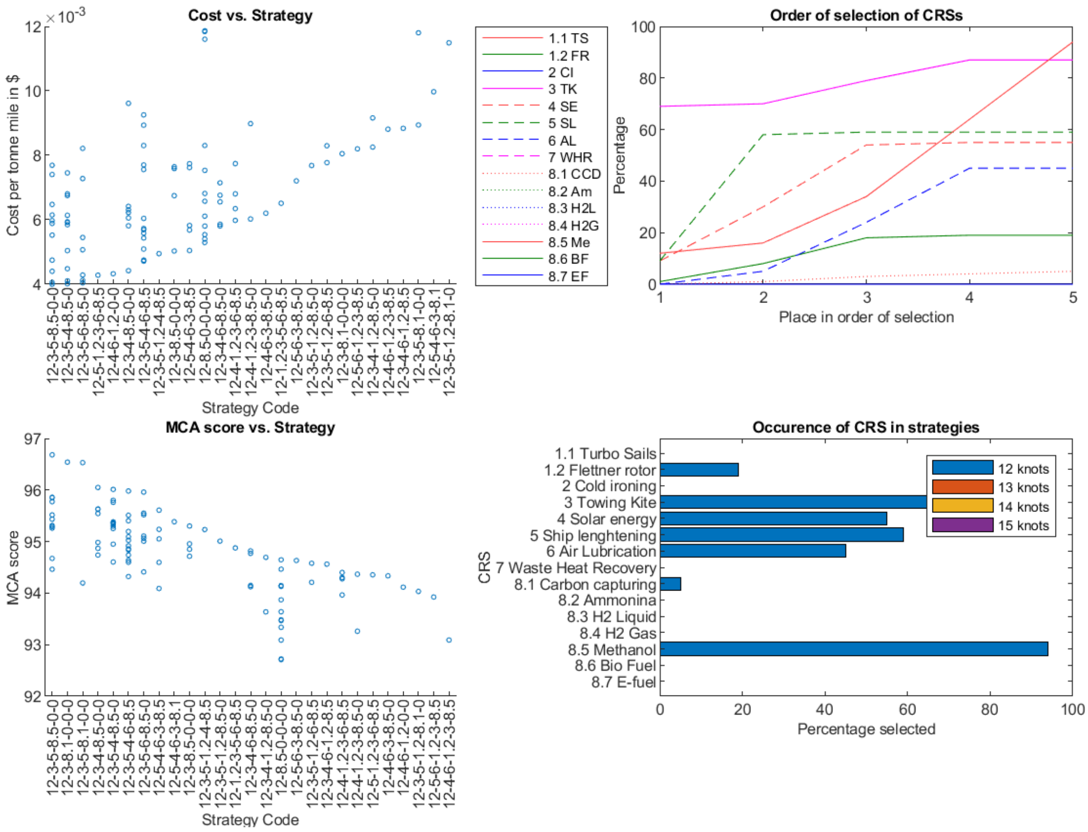

Figure B.6: High increase in fossil fuel prices (25%) scenario

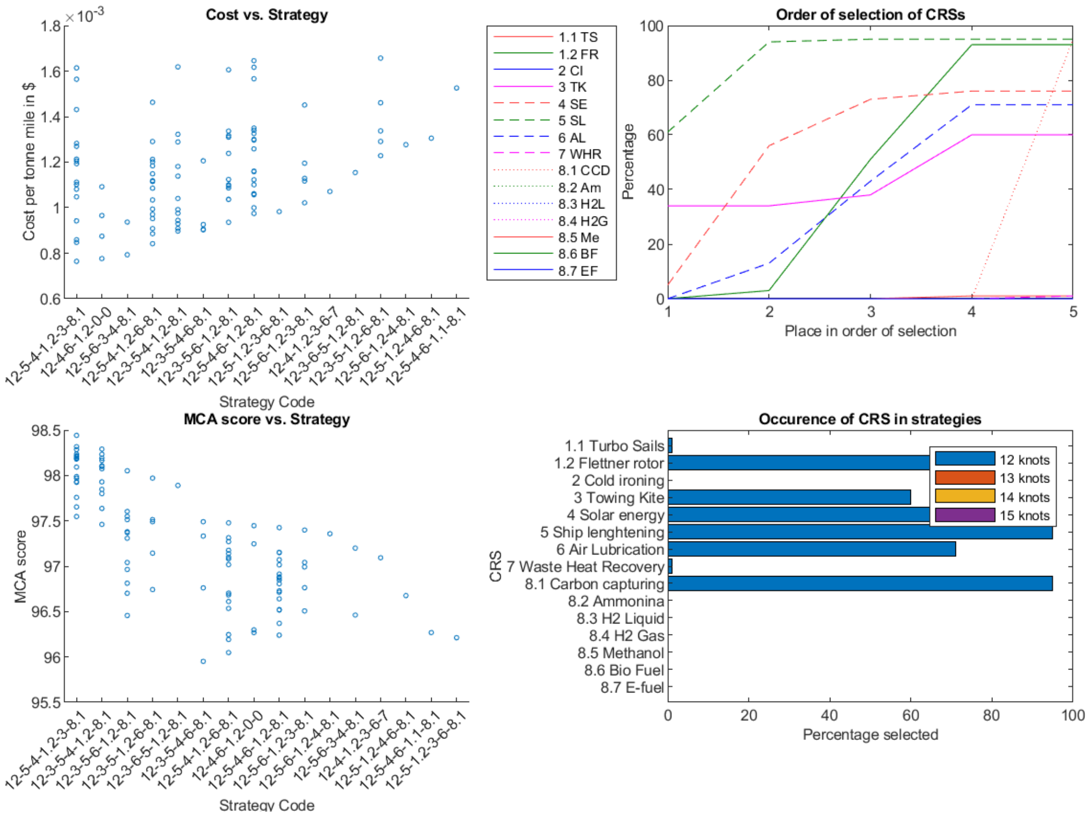

Figure B.7: No alternative fuels scenario

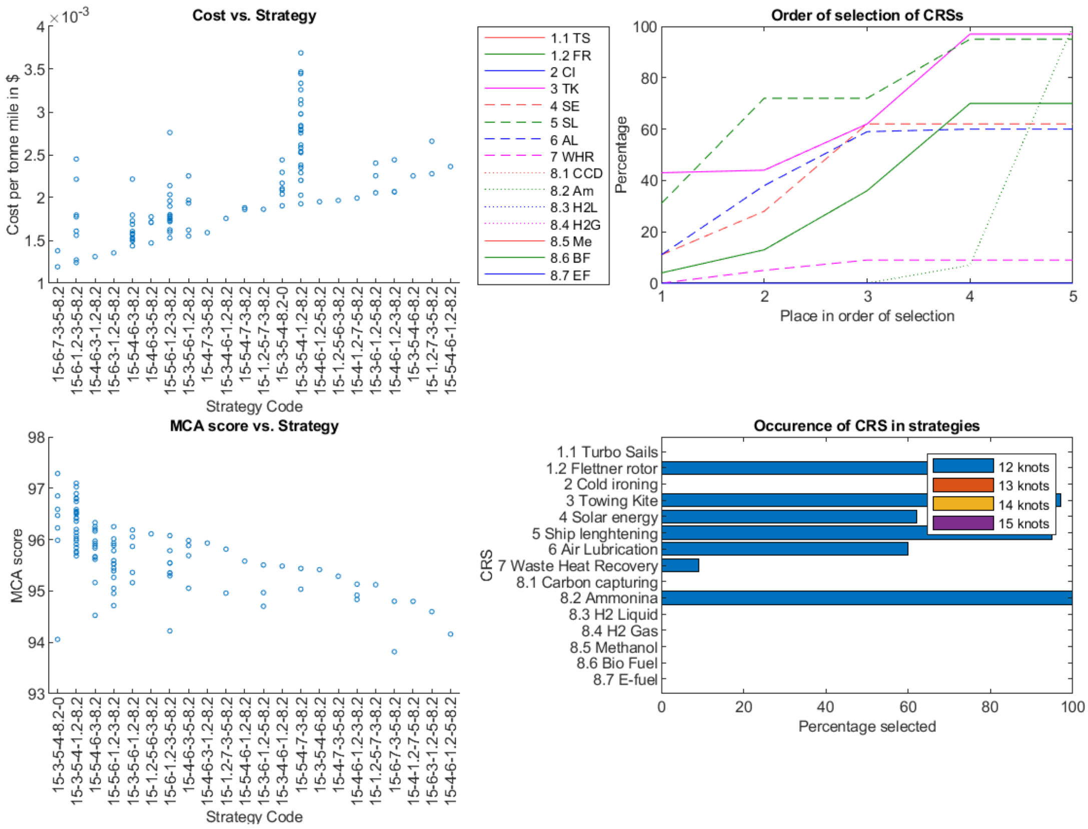

Figure B.8: 0 in 2050 scenario; no slow steaming

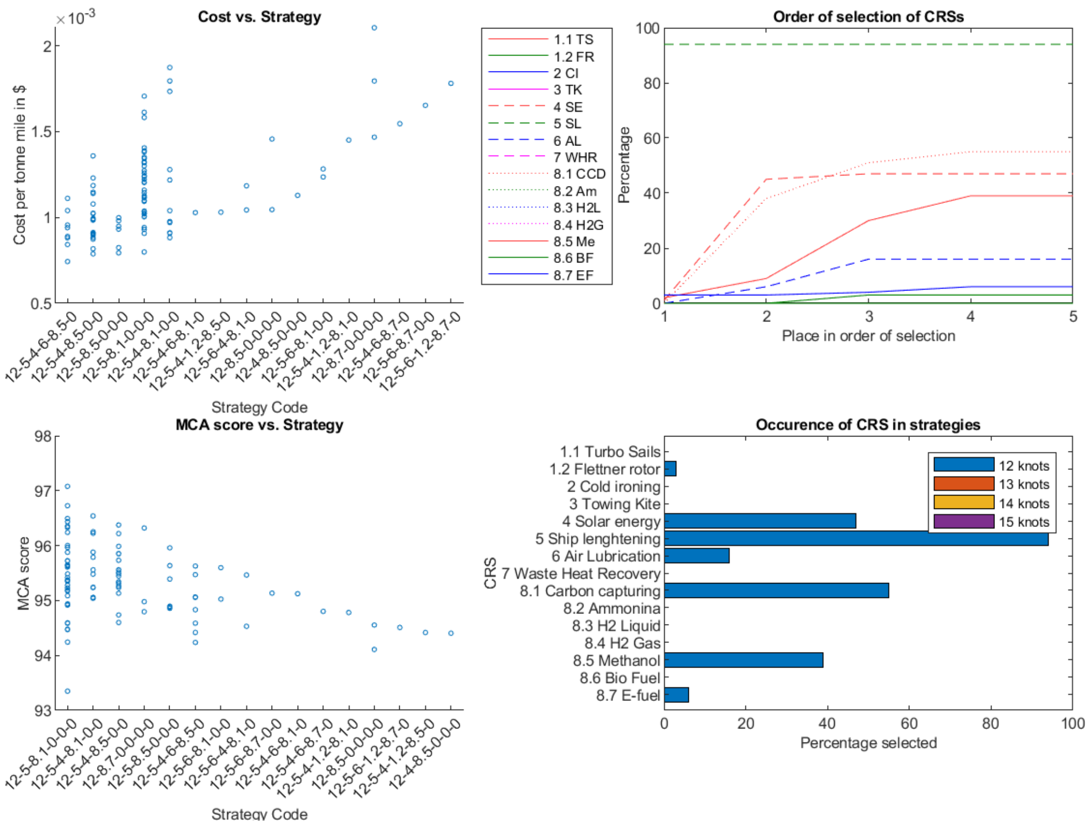

Figure B.9: No towing kite scenario

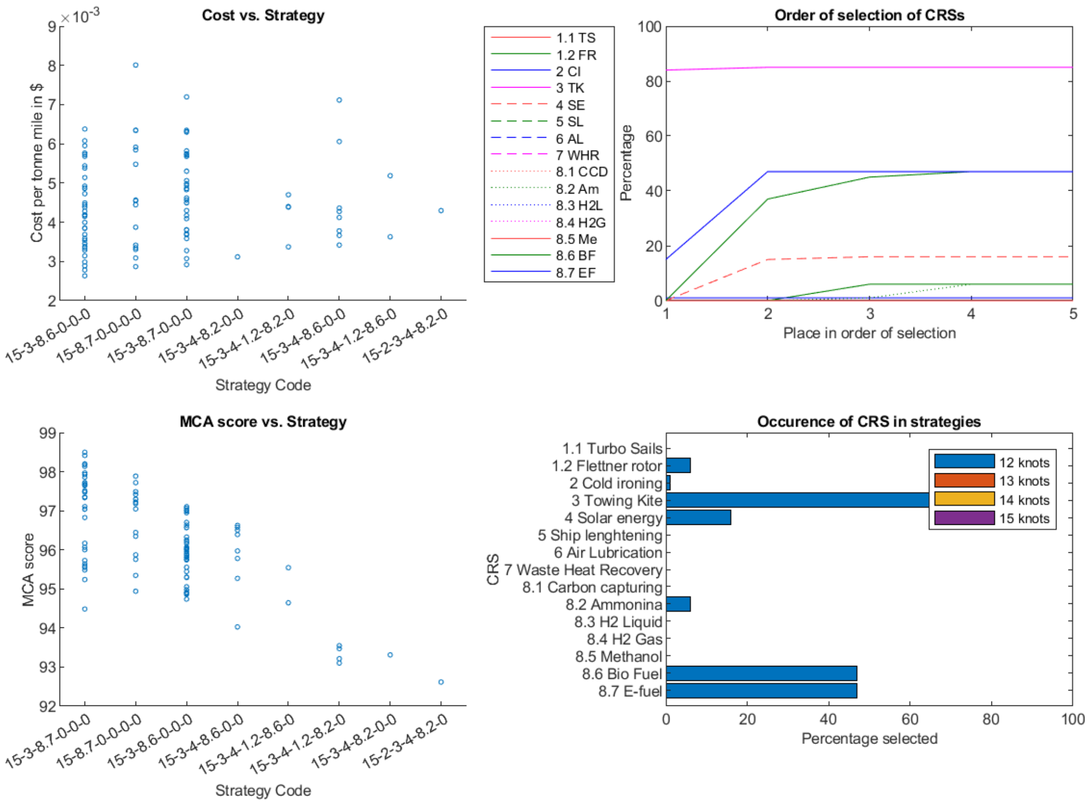

Figure B.10: Only WASP and alternative fuel scenario

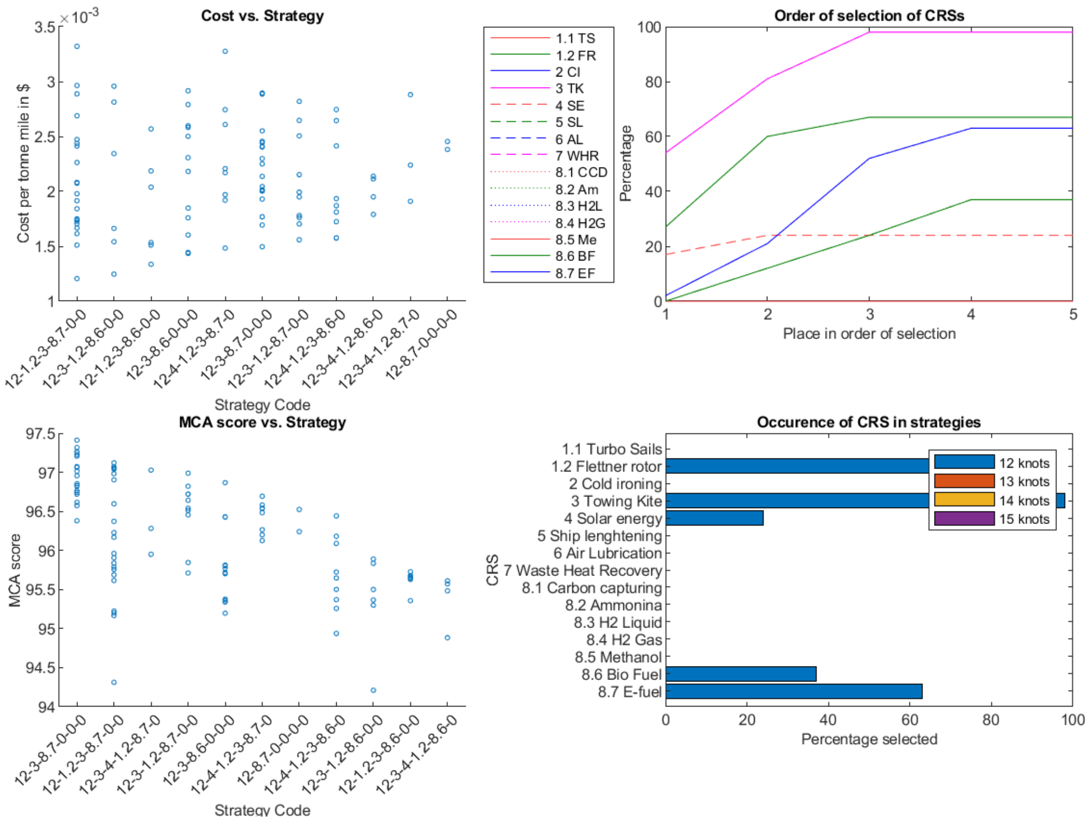

Figure B.11: 0 in 2050 scenario; only WASP and alternative fuel

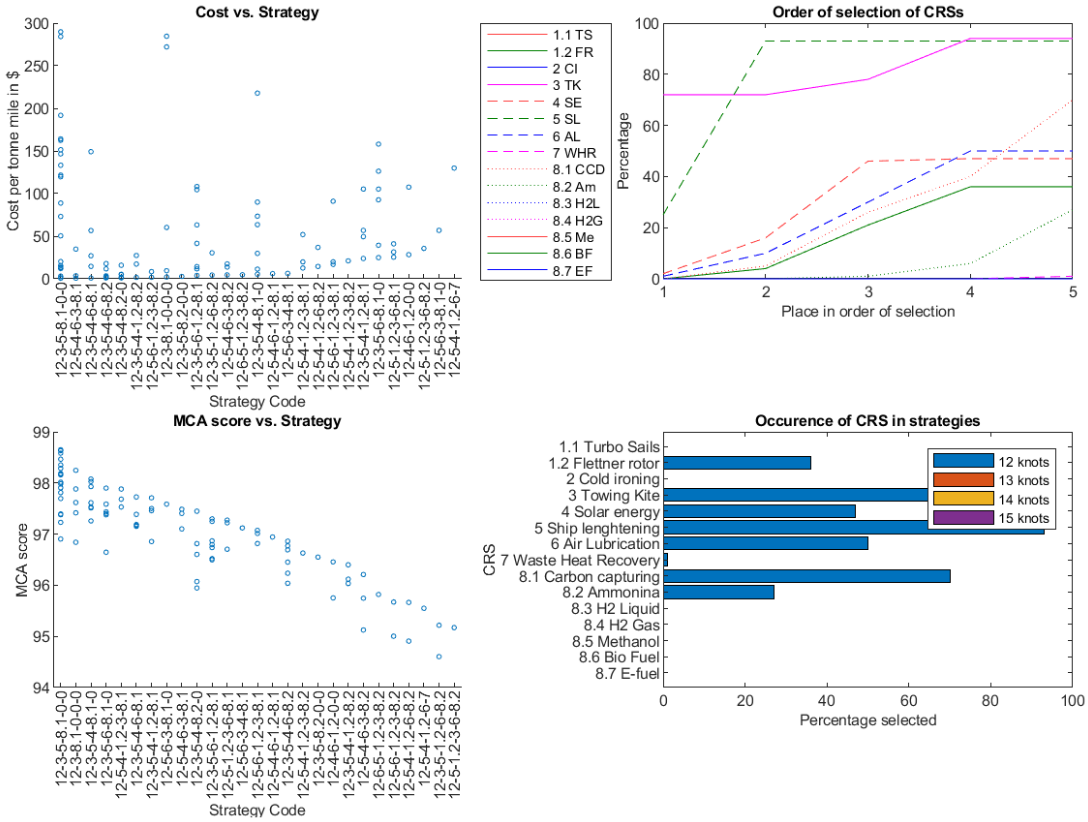

Figure B.12: Only alternative fuel ammonia; high fossil fuel price increase (20%)

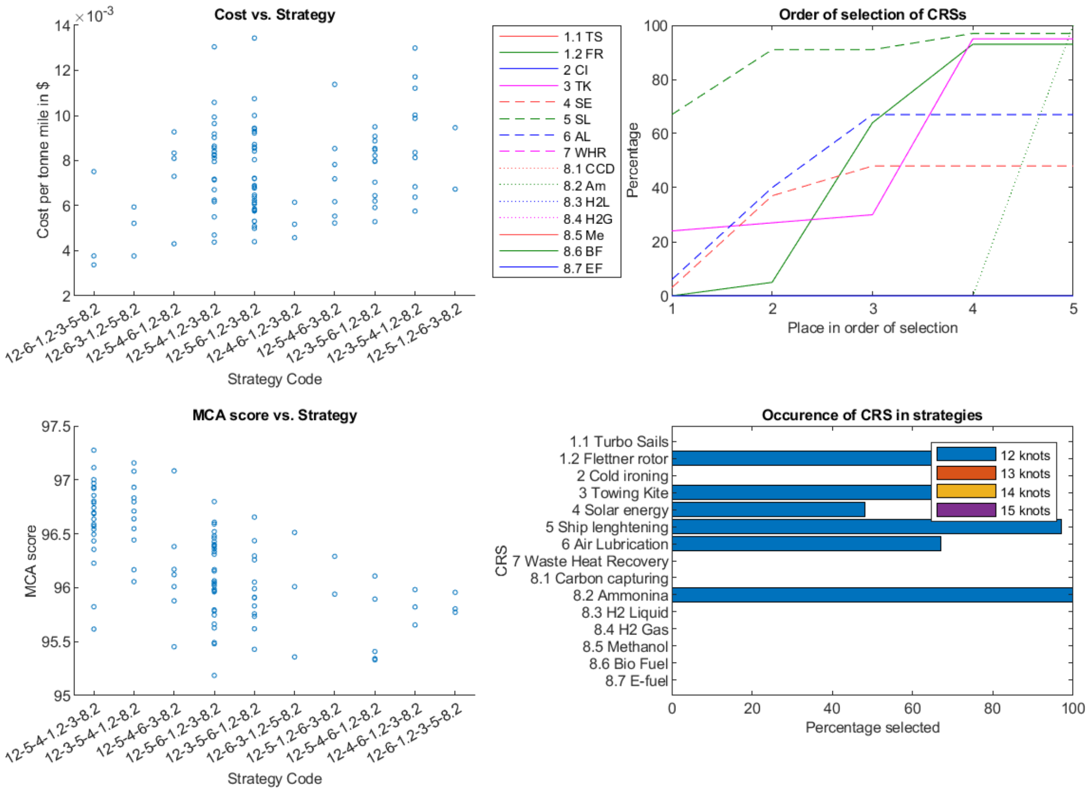

Figure B.13: 0 in 2050 scenario; high fossil fuel price increase (20%)

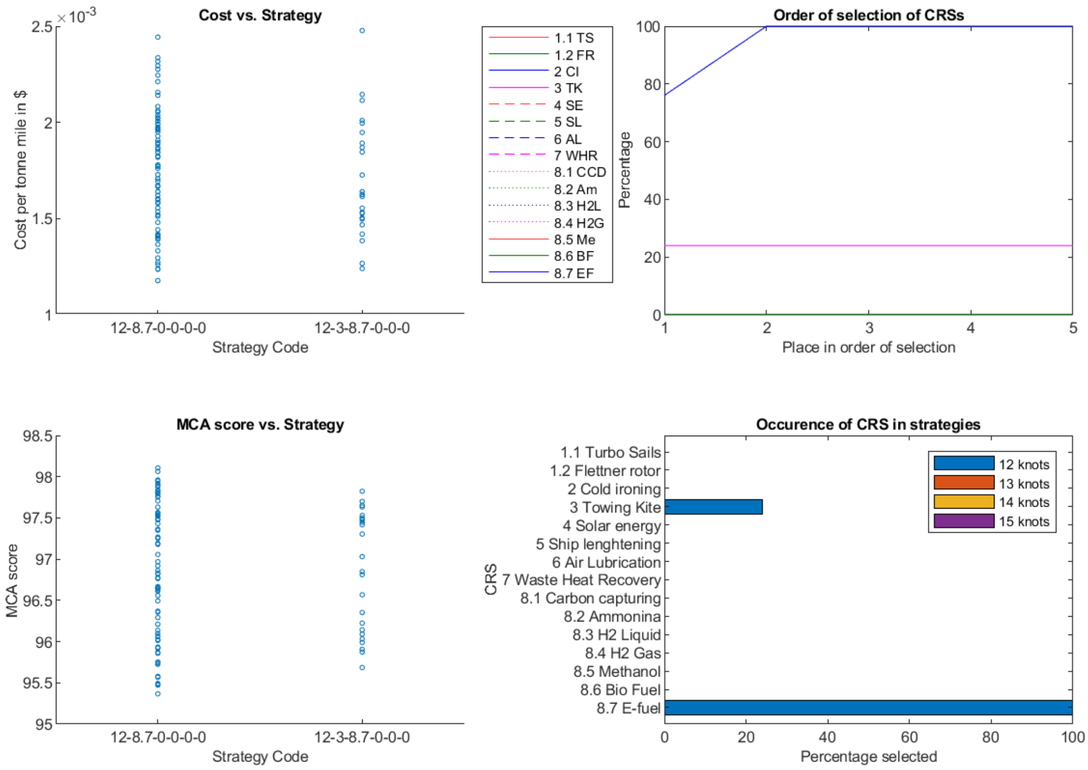

Figure B.14: MCA Weight safety to 100

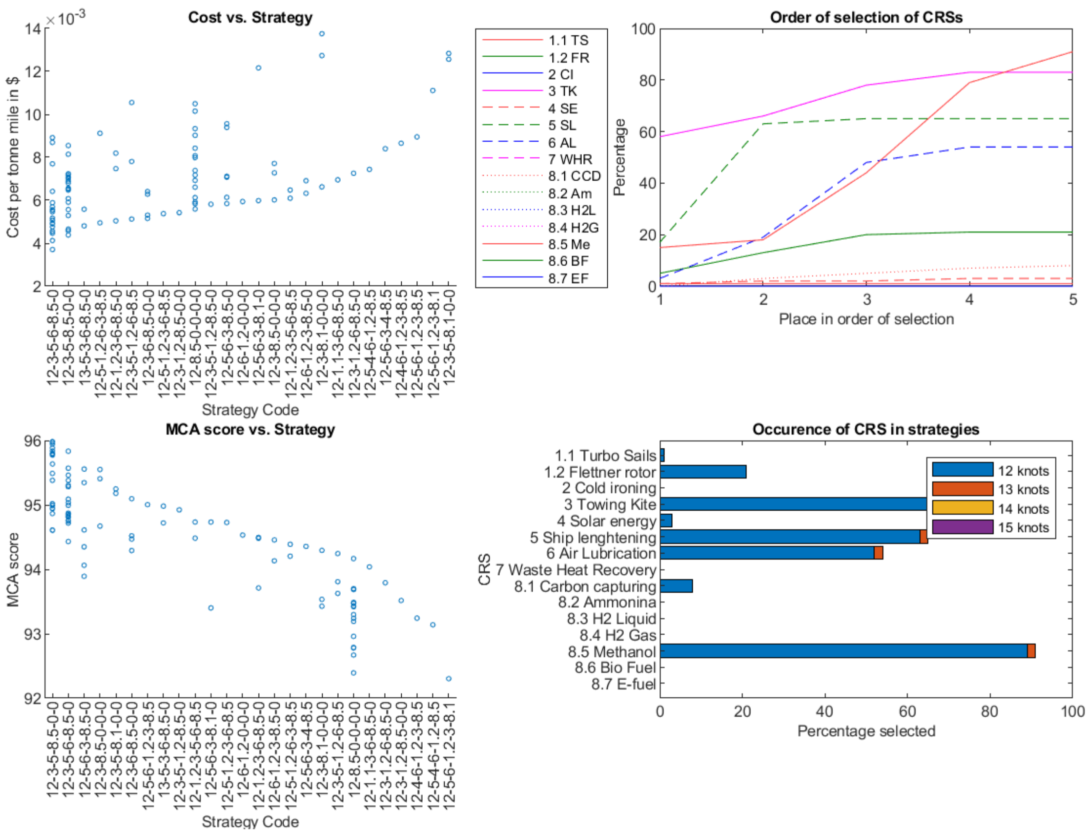

Figure B.15: MCA Scores Towing Kite two points lower