Master's thesis

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A multi-period fleet retrofit and renewal problem for strategic green corridor planning and emission control in maritime shipping

Master's thesis in Marine Systems Design and Logistics
Supervisor: Professor Stein Ove Erikstad
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Master Thesis in Marine Systems Design

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Background

Following the Clydebank declaration in 2021, several green corridor initiatives have been taken. In order to realize the initiatives challenges related to fleet renewal arises. Fleet size and mix, along with the transition phase will become an important part of the announced projects and strategic decisions will play an important role. Decisions made in the here-and-now will have significant implications on both short- and long-term success. To support such development, it could be of value to have a decision-making support tool evaluating different scenarios with the aim of providing useful insights to both generic and specific projects.

Overall aim and focus

The aim of this report is to propose a generic formulation of a multi-period fleet retrofit and renewal model that can be utilized as a decision-making tool for both green corridors and general decarbonization purposes. The model should be evaluated through a computational study using a commercial solver to assess the model's strengths and limitations before employing it in practical applications. The iron ore trade between Australia and Japan will serve as a case study to illustrate the application of the model. The case study should aim to provide insightful strategic decision support based on available literature and AIS-data.

Scope and main activities

The candidate(s) should presumably cover the following main points:

1. Introduce the impact of shipping emissions in the global climate discussion.
2. Go through available literature and present up-to-date status and overview on current publications relevant for the problem description.
3. Develop a multi-period fleet renewal model in accordance with the problem description and defined assumptions.
4. Implement the model in a commercial solver to test and verify its strength and limitations in addition to logical connections.

5. Employ the model to a specific green corridor case, where strategic fleet renewal insight should be provided and/or discussed.
6. Conclude the thesis with a (1) discussion of findings and (2) and further work for future master thesis students.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The candidate should aim to be brief and clear in its communication. The following elements / structure should be included:

1. A text defining the scope.
2. Preface, list of content.
3. Summary.
4. Main body of thesis.
5. Conclusion with further recommendations.
6. List of symbols, acronyms, references, and appendices.
7. All figures, tables, and equations should be numerated.

Deliverables:

1. Task description.
2. Report to be submitted electronically.
3. Programming scripts and other relevant attachments shall be delivered in a zip-file along with the thesis.
4. Deadline: 11.06.2023.

Supervision:

Supervisor:
Stein Ove Erikstad

Preface

This thesis represents the culmination of our Master of Science in Marine Technology, where both of us has specialized in marine systems design and logistics. As part of our academic journey, we had the opportunity to spend a year abroad at the University of Strathclyde during the 2021/2022 school year working together on several subjects. The experience gained at both Strathclyde and NTNU laid the groundwork for our collaboration on this thesis. The research presented in this thesis were conducted during the spring semester of 2023.

We believe that having worked together compared to writing alone, has been a huge benefit for us and we have learned a lot about how to defend and discuss complex topics. We have contributed equally to the results.

We would like to extend our gratitude to our supervisor, Professor Stein Ove Erikstad for his patience, deep knowledge within field and as a solid discussion partner. Additionally, we would like to thank Erik Nikolai Stavseth (Golar LNG) for market data, Ekatarina Kim (IMT) for support with AIS-analysis, Andreas Breivik Ormevik (IØT) for support on thesis structure, and Øyvind Endresen (DNV) for information about green corridors.

Trondheim, 11/06/2023

Signed by:

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Abstract

In this master's thesis we develop a multi-period maritime fleet retrofit and renewal model for strategic green corridor planning and general emission reduction purposes. A parametric study on different emission reduction strategies, carbon tax and green premium developments has been performed as well as a case study on the iron ore trade between Australia and Japan. During our research we have identified that the abatement options selected are independent of emission reduction strategy when the final emission target is shared, while the timing of these investments are dependent on strategy.

However, when carbon tax rates surpass the additional cost associated with alternative fuel sources (referred to as green premium), the decarbonization rate becomes primarily influenced by the carbon tax. Consequently, making the emission reduction strategy non-binding for the optimal solution. In addition, we have highlighted optimal carbon tax rates based on a given green premium and emission reduction strategy, where optimal is referred to as the most proactive rates for accelerating the decarbonization without imposing excessive costs for shipowners. Furthermore, the rate of decarbonization is closely correlated with carbon tax rates, indicating that this instrument is effective in decarbonizing shipping.

Using AIS-analysis, 96 unique bulk carriers were identified having contributed with tonnage on the Australia to Japan iron ore trade in 2018. A total of 69 million tons of iron ore was transported the roughly 3500 nautical miles between western Australia and Japan emitting 1.77 million tons of carbon dioxide per annum. Applying the model to the case, suggest retrofitting 21 vessels with ammonia power systems and the ordering of three ammonia powered newbuilds. Over the 25 year planning period, the proposed solution projects that a green corridor will be established around 2037 after a 13 year period of fleet renewal considering a given carbon tax and fuel only green premium scenario. By following the plan, 30 million tons of carbon dioxide can be removed until 2050 in the iron ore trade.

Sammendrag

I denne masteroppgaven har vi utviklet en flerperiodisk modell for oppgradering og fornyelse av den maritime flåten. Målet med modellen er å gi verdifull innsikt i strategisk planlegging av grønne korridorer og generelle tiltak for å redusere utslipp i maritim sektor. Vi har gjennomført en studie av ulike strategier for utslippsreduksjon, karbonskatt og utvikling av alternative drivstoffkilder, samt en casestudie av jernmalmhandelen mellom Australia og Japan. I denne rapporten har vi konkludert med at valg av tiltak for utslippsreduksjon er uavhengig av strategien, mens timingen for investeringene avhenger av valgt strategi.

Når karbonskatten overstiger de ekstra kostnadene forbundet med alternative drivstoffkilder, blir karbonskatten den drivende parameteren for avkarboniserings raten. Som en følge av dette blir utslippsreduksjonsstrategien ikke bindende for den optimale løsningen. Videre har vi identifisert flere optimale satser for karbonskatt basert på gitte priser for alternative drivstoff og reduksjonsstrategier. Hvor optimale satser refererer til diskre punkter som oppnår høyest reduksjon uten å pålegge skipseiere kostnader som ikke direkte bidrar til økt avkarbonisering.

Ved hjelp av AIS-analyse ble det identifisert 96 unike bulkskip som bidro med tonnasje i jernmalmhandelen mellom Australia og Japan i 2018. Totalt ble det transportert 69 millioner tonn jernmalm over de omtrent 3500 nautiske milene mellom Vest-Australia og Japan, noe som resulterte i årlige utslipp på 1,77 millioner tonn karbondioksid. Ved å anvende modellen på denne casen, blir det foreslått å oppgradere 21 skip med ammoniakkbaserte kraftsystemer og bestille tre nybygg som også bruker ammoniakk som drivstoff. I løpet av den 25 år lange planleggingsperioden indikerer den foreslåtte løsningen at en grønn korridor vil bli etablert rundt 2037, etter en 13-års periode med fornyelse av flåten, med hensyn til angitte karbonskatter og priser på alternative drivstoffkilder. Ved å følge denne planen kan det totalt oppnås en reduksjon på rundt 30 millioner tonn karbondioksid i jernmalmhandelen frem til 2050.

Contents

Acronyms

CO_2 Carbon dioxide. 1

AIS Automatic Identification System. 36, 37

CFD Contract for Difference. 51
CII Carbon Intensity Indicator. 1

DWT Deadweight tonnage. 20, 37, 40

ECA Emission Control Areas. 6
ETS Emission Trading System. 47

FMG Fortescue Metals Group. 35

GMF Global Maritime Forum. 37, 38

IMO International Maritime Organization. 1, 51

LOI Letter of Intent. 36

MFRP Maritime fleet renewal problem. 5, 6
MFSMP Maritime fleet size and mix problem. 4
MMSI Maritime Mobile Service Identities. 37

SZEF Scalable Zero Emission Fuels. 51

TCO Total Cost of Ownership. 29

VLSFO Very Low Sulphur Fuel Oil. 20

Chapter 1

Introduction

The modern maritime supply chain has evolved into a highly complicated system, where numerous stakeholders interact continuously to manage the departure, travel, and arrival of vessels at ports worldwide. Roughly 90 % of traded goods are transported by ships creating a multi-billion-dollar market that operates in a symbiotic relationship with several industries. While shipping is known for its cost-effectiveness and environmentally friendly nature in terms of transporting goods per ton, it still has a significant impact on global Carbon dioxide (CO_2) emissions. In 2018, the global shipping sector contributed approximately 1,076 million tons of CO_2 emissions, accounting for 2.9% of the total emissions caused by human beings (IMO 2020).

The shipping industry has significant potential for reducing global emissions, and efforts have been underway for some time. The International Maritime Organization (IMO) has been actively involved in a global approach to enhance ships' energy efficiency and implement emission reduction requirements. In 2013, the first-ever mandatory emission requirements for an entire industry were introduced in shipping. These regulations provided a framework for shipowners to improve energy efficiency in ship design and through operational measures. Furthermore, in 2018, the Paris agreement was introduced where ambitious targets were set with the aim of reducing CO_2 emissions by at least 40% by 2030, pursuing efforts towards 70% by 2050. These ambitions are reflected in the current requirements taking place this decade. The next wave of regulations took place in 2023 and consist of a Carbon Intensity Indicator (CII) measuring all carbon emissions from each vessel and further requirements related to the technical design of new vessels (IMO 2019).

The implemented measures have demonstrated their influence in a positive direction, resulting in a 9% improvement in carbon intensity from 2012 to 2018 in international shipping (IMO 2020). However, in order to achieve the ambitious goals set forth in the Paris Agreement, there is a need to accelerate the transition. In recent years, the concept of green shipping corridors has emerged as a potential catalyst for the decarbonization of the industry. Essentially, a green corridor is defined as a zero-emission route connecting two or more ports, where no emissions are allowed in port-to-port operation. One of the main challenges the industry is facing in the transition is the complexity of all stakeholders involved.

Green corridors have the potential to provide sufficient scale and volume for impacting the global scene as they are large enough to include all essential value chain actors needed to scale zero-emission shipping. Moreover, green corridors can be custom made to reach the entire value chain offering favorable conditions through measures such as special economic zones, allowing policy makers to create fit-to-purpose regulations, and financial incentives which otherwise is difficult on a global scale (GMF 2021b).

The Clydebank Declaration was launched at COP26 in November 2021 with the primary aim to put the maritime sector on track to achieve net zero by 2050. Building on the Zero-Emission Shipping Mission created in July 2021 by US, Norway, and Denmark the initiative is designed to drive forward the scaling of the decarbonization through a collaborative effort in establishing six green corridors by 2025 (Gov.UK 2021). Several initiatives, partnerships, and studies have been announced during 2022 following the Clydebank Declaration. The movement has grown to include 21 initiatives, bringing more than 110 stakeholders together covering all major parts of the value chain. The initiatives are taken by industry and third-party actors, by government, and a combination of the two as an initial first step towards realization (GMF 2022).

Regardless of the decarbonization strategy going forward, the 2050 emission targets entail a change of operative vessels through available technology and zero-emission fuels. Fleet size, mix, and renewal along with the transition phase will become an important strategic question going forward. Decisions made in the here-and-now have significant implications for the stakeholders involved, thus a forward-thinking approach is critical to ensure both short-and long-term success.

To support such decision making, it could be of great value to develop a decision support tool that provides insight in different decarbonization strategies considering uncertain parameters over time such as carbon taxes and fuel only green premiums.

1.1 Objective

The aim of this report is to propose a generic formulation of a multi-period fleet retrofit and renewal model that can be utilized as a decision-making tool for both green corridors and general decarbonization purposes. The proposed model will be subject to a computational study after the implementation to evaluate its strengths, limitations and behaviour through a parametric study. Additionally, the iron ore trade between Australia and Japan will serve as a case study to illustrate the application of the model. The case study aims to provide insightful strategic decision support based on data obtained from 2018 AIS data and available market data.

Chapter 2

Problem description

We consider a heterogeneous fleet of vessels operating between two ports or regions over a fixed time horizon. The fleet must comply with a stepwise emission reduction requirement, while meeting a given transportation demand from one period to the subsequent period. Each vessel has a current emission level, and these emissions can be reduced by introducing a set of abatement options that each gives a certain percentage reduction in emissions. The abatement options could in practice be any technology that reduces a vessels emission through energy saving measures or the energy source itself. Additionally, building a new vessel powered by zero-emission fuels are an option. The abatement options have an associated investment cost that is due on the period it is introduced, and a fixed operational cost each period thereafter.

For each abatement option, a corresponding time lag between the decision-making process and the vessel's operational readiness persists. Thus, in cases of retrofitting a vessel, any shortfall in cargo transportation capacity must be substituted until the vessel becomes operational. A pool of available vessels is defined, ensuring that there always is excessive cargo transportation capacity available to choose from. Constraints on the fleet size and mix only arise from the capacity limitations of the ports, emission requirements, and the necessity to meet demand, resulting in dynamic fluctuations in fleet size and mix from one period to the next to optimize for the fleet renewal schedule.

The constraints from the ports are constant, while the emission- and transportation requirement can vary from one period to the subsequent period. Additionally, market driven forces such as fuel prices and carbon tax are subject to different values through a set of projected scenarios.

Chapter 3

Literature Review

The purpose of this section is to review available literature relevant for our problem description in order to gain an understanding of theories, methodologies, and debates within the field. As our problem description implies, we will focus on three areas of investigation. Firstly, maritime fleet size and mix problem including problems consisting of choosing vessels from an available pool. Secondly, maritime fleet renewal problem including replacement schedule for available vessels while also allowing the fleet size and mix to vary between periods. Lastly, we will explore different approaches to emission control, with a particular focus on proposed modeling methodologies capable of capturing the implementation of emission reduction measures in response to market factors such as carbon taxes and other imposed requirements.

Pantuso *et al.* (2014) published a survey on Maritime fleet size and mix problem (MFSMP) with the primary focus on ships for transportation purposes. During this literature review, we have utilized this paper in two ways. (1) Gain an overview of available papers on the problem, where a majority of our references to the maritime fleet size and mix problem are found through references made in that paper (up until 2014). (2) Drawn inspiration to the categorizing of different sub-problems under the umbrella of MFSMP problems (e.g., difference between strategic and tactical problems for instance).

3.1 Maritime fleet size and mix problem

The Maritime fleet size and mix problem refers to the challenge of determining the optimal size and mix of a fleet. The objective is usually to make decisions on number and types of vessels a shipowner should operate in order to meet the required transportation requirement in the most cost-effective manner. We can divide it into two main ways of analyzing and addressing the problem. Firstly, analyzing the problem on a strategic level involves long-term planning and high-level decision making. The key consideration at this level includes market analysis, capacity-, financial-, and specialization planning. Secondly, analyzing the problem on a tactical level covers a shorter time frame, ranging from a few months to a year. Day-to-day management and optimization of fleet operations are usually in center on these problems.

One of the earliest papers addressing the short-term fleet size and mix problem was published by Schwartz (1968). The problem consisted of determining the number of barges and towboats of each size to move cargo. The barges and boats could be chosen from an available pool, where the problem was modelled as an IP problem. Meng and T. Wang (2010) modelled a problem consisting of deciding which ships to use and their deployment in addition to the number of charters (in or out). To deal with uncertainty in demand they proposed a chance constrained problem.

Murotsu and Taguchi (1975) combined dynamic programming (DP) and non-linear programming to determine the optimal fleet size and mix for a fleet of oil carriers. One origin port and one destination port were used, where the ships size and speed were variables of the problem.

Sigurd *et al.* (2005) studied the problem of establishing a new liner shipping system for container transportation from Norway to Central Europe. They considered the possibility of building several different ships to ensure the desired service speed and frequency. Later, Zeng and Yang (2007) proposed a model deciding both fleet size and mix in combination with ship schedules for a Chinese coal shipping network. Three outbound ports and three demand ports were used, where a tabu heuristic search was used to solve the problem.

3.2 Maritime fleet renewal problem

The Maritime fleet renewal problem (MFRP) refers to the challenge of determining the optimal timing and strategy for replacing or renewing a fleet of vessels. Decisions on when to retire older vessels and acquire new ones to ensure operational efficiency and competitiveness is usually the central objectives. However, there are several objectives that can be the driving factor such as financial considerations, risk management, market and demand, and technological advancement to mention a few. The maritime fleet size and mix problem and maritime fleet renewal problem are closely related, where fleet renewal can be thought of as an extension of the size and mix problem. At a strategic level, the mix problem focuses on the design of a fleet whose characteristics are meant to remain unchanged over time and therefore do not to consider the evolution of parameters over time. In contrast, renewal problems consider a dynamic adjustment of the fleet in response to the evolution of requirements.

S. Wang *et al.* (2011) developed a multi-period fleet planning model for liner shipping companies, where a set of scenarios are proposed including the number of vessels owned, bought, chartered in or out for a given time period. Furthermore, the fleet deployment schedule is obtained by solving a MIP for each period.

Jin and Kite-Powell (2000) examined the replacement problem of a ship by developing an optimal control model that provided guidance on (1) utilization of individual ships, (2) ordering new ships, and (3) scrapping old ships. They focused on the deterministic case, with a homogeneous fleet and showed that the determination of replacement schedules and utilization rates are related problems that should be solved jointly. Alvarez *et al.* (2011) proposed a MIP model of the multi-period fleet sizing problem. They extended the basic MIP model into a robust optimization model in order to account for uncertainty in the market (selling and purchasing prices of ships).

More closely related to our problem is the paper published by Wijsmuller and Beumee (1979), where they presented an LP model for a ship investment and replacement problem. The fleet size and mix could be adjusted within an upper and lower bound while finding the optimal replacement schedule.

3.3 Emission control papers

In recent years more requirements on emissions in shipping have emerged and resulted in new problems subject to optimization in the industry. The impacts of Emission Control Areas (ECA) in shipping have received a lot of attention in recent years addressing ship operator's optimal selection among different compliance measures in response.

Ø. S. Patricksson *et al.* (2015) extended the Maritime fleet renewal problem to include regional limitations in the form of emission control areas. In the proposed model, they present various means to cope with stricter emission regulations for new vessels and the possibility of upgrading existing vessels with new emission reducing technology. The modeling concept was based on the maritime fleet retrofit model presented in Johnsen et al. (2015), where a set of fleet renewal decisions are made based on an underlying deployment problem for a liner shipping fleet. In order to cope with uncertainty in fuel prices and the ECA regulations, a two-stage stochastic approach was used to model the problem. They demonstrated their model on a case study considering whether to use low Sulphur fuel or have an exhaust gas scrubber system installed to comply with emission requirements.

Furthermore, Ø. Patricksson and Erikstad (2016) presented a two-stage optimization model for the machinery system selection problem. The objective was to minimize cost, while aggregated power requirement and emission regulations are constraining the problem. Additionally, design flexibility in terms of future retrofitting possibilities was taken into account.

Gu and Wallace (2017) considered the impact on sailing pattern and its corresponding cost effects in the evaluation and selection process for sulphur abatement technology. They integrated the optimization of a ships sailing pattern into the lifespan cost assessment of the emission control technology, to evaluate expensive and irreversible decisions made in the here-and-now.

Some studies have focused on the rerouting of vessels' sailing path to avoid operating through ECAs (Zhen *et al.* (2020), Chen *et al.* (2018)). Additionally, measures such as speed optimization for both environmental and economic concern has been evaluated (Fagerholt and Psaraftis (2015), Ma *et al.* (2020)).

Balland *et al.* (2012) presented an optimization model providing support to ship owners on which air emission controls to be installed in a given vessel and when this should be done in order to comply with the IMO regulation in the most cost-efficient way. They investigated the technical and economical interaction effects between different emission controls measuring the emission reduction of the controls as a percentage relative to the vessels' emission before any controls are implemented. A modelling approach closely related to our problem description have been utilized. The objective value minimizes total capital and operational cost for implementing a set of air emission controls. The updated emission for the vessel is captured by subtracting the interaction effect between emission controls chosen.

3.4 Summary and modelling approach

Regarding the fleet size and mix problem considering both tactical and strategic approaches, our model formulation lays somewhat in between. On a tactical level, the paper published by Schwartz (1968) possesses some similarities in choosing the best fleet size and mix from a pool of available vessels. Moreover, our problem entails short term planning in terms of choosing the best fleet size and mix for each specific period. On the other hand, the main objective is long term planning on a high level, leaning towards a strategic approach. Notably, the fleet renewal problem, which can be thought of as an extension on the fleet size and mix problem, considers multiple time periods where dynamic adjustments of the fleet in response to the evolution of requirements are taken into account. The paper published by Wijsmuller and Beumee (1979) reflect our problem in terms of adjusting the fleet size and mix within and upper and lower bound to find the optimal replacement schedule.

Regarding emission controls, the number of papers published are far less compared to the above. This is understandable since the topic only became relevant in the 2000s. The majority of the papers highlighted focuses on Emission Control Areas, and its impact on routing, fuel choice and machinery selection. The extension of the fleet renewal problem done by Ø. S. Patricksson *et al.* (2015) possesses similarities to our problem in terms of evaluating the possibility of retrofitting existing vessels to comply with stricter emission requirements. Additionally, Balland *et al.* (2012) proposes an interesting modelling approach towards interaction effects between different emission reducing abatement options. Stein Ove Erikstad, which is our supervisor on this master thesis, was co-writer in the Balland *et al.* (2012) paper. Publicly on GitHub (Erikstad 2023), he published a short model formulation which dealt with emission reduction abatement options which possesses similarities to the modelling approach presented in Balland *et al.* (2012).

There is limited literature available on fleet retrofit and renewal in green corridors, with the majority of studies focusing on the pre-feasibility and feasibility phases rather than the execution phase. Nevertheless, we have chosen to proceed with a deterministic modelling approach that takes into account uncertainties in fuel prices by considering a set of projected scenarios. Our model formulation builds upon the work of Erikstad (2023) with inspiration from the modeling approach presented by Balland *et al.* (2012) for modelling emission-reducing abatement options. Additionally, we have incorporated elements from a basic maritime fleet size and mix problem, along with a maritime fleet renewal problem, to capture dynamic fluctuations in fleet size and mix while optimizing a fleet renewal schedule to adhere to the set reduction strategy.

Chapter 4

Model formulation

In this chapter we will present a model formulation accordingly to the problem description introduced in chapter 2. The model formulation chapter is structured into three sections. Section 4.1 aims to establish the foundation and central elements of the model. The problem statement will be simplified, to reduce the number of parameters involved. Section 4.2 encompass a series of model extensions, while section 4.3 summarizes the model formulation.

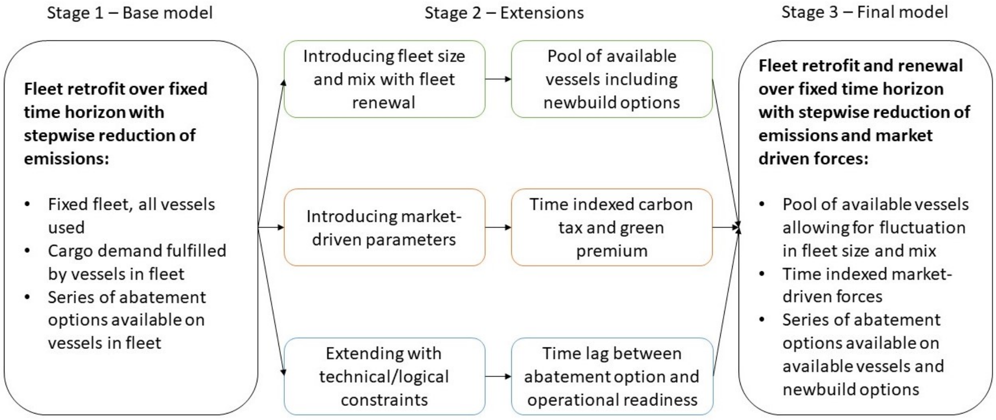

Figure 4.1: Structure of chapter 4

4.1 Stage 1 - Abatement options

We start with a simplification of the problem in order to capture the important aspect of the problem statement. We consider a heterogeneous fleet of vessels operating between two ports or regions. Each vessel has a current emission level, and these emissions can be reduced by introducing a set of abatement options that each gives a certain percentage reduction in emissions. The abatement options have an associated investment cost that is due on the period it is introduced, and a fixed operational cost each period thereafter. Note that in this model, no transportation demand is defined and all vessels in the fleet is assumed to be available at any time for the installation of an abatement option.

In table 4.1 all sets, parameters and variables is presented.

Sets	Explanation
V	The set of all vessels in the fleet, indexed v
A	The set of emission abatement options, indexed a
T	The set of time period in the planning horizon, indexed t
N^l	The last time period in T
N^f	The first time period in T
Parameters	
E_v^V	The emission from vessel v at the start of the planning period
γ_a	The emission reduction effect of abatement option a
C_a^{AI}	The installation cost of introducing abatement option a
C_a^{AO}	The operation cost per period of introducing abatement option a
E_t^{TOT}	The total allowed emission for time period t
Variables	
x_{vat}	1 if abatement option a is being installed on vessel v in time period t, 0 otherwise
y_{vat}	1 if abatement option a is already installed on vessel v in time period t, 0 otherwise

With the following model formulation:

$$min \sum_{v \in V} \sum_{a \in A} \sum_{t \in T} (C_a^{AI} x_{vat} + C_a^{AO} y_{vat}) \tag{4.1}$$

Subject to:

$$\sum_{v \in V} (E_v^V - \sum_{a \in A} \gamma_a E_v^V y_{vat}) \leq E_t^{TOT}, \qquad t \in T \tag{4.2}$$

$$\sum_{a \in A} \sum_{t \in T} x_{vat} \leq 1, \qquad v \in V \tag{4.3}$$

$$M \sum_{t \in T} x_{vat} \geq \sum_{t \in T} y_{vat}, \qquad v \in V, a \in A \tag{4.4}$$

$$y_{vat} \geq x_{va(t-1)}, \qquad v \in V, a \in A, t \in T / \{N^f\} \tag{4.5}$$

$$y_{vat} \geq y_{va(t-1)}, \qquad v \in V, a \in A, t \in T / \{N^f\} \tag{4.6}$$

$$y_{vat} - y_{va(t-1)} = x_{vat}, \qquad v \in V, a \in A, t \in T / \{N^f\} \tag{4.7}$$

$$x_{vat} = 0, \qquad v \in V, a \in A, t = N^l \tag{4.8}$$

$$x_{vat} \in \{0, 1\}, \qquad v \in V, a \in A, t \in T \tag{4.9}$$

$$y_{vat} \in \{0, 1\}, \qquad v \in V, a \in A, t \in T \tag{4.10}$$

Equation 4.1 represent the objective function where the objective is to minimize total cost. The investment cost C_a^{AI} is multiplied with the x_{vat} variable, ensuring that the cost is a one-time investment. The operational cost is multiplied with the y_{vat} variable ensuring that the operational cost of implementing abatement option a is included for all remaining periods. Note that the operational cost can contribute to an additional- or reduced cost, depending on the abatement option.

Constraint 4.2 ensures that the emissions from the fleet for a particular period is less than the allowed emission requirement. Each vessel has a certain amount of emission, E_v^v, which can be reduced by γ_a percentage through installing an abatement option.

Constraint 4.3 ensures that only one abatement option can be introduced per vessel during the planning horizon. A more detailed explanation of why this restriction is implemented is discussed in chapter 8.

Constraint 4.4 is a technical constraint that make sure an abatement option is installed if used, and constraint 4.5 ensures that the abatement option is put into use the same period it is installed.

Constraint 4.6 make sure that if an abatement option is installed, it will be used for the remaining periods, while constraint 4.7 is a logical constraint ensuring the relationship between the decision variables. When y_{vat} switches from zero to one, x_{vat} switches to one.

Constraint 4.8 make sure no abatement option in last period. This is a technical constraint which is needed in order to solve the model in a commercial solver. Constraint 4.9 and 4.10 are binary requirements.

The presented model proposes to model emission reduction measures as abatement options while incorporating restriction 4.2 to capture the effects. This method offers the advantage of allowing the introduction of any abatement options by modifying the abatement option set without requiring modifications to the mathematical formulation.

4.2 Stage 2 - Extending the model

So far, we have proposed a model that considers a range of abatement options and is capable of optimizing the timing and selection of such measures without taking the operational requirements into account. In this section we will present a series of extensions to enhance the model's ability to offer insightful information for a more complete problem involving operational functions such as meeting transportation demands. The common denominator for these extensions lay in the introduction of a third decision variable z_{vt}. In its simplest form, z_{vt} allows the model to keep track of which vessels that contributes with tonnage towards the demand in question and those who trade elsewhere.

4.2.1 Cargo transportation requirement

The fleet of vessels needs to transport a certain demand of cargo each period; thus, we need to extend the model to include a cargo transportation requirement. We start by introducing a pool of vessels which is assumed available throughout the problem. Meaning that we always have more cargo transportation capacity available than required, allowing the model to choose the best fleet size and mix from period to period. In order to keep track of all vessels in use for a certain period we introduce a third decision variable Z_{vt}. To better understand the relationship between the decision variables two small five-period examples is presented in table 4.1 and 4.2.

Time Period	1	2	3	4	5
x_{vat}	0	0	1	0	0
y_{vat}	0	0	1	1	1
z_{vt}	**1**	**1**	1	1	1

Table 4.1: Example A

Time Period	1	2	3	4	5
x_{vat}	0	0	1	0	0
y_{vat}	0	0	1	1	1
z_{vt}	**0**	**0**	1	1	1

Table 4.2: Example B

Let's say we have a vessel available in our pool of vessels, called vessel A. In period three an abatement option for vessel A is decided, thus variable x_{vat} switches from zero to one in that period while y_{vat} switches from zero to one for the remaining periods. This is incapsulated in restriction 4.4 to 4.7, implying that both x_{vat} and y_{vat} must be zero before any abatement option is chosen. However, in the context of introducing a cargo transportation requirement, we have the possibility of using vessel A in period one and two, before any abatement option is chosen. This is shown in table 4.1 were z_{vt} is equal to one in the first two periods. In table 4.2 the alternative option is illustrated with z_{vt} being zero in the first two periods, implying that the vessel is not part of the optimal solution in the first two periods. The z_{vt} variable is independent of abatement option a and can therefore incorporate this logic in our model.

By introducing constraint 4.11 we ensure that z_{vt} is active once y_{vat} is activated, without restricting the variable in the periods before an abatement option is decided. It says that if an abatement option is installed, the vessel will be part of the active fleet.

$$z_{vt} \geq y_{vat}, \qquad v \in V, a \in A, t \in T/\{N^f\} \tag{4.11}$$

The cargo transportation demand can then be expressed as shown in constraint 4.12, where D_t^{TOT} is the minimum required cargo that must be transported by the active fleet z_{vt} for each period and Q_v is the annual transportation capacity of vessel v.

$$\sum_{v \in V} Q_v z_{vt} \geq D_t^{TOT}, \qquad t \in T \tag{4.12}$$

4.2.2 Time lag

For every abatement option, there is an associated construction period which must be accounted for. If we choose to retrofit a vessel, the vessel must attend a yard stay for the construction period resulting in shortfall in cargo transportation capacity that period. This can be modelled by assuring that y_{vat} and z_{vt} is zero when x_{vat} is one. In practice, it implies that when a decision to retrofit a vessel is taken, it cannot be included in the active fleet that period and the reduction effects should not be accounted for in the same period. The relationship between the decision variables presented in table 4.3 must be maintained to capture this logic. Here the construction time is set to one period for all options.

Time period	1	2	3	4	5
x_{vat}	0	0	1	0	0
y_{vat}	0	0	0	1	1
z_{vt}	1	1	0	1	1

Table 4.3: Relationship between decision variables

We introduced constraint 4.7 in section 4.1, with the purpose of triggering x_{vat} when y_{vat} switches from zero to one. The Constraint was as follows:

$$y_{vat} - y_{va(t-1)} = x_{vat}, \qquad v \in V, a \in A, t \in T/\{N^f\} \tag{4.13}$$

By modifying the left hand side of the equation, as shown in 4.14, we can shift the period where x_{vat} is triggered, thus ensuring y_{vat} is zero when x_{vat} is one.

$$y_{va(t+1)} - y_{vat} = x_{vat}, \qquad v \in V, a \in A, t \in T/\{N^l\} \tag{4.14}$$

Furthermore, constraint 4.15 ensures that z_{vt} is zero once x_{vat} is one while allowing it to be one in the periods before an abatement option is decided using big M notation.

$$z_{vt} + y_{vat} \leq (1 - x_{vat})M, \qquad v \in V, a \in A, t \in T \tag{4.15}$$

4.2.3 Newbuild option

The current model is limited to the pool of available vessels, with a set of abatement options to meet the emission requirements from period to period. In this section we are extending the model to include the option of ordering a newbuild vessel. This can be achieved through modelling it as an additional abatement option with placeholders for various newbuild characteristics in the set of vessels. In order to use this modelling approach there are some logical connection that needs to be maintained.

1. The newbuild options cannot be added to the cargo transportation capacity until the newbuild abatement option is chosen.

2. The model must prevent the newbuild abatement option from being applied to existing vessels.

To address point 1, the cargo transportation capacity can be represented as a scalar in the dataset, which can be activated upon selection of the newbuild option. To achieve this, the cargo transportation capacity constraint 4.12 can be extended using a similar approach as the emission requirement constraint 4.2.

$$\sum_{v \in V} Q_v z_{vt} + \sum_{v \in V/\{V^{EX}\}} \sum_{a \in A} Q_a^{ADD} Q_v y_{vat} \geq D_t^{TOT}, \qquad t \in T \tag{4.16}$$

In the extended constraint 4.16, Q_a^{ADD} represents a constant value of 1 million for the newbuild option a, and zero for the other abatement options. The summation over V includes all vessels except V^{EX}, which represents the existing vessels in the dataset, thus avoiding double counting of their capacity. Since the capacity (Q_v) of a newbuild is represented as scalar, the newbuild placeholders will never be included in the solution before it is chosen because it does not contribute with tonnage before a newbuild option is decided with y_{vat} becoming one.

A cost penalty can be used to model point 2, where attempting to newbuild an existing vessel results in a very high cost that will never be part of an optimal solution. This penalty can be incorporated into the objective function using the following expressions:

$$\sum_{v \in V^{EX}} \sum_{a \in A} \sum_{t \in T} P_a y_{vat} \tag{4.17}$$

In case the model attempts to newbuild an existing vessel, a penalty cost P_a will be imposed on the existing vessel. The penalty P_a for other abatement options is zero. The summation over all vessels is limited to the subset V^{EX}, ensuring that the penalty does not apply to newbuild placeholders. The updated objective function is presented in 4.18.

$$min \sum_{v \in V} \sum_{a \in A} \sum_{t \in T} (C_a^{AI} x_{vat} + C_a^{AO} y_{vat}) + \sum_{v \in V^{EX}} \sum_{a \in A} \sum_{t \in T} P_a y_{vat} \tag{4.18}$$

4.2.4 Carbon Tax

In the context of fleet renewal strategies carbon tax policies becomes highly relevant and have the potential of being a decisive parameter. We therefore intend to extend the model to include carbon tax, with the assumption of a stepwise increase in intensity from period to period. Carbon tax pricing in shipping today varies depending on the country or region but can be divided into two main approaches.

The first approach is a cap-and-trade system, which involves setting a maximum cap on emissions within a specific sector. Under this system, operators can trade carbon quotas to comply with the set limit. The resulting carbon price is therefore determined by market forces and subject to fluctuations. The second approach involves setting a fixed carbon price, measured in USD per ton of emission. Essentially, the cap-and-trade scheme ensures the quantity of emissions, whereas carbon tax pricing ensures the price.

In our model we intend to use the second approach, with a fixed carbon tax price per ton emission. In order to analyze different carbon tax pricing strategies and its impact on the fleet renewal problem, it has been considered the easiest way to capture the effect of carbon tax, without introducing unnecessary complexity. Since each vessel has a current emission level, we can extend the objective function to include the following expression:

$$\sum_{t\in T} C_t^{CT}\Big(\sum_{v\in V} E_v^V z_{vt} - \sum_{v\in V}\sum_{a\in A}\gamma_a E_v^V y_{vat}\Big) \tag{4.19}$$

C_t^{CT} is the price per ton emission, dependent on period t, multiplied with the total emission from vessel v in period t. Note that the total emission is the same expression as presented in the emission requirement constraint 4.2. The updated objective function then becomes:

$$\begin{aligned}\min \sum_{v\in V}\sum_{a\in A}\sum_{t\in T}(C_a^{AI}x_{vat} + C_a^{AO}y_{vat}) + \sum_{v\in V^{EX}}\sum_{a\in A}\sum_{t\in T} P_a y_{vat}\\ + \sum_{t\in T} C_t^{CT}\Big(\sum_{v\in V} E_v^V z_{vt} - \sum_{v\in V}\sum_{a\in A}\gamma_a E_v^V y_{vat}\Big)\end{aligned} \tag{4.20}$$

4.2.5 Green Premiums

Currently alternative fuel sources with low or zero emissions characteristics comes with a higher cost than fossil fuel-based sources with higher emissions. This additional cost of choosing clean technology over its more polluting counterparts is known as the "Green Premium". In our case the green premium is defined as the cost gap between fossil fuels and alternative fuels. Note that the green premium can both be positive or negative, and it is only the fuel cost that is included.

To address this cost differential, we intend to extend the model by incorporating the Green Premium to capture its effects on fleet renewal strategies. This can easily be done by extending the objective function with the following expression:

$$\sum_{v\in V}\sum_{a\in A^{GP}}\sum_{t\in T} F_v C_t^{GP} y_{vat} \tag{4.21}$$

The Green Premium, denoted by C_t^{GP} in USD per MWh is dependent on period t allowing for different values from period to period. Furthermore, it is multiplied with the vessel specific energy consumption F_v that is summed across all vessels in the dataset. This ensures that the relative green premiums to be paid is scaled to size and speed of the vessel in question. Additionally, the Green Premium is multiplied by the decision variable y_{vat}, where a is summed over A^{GP}. A^{GP} is a subset of A, which includes all abatement options that require a change of fuel source. The updated objective function then becomes:

$$\begin{aligned}\min \sum_{v\in V}\sum_{a\in A}\sum_{t\in T}(C_a^{AI}x_{vat} + C_a^{AO}y_{vat}) + \sum_{v\in V^{EX}}\sum_{a\in A}\sum_{t\in T} P_a y_{vat} \\ + \sum_{t\in T} C_t^{CT}(\sum_{v\in V} E_v^V z_{vt} - \sum_{v\in V}\sum_{a\in A}\gamma_a E_v^V y_{vat}) + \sum_{v\in V}\sum_{a\in A^{GP}}\sum_{t\in T} F_v C_t^{GP} y_{vat}\end{aligned} \tag{4.22}$$

4.3 Model summary

The final model formulation is presented below, which captures the essential elements of the problem description. The model exhibits the ability to accommodate a set of predefined vessels and determine the optimal fleet size and mix for each period, based on a defined cargo transportation- and emission requirement. Additionally, uncertain variables, such as carbon tax and green premium development, are accommodated through time-indexed variables. The model seeks to minimize TCO and to maintain clarity of what is included in the total cost, a breakdown of all cost elements is presented in figure 4.2.

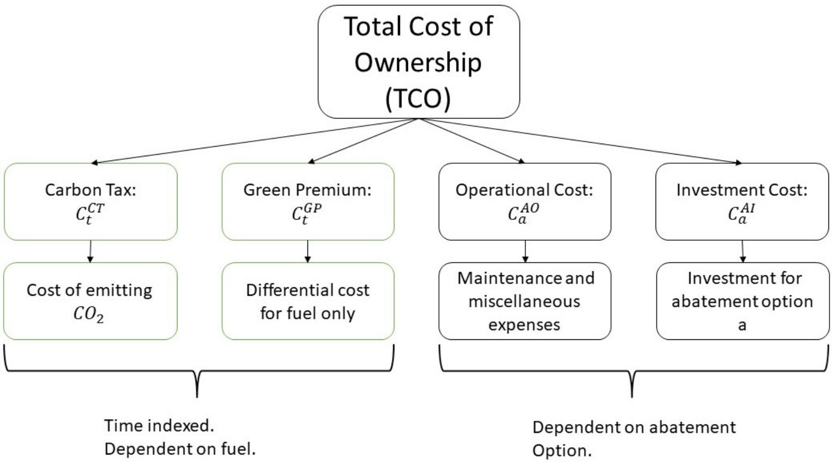

Figure 4.2: Cost breakdown

Sets	Explanation
V	The set of all vessels, including placeholders for newbuild option, in the fleet, indexed v
V^{EX}	Set of exisiting vessels, $V^{EX} \subseteq V$
A	The set of emission abatement options, indexed a
A^{GP}	Set of abatement options that require a change of fuel source, $A^{GP} \subseteq A$
T	The set of time period in the planning horizon, indexed t
N^l	The last time period in T
N^f	The first time period in T
Parameters	
E_v^V	The emission from vessel v at the start of the planning period
γ_a	The emission reduction effect of abatement option a
C_a^{AI}	The installation cost of introducing abatement option a
C_a^{AO}	The operation cost per period of introducing abatement option a
E_t^{TOT}	The Total allowed emission for time period t
F_v	Energy consumption in MWh for vessel v per period
C_t^{GP}	Fuel only green premium in for time period t
D_t^{TOT}	Total demand in time period t
Q_v	Total transportation capacity for vessel v per time period
Q_a^{ADD}	Added or removed cargo capacity for abatement option a
P_a	Cost penalty for trying to newbuild an existing vessel (technical), zero for the other abatement options
C_t^{CT}	Carbon tax level in time period t
Variables	
x_{vat}	1 if abatement option a is being installed on vessel v in time period t, 0 otherwise
y_{vat}	1 if abatement option a is already installed on vessel v in time period t, 0 otherwise
z_{vt}	1 if vessel v is active in time period t, 0 otherwise.

$$\begin{aligned}\min \sum_{v\in V}\sum_{a\in A}\sum_{t\in T}(C_a^{AI}x_{vat}+C_a^{AO}y_{vat})+\sum_{v\in V^{EX}}\sum_{a\in A}\sum_{t\in T}P_a y_{vat}\\ +\sum_{t\in T}C_t^{CT}(\sum_{v\in V}E_v^V z_{vt}-\sum_{v\in V}\sum_{a\in A}\gamma_a E_v^V y_{vat})+\sum_{v\in V}\sum_{a\in A^{GP}}\sum_{t\in T}F_v C_t^{GP}y_{vat}\end{aligned} \tag{4.23}$$

Subject to:

$$\sum_{v\in V}(E_v^V z_{vt}-\sum_{a\in A}\gamma_a E_v^V y_{vat})\leq E_t^{TOT}, \qquad t\in T \tag{4.24}$$

$$\sum_{v\in V}Q_v z_{vt}+\sum_{v\in V/\{V^{EX}\}}\sum_{a\in A}Q_a^{ADD}Q_v y_{vat}\geq D_t^{TOT}, \qquad t\in T \tag{4.25}$$

$$\sum_{a\in A}\sum_{t\in T}x_{vat}\leq 1, \qquad v\in V \tag{4.26}$$

$$M\sum_{t\in T}x_{vat}\geq\sum_{t\in T}y_{vat}, \qquad v\in V, a\in A \tag{4.27}$$

$$y_{va(t+1)}\geq x_{vat}, \qquad v\in V, a\in A, t\in T/\{N^f\} \tag{4.28}$$

$$y_{vat}\geq y_{va(t-1)}, \qquad v\in V, a\in A, t\in T/\{N^f\} \tag{4.29}$$

$$y_{va(t+1)}-y_{vat}=x_{vat}, \qquad v\in V, a\in A, t\in T/\{N^l\} \tag{4.30}$$

$$z_{vt}\geq y_{vat}, \qquad v\in V, a\in A, t\in T \tag{4.31}$$

$$z_{vt}+y_{vat}\leq(1-x_{vat})M \qquad v\in V, a\in A, t\in T \tag{4.32}$$

$$x_{vat}=0, \qquad v\in V, a\in A, t=N^l,N^f \tag{4.33}$$

$$y_{vat}\in\{0,1\} \qquad v\in V, a\in A, t\in T \tag{4.34}$$

$$x_{vat}\in\{0,1\}, \qquad v\in V, a\in A, t\in T \tag{4.35}$$

$$z_{vt}\in\{0,1\}, \qquad v\in V, t\in T \tag{4.36}$$

Chapter 5

Computational Study

Software and computer specification
The integer linear program (ILP) was solved to optimality using FICO Xpress v8.14.2 optimization engine. The problem was implemented in a jupyter notebook using Python as the programming language. After implementation, the program was executed on a computer running Windows 10 Home operating system using a AMD Ryzen 5 2500U Quad core CPU @2GHz and 8GB RAM. Peak heap usage was 1345KB.

The original problem has 2678 rows and, 1232 columns, 8626 elements and 1232 globals. Solved by a branch and bound (B&B) algorithm using root cutting, iteratively solving the LP relaxation and separating cuts for the current problem. In between, primal heuristics (local search) are run to find feasible solutions to the original ILP.

5.1 Case and dataset

In this computational study, we consider a hypothetical case illustrated in figure 5.1, where the transportation of 15 million tons of cargo from port A to port B is required for ten consecutive periods. Our reference ship is a 200,000 Deadweight tonnage (DWT) bulk carrier, and we assume that it takes 30 days to complete one round trip. In a single period, the vessel is capable of discharging ten cargoes, equating to a total transportation capacity of two million tons. Additionally, the vessel is powered by fossil fuel engines utilizing Very Low Sulphur Fuel Oil (VLSFO) as its fuel source. We assume that the vessel's fuel consumption is 40 tons per day, leading to a total fuel consumption of 12,000 tons (approx 120 GWh) per period. Using a carbon factor of 3.17 (SSB 2023), the total emission amounts to 38,040 tons per period. For the sake of simplicity, we have rounded it up to 40,000 tons as presented in table 5.1.

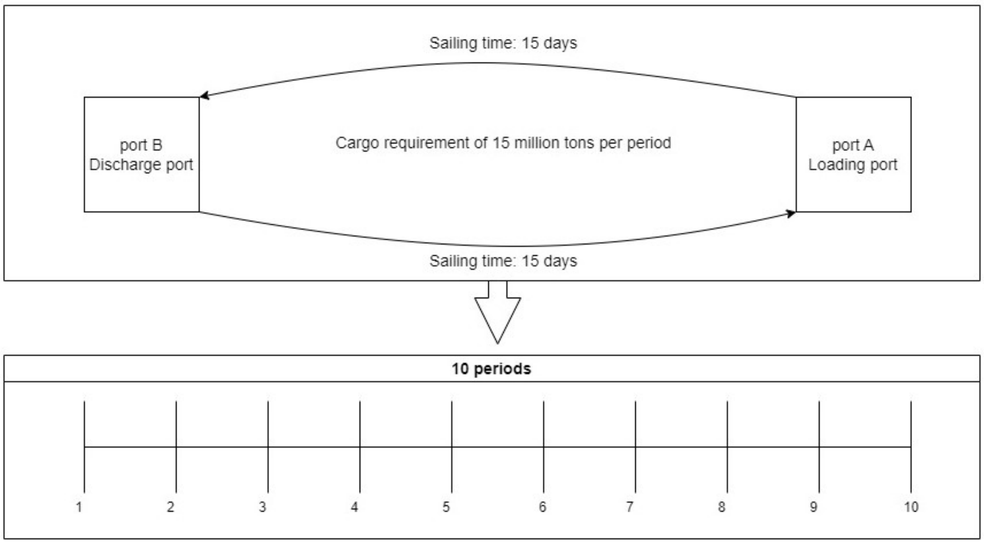

Figure 5.1: Case illustration

The reference ship forms the pool of available vessels, where ten identical vessels are presented in table 5.1. Since the cargo transportation requirement is set to 15 million tons per period, we ensure that we have excessive capacity available in the pool of available vessels. By having ten vessels, we have a transportation potential of 20 million tons each period which is sufficient to not restrict the model. In addition to the pool of available vessels, we have defined three different newbuild options with a cargo transportation capacity of two, two point five, and three million tons per period. We only consider green newbuilds in this problem, thus the total emissions are set to zero.

Vessel	Emission E_v [kTon]	Transportation capacity Q_v [mTon]	Energy usage F_v [GWh]
Existing Vessel 1	40	2	120
Existing Vessel 2	40	2	120
Existing Vessel 3	40	2	120
Existing Vessel 4	40	2	120
Existing Vessel 5	40	2	120
..	..	..	..
Existing Vessel 10	40	2	120
Newbuild 1	0	2	120
Newbuild 2	0	2.5	156
Newbuild 3	0	3	190

Table 5.1: Vessel dataset. All values are per period.

Abatement options

To reduce the total emissions from the fleet, the model can choose from a set of abatement options. There are several measures available to reduce emissions, and they can range from measures such as air lubrication to ordering a newbuild powered by zero emission fuel sources. To avoid focusing on specific measures rather than the big picture in this study, we have decided to group the abatement options into three tiers as presented in table 5.2.

Grouping	Explanation
A1	Includes measures with a 30% reduction factor.
A2	Includes measures with a 50% reduction factor.
A3	Includes measures with a 100% reduction factor.

Table 5.2: Abatement option grouping

The highest tier, A3, signifies the acquisition of a new vessel running on alternative fuel sources, resulting in a 100% reduction factor. The second tier, A2, encompasses measures such as retrofitting a vessel with dual-fuel engines. The lowest tier, A1, can be installation of air lubrication or wind assistant propulsion to mention a couple of examples. In practical terms, the lower tier represents measures reducing fuel consumption, while A2 signifies partial change of fuel source and A3 a complete change of fuel source.

For each abatement option there is an associated investment- and operational cost. We have defined a cost metric for this computational study expressed in a unit cost. Abatement option 3 has the highest reduction potential, thus the highest investment cost with a unit cost of 100. Furthermore, abatement option 1 and 2 are scaled relative to abatement option 3 in table 5.3.

For the operational costs, we are only interested in the differential cost in comparison to our reference fleet. Consequently, all operational cost values presented reflect either a reduction or increase relative to the reference vessel. Abatement option 1 is assumed to reduce the operational cost as a result of reduction in fuel consumption. Furthermore, abatement option 2 and 3 is assumed to increase the operational cost due to additional maintenance of new systems.

Abatement Option	Reduction Factor	Investment Cost, C_a^{AI}	Operational Cost, C_a^{AO}
A1	0.3	30	-2
A2	0.5	50	0.5
A3	1.0	100	1

Table 5.3: Abatement option dataset

Variable input

The last dataset is time dependent and subject to different scenarios. The variable parameters are (1) emission requirement strategy, (2) carbon tax and lastly (3) fuel only green premiums.

We have chosen to look at three step-wise emission reduction strategies. The first being a standard linear approach meaning that each consecutive period sees a constant reduction in allowed emissions for the fleet. For the second strategy which we have called the reactive or compliance approach centers around a convex development that have smaller decreases the first periods, but rapidly decreases for the second half of the planning horizon. This strategy aims to reflect a shipowner interested in waiting for technological progress or/and the availability and price of alternative fuels to become known. The last and third strategy revolves around an aggressive or proactive approach to decarbonization. In this approach, the emission reduction curve takes a concave form, resulting in taking larger investments early on reflecting an 'early mover' in decarbonization. The three strategies are visualized in figure 5.2.

The starting value for all strategies is set to 320,000 tons CO_2, which equates to the emissions of eight vessels. Eight vessels have an accumulated cargo transportation capacity of 16 million tons per period, which is sufficient to meet the requirement of 15 million tons. The allowed emission in the last period is set to 95,000 tons, which allows two vessels to operate without undergoing any emission reduction measures. The reason for not setting a hard constraint on zero emissions in the last period is to keep the solution space open for smaller abatement options.

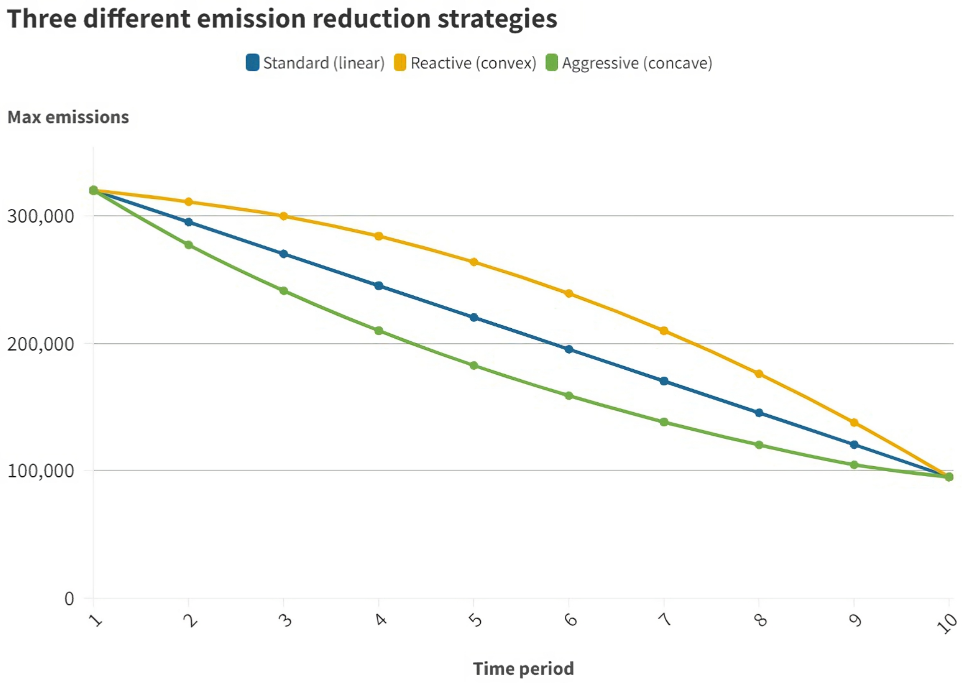

Figure 5.2: Emission reduction strategies

The carbon tax is also divided into three categories, represented by a low, medium, and high growth rate on the development in carbon taxes. At the time of writing EU carbon permits trade for 98.20 Euros per ton equal to 107 USD per ton on the European carbon market (CarbonCredits 2023). Combusting one ton of VLSFO releases 3.17 tons of CO_2 (SSB 2023), resulting in the shipper having to buy carbon permits for a total of 339 USD to combust that one ton of fuel. This is approximately 58% of the 580 USD per ton VLSFO in Rotterdam at the time of writing. In that market, carbon taxes effectively add around 50% to the fuel related expenses on a vessel if they were to be covered by carbon taxes. With this rough estimate in mind, we construct three main scenarios; a low, medium and high carbon tax growth rate or gradient (figure 5.3). When carrying out the actual analysis, several intermediate growth rates are also included to capture effects taking place in between the three discrete growth rates displayed in figure 5.3.

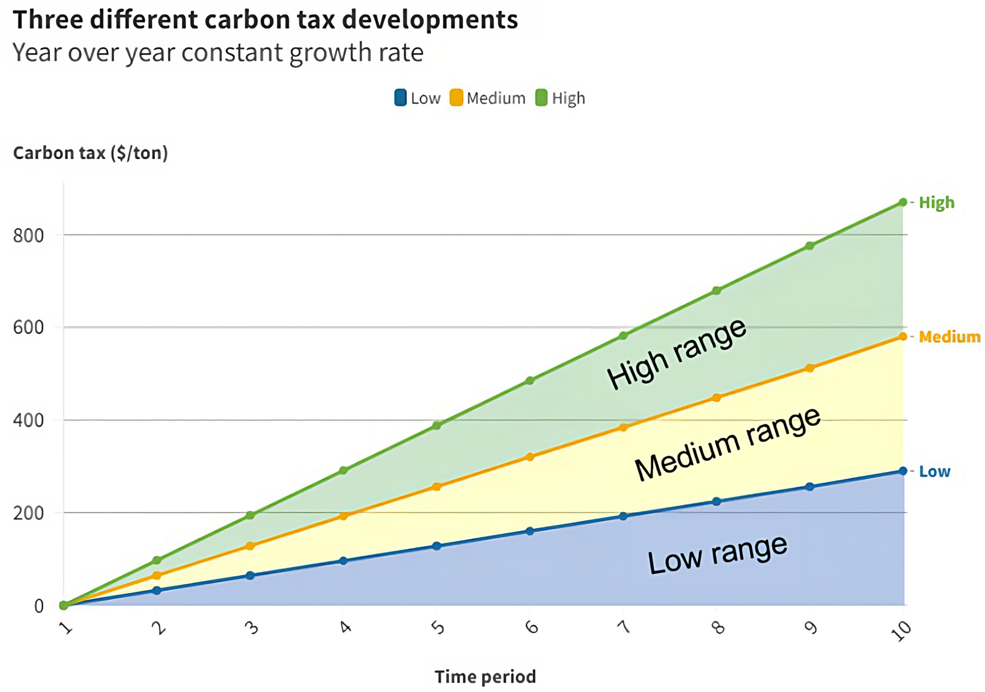

Figure 5.3: Three different carbon tax growth rate scenarios

The green premium follows the same category system based on low, medium, and high growth rates, outlined in figure 5.4. We assume that all scenarios start with a fuel only green premium of 100% of the VLSFO cost. Note that the high range indicates a negative green premium towards the end of the planning horizon, signifying that the cost of alternative fuels is lower than that of fossil fuels for the last time periods.

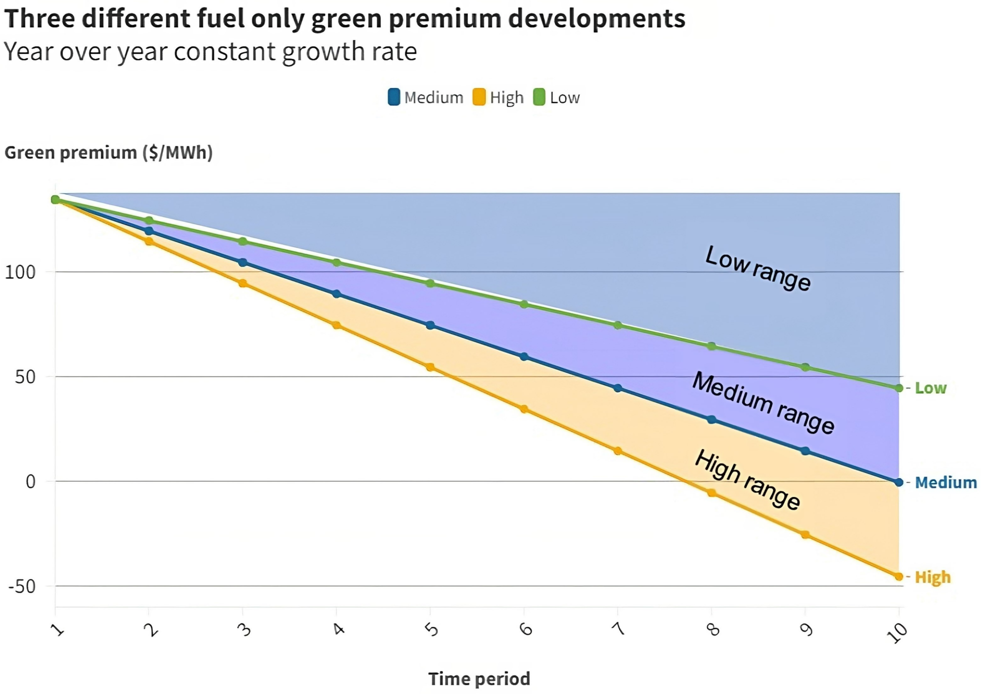

Figure 5.4: Three fuel only green premium scenarios

5.1.1 Testing approach

To effectively assess the impact of each variable, our study is structured into three stages. Initially, we focus on examining various emission requirement strategies. To ensure that our analysis remains centered on emission requirement strategies, we are using insignificant levels for both the carbon tax and green premium.

Subsequently, we introduce the various scenarios of carbon tax outlined in figure 5.3 for each emission curve, while the green premium is kept constant and insignificant. Finally, we introduce various scenarios of green premium with the aim of analyzing green premium effects. The key performance indicators (KPI) between the analyses will be (1) total cost of ownership (TCO) and (2) ton reduction per TCO and finally (3) the total emissions reduction compared to the business as usual case over the planning horizon. In addition, the fleet composition in combination with strategic differences on abatement option selection will be highlighted.

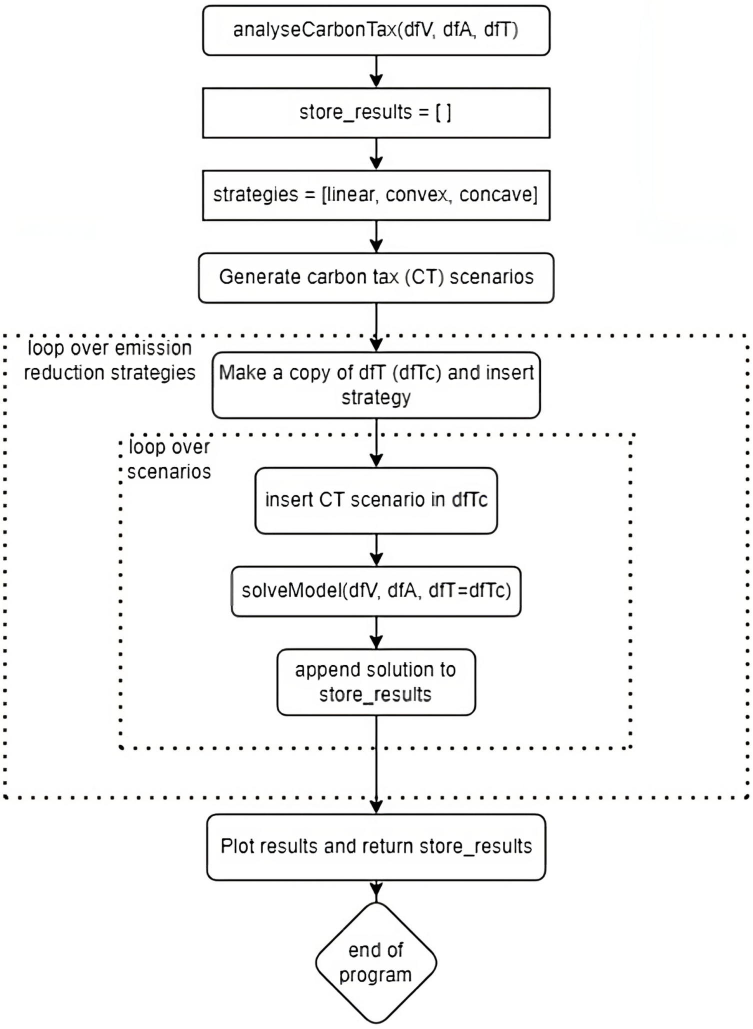

Figure 5.5: Program description for analysing carbon taxes. The green premium (GP) analysis is done in a similar way only by generating GP scenarios instead of CT scenarios.

5.1.2 Decarbonization strategies

In this analysis both green premiums and carbon tax levels are sufficiently low in a way that makes the emission restriction binding and is driving the decarbonization of the fleet. We will use the model to investigate and try to answer the following questions:

1. **How does different decarbonization paths or strategies influence the types of abatement options applied?**
2. **How is the total cost and timing of investments affected by different strategies?**
3. **Does there exist a preferred strategy?**

The reactive strategy exhibits the smallest decrease between consecutive periods during the first three to four time periods, indicating that vessel owners could continue running their fleet with minimal emission reduction efforts. Moreover, the reactive strategy has the largest area under its curve, indicating that this strategy demands the over all lowest accumulated emission reduction.

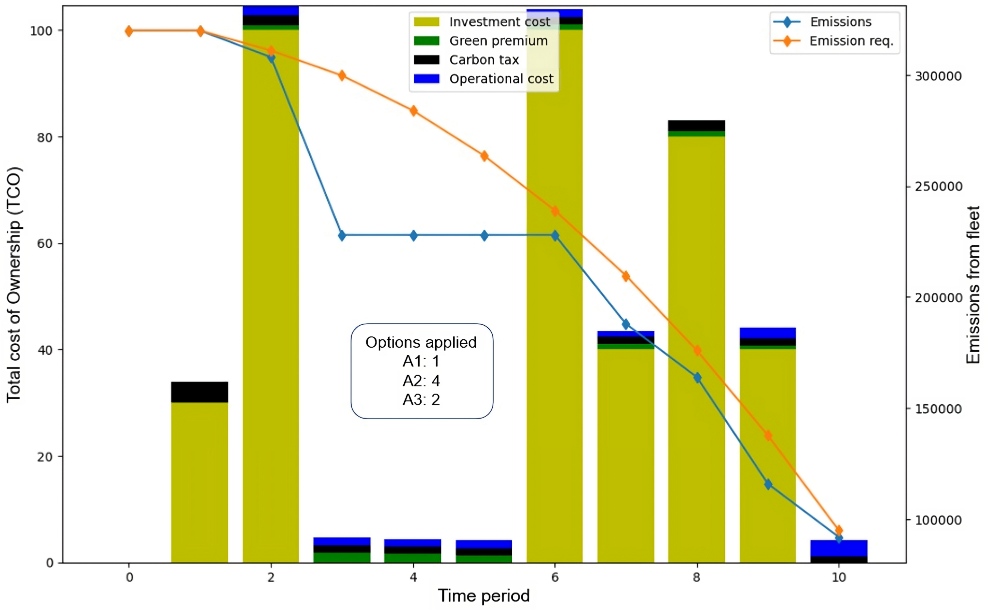

Figure 5.6: Reactive strategy (convex)

Compared to the figure 5.7 and 5.8 we notice that all solutions include the installation of two abatement option 3 (A3). However, in the reactive (figure 5.6) case, we see that these investments are realised at a later time compared to the standard (5.7) and aggressive (5.8) approach. This is in general a positive attribute when considering the time value of money and technological progress. Keep in mind that delaying the retrofit and/or renewal decision will have negative effects in the case of high carbon tax levels. In addition, all three solutions include proposals of installing one of A1 and two of A2. In summary the content of each solution, being what type and how many of each abatement option to decide upon is the same in the three different strategies, but the timing and performance is different. The aggressive approach is under these conditions the best performer when considering the total emission reduction over the planning horizon seen in table 5.4. The actual accumulated reduction is higher, but also closer to the required amount compared to the two former cases. The aggressive approach take the investments the earliest, hence benefiting from these early reductions for the rest of the planning period.

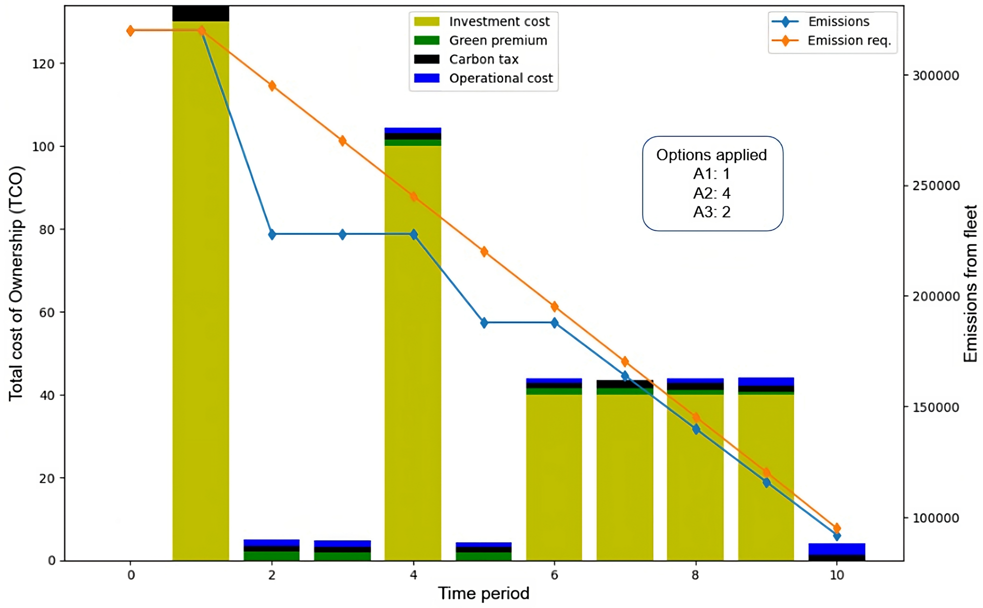

Figure 5.7: Standard strategy (linear)

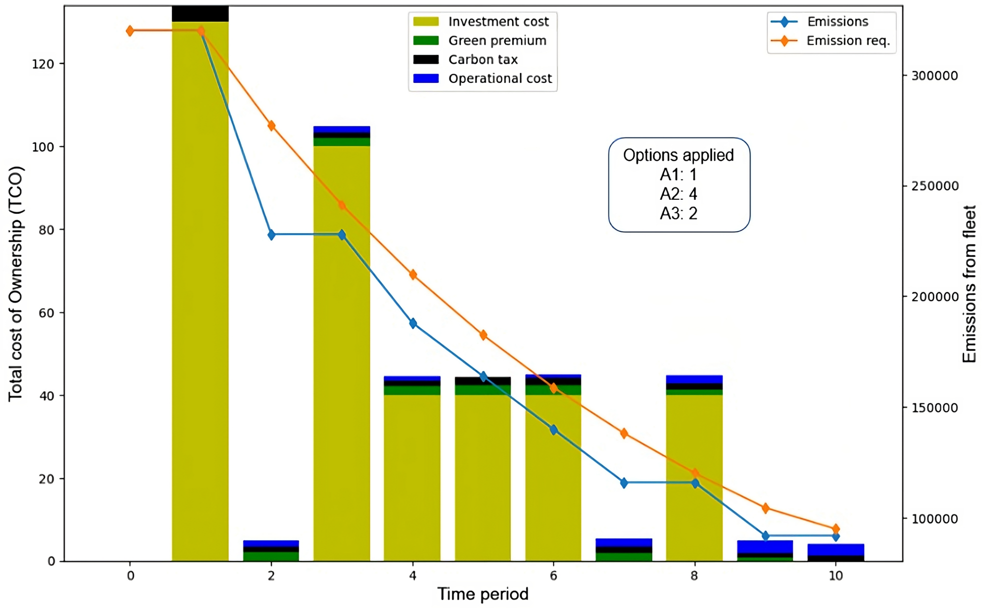

Figure 5.8: Aggressive/proactive strategy (concave)

To conclude on what effect the step wise emission reduction strategy has under the same conditions, we have to apply our key performance indicators; the total emission reduction divided by TCO and TCO by itself.

Strategy	Tons emission reduced	TCO	Reduction per TCO
Standard (5.7)	1,307,994	425	3077
Reactive (5.6)	1,100,000	422	2606
Aggressive (5.8)	1,516,000	433	3501

Table 5.4: KPIs for the different function forms.

To conclude the questions initiated at the beginning of the section:

1. **How does different decarbonization paths or strategies influence the types of abatement option applied?**
   All strategies include the exact same type and quantity of abatement options. This was expected as all strategies end at the same value for allowed emissions. Meaning that this combination of options ensures that the fleet is compliant in the last period with minimal investment cost.

2. **How is the total cost and timing of investments affected by different strategies?**
   As seen in table 5.4, The reactive strategy is the over all cheapest, while the aggressive is the most expensive (2% difference over the entire planning horizon). This difference is in other words negligible. This is to be expected as time value of money is not included. Timing of investments are pushed forward in time with increasingly aggressive strategies and are to be expected.

3. **Does there exist a preferred strategy?**
   Picking one strategy as the superior is not easy as stakeholders value different attributes differently. From a global warming perspective, the aggressive form makes the most sense because it removes emissions early netting the highsest total reduction. From a shipowners perspective, he or she might value to wait for green premiums to come down or for technological progress in general before committing to a certain strategy and technology selection through the available abatement options at the time. Hence, a reactive approach could be the best choice as it is marginally cheaper and the investments are further in the future when compared to the other two. The linear function fits somewhere in between the reactive and aggressive strategy and might be the preferred choice of a mediator trying to meet each stakeholder interest.

5.1.3 Carbon tax

This section will seek to investigate and answer three main questions regarding the introduction of carbon taxes.

1. **At what price level or growth rate does carbon tax become the sole**

driver of decarbonization?

2. **How is the fleet investments and renewal strategy affected by the introduction of carbon tax? Especially focusing on the types of abatement options chosen under varying carbon price levels.**
3. **Does there exist a preferred emission reduction strategy for a future carbon tax scenario?**

Our hypothesis is that when carbon tax or price levels surpass green premiums, we will see a significant increase in fuel dependant green retrofits (A2) and newbuilds (A3) being chosen compared non-green fuel dependant options covered in A1. Further, we expect that after carbon taxes reach a certain level, the required emission curves become non-binding for the solution as the cost now becomes the main driver.

In figure 5.9 both key performance indicators are plotted for different carbon tax scenarios. The smooth curves which are strictly increasing is the objective values (TCO) obtained for all scenarios while the jagged curves is the ton reduction per unit cost indicator.

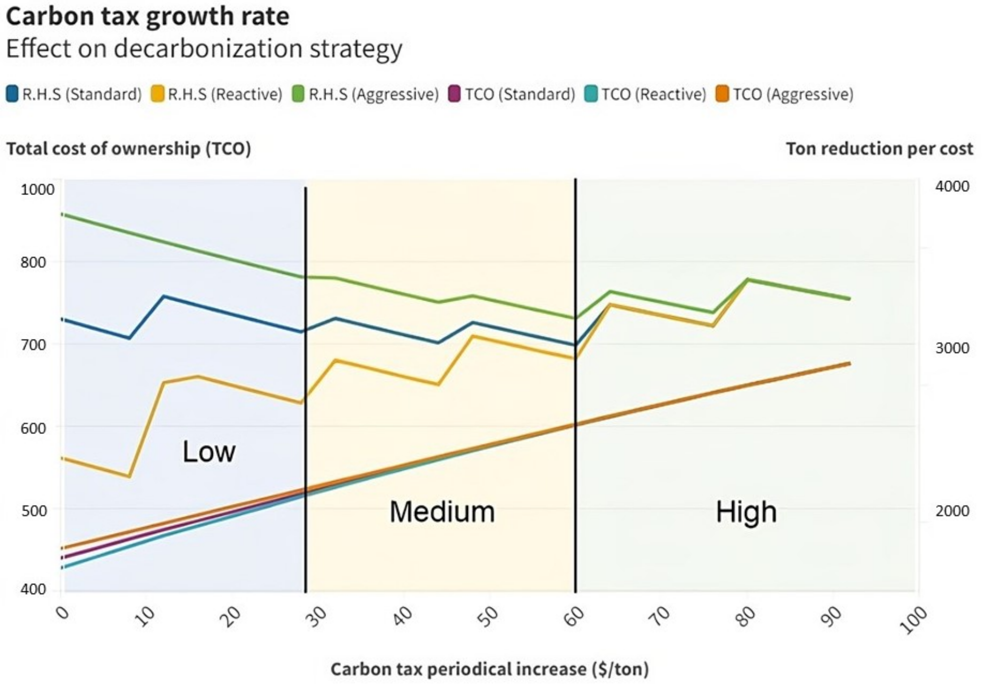

Figure 5.9: Key performance indicators for different carbon tax scenarios

First we notice that the cost is strictly increasing for an increase in carbon tax growth (CT). The reason for this relationship is that for our defined CT range, the total carbon tax cost does not exceed the investment and aggregated operational costs of installing an abatement option. Common for the linear, convex and concave reduction form is that they develop in a step-wise manner. These steps describe the logic that increasing carbon prices move emission reduction investments earlier in time to mitigate carbon tax bills. Each 'jump' represents that one or more investments have been moved to an earlier time period compared to the former solutions. An important effect of investments being done earlier is that the accumulated emissions saved over the entire planning horizon increases quite a lot. With an incremental increase in total cost, mainly from an increase in operational costs, the larger total reduction is achieved by moving investments forward yields a greater ton reduction per unit cost which is plotted in figure 5.9 for the different decarbonization strategies.

Lets have a look at the aggressive strategy which is the green line. As explained in section 5.1.2 this strategy implies big and early investments to comply with the aggressive strategy. Hence, when increasing carbon tax gradients from zero up to the low and medium range, it only becomes more expensive for the shipowner to finance the carbon tax responsible by the remaining vessels not undergone any reduction measure. This leads to a worsened performance, here showed as the total reduction per unit cost. In other words, the total emission savings stay the same while cost increases resulting in the development seen. For the standard and reactive strategy, the story is quite different. In the low and medium carbon tax regime, stricter carbon price policy moves emission reducing measures forward in time and getting a relative large increase in savings compared to the additional cost that comes with higher carbon tax bills. If we continue to use the total reduction divided by cost as our performance indicator, the reactive strategy benefits from higher carbon price levels, as each local peak is greater than the former. As before, the standard strategy has attributes from both the reactive and aggressive strategies. Decreasing in general with larger jumps like in the aggressive and reactive, respectively. The reason for this behavior is founded in the same arguments that moving investments forward accumulates larger emission reductions.

If we look at the high carbon tax scenario, we notice that both the cost and accumulated reduction per cost converge respectively. The reason for this is that the cost of emitting has become the main driver in the decarbonization of the fleet. For all three strategies, all investments are done in the first period, effectively returning the same exact solution independent of strategy. If we were to continue increasing the carbon tax gradients beyond the high regime, we would start to see that additional vessels beyond what is required in the last time period would be retrofitted and/or replaced by green alternatives only because the investment is cheaper than running them on fossil fuels and paying carbon tax.

To conclude and summarize the carbon tax effect, we will answer the questions introduced at the beginning of this section:

1. **At what price level does carbon tax become the sole driver of decarbonization?**
   In the high growth rate carbon tax scenarios, taxes are the main driver of investments and can be seen by the converging KPIs yielding predetermined strategies non-binding. This result could be debated because the green premium level dictates the exact point where we observe this transition. Higher green premiums moves the breaking point to a higher effective VLSFO price and vice versa.

2. **How is the fleet investments and renewal strategy affected by the introduction of carbon tax? Especially focusing on the types of abatement options chosen under varying carbon price levels.**
   As expected we see a trend in applying more abatement options that have large reduction potentials including fuel conversion (A2 and A3) and less of the smaller options (A1) when taxes increase. Investments are also moved to an earlier time period to mitigate carbon tax bills for increasing tax pressure.

3. **Does there exist a preferred emission reduction strategy for a future carbon price scenario?**
   From figure 5.9 and seen from a global warming perspective, the aggressive strategy outperforms the other two for all carbon tax growth regimes although it is the most expensive solution. Although the reactive strategy could be beneficial for alternative fuel infrastructure developers as they have more time to develop a supply chain.

5.1.4 Fuel only green premium

Green premiums effect the solution in a similar way to carbon taxes but have a opposite development. Meaning that projections show that alternative green fuels will become cheaper and cheaper as the technology and renewable energy becomes cheaper. In this study we experiment with different green premiums ranging from being 2 times more expensive than fossil fuels through being cheaper than fossil fuels (negative green premiums).

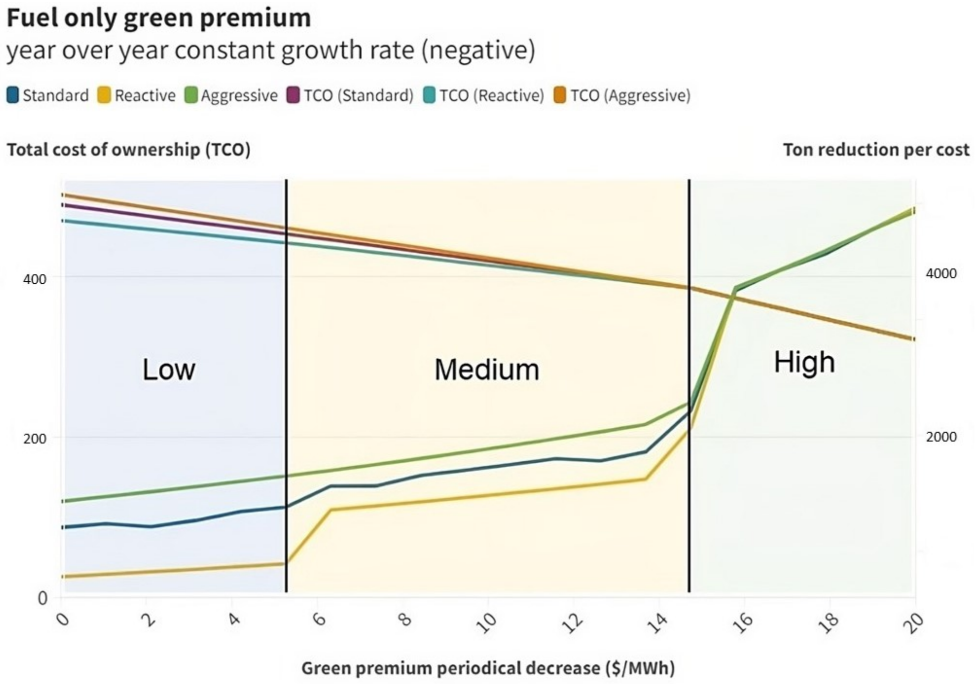

Figure 5.10: How green premiums effect the key performance indicators

In the high green premium growth scenario, the solution provided by the model is unaffected by the emission reduction strategy. Because vessels can save money by converting to a renewable fuel source, the conversion is applied as soon as possible resulting in the highest ton reduction per unit cost so far. A key difference between how carbon tax and green premium levels effect the solutions is that green premiums can become negative while carbon taxes in practise can not. As we saw in our carbon tax analysis, the model does not want to convert all vessels and always left some vessels as is due to the last period emission requirement allowed for some emissions and a fuel conversion would be more costly. In the case with negative green premiums this is not true because it now can become cheaper to run on green fuels, which leads to the model suggesting a increase in fuel conversion abatement options (A2 and A3) instead of a energy reducing option (A1) which is still dependant on fossil fuels. For the medium growth range this is no longer the case and a large drop in ton reduction per unit cost can be observed in figure 5.10. Otherwise, the behaviour of the model is as expected. For increasing green premium gradients the total cost decreases and more abatement options including a fuel conversion are suggested while the popularity of energy reducing measures is decreased.

5.2 Discussion

A computational study has been performed to gain a deeper understanding of the system being modeled and the robustness of the model. From this research we have deducted some key operational theories that we will summarize.

1. When examining different decarbonization strategies where all pathways end at the same allowed emission quantity, the pathway is irrelevant for the type and amount of abatement measures selected. The only distinction is the timing of these investments. When a predetermined end goal for emission reductions is set, there will always be an optimal combination of abatement options that can be analytically determined by selecting the combination of options that gets the fleet closest to the predetermined goal. This optimal combination will yield the lowest cost and can be identified in the first time period. It is assumed that more investment is required for measures that reduce emissions more. To justify changing the current selection of abatement options, the cost of a higher impact option must become cheaper in absolute money terms to replace the lower tier option. This is because it is not logical to invest more to reduce emissions beyond what is required by the strategy when the incentives provided by carbon tax and green premium is absent. The model is then very robust to abatement option price fluctuations, but less robust when considering the actual emission reduction potential of the options, as the required reductions are hard constraints and must be met. This is under the assumptions of insignificant carbon tax and green premiums.

2. The introduction of sufficiently high carbon tax and low green premium on the extreme side will override the step-wise reduction strategy as economic considerations take precedence, rendering it non-binding. In such a scenario, these market-based instruments will emerge as the primary drivers of decarbonization. Our analysis reveals that this occurs when the cost of

carbon tax surpasses the green premium. Contradictory to extreme levels of carbon tax and green premium, the model displays a high sensitivity to incremental changes in the outlooks for these subjects, especially in the medium range. We observe that there exists frequent discrete points where the solution changes structure both in timing of investments and the combination of measures applied for incremental changes. Contradictory to the conclusion in point 1 where the model always will try to get as close as possible to the predetermined goal, outperforming the strategy may become the cheaper alternative. Typical solutions in this range consist of following the strategy for some time, but then at a point abandon the strategy and reduce emissions even more than strictly required. In the presence of carbon tax and green premium, we loose a bit of robustness which is shown in section 5.1.3 figure 5.9.

The computational study has given us an understanding of the strengths, weaknesses and abilities of the model. This information has given valuable insight as we are about to apply the model to a real case. We are then able to provide a robust solutions and avoiding abnormalities. Furthermore, it is important to understand the models ability and what it can do and what it can not do. The model performs well on timing of investments to minimize green premium and carbon tax expenses, meanwhile the actual selection of abatement options carries some more uncertainty as it is very sensitive to each periods emission target. In the worst case the model is restricted in choosing a lower impact measure if the emissions exceeds the target by only one ton. Hence, having to go for the high impact more expensive alternative that reduced the emissions a lot more than required. In a real case this would of course not be a problem if the owner can save substantial money on allowing it and still be very close to the set strategy.

Chapter 6

Case study

In this chapter we are going to apply our model on a realistic green corridor case. Moreover, the iron trade between Australia and Japan will serve as our case, where the aim is to provide insightful strategic decision support mainly on what to invest in and when to do so. The chapter is structured into four main steps as illustrated in figure 6.1.

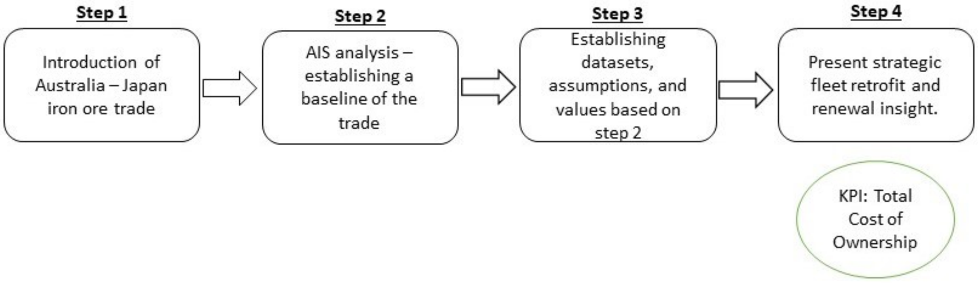

Figure 6.1: Structure of case study

6.1 Australia - Japan iron ore trade

The Australia – Japan iron ore trade has a great potential to be a first-mover green corridor. The trade involves the Pilbara ports (Port Hedland, Dampier, Cape Lambert) in Australia and three ports in Japan (Fukuyama, Kisarazu, Kashima) where iron ore is loaded in Australia and shipped to Japan. Furthermore, the three mining companies Rio Tinto, BHP, and Fortescue Metals Group (FMG) supplies the trade with iron ore, while Japanese steel mills are the consumer (GMF 2021b).

Australia and Japan enjoy a stable and well-developed trading relationship, and many stakeholders are committed to achieving net-zero targets for the entire value chain. Rio Tinto and BHP have committed to net-zero targets by 2050, including all shipping-related emissions (BHP 2022, RioTinto 2022), while FMG has committed to net-zero for all scope 3 emissions by 2040 (FMG 2021). Additionally, Japanese steel makers are exploring possibilities for decarbonizing their production at a faster rate than the 2050 requirements (GMF 2021b).

There are favorable conditions, and significant planned capacity for zero-emission fuel production in the region. Australia has taken initial steps towards positioning itself in the hydrogen industry by launching initiatives such as the Hydrogen Energy Supply Chain project and investing in research, development, and trial projects aimed at hydrogen development. Currently, there are 103 hydrogen projects underway in Australia, with a projected electrolyser capacity of 30 GW by 2030 (CleanEnergyCouncil 2021).

As of April 2022, BHP, Rio Tinto, Oldendorff Carriers and Star Bulk Carriers signed a Letter of Intent (LOI) to assess the development of a green corridor between Australia and Japan. Additionally, both Australia and Japan signed the Clydebank declaration for green shipping corridors following the COP26 conference in 2021 (Oldendorff 2022). In figure 6.2 an overview of the stakeholders directly involved is presented.

Figure 6.2: Stakeholders overview for green corridor initiative

6.1.1 Establishing a corridor baseline by AIS-analysis

In order to establish a corridor baseline and map the trade characteristics we have conducted an AIS analysis of the trade with the aim of answering the following questions:

1. **What is the decarbonization potential?**

2. **Current fleet size and mix - what is the vessel distribution and the op-**

erating pattern like?

We acquired AIS data from 2018 containing information about vessel activity for the area between 27.75N-35.9N and 116.7E-140.7E. The area covers the ports of interest, with a dataset containing 9 columns and over 150 million rows.

To begin, we develop a filtering algorithm to isolate the fleet trading iron ore between Australia and Japan from other traffic. This is done by web scraping *vesselfinder.com* and extracting vessel information from MMSI numbers provided in the AIS data. All bulk carriers above 180,000 DWT are selected and geofencing is applied to isolate all bulk carriers that have visited relevant ports in both Australia and Japan within a reasonable voyage time at least once. This is a high level description of the filtering process, a more detailed data flow is presented in Figure 6.3.

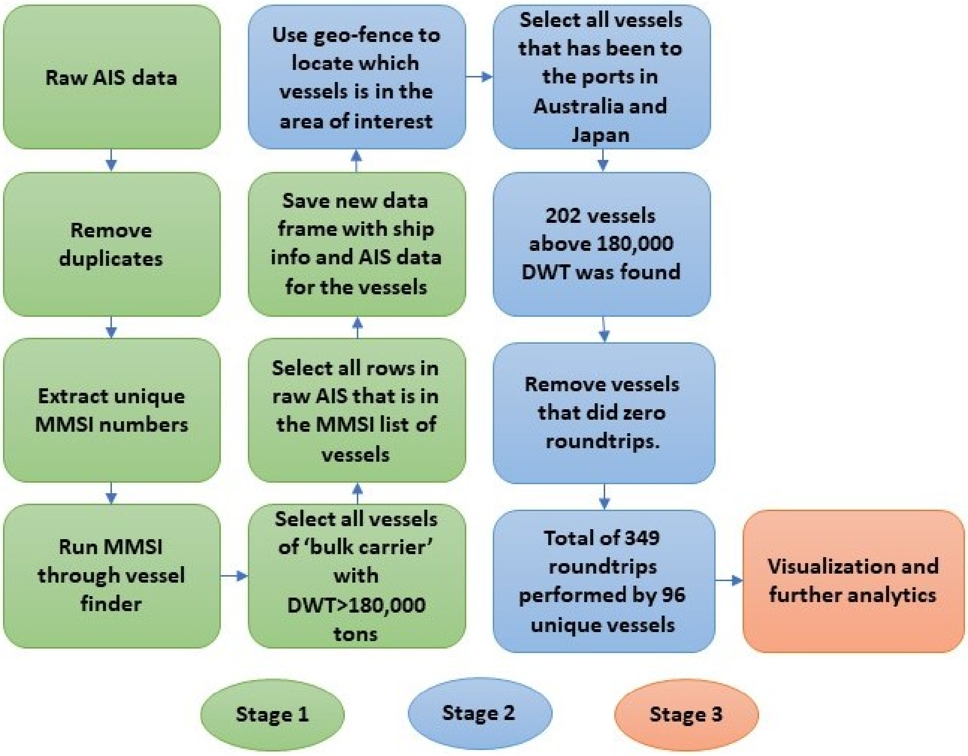

Figure 6.3: AIS data filtering algorithm

Our AIS analysis found that 96 unique bulk carriers performed a cumulative total of 349 round trips, transporting about 69 million tons of iron ore in 2018. Each ship performed on average 4.5 round trips where two ships made 10 round trips which was the maximum round trips completed by a single vessel on the trade. Furthermore, the emissions from the entire fleet in 2018 aggregated to approximately 1.77 million tons CO_2.

Global Maritime Forum (GMF) conducted a similar study with 2019 data, where the result is presented in table 6.1 (GMF 2021b).

Parameter	GMF result (2019 data)	Our analysis (2018 data)
Iron ore transported [mTon]	65	69
Unique vessels involved	111	96
Total emissions [mTon]	1.7	1.77

Table 6.1: AIS analysis benchmarked with Global Maritime Forum findings

Not surprisingly there are some differences in our findings, which most likely is due to different datasets. Nevertheless, we continue this study with our findings from this analysis.

Current fleet size and mix

In figure 6.4 an overview of the vessel distribution by age is presented. There is a considerable amount of lifetime left in the fleet as the average vessel approaches 10 years of age in the time of writing (2023).

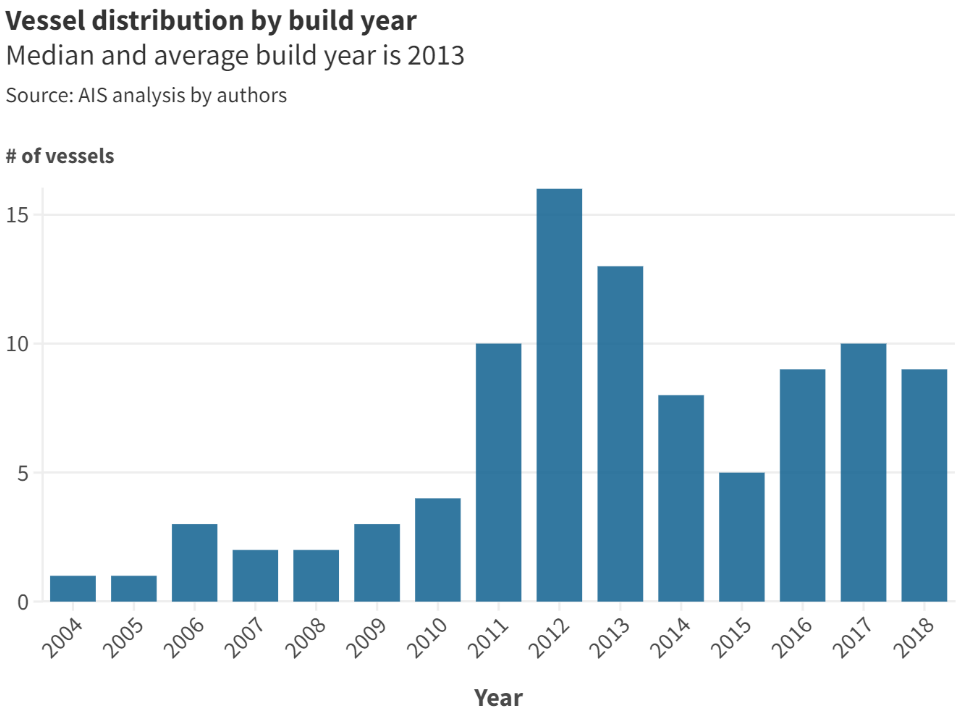

Figure 6.4: Vessel distribution by build year

Several shipowners was identified, all having different exposure to the iron ore trade. Nine shipowners had three or more of their bulk carriers operate the trade while the remaining 53 vessels is divided by shipowners having one or two vessels trading.

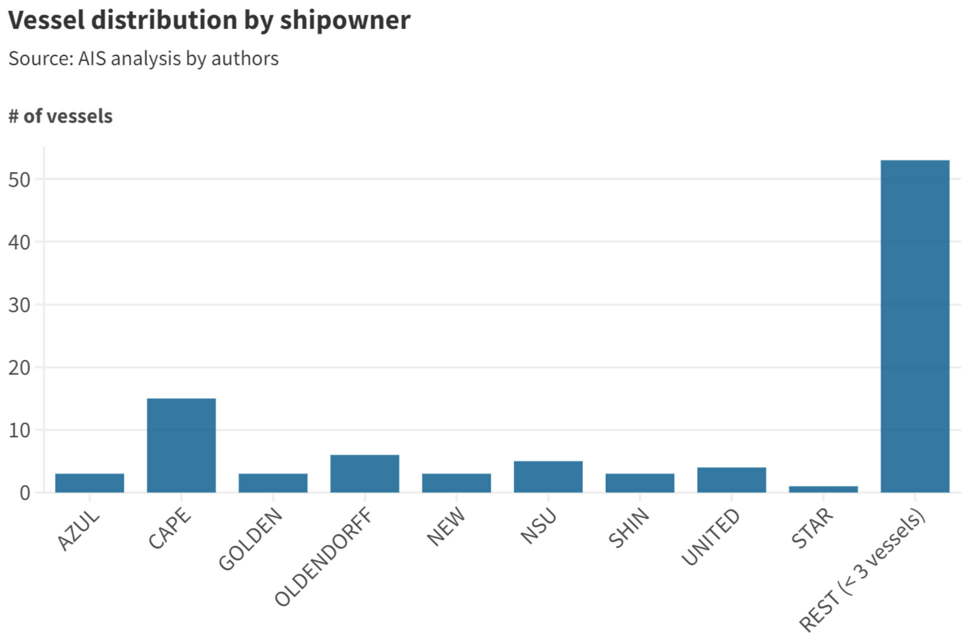

Figure 6.5: Vessel distribution by shipowner.

The dominating deadweight intervals is between 180,000 – 190,000 and 200,000-210,000 as presented in figure 6.6. Furthermore, the average size was close to 200,000 DWT. These results are as expected due to the filtering algorithm only considering vessels above 180,000 DWT.

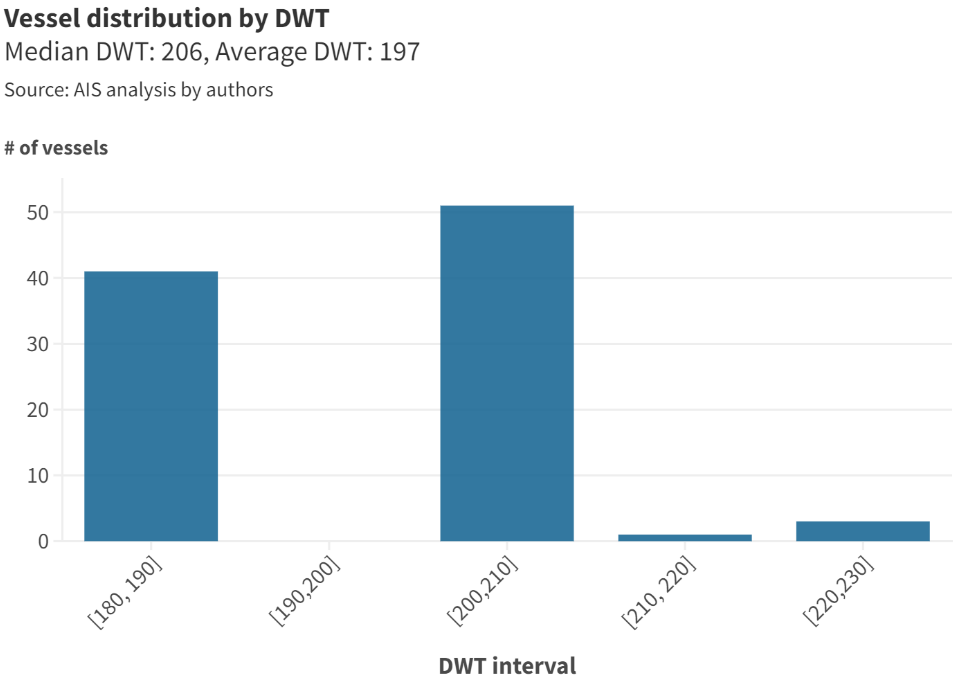

Figure 6.6: Vessel distribution by DWT [in 1000 tons].

Trade flow - an example

The Singapore flagged capesize CAPE VERDE (IMO:9670054) is a typical ship on the Australia to Japan iron ore route. She departs Port Hedland in western Australia shortly after 11 AM the 24th of January 2018 loaded with 200,000 tons of iron ore. Her destination is set to Kisarazu, Japan where she will arrive ten days later after having steamed the 3500 nautical miles at 15 (average) knots. Cape Verde waits for nautical services or for a terminal to become available for 36 hours before she berths to offload her cargo. She spends three full days offloading her cargo while the crew signs off any required documentation and prepares the vessel for departure on the 8th of February 2018 around 5 pm.

It is unknown if Cape Verde loads any cargo for the return trip to Australia. The return trip either in ballast or loaded with cargo for Australia takes 10 days and she arrives outside port Hedland on the 18th of February and waits for 15 hours before berthing and starting the loading of a new load iron ore. The loading is completed in 24 hours as the loading rate (12,000 tons/hour) is much greater than the unloading operation in Japan. Cape Verde then leaves Australia, thus completing a round trip in 27 days (rounded up). In 2018, Cape Verde performed 7 of these round trips transporting 1.4 million tons of iron ore (2.1% of the annual transport demand of iron ore between Australia and Japan).

Figure 6.7: AIS data CAPE VERDE 2018.

Summary of AIS analysis

to conclude and summarize our findings, we will answer the questions introduced at the beginning of this section.

1. **What is the decarbonization potential?**
   The decarbonization potential was found to be approximately 1.77 million tons CO_2, equivalent to 384,782 gasoline powered vehicles for one year. The results coincide with the findings of Global Maritime Forum with 2019 data.

2. **Current fleet size and mix - what is the vessel distribution and the operating pattern?**
   96 distinct vessels have been identified, with an average size of 200,000 DWT. Moreover, the average vessel age was ten years, signifying that there is substantial lifetime left and they pose as strong candidates for a potential retrofit. Additionally, nine distinct shipowners possessing three or more vessels were identified, while the remaining 53 vessels were distributed among shipowners possessing one or two vessels operating on the route. The average number of roundtrips conducted was 4.5. Based on the trade flow of CAPE VERDE using roughly 27 days on a full roundtrip, this equates average operating days of 121 days for each vessel. The results imply that the route is operated in a tramp shipping service pattern without any strict schedule or long-term contracts between stakeholders. However, it is reasonable to assume that most of the vessels are participating in other trades in southeast Asia, such as transporting iron ore from Australia to China.

6.2 Case assumptions

An illustration of the case is presented in figure 6.8. The 96 vessels identified from the AIS analysis, illustrated in black, forms the pool of available vessels. Additionally, a set of newbuild options, illustrated in white, is defined. Constraints on the fleet size and mix only arise from the emission targets and the necessity to meet demand, allowing for dynamic fluctuations in fleet size mix from year to year.

We are taking the shipowners perspective with certain assumptions. The pool of vessels can be used freely as is. Meaning that no charter- or purchase cost is included. However, in the case of retrofitting a vessel, the vessel must be bought, resulting in 100% ownership of the vessel. The same ownership goes for building a new vessel. Since the model needs to generate an initial fleet the first year to meet the demand, we have considered it unnecessary to include an extra charter- or purchase cost as it would not change the solution space within our purpose of the analysis. Moreover, including it for the abatement options provides a common basis for comparison between retrofitting a vessel or building a new one.

The three ports in both Australia and Japan are grouped to represent one loading and discharge node, respectively. Additionally, we assume unlimited availability of green ammonia in Australia. We are analyzing a fixed time horizon with a hard constraint of zero emissions by 2050.

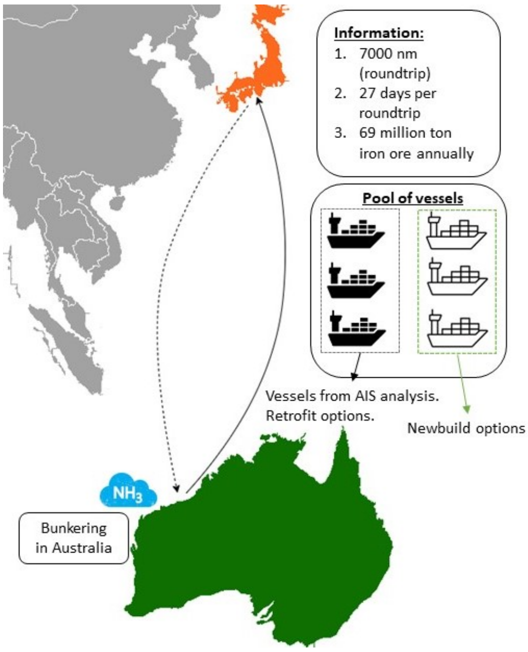

Figure 6.8: Case illustration

6.3 Dataset

In this section we will present the datasets and associated values used as input parameters in our case. Various sources and assumptions have been used but in essence the values are based on (1) estimates from Grieg Star shipping and Ammonia Energy Association, (2) futures and historical data from Bloomberg (provided by Erik Nikolai Stavseth, commercial manager Golar LNG), and (3) AIS data with python script to calculate vessel information.

6.3.1 Vessel dataset

The 96 identified vessels on the trade are now forming our pool of available vessels. Based on the trade flow of CAPE VERDE presented in section 6.1.1, we have developed a python script which pre-processes required vessel information for the 96 vessels. The following input parameters in table 6.2 is used for each vessel.

Parameter	Value (per roundtrip)
Sailing time	20 days (15 knots)
Waiting time	3 days
Port time	4 days
Distance	7000 Nm
Tot days per roundtrip	27

Table 6.2: Constant parameters for each vessel

Based on the input parameters and different deadweight values for each vessel, the script is returning the following output presented in table 6.3. The script with assumptions are attached in Appendix B.

Vessel	DWT [1000 tons]	# of Roundtrips	Prop. Power [kW]	Fuel Cons. [Ton]	CO2 [Ton]
FOMENTO THREE	210	13	16,667	1645	5214
STAR LEO	208	13	16,586	1637	5189
GOOD HORIZON	182	13	15,533	1533	4859

Table 6.3: First three vessels in dataset. Fuel consumption and CO2 emissions are per roundtrip.

Additionally, the dataset contains three different newbuild options presented in table 6.4. The maximum capacity in the ports of interest is 300,000 DWT, thus the maximum size is defined thereafter. Note that the fuel consumption is in ton ammonia, not VLSFO, hence the increase in tons consumed compared to table 6.3.

Vessel	DWT [1000 tons]	# of Roundtrips	Prop. Power [kW]	Fuel Cons. [Ton]	CO2 [Ton]
Newbuild 1	200	13	16,267	3665	0
Newbuild 2	250	13	18,187	4099	0
Newbuild 3	300	13	19,923	4489	0

Table 6.4: Newbuild options. Fuel consumption are per roundtrip.

6.3.2 Abatement option dataset

We consider two abatement option in this study. The first option involves retrofitting one of the vessels from our pool of vessels to operate on green ammonia. The second option entails building a new vessel that is powered by green ammonia. Both options effectively achieve a 100% reduction in emissions. However, the associated costs of each option differ.

Retrofit

There are several technical challenges in retrofitting a bulk carrier powered by fossil fuels to ammonia, and it can be hard to get a clear picture of all cost elements. However, we have narrowed down our analysis to four main areas of focus: retrofitting the main engine, installing a fuel supply system, setting up storage tanks, and carrying out necessary shipyard work. A recent study by Grieg Star and the Green Shipping Programme examined the feasibility of retrofitting one of their L-class vessels to run on ammonia (GriegStar 2023). According to their findings, the estimated costs for the retrofit include:

Capex elements	Million USD
Main engine	10
Fuel supply system	6
Storage tank	4
Shipyard work	2
Total retrofit cost	22

Table 6.5: Retrofit cost breakdown

They have estimated that the operational expenses will increase by 200,000 USD per year, which includes maintenance for new systems and the need for specialized service engineers. It’s worth noting that these estimates are for a smaller supramax bulk carrier (60,000 DWT) compared to a larger capsize bulk carrier (200,000 DWT) in our case. However, we have decided to use the same estimates in our analysis, given the uncertainties involved.

In addition to the retrofit cost, the vessel must be bought from the secondhand market, notably referred to as the pool of available vessels in our case. The average age of the vessels in our dataset is approximately ten years old, and therefore we are examining the price of purchasing a ten-year-old capesize bulk carrier. In figure 6.9 the historical prices from 2000 to 2023 are presented.

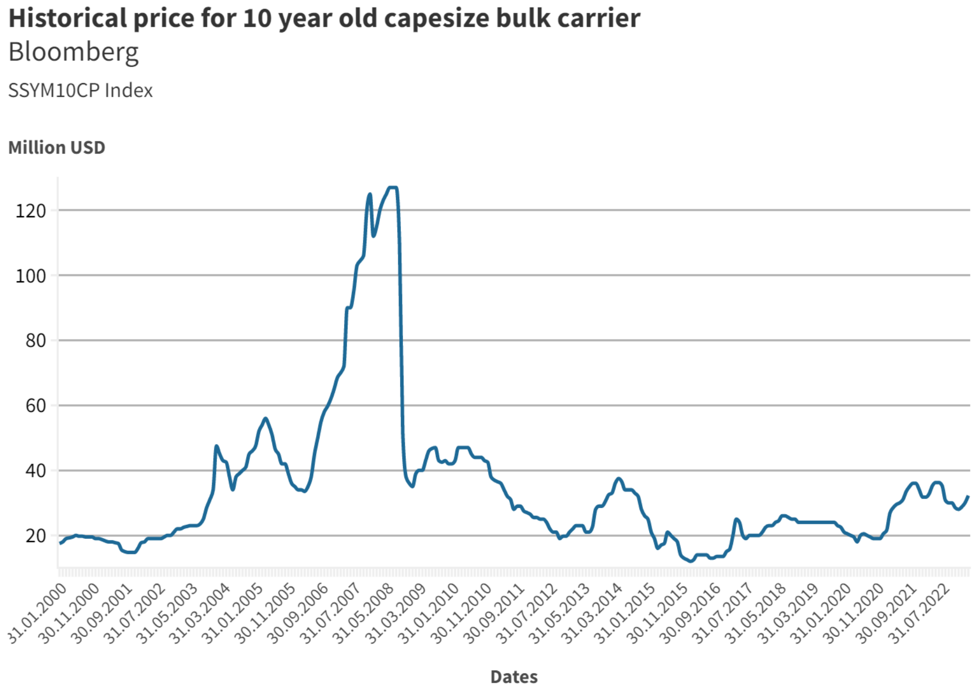

Figure 6.9: Historical price from 2000-2023 for 10 year old capesize bulk carrier

The prices are fluctuating from 12- to 127 million USD, depending on the market conditions. Nevertheless, in our analysis, we have decided to use the 2023 price of 32 million USD, which is relatively close to the mean value of 34 million USD across the entire period. We assume a constant purchase price, with a fixed rate of 32 million USD across the entire planning horizon.

Newbuild

For the newbuild price we observe the same fluctuations in the historical data presented in figure 6.10, ranging from 36 to 105 million USD. Notably these values are for a bulk carrier powered by fossil fuel, not ammonia. We have decided to use the 2023 rate of 66 million USD, with an additional 10 million USD. The additional 10 million USD is taken from the Grieg Star estimates, including the main engines. Meaning that we assume storage tank, fuel supply system, and yard stay is included in the newbuild price of 66 million USD. Furthermore, the total investment cost is set at a fixed rate of 76 million USD for the entire planning horizon.

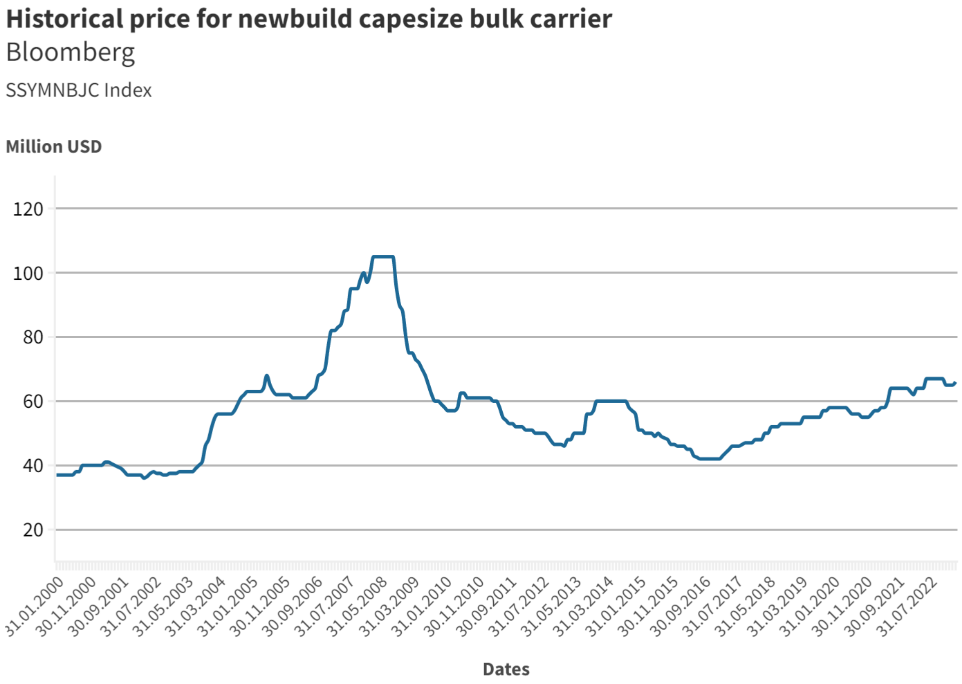

Figure 6.10: Historical price from 2000-2023 for newbuild capesize bulk carrier

For the operational expenses we assume an additional 100,000 USD per year. Given that this is a new vessel, we assume a 50% reduction in additional expenses compared to a retrofitted vessel.

To summarize, the input values are presented in table 6.7.

Abatement Option	Reduction Factor	Investment Cost [mUSD]	Operational Cost [mUSD]
Retrofit	1	54	0.2
Newbuild	1	76	0.1

Table 6.6: Abatement option input

6.3.3 Time dependent dataset

Emission requirement

The emission requirement is set to a linear descending curve towards zero emissions in 2050. As presented in section 6.1 the total aggregated emissions in 2018 was 1.77 million ton CO_2. In order to initialize our model and avoid any restrictions in the first year, we set the beginning value to 1.8 million tons with a stepwise reduction of roughly 70,000 tons in the subsequent periods.

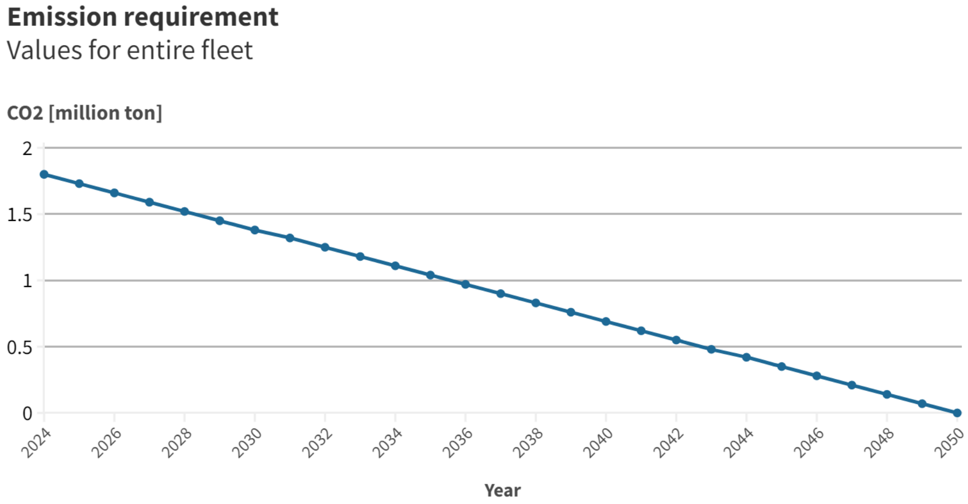

Figure 6.11: Emission requirement for entire fleet per year

Carbon tax

Due to the various proposals and lack of clarity surrounding the development of carbon tax policy in shipping, it is difficult to predict how it will unfold in the future. In order to get a good data foundation, we have decided to use values obtained from the EU Emission Trading System, despite operating in southeast Asia.

In figure 6.12 carbon tax futures from 2023 to 2029 are presented, with an anticipated 28% increase by 2029.

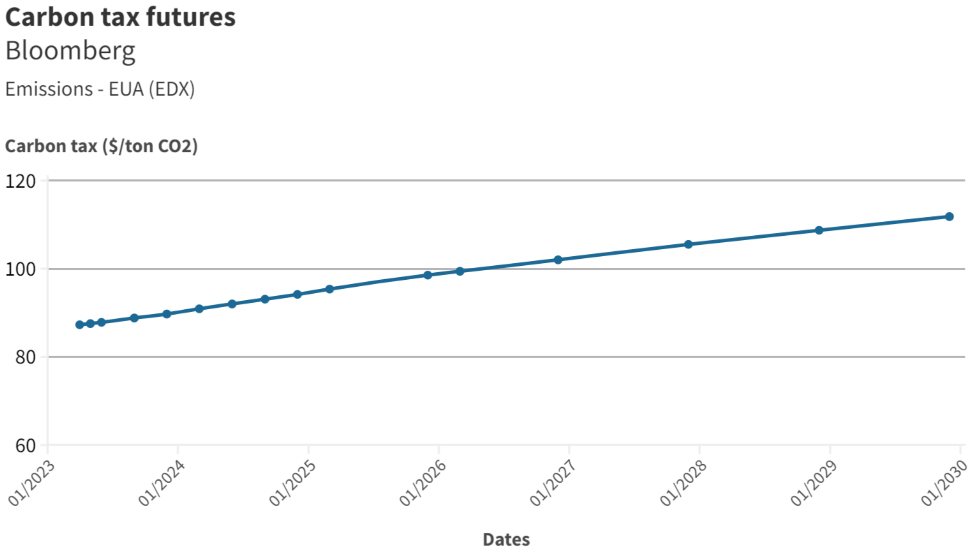

Figure 6.12: Carbon tax futures from 2023-2029

To accommodate our analysis of the period until 2050, we have incorporated this data and conducted a linear regression to obtain a linearly increasing trend until 2050. The data presented in figure 6.13 is used as input in this analysis.

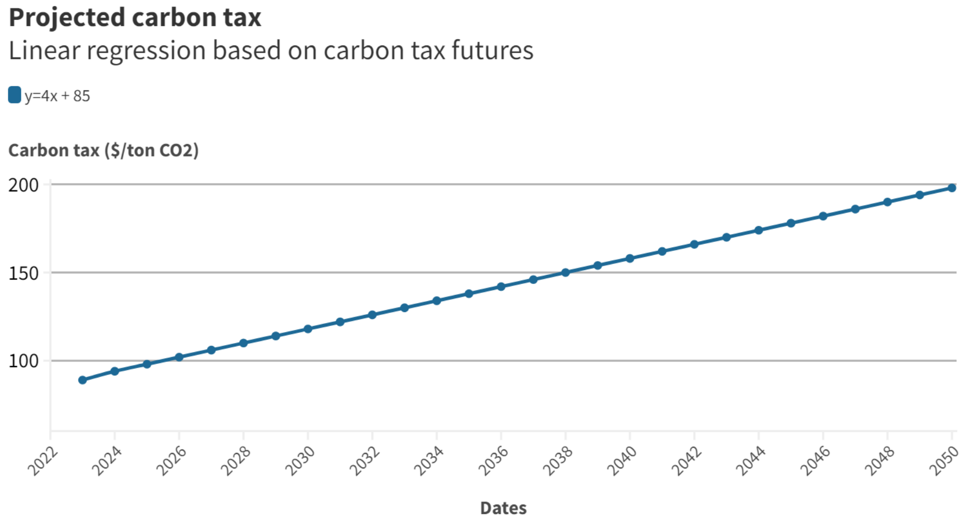

Figure 6.13: Projected carbon tax from 2023-2050

Green premium

The green premium is the cost different between VLSFO and green ammonia in our case. In figure 6.14, VLSFO futures are presented, where we observe a slight decrease in cost until it stabilizes around 500 USD per ton in 2026. Throughout this analysis we assume a flat VLSFO price of 500 USD per ton.

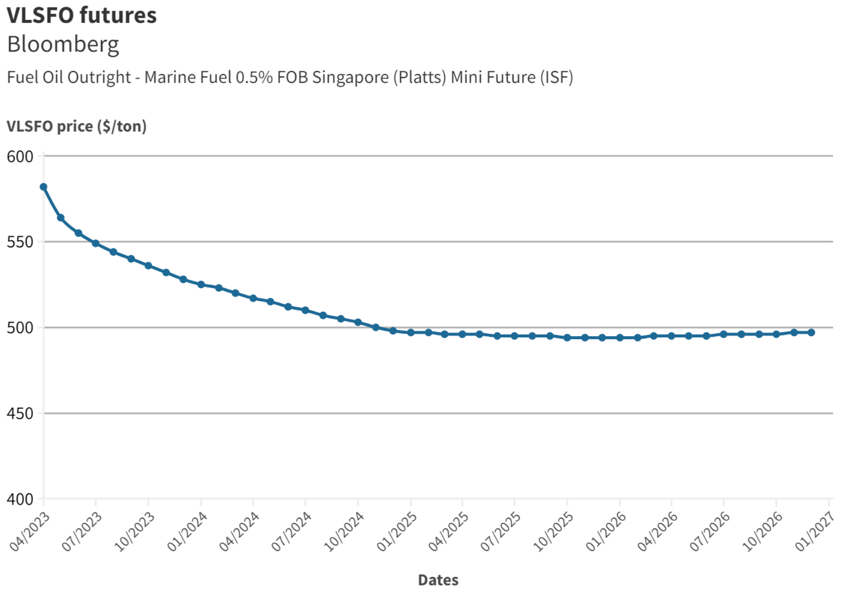

Figure 6.14: VLSFO futures from 2023-2026

The Ammonia Energy Association has estimated the current production cost of green ammonia, based on an electricity price of $50 per MWh in Australia, at approximately $650 per ton (AmmoniaEnergyAssociation 2023). Additionally, we assume that by the year 2050, the price of VLSFO and green ammonia will converge, resulting in a green premium of zero. Furthermore, we assume a linear descend in the price of green ammonia.

The values are plotted in figure 6.15, using a gravimetric energy density of 11.8 MWh and 5.17 MWh per ton for VLSFO and ammonia, respectively.

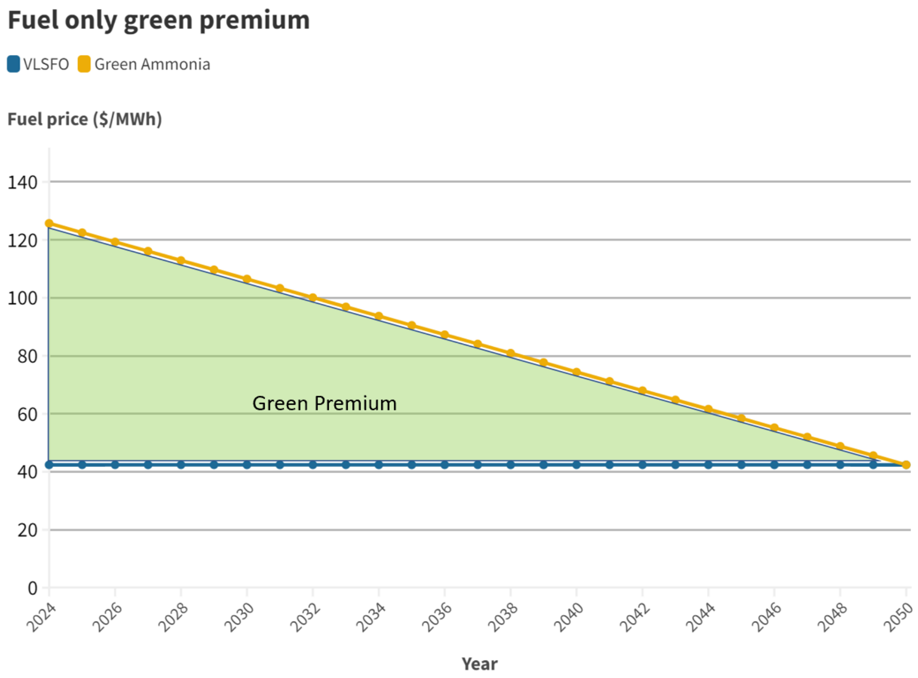

Figure 6.15: Cost difference between VLSFO and green ammonia

6.4 Case results

If the Australia to Japan iron ore trade were to be serviced by the current fleet without implementing any changes or emission reduction measures, the total carbon dioxide emissions over the 25-year planning horizon would amount to 42.5 million tons (based on calculations from table 6.1). The fleet retrofit and renewal strategy presented in figure 6.16 saves 30.2 million tons of carbon dioxide emissions at a differential cost of 6.2 billion USD. This equates to 22,159 tons reduction per million dollar invested in tangible assets. If we where to include the intangible costs of carbon tax and green premiums in what we refer to as the total cost of ownership (TCO), we get 4,881 tons reduction per mUSD spent.

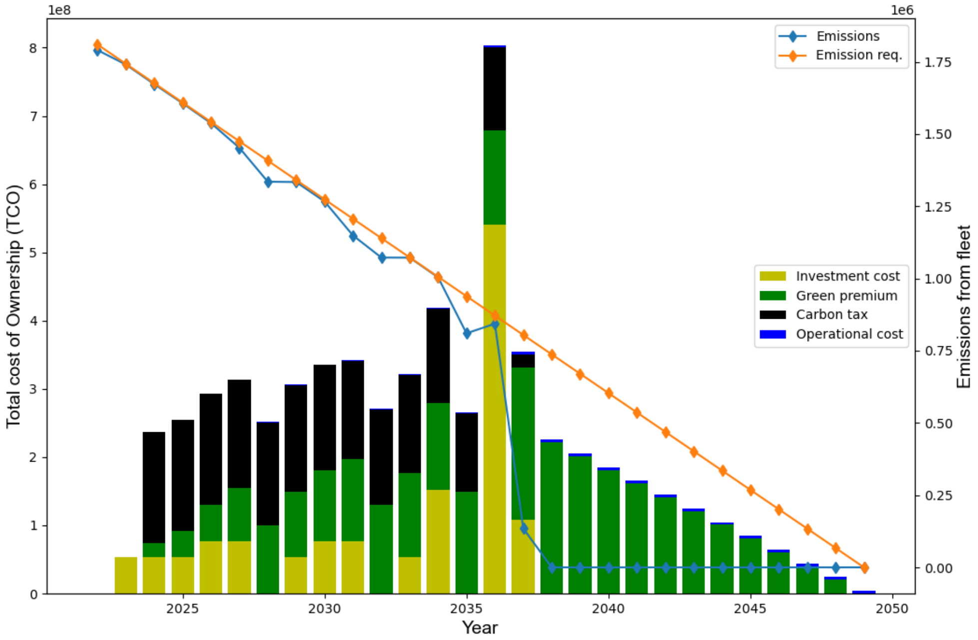

Figure 6.16: Fleet retrofit and renewal strategy

In the context of the specific carbon tax and green premium scenario considered, the attainment of a true green corridor is projected to occur in 2037. Prior to 2037, a comprehensive fleet renewal process spanning a 13-year period has been undertaken, resulting in the complete replacement of older fossil fuel burning vessels with greener alternatives. We observe that the amount of carbon tax paid each year is more or less constant although the carbon price increases each year. This is because the amount of carbon dioxide emitted each year are declining with the same rate as carbon prices increase. Implying that carbon tax growth rate is closely correlated to decarbonization rates. The amount of green premium to be paid increases up until 2037 before it decreases again to zero in 2050. The strategy includes the ordering of 3 newbuilds of the largest type and to retrofit 21 existing vessels with ammonia power systems. Although green premiums persist after 2037, the implied carbon tax bill incurred by combusting one ton of VLSFO surpasses the green premium making green ammonia the cheaper fuel (figure 6.17).

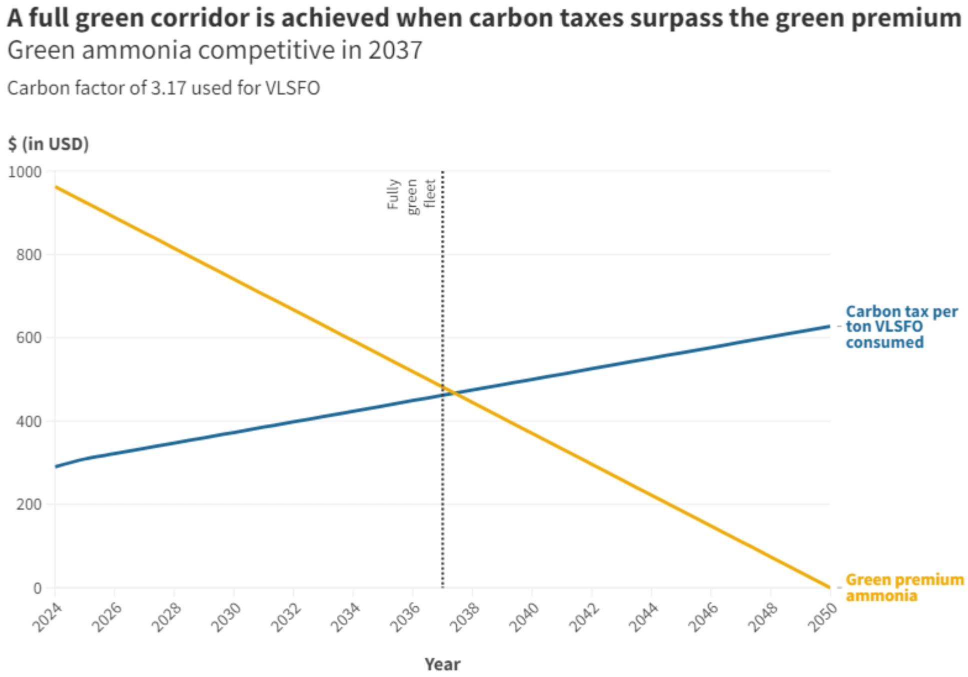

Figure 6.17: Under the applied green premium and carbon tax projections, ammonia becomes competitive in 2037

Beyond the year 2037, it is observed that green ammonia remains more expensive compared to VLSFO, as depicted in figure 6.15. Consequently, a significant green premium continues to represent the largest cost category for the fleet owners, as illustrated in figure 6.18. This highlights the importance of implementing measures to reduce the cost of green ammonia fuel, which would greatly contribute to lowering the overall cost of establishing the Australia to Japan green corridor. As a potential solution, discussions are underway regarding the implementation of a fuel only Contract for Difference (CFD) financed by carbon taxes, aimed at providing financial support and incentivizing the adoption of green fuels. The strike price could be determined through a competitive auction, where bidders submit prices and the lowest bid is awarded the contract, subject to meeting certain conditions such as production capacity. In practice, when the reference price is lower than the strike price (supplier of fuel has negative cash flow), the supplier gets paid the difference. This guarantees that the supplier receives a minimum price for the duration of the CFD. On a large scale, these contracts have to be issued and managed by a central body such as the IMO. For example, a CFD program that supports at least 5% of Scalable Zero Emission Fuels (SZEF)s in EU shipping would cost an estimated 1.2 billion euros annually (GMF 2021a). Our estimates show that the Australia to Japan iron ore trade would generate 1.9 billion USD (1.7 billion euros) in carbon taxes alone.

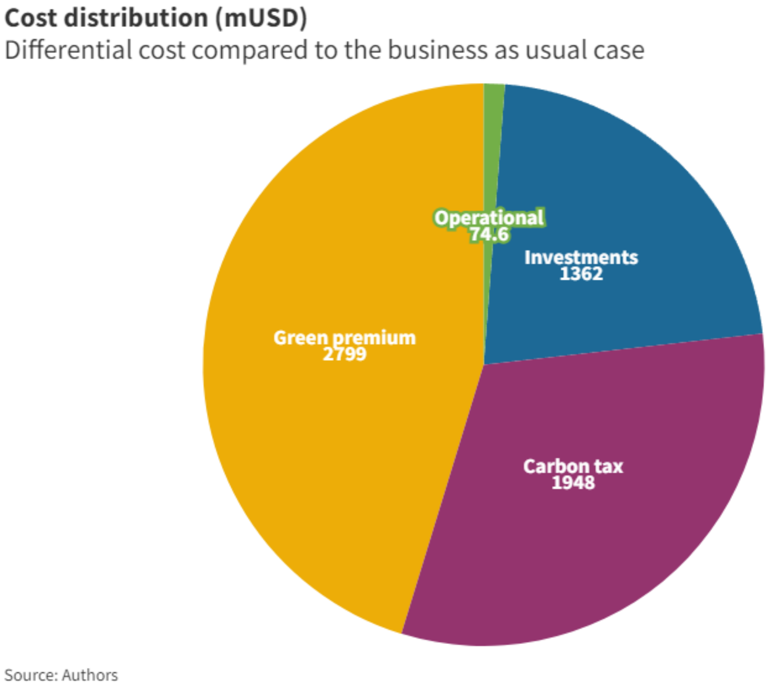

Figure 6.18: Green corridor cost distribution. Costs are displayed as differential costs from the BAU case

The levelized increase in the Required Freight Rate (RFR) over the entire planning horizon is calculated to be 3.32 USD per ton. Presently, Capesize rates on the C10 route (Western Australia to China) are approximately 9.35 USD per ton (Tradewinds 2023), although these rates are subject to fluctuations based on market conditions. To cover the cost of the green corridor while maintaining similar profit margins as today, a freight rate of approximately 12.67 USD per ton would be required, representing a 35% increase compared to the current rates.

Summary (aggregated over 25 yrs)	BAU	Green corridor	Difference
CO_2 emissions, mTon	48.34	18.16	-30.18
Iron ore transported, mTon	1863	1863	0
Freigh rate (FR), USD/ton	9.35	12.67	3.32
Differential cost, billion USD	0	6.18	6.18
Newbuilds à 300,000 dwt	-	3	-
Retrofits	-	21	-

Table 6.7: Summary of the differnce between the business as usual case (BAU) and the proposed green corridor. Accumulated over 25 years until 2050.

To remain competitive despite the higher freight rates, the implementation of a special economic and regulatory zone specific to the trade route could be considered. This zone would aim to promote and support clean shipping practices, providing incentives and benefits to shipping companies that adopt environmentally friendly measures. By creating a favorable environment for clean shipping, such as streamlined regulations, reduced fees, and supportive infrastructure, the zone would encourage the adoption of sustainable and efficient shipping practices. This approach would help offset the increased costs associated with the green corridor, making it more financially viable for shipping companies while simultaneously promoting environmental sustainability in the industry.

Chapter 7

Discussion

Through the computational study we highlighted trends and the relationship between carbon tax, green premium and emission reduction strategies. Furthermore, quantitative results were presented in the case study. With these results in mind, we aim to use this chapter to put the modelling approach in a larger context, with focus on practical applications.

The common denominator in these considerations is, as always, uncertainty and how to handle it. From a shipowner's perspective, it is impractical to follow a long-term investment plan spanning several decades when new information becomes available over time. If the demand on the route should increase, it opens up for alternative solutions such as replacing two smaller poor performing vessels with a larger greener vessel. Such changes requires flexibility in the decarbonization strategy and can be accommodated for by solving the model again when new information is known and react correspondingly. Parameters such as fuel availability, yard availability, and market fluctuations in cargo transportation demand are subject to change over time and require the ability to make short-term adjustments. Such adjustments could be to postpone the ordering of a planned newbuild by one year to have more favorable conditions in the short-term. That said, it is important to remember that the model developed in this thesis provides a actionable plan that minimizes the total cost over a long period. Hence, if we deviate to much from the intital plan to accommodate for short-term gains, the superior goal might get compromised and end up being more expensive overall. This problem is not new in shipping and has been further reinforced by the presence of COVID-19 and the Russia-Ukraine war.

In section 5.2, we discussed that the selection of abatement options is independent of the decarbonization strategy when the strategies share the same predetermined end goal. However, the timing of these investments is naturally dependent on the chosen strategy. The former statement is more complex when applying it to a real investment case because it is not given that the options available today are the same as in for example ten years. This inherent risk will always be present, but there is significant benefits to planning ahead as it allows you optimize the fleet renewal schedule. Nevertheless, we would argue that our model is best suited for conducting high-level "what if" analyses where the results serve as insight and guidance for long term planning.

From a regulatory perspective, we would argue that the model offers a high level of robustness in delivering well-rooted recommendations for carbon tax levels in the shipping industry, particularly concerning the establishment of green corridors. When introducing such legislation, it is important to understand its ripple effects and, equally important, ensure that it effectively serves its intended purpose. Gathering the whole value chain under the same umbrella when considering such legislation is of great value. As presented in the case study, a CFD program directly linked to carbon tax rates to support green premiums in combination with emission reduction strategy can be extracted from the modelling approach presented.

That said, there are improvements to be made and some extensions that can be implemented to increase the value of the results. In the following chapter, we will outline key considerations that we believe should be prioritized as the next steps in expanding the applicability of this model.

Chapter 8

Further work

The model behaves well with high impact abatement options, including green newbuilds and retrofit to green energy sources. It lacks functionality with regards to choosing several low impact measures on the same vessel instead of doing one large investment per vessel. This is not a problem for green corridor projects because the final goal is zero emissions and the pace of decarbonization should be greater and we can expect ships being deployed with zero emissions and not a partial reduction. For general purposes this might not be the case and it would be beneficial for a user to attain decision support on less ambitious emission reduction strategies. The less ambitious strategies where the end goal could for example be a 40% could get away with installing two lower-impact reduction measures in conjunction on the same vessel to reach their goals. Based on the lack of this functionality we recommend that further work on our model should allow for several options per vessel. The main hurdle in achieving this is related to correctly solving the interaction and compliance effects between different abatement options. If this is achieved constraint 4.26 could easily be modified to constraint 8.1:

$$\sum_{t \in T} x_{vat} \leq 1, \qquad v \in V, a \in A \tag{8.1}$$

Constraint 8.1 now implies that a specific abatement option only can be introduced once over the planning horizon, but does not restrict ships in installing several different options. When applying the change, constraint 4.24 also need modifications to prevent having negative emissions and not accounting for interaction effects. The present restriction 8.3 will calculate negative emissions when the sum of the individual abatement option reduction potentials installed exceeds 100%, shown in equation 8.2.

$$\sum_{a \in A} \gamma_a y_{vat} > 100\%, \qquad v \in V, t \in T \tag{8.2}$$

Furthermore, this does not account for interaction effects between reduction measures. This could be solved by exchanging γ_a with γ_{ij} to at least cover the total reduction when both abatement option i and j are installed. To allow for three or more abatement options, one would simply increase the matrix dimension to $I_{ijk...}$ and capture the total costs in a similar way. Together with increasing the granularity and number of available abatement options and allowing to select a multiple of options would provide added insight with regards to determining the optimal investment strategy given a decarbonization strategy.

$$\sum_{v\in V}(E_v^V z_{vt} - \sum_{a\in A}\gamma_a E_v^V y_{vat}) \leq E_t^{TOT}, \qquad t \in T \tag{8.3}$$

Additionally, capturing the time value of money to reflect that investments planned in the future are cheaper compared to immediate investments would provide a new dimension to the problem and solution. This could be achieved by modifying the cost parameters in the objective function to also be indexed by time, t, resulting in the modified parameters $C^{AO}_{(ijk..)t}$ and $C^{AI}_{(ijk..)t}$.

It is our hope that future master's candidates will explore these concepts and apply them to the model presented by us. We believe there is significant potential in doing so, especially for general emission reduction purposes outside the green corridor domain.

Chapter 9

Conclusion

This master thesis introduces a model formulation aimed at supporting decarbonization efforts in the shipping industry. Drawing inspiration from three different modelling approaches found in existing literature, we have developed a model that has been implemented in a commercial solver and subjected to a computational study. The study aimed to identify the model's strengths and limitations in order to provide insights into its practical applications. The results demonstrated the model's robustness in offering specific and insightful information on the relationship between carbon tax rates, fuel prices, and emission reduction strategies, highlighting how different values impact the optimal solution.

Furthermore, we conducted a case study focusing on the iron ore trade between Australia and Japan. The model showed great flexibility in handling large datasets while providing strategic insights. The case study can be easily adapted to other shipping routes by modifying input values, thereby allowing for the assessment of various green corridor candidates. Notably, the developed AIS filtering script serves as a powerful tool to ensure the use of firsthand data and the alignment of assumptions with the analysis's primary objective.

In summary, this thesis presents a generic model formulation suitable for green corridor projects and other maritime decarbonization initiatives with ambitious emission reduction targets. Additionally, we have developed an AIS data filtering script combined with a Python script for preprocessing of vessel information, enabling the execution of high-level analyses on any chosen shipping route.

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Appendix A

Model implementation Xpress

```
def gc_fleet_model(dfV,dfA,dfT):

    nV = dfV.shape[0]
    nA = dfA.shape[0]
    nT = dfT.shape[0]

    V = [v for v in range(nV)]
    A = [a for a in range(nA)]
    T = [t for t in range(nT)]

    bigM = 100000


    p = xp.problem()

    #Variable x; 1 if abatement option a is being installed on vessel v in time
        period t
    x = {(v,a,t): xp.var (vartype = xp.binary, name=’x_{0}_{1}_{2}’.format (v,a,t))
         for t in T for a in A for v in V}


    #Variable y; 1 if abatement option a is already installed on vessel v in time
        period  t
    y = {(v,a,t): xp.var (vartype = xp.binary, name=’y_{0}_{1}_{2}’.format (v,a,t))
         for t in T for a in A for v in V}

    #Variable z: 1 if vessel v is used(active) in time period t, 0 otherwise
    z = {(v,t): xp.var (vartype = xp.binary, name=’z_{0}_{1}’.format (v,t)) for t
        in T for v in V}

    p.addVariable(x,y,z)

    #Objective function
    totCost = xp.Sum(x[v,a,t]*dfA.C_I[a] + y[v,a,t]*dfA.O_Add[a]  for v in V for a
        in A for t in T)\
    +xp.Sum(z[v,t]*dfV.FuelCons[v]*dfT.VlsfoCost[t] for v in V for t in T)\
    +xp.Sum(y[v,a,t]*dfT.AddCost[t]*dfV.FuelCons[v] for v in V for a in A for t in
        T)\
    +xp.Sum(dfT.CT[t]*dfV.E[v]*z[v,t] for v in V for t in T)\
    -xp.Sum(dfT.CT[t]*dfA.Red[a]*dfV.E[v]*y[v,a,t] for v in V for a in A for t in T
        )\
    +xp.Sum(y[v,a,t]*dfA.punish[a] for v in V[:20] for a in A for t in T)
    p.setObjective(totCost, sense = xp.minimize)

    #Constraint 1: Ensure that demand is met by the active fleet for each time
        period t (here round trips are set to 10 for now)
```

```
    c1 = [xp.Sum(z[v,t]*dfV.Q[v] for v in V) + xp.Sum(dfA.DWT_Add[a]*dfV.Q[v]*y[v,a
        ,t] for a in A for v in V[20:])>= dfT.Demand[t] for t in T]

    #Constraint 2: Max total annual emission
    c2 = [xp.Sum(z[v,t]*dfV.E[v] - xp.Sum(dfA.Red[a]*dfV.E[v]*y[v,a,t] for a in A)
        for v in V)<= dfT.E_req[t] for t in T]

    #Contraint 3: Exactly one abatement option allowed for each vessel
    c3 = [xp.Sum(x[v,a,t] for t in T for a in A)<= 1 for v in V] #This is modified
        from previous steps

    #Contraint 4: (Technical) Make sure that an abatement option is installed if it
         is used
    c4 = [bigM * xp.Sum(x[v,a,t] for t in T) >= xp.Sum(y[v,a,t] for t in T) for a
        in A for v in V]

    #Contraint 5: Abatement option installation triggers option use indicator
    c5 = [y[v,a,t+1] >= x[v,a,t] for t in T[:-1] for a in A for v in V]

    # Contraint 6: Once triggered, option use indicator should last remaining time
        horison
    c6 = [y[v,a,t] >= y[v,a,t-1] for t in T[1:] for a in A for v in V]

    # Contraint 7: Abatement option installation triggers option use indicator.
    # When y switches from 0 to 1, this triggers x=1, else x=0
    c7 = [y[v,a,t+1] - y[v,a,t] == x[v,a,t] for t in T[:-1] for a in A for v in V]

    #Contraint 8: Abatement option should not be installed in last period.
    c8 = [x[v,a,t] == 0 for t in T[-1:] for a in A for v in V]

    #Constraint 9: If abatement option a is installed on vessel v in t, force z to
        1
    c9 = [z[v,t] >= y[v,a,t] for t in T for a in A for v in V]

    #Constraint 10: (Technical) No abatement options can be done in the first
        period due to c7
    c10 = [x[v,a,t] == 0 for t in T[:1] for a in A for v in V]

    #Constraint 11: (Technical) Ensures that that z and y never equals 1 in the
        same time period as x =1
    c11 = [z[v,t] + y[v,a,t] <= (1-x[v,a,t])*bigM for t in T for a in A for v in V]

    p.addConstraint(c1,c2,c3,c4,c5,c6,c7,c8,c9,c10,c11)

    xp.controls.outputlog = 0
    p.solve()

    return p,x,y,z
```

Appendix B

Processing of case study data

```
Constant parameters:
    Speed = 15 #knots

    distance = 7000 #nm round trip

    port_time = 4 #days in port

    waiting_time = 3 #days waiting time

    iron_ore_demand = 69000 #thousand ton
```

```
Dataset - Input from AIS analysis:

    names = [’vessel’, ’year’, ’DWT’]

    AIS_df = pd.read_excel(’AIS_data.xlsx’, header=0, names=names)

Fuel Dataset:

    names = [’Fuel’,’Fuel␣price’, ’LHV’ ,’eff.’,’CF’]

    fuels_df = pd.read_excel(’Fuel_data.xlsx’,header=0, names=names)
```

Calculations:

```
Number of sailing days:

def get_sailing_days(distance, speed, selected_fuel):

    return np.ceil(distance/(24*speed)) #Returning number of days for one voyage (
        at sea)
```

```
Annual roundtrips per vessel:

def get_annual_round_trips(port_time, waiting_time, distance, speed, off_hire,
     selected_fuel):

    sailing_days = get_sailing_days(distance, speed,selected_fuel)

    return np.floor(((365-off_hire)/((port_time+waiting_time+sailing_days)))) #
        returning number of roundtrips per period
```

```
Annual Transport capacity [Thousand Tons]:
```

```
def get_annual_transport_capacity(speed, dwt, port_time, waiting_time, distance,
     off_hire, dwt_utilization,selected_fuel):


    No_sailing_days = get_sailing_days(distance, speed, selected_fuel)

    annual_transport_capacity = dwt_utilization*dwt*((365-off_hire)/(port_time+
        waiting_time+No_sailing_days));

    return int(annual_transport_capacity) #returning total transportation potential
         per period
```

```
Energy demand - AUX. + Propulsion [kW]:

def get_prop_power(speed,dwt,selected_fuel):

    kw_prop = 0.08*np.sqrt(dwt)*speed*speed*speed*np.sqrt(speed)

    kw_aux = 0.1*kw_prop #assuming 10 % of kw_prop for aux. power

    return np.round(kw_prop+kw_aux) #returning energy demand
```

```


Fuel consumption [Tons]:

def get_fuel_consumption(speed, dwt, distance, fuels_df, selected_fuel,
     dwt_utilization):

    fuel_type = fuels_df.loc[fuels_df[’Fuel’]==selected_fuel]

    energy_converter_eff = fuel_type[’eff.’]

    LHV = fuel_type[’LHV’]

    time = get_sailing_days(distance, speed,selected_fuel)*24

    power_trip = get_prop_power(speed,dwt,selected_fuel)

    power_return = get_prop_power(speed,dwt,selected_fuel)

    fuel_cons_trip = np.round((power_trip*time/2*3600)/(energy_converter_eff*LHV))

    fuel_cons_return = np.round((power_return*time/2*3600)/(energy_converter_eff*
        LHV))

    tot_fuel_burn = fuel_cons_trip + fuel_cons_return

    return np.int(tot_fuel_burn/1000) #returning fuel consumption for one roundtrip
         in tons
```

```
Fuel cost [USD]:

def get_fuel_cost(speed, dwt, distance,fuels_df, selected_fuel,dwt_utilization,
    n_bunkers):

    fuel_type = fuels_df.loc[fuels_df[’Fuel’]==selected_fuel]

    fuel_consumption = get_fuel_consumption(speed, dwt, distance, fuels_df,
        selected_fuel, dwt_utilization)

    fuel_cost = int(fuel_type[’Fuel␣price’]*fuel_consumption)

    return int(fuel_cost) #returning fuel cost
```

```
CO2 emissions from combustion:

def get_emissions_CF(selected_fuel,speed, dwt):

    fuel_consumption = get_fuel_consumption(speed, dwt, distance,fuels_df,
        selected_fuel, dwt_utilization)

    fuel_type = fuels_df.loc[fuels_df[’Fuel’]==selected_fuel]

    carbon_factor = fuel_type[’CF’]

    emissions = carbon_factor*fuel_consumption #tons

    return int(emissions) #returning total emissions per roundtrip in tons
```

```
Result / output:

def get_result():

    DWT_list = AIS_df[’DWT’].values.tolist()

    selected_fuel = ’VLSFO’

    data_output = {’Parameters’: [’Sailing␣days’, ’No␣of␣Roundtrips’,’Energy␣demand
        ␣[kWh]’,
                                ’Fuel␣consumption␣[Ton]’, ’Fuel␣cost␣[USD]’, ’CO2
                                    ␣emissions␣[Ton]’]}

    df = pd.DataFrame(data_output)


    for i in range(len(DWT_list)):

        dwt1 = DWT_list[i]

        sailing_days = get_sailing_days(distance, speed, selected_fuel)

        annual_round_trips = get_annual_round_trips(port_time, waiting_time,
            distance, speed, off_hire, selected_fuel)

        energy_demand = get_prop_power(speed,dwt1,selected_fuel)

        fuel_consumption = get_fuel_consumption(speed, dwt1, distance,fuels_df,
            selected_fuel ,dwt_utilization)

        fuel_cost = get_fuel_cost(speed, dwt1, distance, fuels_df, selected_fuel,
            dwt_utilization, n_bunkers)

        CO2_combustion_emissions = get_emissions_CF(selected_fuel, speed,dwt1)
```

```
        df[DWT_list[i]] = [sailing_days, annual_round_trips, energy_demand,
            fuel_consumption,
                        fuel_cost, CO2_combustion_emissions]


    return df
```

Appendix C

AIS Analysis

Import lib

```
import pandas as pd
import numpy as np
import folium
from folium import plugins
import matplotlib.pyplot as plt
import requests
import bs4
from bs4 import BeautifulSoup
from mpl_toolkits.basemap import Basemap
```

```
names = [’mmsi’,’unixtime’,’latitude’,’longitude’, ’heading’,’sog’,’nav_status’,’
     cog’,’rot’]
# Reading in the AIS data
raw_data = pd.read_csv(’aisdata_final.csv’, sep=’;’,header=0, names=names)
# Sort by unix time
raw_data = raw_data.sort_values(by=’unixtime’)
# Convert unix time to DateTime object
raw_data[’DateTime’] = pd.to_datetime(raw_data[’unixtime’],unit=’s’)
# Extract unique ships by their mmsi number
ship_id = raw_data.mmsi.unique()
raw_data.head()
```

Search for vessel on vesselfinder

```

def get_int_value(v):
    if v.isdigit():
        return int(v)
    else:
        np.nan

def get_data(ship_id):
    res = None
    if ship_id < 999999: return res
    headers = {’user-agent’: ’app/0.0.2’}
    r = requests.get(f"https://www.vesselfinder.com/vessels?name={ship_id}",
         headers=headers)
    soup = BeautifulSoup(r.text, ’html.parser’)

    if soup is not None:
        try:
            table = soup.find(’tbody’).find_all(’tr’)
            if table is not None:
                try:
                    for row in table: #looping through every tr
                        columns = row.find_all(’td’)
```

```
                    res = {}
                    res[’name’] = columns[1].find(’div’, {’class’: ’slna’}).
                        contents[0]
                    res[’type’] = columns[1].find(’div’, {’class’: ’slty’}).
                        contents[0]
                    res[’year’] = get_int_value(columns[2].contents[0])
                    res[’gt’] = get_int_value(columns[3].contents[0])
                    res[’dwt’] = get_int_value(columns[4].contents[0])
                    size = columns[5].contents[0].split(’/’)
                    if len(size) == 1:
                    size = [’-’, ’-’]
                    res[’length’] = get_int_value(size[0].strip())
                    res[’width’] = get_int_value(size[1].strip())
                    return res
                except:
                print(ship_id)
        except:
        print(ship_id)
    return res
```

```
def get_vessel_particulars(mmsi_u):
    bulkers = []
    n = 0
    for i in range(len(mmsi_u)):
        vessel = get_data(mmsi_u[i])
        if vessel == None:
            continue
         #Select all bulk carriers above 80,000 dwt
        elif vessel[’type’] == ’Bulk␣Carrier’ and vessel[’dwt’] >= 80000:
            vessel[’mmsi’] = mmsi_u[i]
            bulkers.append(vessel)
            n += 1
        else:
            continue
    return pd.DataFrame.from_dict(bulkers)
```

```
def get_all_timestamps(mmsi_list,df):
    return df.loc[df[’mmsi’].isin(mmsi_list)]
# DataFrame of in this case bulk carriers above 80,000 dwt
vessel_info = get_vessel_particulars(ship_id)
# Convert relevant ships mmsi numbers to a list
bulk_id = vessel_info[’mmsi’].to_list()
# Get all timestamps for bulk carriers in interest
bulk_ais = get_all_timestamps(bulk_id,raw_data)

# Main particulars for all bulk carriers of interest
vessel_info.to_csv(’Bulk_carriers_info.csv’, index=False)
# AIS data for all bulk carriers of interest
bulk_ais.to_csv(’Bulk_carriers_ais.csv’, index=False)
```

```
# creates a DataFrame that includes all vessels main particulars
ship_information_agg = pd.read_csv(’Bulk_carriers_info.csv’)
# creates a DataFrame including the AIS data for the vessels
ship_ais_agg = pd.read_csv(’Bulk_carriers_ais.csv’)
bulk_id = ship_information_agg[’mmsi’]
```

```
def hedland_port_check(unique_mmsi, df):
    vessels_visited_port = []
    hedland_lat_upper = -20.290000
    hedland_lat_lower = -20.350000
    hedland_long_right = 118.602500
    hedland_long_left = 118.513600
    for mmsi in unique_mmsi:
```

```
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(hedland_lat_lower,
                                                      hedland_lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(hedland_long_left,
                                                    hedland_long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
def kashima_port_check(unique_mmsi, df):
    vessels_visited_port = []
    lat_upper = 35.900000
    lat_lower = 35.801400
    long_right = 141.718500
    long_left = 140.647600
    for mmsi in unique_mmsi:
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(lat_lower, lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(long_left, long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
def fukuyama_port_check(unique_mmsi, df):
    vessels_visited_port = []
    lat_upper = 34.486900
    lat_lower = 34.417200
    long_right = 133.491900
    long_left = 133.395000
    for mmsi in unique_mmsi:
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(lat_lower, lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(long_left, long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
def kisarazu_port_check(unique_mmsi, df):
    vessels_visited_port = []
    lat_upper = 35.414100
    lat_lower = 35.338400
    long_right = 139.933500
    long_left = 139.821900
    for mmsi in unique_mmsi:
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(lat_lower, lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(long_left, long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
def ports_australia(unique_mmsi, df):
    vessels_visited_port = []
    lat_upper = -19.90000
    lat_lower = -20.620000
    long_right = 118.600000
    long_left = 116.650000
    for mmsi in unique_mmsi:
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(lat_lower, lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(long_left, long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
def ports_japan(unique_mmsi, df):
    vessels_visited_port = []
    lat_upper = 35.90000
    lat_lower = 32.160000
    long_right = 140.700000
    long_left = 131.530000
    for mmsi in unique_mmsi:
        vessel = df.loc[df[’mmsi’] == mmsi]
        lat_check = vessel[vessel[’latitude’].between(lat_lower, lat_upper)]
        lat_check.sort_values(by=[’unixtime’])
        port_check = lat_check[’longitude’].between(long_left, long_right)
        if port_check.any() == True:
            vessels_visited_port.append(mmsi)
        else:
            continue
    return vessels_visited_port
```

```
australia = hedland_port_check(bulk_id,ship_ais_agg)
japan = ports_japan(bulk_id,ship_ais_agg)
hedland = hedland_port_check(bulk_id,ship_ais_agg)
kashima = kashima_port_check(bulk_id,ship_ais_agg)
fukuyama = fukuyama_port_check(bulk_id,ship_ais_agg)
kisarazu = kisarazu_port_check(bulk_id,ship_ais_agg)
```

```
print(len(bulk_id),’␣is␣the␣total␣number␣of␣unique␣bulk␣carriers␣in␣the␣AIS␣data’)
print(len(australia),’␣unique␣vessels␣has␣visited␣Australia’)
print(len(japan), ’unique␣vessels␣has␣visited␣Japan’)
print(len(hedland), ’unique␣vessels␣has␣visited␣Hedland’)
print(len(kashima), ’unique␣vessels␣has␣visited␣Kashima’)
print(len(fukuyama), ’unique␣vessels␣has␣visited␣Fukuyama’)
print(len(kisarazu), ’unique␣vessels␣has␣visited␣Kisarazu’)
```

```
in_common = set(hedland) and set(japan)    #Vessels that visitied both Australia
    and Japan
print(len(in_common),’unique␣vessels␣has␣visited␣both␣Australia␣and␣Japan’)
final_vessels = list(in_common)
```

```
vsldf2 = ship_ais_agg.loc[ship_ais_agg[’mmsi’]==563640000]  #432996000
#vsldf3 = ship_ais_agg.loc[ship_ais_agg[’mmsi’]==431417000]
#vsldf2 = ship_ais_agg.loc[ship_ais_agg[’mmsi’].isin(final_vessels)]
minlon = max(-180,min(vsldf2[’longitude’])-20)
minlat = max(-90,min(vsldf2[’latitude’])-20)
maxlon = min(180,max(vsldf2[’longitude’])+20)
maxlat = min(90,max(vsldf2[’latitude’])+20)
lat0 = (maxlat+minlat)/2
```

```
lon0 = (maxlon+minlon)/2
lat1 = (maxlat+minlat)/2-20

fig,ax=plt.subplots(figsize=(15,15))
m = Basemap(llcrnrlon=minlon,llcrnrlat=minlat,urcrnrlon=maxlon,
            urcrnrlat=maxlat,rsphere=(6378137.00,6356752.3142),
            resolution='l',projection='cyl',lat_0=lat0,lon_0=lon0,
            lat_ts = lat1)

m.drawmapboundary(fill_color='white')
m.fillcontinents(color='lightgrey',lake_color='white')

x, y = m(vsldf2['longitude'],vsldf2['latitude'])
#x1,y1 = m(vsldf3['longitude'],vsldf3['latitude'])
m.scatter(x,y,0.5,marker='o',c='dodgerblue',)
#m.scatter(x1,y1,0.5,marker='o',c='red',)
```

```
def find_round_trips(df, mmsi):
    vessel = df.loc[df['mmsi']==mmsi]
    lat_upper = -19.90000
    lat_lower = -20.620000
    long_right = 118.600000
    long_left = 116.650000
    times = []
    for index, row in vessel.iterrows():
        if row['latitude'] > lat_lower and row['latitude'] < lat_upper:
            if row['longitude'] > long_left and row['longitude'] < long_right:
                times.append(index)
            else:
                continue
        else:
            continue
    australien = df.iloc[times]
    actual_trips = 0
    rt = australien['unixtime'].diff()

    for elem in rt:
        if elem >800000:
            actual_trips += 1
    return actual_trips

find_round_trips(ship_ais_agg,351950000)
```

End of AIS Analysis

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