Norwegian School of Economics
Bergen, Spring 2023

Optimization Models for Collaborative Vessel Allocation

A Computational Study of How Collaboration Between Shipping Companies Can Reduce Fuel Costs and CO_2 Emissions

Maria Heggestad & Martine Bjerken Solbakken

Supervisor: Mario Guajardo

Master thesis, Economics and Business Administration

Major: Business Analytics

NORWEGIAN SCHOOL OF ECONOMICS

Acknowledgements

This thesis was written as a part of our Master of Science in Economics and Business Administration, with a major in Business Analytics, at the Norwegian School of Economics (NHH). The writing process has been exciting, challenging, and educational.

We want to express our gratitudes towards our supervisor, Mario Guajardo, for great motivation regarding the chosen topic for our thesis and for providing us a valuable dataset. We greatly appreciate the feedback, insights and quick replies that he has provided in this process. We would also like to thank The Norwegian Shipowners' Associations Fund at NHH for the grants provided.

Lastly, we want to express a thank you to our family and friends for valuable support during the process of working with this thesis.

Norwegian School of Economics

Bergen, June 2023

Maria Heggestad

Martine Bjerken Solbakken

Abstract

Transportation by sea entails costs for shipping companies as well as emissions that contributes to the challenges regarding global warming. A variety of approaches can be implemented in order to facilitate reductions of these measures. In our thesis, we study how collaboration between shipping companies that carries out a sequence of deliveries with time windows can be a way of reducing fuel costs and CO_2 emissions. To explore this, we formulate two optimization models in terms of mixed integer linear problems that minimizes the fuel costs resulting from the sequence of deliveries. The main decisions to be made in these models are the vessel allocation and the choice of speed levels. Fuel consumption forms the basis for the fuel costs and the CO_2 emissions. Because the relationship between speed and fuel consumption is nonlinear, the relationship is linearized to formulate linear models. Collaboration is defined in terms of a collaborative decision of vessel allocation and speed levels where the shipping companies join their fleets of vessels and the deliveries that are requested to be carried out.

In our computational study, the models are implemented using a dataset obtained from the company Signal Ocean. In addition, data regarding fuel consumption is collected from the Clarksons Research Portal. A variety of time window scenarios are implemented in order to explore the effects of collaboration when the underlying assumptions changes. The results show that joining the fleets of vessels and the requested deliveries in the decision of vessel allocation and choice of speed levels implies considerable reductions in both fuel costs and CO_2 emissions.

Keywords – Collaboration, Vessel Allocation, Speed Optimization, Mixed Integer Linear Programming, Fuel Costs, CO_2 Emissions

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

The trade of commodities is a crucial part of the world economy. Several means of transport are utilized in order to satisfy the need of delivering goods between different countries. According to UNCTAD (2022, p. XV) the shipping industry accounts for 80% of the world trade. This entails costs for the shipping companies and substantial emissions that contributes to the challenges regarding global warming.

Four groups of commodities form the building-blocs of the world's economic activity (energy, mining, agriculture and forestry). In order for the world economy to work efficiently these commodities need to be transported, often by sea, from areas of surplus to areas of shortage, and this need forms the basis for the demand faced by shipping companies (Stopford, 2008, p. 54). The group of liquid bulks, as a part of the energy commodities, accounts for about one-third of the global shipping cargoes (Lyridis and Zacharioudakis, 2012, p. 205). The demand for transportation of liquid bulks by sea regards transporting the products from producing countries to the rest of the world. The demands are formulated as a requested delivery of a product from a point of pickup to a point of delivery, within a given time window. The overall demand are faced by a large group of companies, which operates with a variety of economic goals. Typically, the type of company that engage in the deliveries of oil and other liquid bulks manage a fleet of vessels that needs to be allocated in order to fulfill the requested deliveries. The vessel allocation could have great impact on the company's costs.

One important aspect of the company's vessel allocation that affects the costs is that the various vessels in the fleet have different characteristics regarding fuel consumption. This is related to factors such as the design of the main engine of the vessel (Stopford, 2008, p. 234). The shipping company will thereby benefit from utilizing the fleet of vessels in a efficient way, because the fuel consumption required to sail a given distance can be quite different if two vessels are compared. Another important aspect is that in the transportation of oil, as a liquid bulk, it is typical that the vessels sail either fully loaded or empty (Psaraftis and Kontovas, 2014). In order for a shipping company to fulfill a sequence of deliveries, the vessels will need to sail empty from the delivery point of one delivery to the pickup point of the next. Thereby, when allocating the vessels to the deliveries, empty sailings need to be considered because the difference in fuel consumption between loaded and empty sailings can be substantial (Psaraftis and Kontovas, 2014). In this thesis, empty sailings are referred to as ballast sailings. Another aspect that the shipping company can benefit from in terms of fuel consumption is choosing the speed level of the sailings in an efficient way. A speed reduction will reduce the fuel consumption, which is due to the fact that fuel consumption can be represented as a nonlinear function of speed where low speed levels correspond with low fuel consumption (Norstad et al., 2011). However, the shipping company often needs to satisfy a given time window in the delivery, which may limit the possibility of sailing with low speed.

From the economic point of view, the shipping company will try to maximize their profits. Facilitating cost reductions is one way of working towards this goal, and for a shipping company the cost of carrying out a delivery is a major cost. When quantifying these costs, the fuel consumption is a crucial parameter because the fuel cost represents a substantial part of the total cost associated with sailing a given distance. Reducing the fuel consumption will result in a reduction of fuel cost. This means that a shipping company may be able to reduce their costs by allocating their vessels in a way that facilitates the use of efficient vessels combined with choosing appropriate speed levels. In addition, the vessel allocation should be carried out in a way that considers the empty sailings in order to optimize the fuel consumption.

Regarding the emissions from the shipping industry on a global basis, there has been a negative trend. Between 2012 and 2018 the greenhouse gas emissions produced by the shipping industry increased with 9,6% (IMO, 2021, p. 1). In addition, the CO_2 emission levels are projected to be between 90% and 130% in 2050 compared to 2008 (IMO, 2021, p. 3). The shipping companies such as the companies carrying oil products have a social responsibility to work towards reducing the emissions. The International Maritime Organization (IMO) have formulated a GHG Strategy with two main goals (IMO, nd). The first goal is to reduce the carbon intensity of international shipping by at least 40% by 2030 compared to 2008 levels. The second goal involves reducing the total annual GHG emissions from international shipping by at least 50% by 2050, also compared to

2008 levels. In order to achieve these goals, the shipping companies need to commit to the work of reducing their carbon footprint. Fuel consumption is an important determinator of the emissions, and thereby working towards reducing the fuel consumption that results from carrying out deliveries is one way of committing to this work.

Collaboration between shipping companies could be one approach of working towards reducing the fuel consumption in the shipping industry. By collaborating, the companies can join their fleet of vessels as well as their requested deliveries and work with this joined fleet when allocating vessels to the deliveries. In this way the companies could exploit the most efficient vessels in a different way. This may lead to a reduction in the total fuel consumption produced by the fleet, and thereby reductions of both costs and emissions. This way of vessel sharing in terms of container allocation is studied by Qiu et al. (2018) where it is concluded that vessel sharing provides benefits both in terms of significant profit improvements and reductions in CO_2 emissions. In addition, Lei et al. (2008) concludes that the largest cost savings from collaboration is possible if the carriers engage in a total collaboration of all the companies.

1.2 Scope of Research

In this thesis, we want to explore if the fuel cost and the CO_2 emissions resulting from a given sequence of pickup and deliveries could be reduced if the shipping companies that are responsible for the deliveries collaborates. The way we define collaboration is that the companies decide the vessel allocation and speed levels as a joint decision where the fleets of vessels are joined as well as the requested deliveries. Fuel consumption is assumed to be the main determinator of both fuel costs and emissions. With this basis, the research question for our thesis is as follows:

How collaboration between shipping companies can reduce the fuel costs and CO_2 emissions by exploring the optimal vessel allocation and speed levels in a sequence of pickup and deliveries with time windows

The research question is explored by formulating mathematical optimization models and conducting several computational implementations of the models with data obtained from the company Signal Ocean and the Clarksons Research Portal. The use of optimization models for the purpose of planning in the shipping industry is well documented in literature, where several models for problems like vessel allocation and speed optimization are formulated by different researchers. When the scale of the problems becomes large, the use of manual planning will be complicated, and optimization models are a tool to make the planning processes more effective. In order to implement the formulated models in the computational study A Mathematical Programming Language (AMPL) is utilized as the computer tool.

1.3 Structure of the Thesis

In the first chapter of the thesis, we introduce the background and the scope of research for our work. Chapter 2 describes central aspects of the shipping industry. In Chapter 3, we present a literature review of relevant research. Chapter 4 provides a detailed problem description. The mathematical formulations of our optimization models are presented in Chapter 5. In Chapter 6 we describe relevant aspects of the data inputs, the estimation of CO_2 emissions, the computational implementation as well as the dataset obtained from Signal Ocean. In Chapter 7 we present the results of the computational implementation, while the managerial considerations, limitations of the models and suggestions for future research are discussed in Chapter 8. The work and main results from our thesis are concluded in Chapter 9.

2 Central Aspects of the Shipping Industry

Shipping is one of the three key players that together with port/terminal operating and freight forwarding make up the maritime logistics system (Lee et al., 2012, p. 11). The maritime logistics system is defined as “the process of planning, implementing and managing the movement of goods and information involved in the ocean carriage” (Lee et al., 2012, p. 11). In this chapter we will describe some relevant aspects of the shipping industry that relates to the maritime logistics system.

2.1 Bulk Shipping

According to Stopford (2008, p. 62), world trade can be divided in three streams: bulk cargo, general cargo and specialized cargo. These streams create demands for the three segments of bulk shipping, liner shipping, and specialized shipping. Specialized shipping concerns large parcels of heterogenous cargo like motor cars and forest products, while liner shipping concerns individual parcels like containers and loose cargo that are too small to fill a vessel. Bulk shipping involves the transportation of large individual parcels. Stopford (2008, p. 64) defines three classes of commodities within bulk shipping: liquid bulk, major bulks and minor bulks (the last two together are also referred to as dry bulk). There are five major bulks; iron ore, grain, coal, phosphates and bauxite, while minor bulks consist of, among other things, steel products, cement, sugar and chemicals. Liquid bulk requires transportation with tankers, and the main types of liquid bulks are crude oil, oil products, liquid chemicals, vegetable oils and wine.

2.2 Cost Classification

There is no standard cost classification method that is universally accepted in the shipping industry. Stopford (2008, p. 221) presents a classification where the cost of a shipping company is divided in five categories. These categories and selected costs are presented in Table 2.1. A common feature of these costs is that they vary depending on the vessels age and size.

Operating Costs	**Periodic Maintenance Costs**	**Voyage Costs**	**Capital Costs**	**Cargo-Handling Costs**
Expenses related to the day-to-day running of the vessel, excluding fuel cost	Costs of major repairs	Variable costs associated with each voyage, including fuel cost	Dividends, interest and capital payments	Costs of loading and discharging

Table 2.1: Five categories of costs for a shipping company

2.2.1 Voyage Costs

The voyage costs constitute about 40% of the total costs (Stopford, 2008, p. 232). In the classification described by Stopford (2008, p. 233) fuel cost is identified as the most essential component of the voyage costs, as it accounts for approximately 47% of these costs. The cost of fuel is vulnerable to several different external factors that is beyond the shipping company's control. Thereby, it is hard for the shipping company to control the fuel cost component of the voyage costs. However, the fuel cost is determined by both the cost of fuel and the fuel consumption, where the fuel consumption is possible to influence to a greater extent. Various measures in order to reduce the fuel consumption can result in reductions of fuel costs and thereby the voyage costs. Other types of voyage costs listed by Stopford (2008, p. 233) are port dues, tugs, and canal charges. Besides the fact that these costs often depend on vessel characteristics, they are often outside of the shipping company's control.

2.3 Greenhouse Gas Emissions in the Shipping Industry

According to Ritchie and Roser (2020), the yearly greenhouse gas emissions resulting from all human activity are about 50 billion tons, which corresponds to an increase of 40% compared to measures from 1990. The greenhouse gas emissions consist of several gases: carbon dioxide (CO_2), methane, nitrous oxide and fluorinated gases. Carbon dioxide is the most dominant of these greenhouse gases, and in discussions of climate change the focus tend to be on this measure (Ritchie and Roser, 2020).

The shipping industry contributes to about 3% of the total greenhouse gas emissions (King, 2022). As mentioned above, CO_2 emissions are the main part of the greenhouse gas emissions. Over the last years, CO_2 emissions from the world fleet in the shipping industry show an increasing trend (UNCTAD, 2022, p. 107). In order to work towards changing this trend several initiatives for measures have been taken, among others from IMO as mentioned in Section 1.1. The three major categories of measures, as discussed by Psaraftis (2012), are the technological measures, the logistics-based measures and the market-based measures. These categories represent different ways of working towards reducing the projected increase in CO_2 emissions. The technological measures concerns factors such as developing more efficient vessel engines or using cleaner and alternative fuel types. The logistics-based measures include the implementation of speed optimization, optimal fleet management/deployment and other factors that concerns the logistical operations. Lastly, the market-based measures include a variety of measures like emission trading schemes and international funds based on a contribution imposed on fuel.

2.4 Fuel Consumption

The amount of fuel that a vessel consumes depends on a variety of factors, mainly different vessel characteristic and sailing speed. Regarding the vessel, the design of the main engine is important as well as the hull condition and auxiliary equipment (Stopford, 2008, p. 234). In addition, the vessel size and age are important determinators of the amount of fuel consumed. Often, the engines of older vessels are less efficient compared to new engines and thereby consumes a larger amount of fuel on the same distance.

In addition to the vessel specific characteristics, fuel consumption is sensitive to speed (Stopford, 2008, p. 234). Lower speed results in lower fuel consumption levels, which is a result of lower water resistance. The fuel consumption per time can be expressed with the rule presented in Equation (2.1). Most of the modern vessels have diesel engines (Stopford, 2008, p. 229). For diesel engines, the exponent a has a value of 3, which implies that the equation is referred to as the cube rule. Thereby, the relationship between speed and fuel consumption is a nonlinear relationship where fuel savings will be approximately proportional to the cube of the proportional reduction in speed (Stopford, 2008, p. 234).

$$\text{Fuel consumption (tpd)} = \text{Design fuel consumption} \times \left(\frac{\text{Actual speed}}{\text{Design speed}}\right)^{a} \tag{2.1}$$

3 Literature Review

In this chapter we present a literature review of research that is relevant for the scope of our thesis. The chapter is introduced by a summary of research in the field of the pickup and delivery problem with time windows, which is followed by the topic of the fleet deployment problem. Further, papers introducing speed optimization in decision models as well as linearization of the relationship between speed and fuel consumption are presented. The chapter ends with a description of studies that examines collaboration in terms of vessel sharing agreements.

The pickup and delivery problem with time windows where vehicles transport loads from origins to destinations were studied by Lau and Liang (2002). In the paper, they presented a two-phase method. In the first phase construction heuristics were applied to generate an initial solution, while the second phase consisted of a tabu search method to improve the solution. The results from implementing these two phases were close to a benchmark designed by the authors. Liu et al. (2023) presented another two-stage model regarding the pickup and delivery problem with time windows, applied to the case of battery-powered electric vehicles. The two stages in this paper involved decomposing the problem into a master problem and an adversarial separation problem. Two different algorithms were applied to solve the problems (a tailored branch-price-and-cut algorithm for the master problem and a dynamic programming algorithm for the adversarial separation problem). The results indicated that the developed algorithm was able to solve large-scale instances within reasonable computational times (Liu et al., 2023).

Within the field of maritime transportation, Andersson et al. (2011) studied the pickup and delivery problem with time windows from the perspective of a bulk shipping company, introducing split loads as an important part of the problem formulation. Split loads implies that each cargo can be distributed among several vessels. In the paper they presented several solution methods to solve the problem, including an arc flow formulation, an a priori generation of single ship schedules, and two alternative path flow formulations. The paper concluded that introducing split loads improved the solution quality, while at the same time it made the problem more computationally demanding as solving larger instances were not possible (Andersson et al., 2011).

In the literature we found several approaches for studying the fleet deployment problem. Gelareh and Meng (2010) developed a model for a short-term fleet deployment problem of liner shipping operations by first formulating a mixed integer nonlinear programming model and linearizing this formulation into a mixed integer linear programming (MILP) model. The model minimized costs by determining the optimal route service frequency pattern considering time windows. Fagerholt et al. (2009) also presented a model for the fleet deployment problem in liner shipping, implemented in the context of Roll-On, Roll-Of (RoRo) vehicle transportation services. To solve the problem, they presented a multi-start local search heuristic as a part of a prototype decision support system, which produced high-quality solutions compared to manual planning.

The fleet deployment problem was addressed together with the optimal routing problem by Alvarez (2009). In this paper, he presented a model and an algorithm in order to solve these problems jointly in the context of a single liner shipping company operating container vessels. The model included the revenues and operating costs of the shipping company and incorporated characteristics such as the possibility of rejecting demand against a penalty. In the paper, benchmark comparisons indicated that the algorithm worked well and managed to find solutions in a relatively quick manner. Wang and Meng (2012) studied the fleet deployment problem regarding container operations by formulating a MILP model that allowed transshipment of containers. The model minimized the total weekly costs of a liner shipping company (operating costs, berth occupancy charge, transshipment costs, loading and discharge cost, cost of chartering in ships and accounting for the profits from chartering out ships) while allowing for transshipments at any port any number of times. The model accounted for transshipment in a way that, according to the authors, were not captured in earlier literature. The main contributions from the paper were the insights from the transshipment considerations and how the ship utilization in the optimal solution can be used to redesign liner shipping routes.

Andersson et al. (2015) also studied the fleet deployment problem. In this study, they combined the deployment problem with speed optimization applied in a case study from RoRo-shipping. In the paper a new modeling approach were introduced to combine the two concepts into one model, as well as a rolling horizon heuristic to solve the problem. The paper concluded that the integrated modelling of fleet deployment and speed optimization together with the rolling horizon heuristic provided significantly better solutions compared to solving the problem with a commercial solver.

Speed optimization is a well studied topic in the field of maritime transportation. Andersson et al. (2015) argued that up until they conducted their study, sequential approaches were the most common when studying speed optimization. However, we found studies where other approaches were used. In Norstad et al. (2011) the tramp ship routing and scheduling problem with speed optimization was presented, where speed on each sailing leg was defined as a decision variable. To solve the problem, they presented a multi-start local search heuristic. The model maximized the profit from operating the fleet, where the company carry some contracted cargoes and gain additional revenue from spot cargoes. In the model, a quadratic relationship between fuel consumption per distance unit and speed was highlighted. Thereby, they formulated a nonlinear model, and solved it with the local search heuristic. The paper concluded that the speed optimization improved the profits significantly compared to integrating fixed speed. This could be explained by the fact that that speed increases makes it possible to carry more spot cargoes and that speed reductions results in lower fuel consumption (Norstad et al., 2011).

Wang et al. (2020) studied speed optimization in the context of the interaction between speed and route under the influence of multiple environmental factors. Based on this interaction, they formulated a nonlinear joint optimization model with a goal of exploiting the potential energy efficiency. To solve the model, the particle swarm optimization (PSO) algorithm was adopted. A case study that implemented the model and the algorithm for a single vessel showed that fuel consumption and CO_2 emissions were reduced with about 4% compared to the original operational mode.

As mentioned in Section 2.4, the relationship between speed and fuel consumption can be represented by a nonlinear function. The papers regarding speed optimization presented above assume this relationship to hold and thereby formulate nonlinear models. Other papers formulate linear models by linearizing this relationship. One example of this approach was found in Pasha et al. (2021), where an integrated optimization model was formulated to maximize the total turnaround profit generated from liner shipping operations. In the model formulation, the ship sailing speed were replaced by its reciprocal while at the same time the fuel consumption function was linearized using a piecewise linear approximation. Another example is observed in Andersson et al. (2015), where the non-linear fuel consumption function was approximated by discrete speed alternatives and linear combinations of these. This method represents a piecewise linearization. It is important to recognize that the linearization methods implies an overestimation of the fuel consumption because of the convexity of the non-linear function.

Collaboration between shipping companies can take different forms, where vessel sharing agreements were found to be implemented in several studies. Qiu et al. (2018) formulated different mathematical models with and without vessel sharing. In this paper, the authors quantified both the economic and environmental impact of vessel sharing by conducting numerical studies where the results from the two mixed integer linear programming models were compared. The models aimed to maximize the profits by deciding the optimal fleet deployment and container allocation. The model that included vessel sharing maximized the joint profits of all the shipping alliance members, while the model that excluded vessel sharing maximized the profits of each company. Results from implementing these models showed that vessel sharing provided benefits both in terms of significant profit improvements and reductions in CO_2 emissions. The paper concluded that such vessel sharing benefits both the companies and the environment.

Another approach to the study of collaboration was observed in Lei et al. (2008). They studied collaborative container-vessel scheduling by modeling three different managerial policies (non-collaborative, slot-sharing and total collaboration), where operating costs were the measure to be minimized in the models. The operational performance of container-vessel schedules resulting from these policies were investigated by conducting an empirical study involving two hypothetical carriers serving the same route. The result of the empirical study indicated that there were large differences in the operating costs when implementing the different policies, and that the largest potential cost saving was possible if the carriers engaged in total collaboration.

In this literature review we found several approaches to the formulation of optimization models related to the pickup and delivery problem with time windows, the fleet deployment problem and speed optimization. In addition, we described some studies conducted in the field of collaborative agreements.

4 Problem Description

The problem to be explored in this thesis is how collaboration between different shipping companies can reduce the fuel costs and CO_2 emissions that results from a sequence of deliveries in a given period of time. The problem is explored by formulating optimization models that aim to allocate a fleet of vessels and decide speed levels while ensuring that all the deliveries in the time period are fulfilled. In this chapter, we describe the characteristics of the problem that forms the basis for these models.

The models are based on a collection of observations in a given time period. Each observation constitutes a pickup and delivery performed by a given vessel, where all deliveries are of the same single commodity. The pickup occurs in a load port at a given time. Correspondingly, the delivery occurs in a discharge port at a given time. The observations are one-to-one deliveries, in the way that there are neither any intermediate stops in the delivery, nor any transshipment within the ports. This set of observations will be referred to as the base situation.

In the base situation, a heterogeneous fleet of vessels are carrying out the deliveries. It is assumed that all the vessels can carry out all the deliveries within its given capacity and that all vessels are available in the time period. The heterogeneity of the vessels relates to the fact that they have varying characteristics regarding capacity and fuel consumption.

A delivery is defined as a laden voyage. All laden voyages are required to be carried out, with the same quantity, from the same load port and to the same discharge port as in the base situation. If a given vessel is assigned several laden voyages, it is required to carry out a ballast sailing. A ballast sailing is defined as the sailing from the discharge port of one laden voyage to the load port of another laden voyage.

Regarding time, the vessel is required to start the sailing of a laden voyage (from the load port) at the same date as in the base situation +/- a time window. Correspondingly, the same applies to the time of arrival in the discharge port. The time windows are hard (no violations allowed) because the shipping companies are obliged to fulfil the requested deliveries by satisfying the time windows.

The fact that the fuel consumption (and thereby both fuel cost and CO_2 emissions) is dependent on speed, implies that speed is an important part of the problem. For each laden voyage and each ballast sailing, the speed is decided in order to minimize the fuel costs. The relationship between speed and fuel consumption per time can be illustrated as a cubic function (Stopford, 2008, p. 234). Another feature of the fuel consumption function is that it is convex over the range of feasible speeds (Norstad et al., 2011). To keep the problem tractable in computational terms and be able to formulate a linear model, some modifications are made in order to linearize this relationship. For these purposes, speed is defined in terms of distinct speed levels. As for the fuel consumption, the values of these speed levels are inserted in Equation (4.1) as the actual speed together with the design speed and the design fuel consumption for a given vessel. The result of this is a fuel consumption parameter for each distinct speed level for each individual vessel. Because of the cubic and convex features of the fuel consumption function, this linearization will lead to an overestimation of the fuel consumption. Note that Equation (4.1) is the same as Equation (2.1), except that a is replaced with 3.

$$\text{Fuel consumption (tpd)} = \text{Design fuel consumption} \times \left(\frac{\text{Actual speed}}{\text{Design speed}}\right)^3 \tag{4.1}$$

In the base situation, the deliveries are carried out by different commercial operators (shipping companies) that manages their separate fleets of vessels. It is assumed that the commercial operator that carries out a delivery with a given vessel manage this particular vessel. In the collaboration it is assumed that all laden voyages can be carried out by all the vessels (given the vessel capacity) regardless of what commercial operator manage the vessel in the base situation. In other words, the collaboration involves gathering the vessels into a joint fleet as well as the requested deliveries, where the vessel allocation and choice of speed level are carried out as a collaborative decision.

As mentioned in Section 2.2.1, fuel cost is identified as the most essential component of the voyage costs. The calculation of total fuel cost is expressed in Equation (4.2). The vessels vary in terms of characteristics related to their fuel consumption. Together with the vessel dependent factors, the fuel consumption is also dependent on speed level. These differences create the basis for the vessel allocation and choice of speed levels with the purpose of minimizing fuel costs. In addition to being the determinant of the total fuel cost, the fuel consumption forms the basis for the CO_2 emissions. In general terms, higher fuel consumption leads to higher CO_2 emissions. The assumed relationship between the fuel consumption and the CO_2 emissions will be described in detail in Section 6.2.

$$\text{Total fuel cost (USD/ton)} = \text{Fuel cost (USD/ton)} \times \text{Fuel consumption (ton)} \tag{4.2}$$

Two different models are formulated in order to solve the problem. The first model minimizes total fuel cost of the laden voyages and the ballast sailings. One characteristic with this model is that there is a form of punishment of sailing several voyages with the same vessel because the cost of the ballast sailing will increase the objective value. When this punishment is present it will often be better to utilize all the vessels and assign as few ballast sailings as possible. This holds unless there is a lower cost associated with sailing both the laden voyages and a ballast sailing with one vessel than sailing only the laden voyage with another less efficient vessel. To explore how the solutions change when this punishment is absent, we present a second model where the fuel costs of only the laden voyages are minimized. An important feature of this model is that when the fuel cost of the ballast sailings are left out of the minimization, it will be possible to choose high speed levels in the ballast sailings without affecting the value of the objective function. To avoid the possibility of choosing the highest speed levels in the ballast sailings (because this implies high fuel costs), a constraint is added to regulate the speed levels to be below a certain value. In the next chapter, the mathematical formulations of the optimization models are presented.

5 Optimization Models

The models in this thesis are formulated as MILPs. This means that the formulation of objective functions and constraints are linear (Linear Problem), while some of the variables are continuous and some discrete (Mixed Integer). In our models, the discrete variables are integer variables. This chapter presents the mathematical formulation of both optimization models. The total fuel cost model (model 1) is presented first. Then, the laden voyage fuel cost model (model 2) is presented. Because the second model represents minor changes relative to the first model, only the new elements are presented.

5.1 Model 1: Total Fuel Cost Model

This section presents model 1, which minimizes the total fuel costs of both laden voyages and ballast sailings. Sets, parameters, variables, objective function, and constraints are presented in separate sections.

5.1.1 Sets

V	Set of vessels
I	Set of load ports
J	Set of discharge ports
T	Set of laden voyages
S	Set of speed levels
LP_t	Set consisting of the load port for laden voyage t
DP_t	Set consisting of the discharge port for laden voyage t

5.1.2 Parameters

qu_t	Quantity (tons) to be transported for voyage t
n	Total number of voyages
c_v	Capacity (tons) of vessel v
g_t	The day that voyage t should start (as realized in base situation)
h_t	The day that voyage t should end (as realized in base situation)
p	Number of days required to stay in a port for loading/discharging
tl	Time window (days) for load port
td	Time window (days) for discharge port
d_t	Distance (nautical miles) for voyage t
f_{vs}	Fuel consumption (tons per day) for a given vessel v at a given speed level s
o_{ij}	Distance (nautical miles) between two given load/discharge ports i and j
k_s	Speed level s in knots
fc	Fuel cost (USD per ton)
r	Consumption ratio of a ballast sailing compared to a laden voyage
M	Sufficiently large number

5.1.3 Variables

x_{tv}	Quantity transported by vessel v for voyage t
y_{tvs}	Takes the value 1 if a vessel v sails voyage t with speed s, 0 otherwise
a_t	The day that the voyage t starts in terms of sailing from load port
ls_t	Number of sailing days for laden voyage t
z_{ttvs}	Takes the value 1 if vessel v carries out a ballast sailing between two laden voyages t and t with speed s, 0 otherwise
bs_{tt}	Number of sailing days for the ballast sailing between two laden voyages t and t

5.1.4 Objective Function

$$min \sum_{t\in T}\sum_{v\in V}\sum_{s\in S} fc \times f_{vs} \times ls_{tv} \times y_{tvs} + \sum_{t\in T}\sum_{v\in V}\sum_{s\in S}\sum_{u\in T:u>t} fc \times f_{vs} \times r \times bs_{tu} \times z_{tuvs} \quad (5.1)$$

The objective function (5.1) consists of two parts. The first part minimizes the fuel cost of the laden voyages. Mathematically this implies multiplying the fuel cost per ton (fc) with the fuel consumption for each laden voyage. The fuel consumption is calculated with the fuel consumption parameter (f_{vs}) for the specific vessel with the specific speed level. The unit of this parameter is tons per day, and thereby the number of sailing days of the laden voyage (ls_t) are included to obtain the total fuel consumption of the relevant laden voyage. The relevant vessel and speed level for the given laden voyage are clarified by y_{tvs}. In the second part of the objective function the fuel cost of the ballast sailings is minimized. This calculation follows the same reasoning as the calculation for the laden voyages, with some differences. A ballast sailing is assumed to consume less fuel compared to a laden voyage (all else equal), and thereby the consumption ratio of a ballast sailing compared to a laden voyage (r) is included in the calculation. In addition, the z_{tuvs} variable highlights the vessel and speed level for a given ballast sailing between two laden voyages. The bs_{tu} variable express the number of ballast sailing days in order to reach the right unit of fuel consumption to calculate the fuel cost in tons.

5.1.5 Constraints

Quantity and Capacity Constraints

$$\sum_{v\in V} x_{tv} = qu_t \qquad t \in T \qquad (5.2)$$

$$x_{tv} - M(1 - \sum_{s\in S} y_{tvs}) \le c_v \qquad t \in T, v \in V \qquad (5.3)$$

Constraints (5.2) ensure that the quantity that is required to be transported for a given laden voyage is satisfied. Constraints (5.3) ensure that a vessel with sufficient capacity is assigned to each laden voyage.

Laden Voyages Constraints

$$x_{tv} \leq M \sum_{s \in S} y_{tvs} \qquad t \in T, v \in V \tag{5.4}$$

$$\sum_{v \in V} \sum_{s \in S} y_{tvs} = 1 \qquad t \in T \tag{5.5}$$

$$\sum_{t \in T} \sum_{v \in V} \sum_{s \in S} y_{tvs} = n \tag{5.6}$$

Constraints (5.4) assign vessels to the laden voyages, where M is a sufficiently large number in order to assign the binary variable y_{tvs} the value 1 for the relevant laden voyage, vessel, and speed. Constraints (5.5) ensure that only one vessel is assigned to each laden voyage, while Constraints (5.6) ensure that all laden voyages are carried out.

Ballast Sailings Constraints

$$2 \times \sum_{s \in S} z_{tuvs} \leq \sum_{s \in S} y_{tvs} + \sum_{s \in S} y_{uvs} \qquad t \in T, u \in T, v \in V : u > t \tag{5.7}$$

$$\sum_{s \in S} y_{tvs} + \sum_{s \in S} y_{evs} \leq 2 - \sum_{s \in S} z_{tuvs} \qquad t \in T, u \in T, v \in V, e \in T : t < e < u, u > t \tag{5.8}$$

$$\sum_{s \in S} y_{tvs} + \sum_{s \in S} y_{uvs} \leq 1 + \sum_{b \in T : t+1 \leq b \leq u} \sum_{s \in S} z_{tbvs} \qquad t \in T, u \in T, v \in V : u > t \tag{5.9}$$

Constraints (5.7) - (5.9) decide the values of the binary z-variable to be equal 1 for a vessel and a speed level when a ballast sailing is conducted between two laden voyages.

Time Window Constraints

$$a_t \geq g_t - tl \qquad t \in T \tag{5.10}$$

$$a_t \leq g_t + tl \qquad t \in T \tag{5.11}$$

$$a_t + ls_t \geq h_t - td \qquad t \in T \tag{5.12}$$

$$a_t + ls_t \leq h_t + td \qquad t \in T \tag{5.13}$$

Constraints (5.10) and (5.11) ensure that for each laden voyage, the vessel starts sailing from the load port within the time windows. Constraints (5.12) and (5.13) ensure that for each laden voyage, the vessel arrives in the discharge port within the time windows.

Time Constraints

$$a_u \geq a_t + ls_t + 2p + bs_{tu} - M(1 - \sum_{s \in S} z_{tuvs}) \qquad t \in T, u \in T, v \in V : u > t \tag{5.14}$$

$$ls_t \geq \frac{d_t}{k_s} \times \frac{1}{24} - M(1 - y_{tvs}) \qquad t \in T, v \in V, s \in S \tag{5.15}$$

$$ls_t \leq \frac{d_t}{k_s} \times \frac{1}{24} + M(1 - y_{tvs}) \qquad t \in T, v \in V, s \in S \tag{5.16}$$

$$bs_{tu} \geq \frac{o_{ij}}{k_s} \times \frac{1}{24} - M(1 - z_{tuvs}) \qquad t \in T, u \in T, i \in LP_u, j \in DP_t, v \in V, s \in S : u > t \tag{5.17}$$

$$bs_{tu} \leq \frac{o_{ij}}{k_s} \times \frac{1}{24} + M(1 - z_{tuvs}) \qquad t \in T, u \in T, i \in LP_u, j \in DP_t, v \in V, s \in S : u > t \tag{5.18}$$

$$M \sum_{v \in V} \sum_{s \in S} z_{tuvs} \geq bs_{tu} \qquad t \in T, u \in T : u > t \tag{5.19}$$

Constraints (5.14) ensure that when a vessel is occupied (in terms of carrying out a laden voyage or a ballast sailing), it cannot start another laden voyage or a ballast sailing. Constraints (5.15) and (5.16) calculate the number of sailing days for each laden voyage. Constraints (5.17) – (5.19) calculate the number of sailing days for each ballast sailing.

Auxiliary Constraints

$$x_{tv} \geq 0 \qquad t \in T, v \in V \tag{5.20}$$

$$bs_{tu} \geq 0 \qquad t \in T, u \in T : u > t \tag{5.21}$$

$$ls_t \geq 0 \qquad t \in T \tag{5.22}$$

$$a_t \in \mathbb{Z}^+ \qquad t \in T \tag{5.23}$$

$$z_{tuvs} \in \{0,1\} \qquad t \in T, u \in T, v \in V, s \in S : u > t \tag{5.24}$$

$$y_{tvs} \in \{0,1\} \qquad t \in T, v \in V, s \in S \tag{5.25}$$

Constraints (5.20) – (5.25) define the domain of the variables.

5.2 Model 2: Laden Voyage Fuel Cost Model

In this section, model 2 is presented. As mentioned in Chapter 4, this model is formulated in order to explore the differences when the punishment for the ballast sailings in model 1 are modified. Model 2 is mainly the same as model 1, with some changes. In the objective function only the fuel cost of the laden voyages is minimized. In addition, one constraint is added. Apart from these changes all sets, parameters, variables, and constraints are the same as in model 1.

5.2.1 Objective function

$$min \sum_{t \in T} \sum_{v \in V} \sum_{s \in S} fc \times f_{vs} \times ls_{tv} \times y_{tvs} \tag{5.26}$$

The objective function (5.26) minimizes the fuel cost of the laden voyages. The calculation of fuel cost is the same as the first part (the laden voyages)of the objective function in model 1 (Equation (5.1)).

5.2.2 Constraints

$$\sum_{t \in T} \sum_{u \in T : u > t} \sum_{s \in S : s \leq 10} \sum_{v \in V} z_{tuvs} = 0 \tag{5.27}$$

Constraints (5.27) restrict the speed levels of the ballast sailings to be maximum ten knots. Note that these constraints, that assign binary variables the value 0, is equivalent to removing these variables from the variable declarations.

6 Computational Implementation

In this chapter, the computational implementation of the models is described and presented. First the data inputs are described. Then we describe our approach for calculating the CO_2 emissions. Further, other relevant aspects of the implementation are described. Lastly, we present relevant measures and data instances from the base situation. To analyze the base situation and prepare the data for the implementation of the models, R is used as a data analysis tool.

6.1 Data Description

In this section we first describe our assumptions and reasonings related to different parameter values. The estimation of fuel cost is assigned its own section. Then, the process of estimating fuel consumption is described in detail. As mentioned in the introductory part of the thesis, the main dataset used in the computational implementation is obtained from the company Signal Ocean. This dataset represents the base situation. In addition, fuel consumption data is obtained from the Clarksons Research Portal.

6.1.1 Description of Different Data Inputs

In the implementation of the optimization models, all the runs are performed by using the same dataset (the base situation). The time period considered is the month of May in 2019, which makes the time period of the base situation 31 days. During this time period, 51 laden voyages are carried out by a fleet consisting of 48 vessels. Regarding ports, 29 different load ports are visited. The port in Rotterdam is the only discharge port included, because of computational considerations related to the size of the dataset.

The laden voyages in the base situation are happening in a given order, which is required to be sustained in the new collaborative solution. Each laden voyage in the base situation is thereby assigned an unique ID from 1 to 51 referred to as the voyage number. The voyage numbers are included in the models as set T. The voyage number is based on the sequence of the laden voyages, ordered by the day and time that the vessel started sailing from the load port in the base situation. Eight different speed levels are included in set S (2, 4, 6, 8, 10, 12, 14 and 16 knots). These speed levels are divided into speed categories to ease the discussion of the results. Table 6.1 provides an overview of the defined speed categories.

Speed Category	**Speed**
Very Low Speed	2 knots
Low Speed	4 knots & 6 knots
Medium Speed	8 knots & 10 knots
High Speed	12 knots & 14 knots
Very High Speed	16 knots

Table 6.1: Speed categories

It is assumed that all vessels in the base situation sail the laden voyages with full capacity. The vessel capacity is assumed to be 95% of the vessel's deadweight (Stopford, 2008, p. 752). The quantity that is required to be delivered in a given laden voyage is thereby calculated based on the deadweight of the vessel carrying out the voyage in the base situation.

To ensure that all deliveries satisfies the time windows, each laden voyage in the base situation is assigned a start and end day in terms of integer numbers. The start day parameter ranges from 8 to 38. The total time period of 31 days is the basis for these values, while seven days are added in the beginning of the time period in order to facilitate the use of different values for the time windows (the maximum value of time windows applied in the implementation is four days, but it would be possible to explore up to seven days). The first laden voyage (that started 01/05 in the base situation) is thereby assigned start day 8, while the last laden voyage (that started 31/05 in the base situation) is assigned start day 38. The end day parameter follows the same reasoning as the start day, except that the end day does not have an upper bound.

It is assumed that both the loading process and the discharging process of the cargo requires one day, regardless of the port and the vessel. In each laden voyage, the vessel is thereby required to stay in the load port one day before the sailing can start, and equally one day in the discharge port after the sailing is completed.

As described in Chapter 4, there is a time window for both the loading and the discharging of the vessel for the laden voyages. The time windows are expressed as a number of days.

We assume that the time of pickup is somewhat more flexible than the time of delivery. Thereby, we assume that the time windows are one day greater for the load port than the discharge port. The specific values of these time windows vary between the different runs of the models to explore how the effects of collaboration changes when different time windows are implemented. The time windows range from one to four days. The greatest value, four days, allows for a total pickup window of nine days (the requested day of pickup +/- four days), which is considered to be quite flexible. Table 6.2 presents an overview of the time window variations explored throughout the implementation.

	Tighter Time Windows	**Medium Time Windows**	**Wider Time Windows**
Load Port	2 days	3 days	4 days
Discharge Port	1 day	2 days	3 days

Table 6.2: Overview of time windows

The distance of each laden voyage is given in the base situation, which forms the basis for the value of the distance parameter in the models. The sailing distance of a ballast sailing is assumed to be the average of the distances of all the laden voyages between two given ports in the base situation. The reasoning behind calculating the average is that the actual distance between two given ports varies in different laden voyages. These variations could be explained by factors such as weather conditions or availability of canals. Some distances in the base situation seem to be affected by the availability of canals. In some cases, vessels carrying out deliveries from Asia to Rotterdam sail a distance that resembles sailing through the Suez Canal. In other cases, the vessel sails a distance resembling a sailing around the African continent. In the dataset, this does not seem to be decided by the size of the vessels, and no other clear patterns were detected in these laden voyages. Thereby, the average distance is perceived to be a reasonable assumption for the ballast sailings.

6.1.2 Fuel Cost

According to Ship & Bunker News Team (2021), high sulfur fuel oil (HSFO) was the fuel type used by the majority of vessels in 2019. The fuel cost is assumed to be USD 405 per ton, which equals the global 20 ports average price for HSFO in the year of 2019 (Ship & Bunker News Team, 2021). The price is assumed to be fixed in the time period. As a simplification in the implementation of the models, it is assumed that all the vessels in the fleet use the HSFO fuel type. It is important to recognize that the fuel price is a fluctuating measure. The assumption that the price is fixed through the whole time period is somewhat unrealistic. However, this simplification is considered acceptable for the scope of this thesis, because the focus is vessel allocation and choice of speed levels, not the adaption to fluctuating external costs.

6.1.3 Estimation of Fuel Consumption

In order to estimate each vessel's unique fuel consumption for each speed level, several steps of data collection and assumptions were required. The cube rule presented in Equation (4.1) forms the basis for the estimation of the fuel consumption. In this section, we describe the data collection steps and assumptions.

The design fuel consumption and design speed are fixed for each vessel, while the actual speed varies with the different speed levels in the set S. The vessel specific measures were collected from Clarksons Research Portal, which is a collection of databases that requires a license in order to access data. This license was provided by NHH. Clarksons Research Portal consists of several databases, among others the Clarksons Fleet Register and the Clarksons Shipping Intelligence Network which the licence provided access to. The measures of design fuel consumption and design speed for individual vessels were collected from Clarksons World Fleet Register (Clarksons Research, ndb). For some vessels this data was missing, and for these cases it was assumed that average data for a peer group based on vessel size and age provided an appropriate estimate. This peer group data was collected from Clarksons Shipping Intelligence Network (Clarksons Research, nda). Some of the vessels were missing available data about a peer group. In these cases, we replicated the approach of creating a group of vessels with similar size and age and based the estimates of design speed and design fuel consumption on the average measures in this group. In the creation of these groups, some vessels needed an estimate for size. The size estimate for these vessels was calculated as an average of the size of a group of other vessels with similar deadweight tonnage and age. It is important to recognize that in this process several critical assumptions were made. Among others, the use of average measures is less precise than accurate measures, and the choice of vessels groups are crucial. However, for the purpose of this thesis these limitations are considered appropriate.

In a ballast sailing, compared to a laden voyage, the fuel consumption is generally lower, as mentioned in Section 1.1. Based on the vessel fuel consumption function presented in Wang et al. (2019), it is assumed that in a ballast sailing the fuel consumption will be 80% of the fuel consumption with a fully loaded vessel (laden voyage). This ratio is assumed to hold for all vessels in the dataset. For the purpose of calculating the fuel consumption of a ballast sailing, the Equation (4.1) is thereby multiplied by 80%, expressed in Equation (6.1).

$$\text{Fuel consumption (tpd)} = \text{Design fuel consumption} \times \left(\frac{\text{Actual speed}}{\text{Design speed}}\right)^3 \times 0.8 \tag{6.1}$$

6.2 Estimation of CO_2 Emissions

In order to evaluate the CO_2 emissions resulting from the proposed solutions the measure of fuel consumption is utilized. Estimation of CO_2 emissions are calculated in the run files, which means that they are calculated based on the results (the CO_2 emissions are not incorporated as criteria in the model formulations). Equation (6.2) describes how the CO_2 emissions are calculated, obtained from Corbett et al. (2009). Equation (6.3) displays the CO_2 formula with the numerical values, presented by Corbett et al. (2009).

$$\text{CO}_2\text{ (kg)} = \text{Fuel's carbon fraction} \times \text{Carbon to CO}_2\text{ factor} \times \text{Fuel consumption} \tag{6.2}$$

$$\text{CO2 (kg)} = 0.8645 \times \frac{44}{12} \times \text{Fuel consumption} \tag{6.3}$$

The unit of the fuel consumption is tons per day (tpd). To calculate the CO_2 emissions for a given laden voyage the Equation (6.3) is multiplied by the number of sailing days for the laden voyage. The calculation of CO_2 for a given laden voyage is displayed in Equation (6.4). For the purpose of calculating CO_2 emissions for a given ballast sailing, both the sailing days and the fuel consumption ratio for ballast sailings are taken into account, displayed in Equation (6.5).

$$\text{CO2 (kg) Laden voyage} = 0.8645 \times \frac{44}{12} \times \text{Fuel consumption} \times \text{Sailing days} \tag{6.4}$$

$$\text{CO2 (kg) Ballast sailing} = 0.8645 \times \frac{44}{12} \times \text{Fuel consumption} \times 0.8 \times \text{Sailing days} \tag{6.5}$$

Equations (6.4) and (6.5) show the assumed relationship between the fuel consumption and the CO_2 emissions. By comparing these equations to the objective functions of the models it is observed that the fuel consumption is the determinant of both the CO_2 emissions and the fuel cost together with the sailing days. Because fuel consumption and sailing days are the determinants of both measures, the percentage change in these measures will be equal in all runs.

6.3 Implementation

The models were implemented in AMPL, as mentioned in Section 1.2. The solver used in the implementation was Gurobi Optimizer version 10.0.1. A Windows 11 computer with Intel(R) Core(TM) i7-9850H CPU @ 2.60GHz with 32 GB RAM was utilized. 6 of 12 available threads were used. In this section, the AMPL files are described as well as the choice of time limit in the runs.

6.3.1 Description of AMPL Files

To run a model in AMPL, three files are required; the .mod file (model file), .dat file (data file) and .run file (run file). The model file contains the mathematical formulation of the model. In our implementation, two different model files were used, depending on the model. The data files contained the values of the simplest parameters and sets. The majority of the data was imported in the run file by applying AMPLs functionality of reading data from Excel (amplxl.dll). Further, the run files contained the code necessary to run the model, like calling the correct solver, model, and data files, and printing the results to a .txt file. In addition, the run files contained codes for calculating the CO_2 emissions of both the laden voyages and the ballast sailings in the respective solution, as well as the separate measures of fuel costs for the laden voyages and the ballast sailings.

All files needed to run the models are attached as appendices in a separate zip folder.

6.3.2 Time Limits

In the implementation of the models in AMPL, it was discovered that running the models without time limits did not provide the optimal solutions within a reasonable time. Through a process of exploring different time limits and observing the gap, we decided that our criteria for obtaining feasible solutions within a reasonable time was to impose a time limit. The time limits criteria resulted in feasible solutions with gaps of at most 3,78%. In the different runs, depending on the size of the problems, the time limit varied within the range from one to ten hours.

6.4 Base Situation

In this section, the relevant measures from the base situation are presented. These measures serve as the benchmark for the results from the computational implementations. In Table 6.3, the calculated fuel cost and CO_2 emissions of the laden voyages in the base situation are presented.

	Base Situtaion
Fuel Cost Laden Voyages (USD)	7 067 509
CO_2 Emissions Laden Voyages (kg)	55 316

Table 6.3: Fuel costs and CO_2 emissions base situation

Regarding the ballast sailings there is an inconsistency between the data from the base situation and the results from implementing the models. In the base situation, all the laden voyages are recorded with a belonging ballast sailing. In the new proposed solutions, ballast sailings will only be carried out if the same vessel is assigned to multiple laden voyages. Thereby, the ballast sailings that are considered from the base situation when comparing results, are the ballast sailings that belongs to the same voyage numbers as in the new solution.

Table 6.4 presents an overview of the ten first laden voyages in the base situation. In each of the new proposed solutions, a similar overview will be presented to highlight the changes in vessel allocation, start/end day, speed, fuel costs, and CO_2 emissions.

*	**Vessel Name**	**Load Port**	**Discharge Port**	**Start Date**	**End Date**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
1	Dalma	Basrah	Rotterdam	01/05	27/05	10,96	370 040	2 896
2	Nautilus	Kuwait	Rotterdam	01/05	08/06	12,79	841 959	6 590
3	Pelagos	Ust-Luga	Rotterdam	02/05	08/05	10,13	38 876	304
4	Waikiki	Vysotsk	Rotterdam	04/05	10/05	11,99	36 960	289
5	Tartan	Come By Chance	Rotterdam	05/05	14/05	11,83	98 002	767
6	Suvorovsky Prospect	Murmansk	Rotterdam	05/05	11/05	12,05	60 754	476
7	Cap Quebec	Houston	Rotterdam	06/05	21/05	14,4	247 516	1 937
8	Niban	Ras Tanura	Rotterdam	07/05	29/05	10,18	242 340	1 897
9	Hera	Corpus Christi	Rotterdam	07/05	25/05	12,09	193 780	1 517
10	Tahiti	Sidi Kerir	Rotterdam	08/05	24/05	9,27	81 996	642

Table 6.4: Overview of ten first laden voyages, base situation
* represents the voyage number of the laden voyage.

In Figure 6.1 some of the laden voyages from the base situation are illustrated in a map. We have selected a group of four vessels to highlight their movements and how they change in the new solutions. The names of the selected vessels are Jag Leela, Pacific Jewels, Eikeviken and Dalma. The illustration highlights the distance of the laden voyages that the selected vessels carry out, while neither the speed level nor the time of the laden voyages are considered. To illustrate the changes in which laden voyages these selected vessels are assigned to, a similar map will be illustrated related to the proposed solutions from each of the different runs in Chapter 7. The solid line indicates that the sailing is a laden voyage. In the further figures, the ballast sailings will also be included, illustrated as dashed lines.

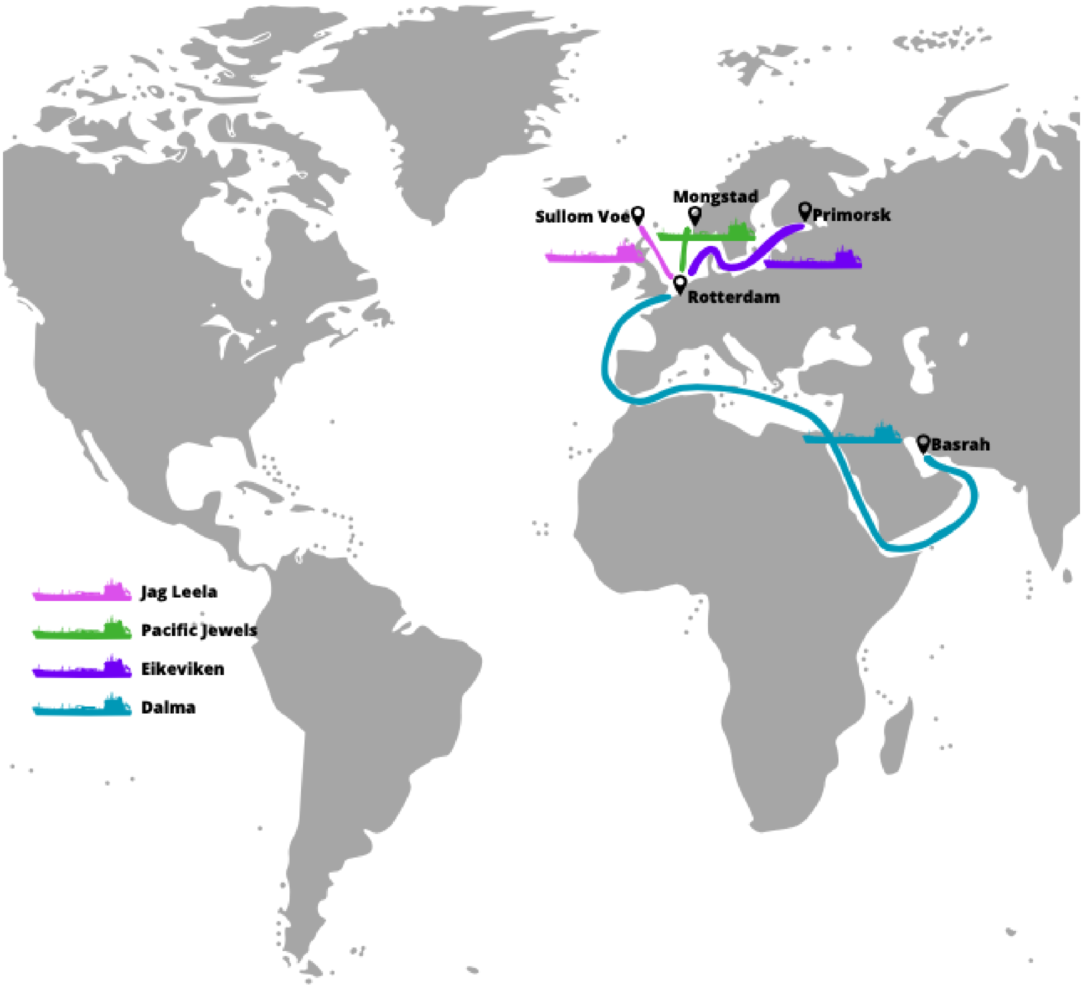

Figure 6.1: Overview of where selected vessels sail in the base situation

7 Results

In this chapter, we present the results from the computational implementation. In the first section, the results from implementing model 1 and model 2 are presented. Then, the resulting effects of the collaboration when implementing different time windows are presented. The last section summarizes the results.

Each run results in a new vessel allocation and choice of speed levels for both the laden voyages and the ballast sailings compared to the base situation. For each result, an overview of the ten first laden voyages is presented. These are comparable to Table 6.4, which represents the same ten voyages in the base situation. All costs are given in USD. In addition, a map with an overview of the movements of the group of four selected vessels, comparable to Figure 6.1, is presented for each solution.

7.1 Implementation of Model 1 and Model 2

In this section, the results from implementing model 1 and model 2 are presented. The time windows are set to three days for the load ports, and two days for the discharge ports (medium time windows).

7.1.1 Implementation of Model 1

When running model 1 with a time limit of ten hours, the new vessel allocation and choice of speed levels results in total fuel costs of 5 092 300 and CO_2 emission of 39 856 kg. The resulting gap of this solution was 2,57%. The reductions of fuel cost and CO_2 emissions are 28,02% compared to the base situation. Because of the construction of the measures of fuel costs and CO_2 emissions, where both are determined by the total fuel consumption, the percentage change in these measures compared to the base situation are equal. This holds for all the further solutions. There are several explanations of the changes in fuel costs and CO_2 emissions. One reason is that the joint fleet of vessels are allocated such that the laden voyages are performed by the vessels that are best suited in terms of their fuel consumption characteristics. Another reason is that efficient vessels are assigned to laden voyages that requires a high speed level in order to satisfy the time windows. A third reason is that these efficient vessels are also assigned to the laden voyages with long distances, given that their capacity is sufficient for the delivery. In addition, the speed levels are chosen such that the time windows are satisfied while the level of fuel consumption is minimized.

In the further presentation of results, the ten first laden voyages and all the ballast sailings will be discussed in detail. Table 7.1 provides an overview of the ten first laden voyages with the new vessel allocation and speed levels. The change in speed level for each laden voyage results in new start days and end days, and correspondingly a change in the duration of each laden voyage.

*	**Vessel Name**	**Load Port**	**Discharge Port**	**Start Date**	**End Date**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
1	Farhah	Basrah	Rotterdam	28/04	28/05	10	303 074	2 372
2	FPMC C Melody	Kuwait	Rotterdam	30/04	10/06	12	711 508	5 569
3	Eikeviken	Ust-Luga	Rotterdam	29/04	10/05	6	9 603	75
4	Eagle Brasilia	Vysotsk	Rotterdam	01/05	12/05	6	10 103	79
5	Dali	Come By Chance	Rotterdam	02/05	14/05	10	45 558	357
6	Libra Sun	Murmansk	Rotterdam	02/05	11/05	8	27 120	212
7	Rhythmic	Houston	Rotterdam	03/05	22/05	12	179 408	1 404
8	Nautilus	Ras Tanura	Rotterdam	05/05	28/05	10	236 303	1 849
9	Lancing	Corpus Christi	Rotterdam	05/05	27/05	10	79 081	619
10	SCF Baikal	Sidi Kerir	Rotterdam	07/05	26/05	8	70 576	552

Table 7.1: Overview of ten first laden voyages, model 1
* represents the voyage number of the laden voyage.

Within the ten first laden voyages, it is observed from Table 7.1 that the vessel allocation is changed compared to the base situation. In the two first laden voyages the speed levels are approximately the same as in the base situation, while at the same time the fuel costs and CO_2 emissions are reduced with 18,1% for laden voyage 1 and 15,49% for laden voyage 2. This means that the model has successfully assigned vessels that are more efficient with regards to the fuel consumption, which in these cases is the main cause of change in the fuel cost and CO_2 emissions. For other voyages, like laden voyage 3, both the speed level and the vessel are changed compared to the base situation. In this case, the speed is still at the medium level, but with a reduction of four knots. Together with a new, more efficient vessel, the resulting reduction of fuel costs and CO_2 emissions are 75,3%.

Laden voyage 8 is an example of a laden voyage where the reductions from the base situation are small compared to the other of the ten first laden voyages. The load port of this laden voyage is Ras Tanura, located in Saudi Arabia, which is one of the ports in the dataset that is located furthest away from Rotterdam. Because the time windows are equal for all load ports, there is less flexibility of changes in speed level when the distances are long. This effect is also reinforced by characteristics related to the choice of speed levels where there is a difference of two knots between the speed levels. Thereby, the reason that the reductions in laden voyage 8 are small is because of the long distance and small changes in speed level in order to satisfy the time windows. The changes in fuel costs/CO_2 emissions results from the fact that a somewhat more efficient vessel is assigned to the laden voyage.

The whole fleet of vessels are utilized in this new solution. The fact that all vessels are utilized means that all the commercial operators carry out at least one delivery. This situation, where all the commercial operators are gathered in the grand coalition, is defined as total collaboration.

Because there are more laden voyages to be carried out (51) than vessels available (48), some vessels have to sail multiple laden voyages and thereby need to conduct ballast sailings. In this solution, three vessels conduct such ballast sailings. The total fuel costs of the ballast sailings are 5 931, with CO_2 emissions of 47 kg. Compared to the base situation, the reduction in fuel cost and CO_2 emissions from the ballast sailings is approximately 13%. The ballast sailings are presented in Table 7.2. In terms of vessel allocation, the vessels conducting multiple laden voyages are not the same as in the base situation. The model assigns the ballast sailings to the most efficient vessels with sufficient capacity and decides the appropriate speed level such that the time windows are satisfied.

In Table 7.2 it is observed that all three ballast sailings are carried out with very low or low speed. One characteristic with the ballast sailings is that there is no time window for the sailing itself. This means that the sailing time is only limited by the fact that the vessel needs to be available for loading the cargo of the following laden voyage within the time window. Thereby, it is possible to assign the ballast sailings such that they are conducted with very low and low speed levels.

From *	**To ***	**Vessel Name**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
3	46	Eikeviken	4	3600	28
4	42	Eagle Brasilia	4	2008	16
5	51	Dali	2	323	3

Table 7.2: Ballast sailings, model 1
* represents the voyage number of the laden voyage.

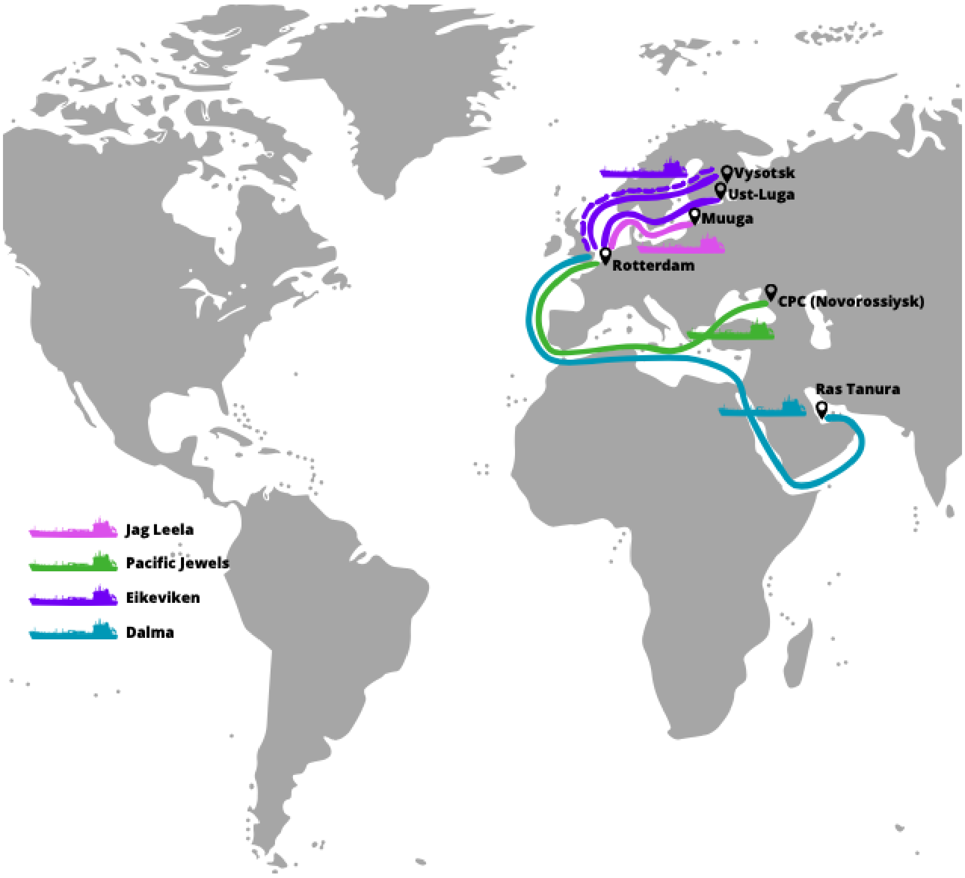

Figure 7.1: Overview of laden voyages and ballast sailings of selected vessels, model 1 medium time windows

In Figure 7.1 the movements of the four selected vessels are illustrated. In this figure, the movements of the vessel Eikeviken (that conducts a ballast sailing) is visualized clearly. The vessel sails a laden voyage (voyage number 3) from the load port in Ust-Luga to the discharge port in Rotterdam. Then, the vessel needs to conduct a ballast sailing to Vysotsk in order to sail a new laden voyage (voyage number 46) from Vysotsk to Rotterdam. The other vessels sail laden voyages from three other load ports, without conducting any ballast sailings.

7.1.2 Implementation of Model 2

Unlike model 1 where both the laden voyages and the ballast sailings are included in the objective function, model 2 seeks to minimize only the fuel cost of the laden voyages. In model 2 a range of the z-variables are left out of the model (because of Constraints (5.27)). This means that the size of the problem is reduced considerably, which implies that the solver requires less time in order to reach a feasible solution. Thereby, the time limit can be reduced while still obtaining a feasible solution with an acceptable gap. The time limit was set to be one hour, which resulted in a solution with a gap of 2,21%. The resulting fuel cost of the laden voyages in this solution is 5 093 550, with CO_2 emissions of 39 866 kg. This corresponds to a reduction of the fuel costs/CO_2 emissions from the laden voyages of 27,93% compared to base situation. However, for the purpose of comparing the results with the solution from model 1, the relevant measures are the total fuel costs and CO_2 emissions of both the laden voyages and the ballast sailings. The reductions in total fuel costs and CO_2 emissions are 27,27%.

Compared to the results from model 1 there are small differences in the fuel cost and CO_2 emission reductions. One of the reasons behind this is that the time windows are equal, which makes the speed level choices in the solution the same as in the results from running model 1. The main difference in the solutions from running model 1 and model 2 is the vessel allocation, where vessels will be assigned to the ballast sailings in a different way because the fuel costs of the ballast sailings are not included in the minimization. This affects the vessel allocation for the laden voyages. Some differences are however observed in the reductions, which is a result of the fact that more ballast sailings will be conducted when their fuel costs are left out of the objective function. The total reduction is somewhat lower than the results from the running of model 1. In Table 7.3, an overview of the ten first laden voyages in the results from running model 2 is presented.

*	**Vessel Name**	**Load Port**	**Discharge Port**	**Start Date**	**End Date**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
1	Farhah	Basrah	Rotterdam	28/04	28/05	10	303 074	2 372
2	FPMC C Melody	Kuwait	Rotterdam	30/04	10/06	12	711 508	5 569
3	Minerva Kythnos	Ust-Luga	Rotterdam	29/04	10/05	6	13 215	103
4	Dugi Otok	Vysotsk	Rotterdam	01/05	12/05	6	13 729	107
5	Pacific Jewels	Come By Chance	Rotterdam	02/05	14/05	10	45 284	354
6	Seatrust	Murmansk	Rotterdam	02/05	11/05	8	28 587	224
7	Neptune Moon	Houston	Rotterdam	03/05	22/05	12	145 522	1 139
8	Nautilus	Ras Tanura	Rotterdam	05/05	28/05	10	236 303	1 849
9	Lancing	Corpus Christi	Rotterdam	05/05	27/05	10	79 081	619
10	SCF Baikal	Sidi Kerir	Rotterdam	05/05	24/05	8	70 576	552

Table 7.3: Overview of ten first laden voyages, model 2
* represents the voyage number of the laden voyage.

The ballast sailings in this solution are presented in Table 7.4. As mentioned in Section 7.1.1, some vessels need to carry out ballast sailings. In this solution, six vessels are assigned multiple laden voyages and thereby six ballast sailings are conducted. A comparison of the number of laden voyages (51) and the number of vessels (48) reveals that three vessels have to conduct a ballast sailing in order for all the deliveries to be carried out. The fact that six vessels conduct ballast sailings means that three vessels are not utilized in the solution. Part of the reason why these vessels are not utilized is that the ballast sailings are not included in the objective function. The most efficient vessels can be assigned multiple laden voyages, and thereby a ballast sailing, without negatively affecting the fuel costs. In model 1, a ballast sailing will increase the objective value, while in model

2 they have no effect. Thereby, the least efficient vessels in the joint fleet can be left out of the allocation. An aspect of this solution is that one of the left out vessels are managed by a commercial operator that does not manage any other vessels in the joined fleet, and thereby this solution does not result in total collaboration. This means that this commercial operator lets another operator carry out the delivery that they carried out themselves in the base situation. However, they are not assigned new deliveries that initially were carried out by other operators.

From *	**To ***	**Vessel Name**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
3	40	Minerva Kythnos	8	19 257	151
5	44	Pacific Jewels	10	20 875	163
13	41	Ise Princess	10	16 738	131
21	46	Eagle Brasilia	10	22 581	177
23	42	Seamusic	6	6 150	48
24	51	Dali	8	5 164	40

Table 7.4: Ballast sailings, model 2
* represents the voyage number of the laden voyage.

Figure 7.2 shows an illustrated overview of the laden voyages and the ballast sailings of the group of selected vessels. In this solution, there is also a ballast sailing among the four selected vessels, conducted by Pacific Jewels. The vessel sails a laden voyage (voyage number 5) from the port of Come By Chance to Rotterdam, before a ballast sailing from Rotterdam to Ust-Luga is conducted in order to sail the next laden voyage (voyage number 44) from Ust-Luga to Rotterdam. The other three vessels sail their assigned laden voyages from three different load ports to Rotterdam. It is observed from this figure that both Jag Leela and Dalma are assigned the same sailing distances in the results from both model 1 and model 2. It is also observed that the distances from Ust-Luga and CPC (Novorossiysk) are covered by the four vessels in both model 1 and model 2, but the vessel allocation has changed.

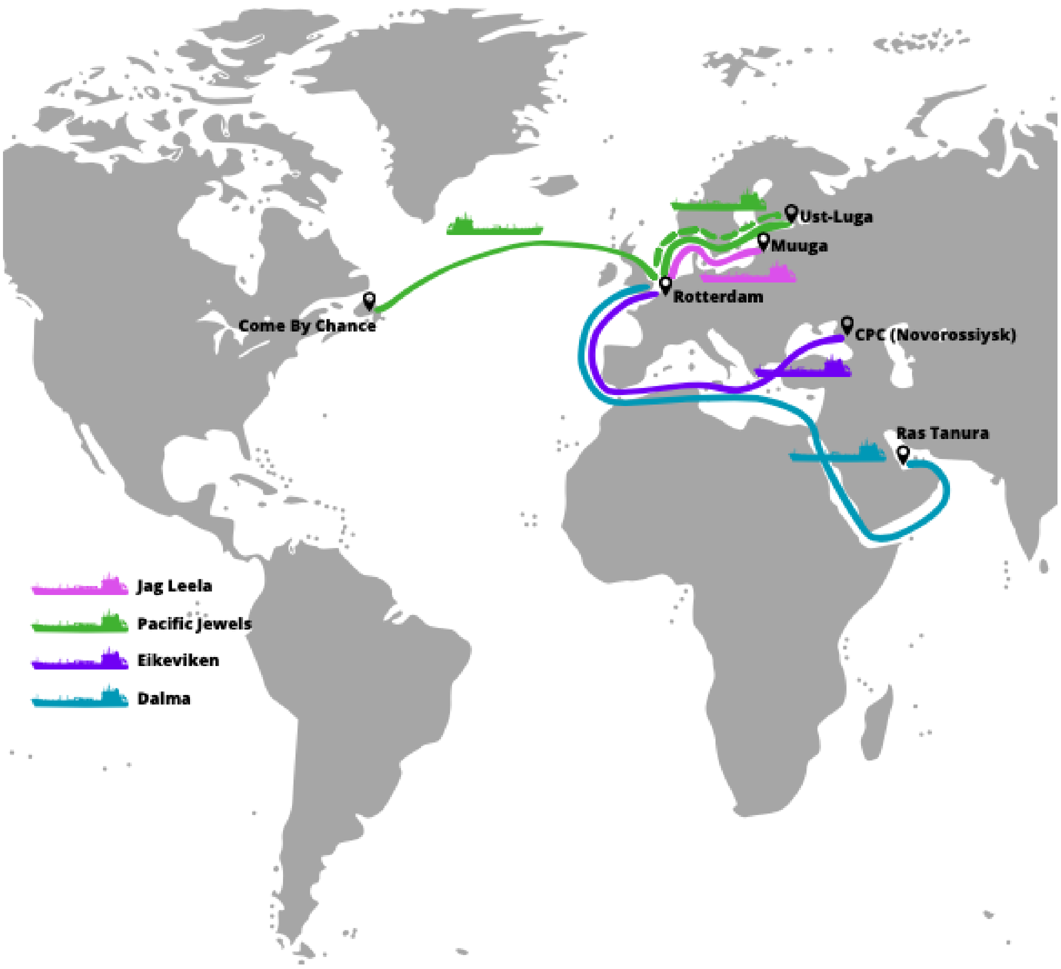

Figure 7.2: Overview of laden voyages and ballast sailings of selected vessels, model 2 medium time windows

7.1.3 Comparison of Results From Model 1 and Model 2

As mentioned and visualized through the first part of the chapter, there are great similarities in the vessel allocation and speed level choices when comparing the results of the ten first laden voyages from the runs of model 1 and model 2. From the collaborational point of view the total fuel costs are the relevant measure when comparing the results from the different models. In terms of total fuel costs, model 1 performs marginally better than model 2. This is explained by some differences in the vessel allocation due to the differing objective functions. Another main difference regarding the results from the two models is that only model 1 propose a solution with total collaboration.

Because there are small differences in the resulting total fuel costs from implementing the two models, we choose to only examine one of them further with time window variations.

Model 1 propose a more desirable solution both in terms of a higher fuel cost reduction and the total collaboration aspect, and thereby this model is chosen for the further analysis.

7.2 Time Window Variations in Model 1

In this section, the results from running model 1 with different time windows are presented. First, a tighter time window is implemented before we implement a wider time window. The goal of implementing these scenarios is to analyze how different time windows affects the collaborational features of the solutions.

7.2.1 Tighter Time Windows

By implementing a time window in the load ports of two days, and a time window in the discharge ports of one day, the model becomes less flexible than with medium time windows. This implies that the size of the problem is reduced (in terms of a stricter constraint in relation to the time windows), such that the solver can use less time in order to obtain a feasible solution. Thereby, the time limit was set to six hours resulting in an observed gap of 3,78%. The resulting total reductions in fuel costs and CO_2 emissions in this solution compared to the base situation are 10,46%, with total fuel costs of 6 388 670 and total CO_2 emissions of 50 003 kg. Compared to the run of model 1 with medium time windows the reductions are lower. This can be explained by the fact that when the time windows are tighter, the vessels need to speed up in order to satisfy the time windows. Higher speed levels result in higher fuel consumption and thereby higher fuel costs and CO_2 emissions. The observed reduction relative to the base situation is a result of the fact that the vessel allocation is a collaborative decision where the most efficient vessels are assigned to suitable laden voyages. In Table 7.5, an overview of the ten first laden voyages in this solution is presented.

*	**Vessel Name**	**Load Port**	**Discharge Port**	**Start Date**	**End Date**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
1	Farhah	Basrah	Rotterdam	02/05	27/05	12	436 386	3 415
2	FPMC C Melody	Kuwait	Rotterdam	29/04	09/06	12	711 508	5 569
3	Waikiki	Ust-Luga	Rotterdam	30/04	08/05	8	15 667	123
4	Eagle Brasilia	Vysotsk	Rotterdam	03/05	10/05	10	28 028	219
5	Pacific Jewels	Come By Chance	Rotterdam	03/05	15/05	10	45 284	354
6	Seatrust	Murmansk	Rotterdam	03/05	12/05	8	28 587	224
7	Rhythmic	Houston	Rotterdam	05/05	21/05	14	244 232	1 912
8	Dalma	Ras Tanura	Rotterdam	06/05	29/05	10	236 394	1 850
9	Lancing	Corpus Christi	Rotterdam	06/05	25/05	12	113 949	892
10	Nordic Vega	Sidi Kerir	Rotterdam	06/05	25/05	8	70 043	548

Table 7.5: Overview of ten first laden voyages, model 1 tighter time windows
* represents the voyage number of the laden voyage.

In laden voyage 1, the fuel costs and CO_2 emissions increases compared to the base situation. This can be explained by the fact that tight time windows and long voyage duration makes the choice of speed level crucial. Because of our choices related to the linearization of the relationship between speed and fuel consumption, the vessel is forced to choose between distinct speed levels. In this particular instance the speed level in the base situation is approximately 11 knots, while in the model the vessel is forced to choose between 10 knots and 12 knots. In order to satisfy the time windows, the resulting choice in this solution is 12 knots, which increases the fuel consumption compared to the base situation with 17,9%. A more efficient vessel is chosen, but the increased speed level results in higher fuel consumption, which leads to higher fuel costs and CO_2 emissions. In the rest of the ten first laden voyages the vessel allocation and choice of speed level results in significant reductions in fuel cost and CO_2 emissions, like in laden voyage 3 and 6 where the reductions are 59,7% and 52,9% respectively.

Compared to the run of model 1 with medium time windows, some differences are observed. In some laden voyages, like laden voyage 2, the only difference is that the vessel starts sailing from the load port and arrives in the discharge port one day earlier than in the solution with medium time windows. Laden voyage 4 is assigned the same vessel, but in order to both pick up and deliver within the time windows the vessel's speed level increases from low speed to medium speed. This results in higher fuel costs and higher CO_2 emissions for this individual voyage. This is the case for several laden voyages, which contributes to higher total fuel costs in the solution with tight time windows compared to the solution with medium time windows.

Four ballast sailings are conducted during the whole month, with medium speed and very high speed. The tighter time windows force the vessels to increase the speed levels compared to the results from the run with medium time windows. Higher speed levels result in significant increases in fuel costs and CO_2 emissions. In Table 7.6 the ballast sailings with their belonging fuel cost and CO_2 emissions are presented.

From *	**To ***	**Vessel Name**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
3	38	Waikiki	8	13 278	104
4	34	Eagle Brasilia	16	51 529	403
5	44	Pacific Jewels	8	13 363	105
12	46	Alfa Alandia	10	22 456	176

Table 7.6: Ballast sailings, model 1 tighter time windows
* represents the voyage number of the laden voyage.

Four ballast sailings conducted by four different vessels means that one of the vessels in the joint fleet is not utilized. This particular vessel belongs to a commercial operator that does not manage any of the other vessels, which means that the proposed solution does not imply total collaboration. The ballast sailing of Pacific Jewels, from Rotterdam to Ust-Luga, is presented in Figure 7.3 together with the movements of the other three selected vessels.

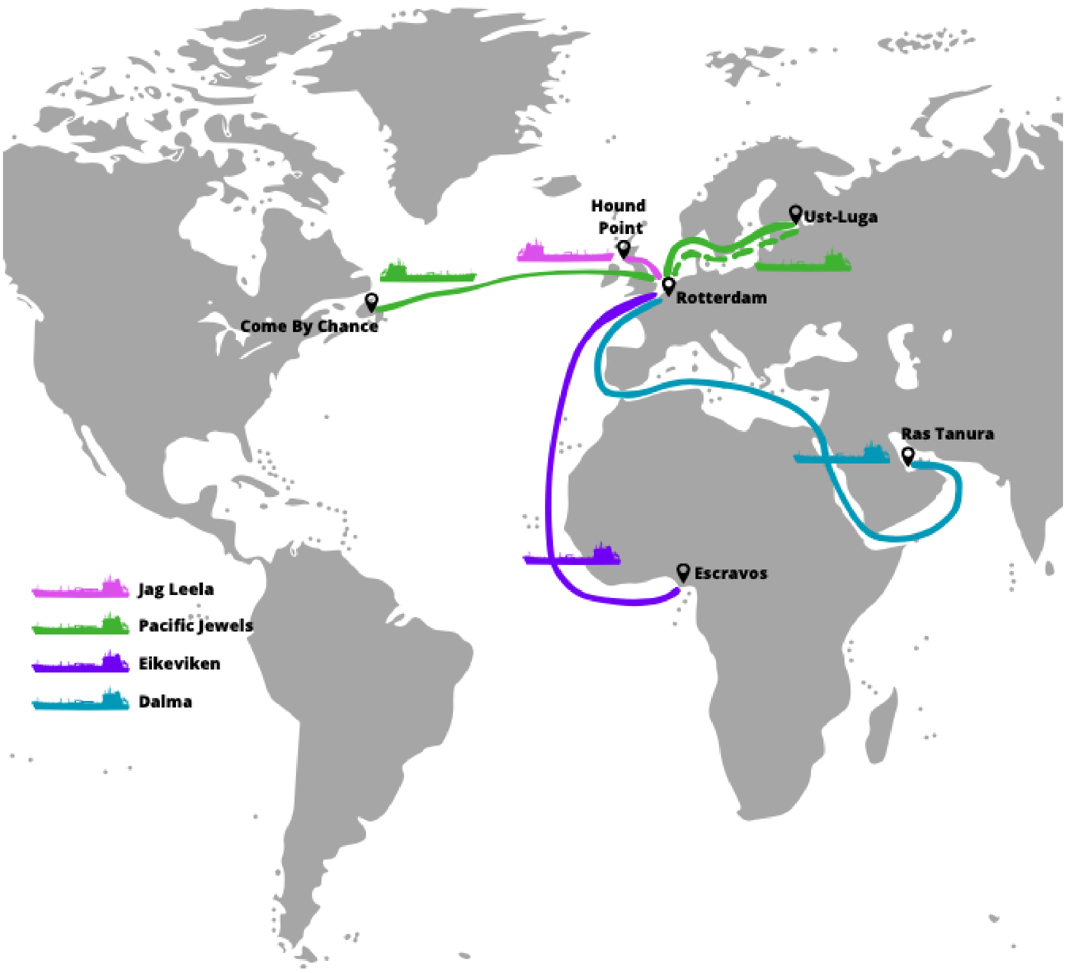

Figure 7.3: Overview of laden voyages and ballast sailings of selected vessels, model 1 tighter time windows

7.2.2 Wider Time Windows

The scenario of wider time windows implies a time window in the load port of four days and a time window in the discharge port of three days. The time limit was set to ten hours (like the initial run of model 1) resulting in an observed gap of 3,72%. Total fuel cost in this solution is 4 815 600, with total CO_2 emissions of 37 690 kg. This corresponds to a reduction of 32,16% compared to the base situation. With wider time windows the model is more flexible in terms of vessel allocation and speed level choices. Table 7.7 provides an overview of the ten first laden voyages in the solution with wider time windows.

*	**Vessel Name**	**Load Port**	**Discharge Port**	**Start Date**	**End Date**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
1	Farhah	Basrah	Rotterdam	30/04	30/05	10	303 074	2 372
2	FPMC C Melody	Kuwait	Rotterdam	01/05	11/06	12	711 508	5 569
3	Waikiki	Ust-Luga	Rotterdam	28/04	09/05	6	8 823	69
4	Eagle Brasilia	Vysotsk	Rotterdam	30/04	11/05	6	10 103	79
5	Pacific Jewels	Come By Chance	Rotterdam	01/05	16/05	8	28 988	227
6	Tartan	Murmansk	Rotterdam	01/05	13/05	6	15 838	124
7	Rhythmic	Houston	Rotterdam	02/05	21/05	12	179 408	1 404
8	Nautilus	Ras Tanura	Rotterdam	03/05	01/06	8	151 264	1 184
9	Lancing	Corpus Christi	Rotterdam	03/05	25/05	10	79 081	619
10	SCF Baikal	Sidi Kerir	Rotterdam	04/05	23/05	8	70 576	552

Table 7.7: Overview of ten first laden voyages, model 1 wider time windows
* represents the voyage number of the laden voyage.

Compared to the base situation, all of the ten first laden voyages are assigned vessels and speed levels such that the fuel cost and CO_2 emissions are reduced. With wider time windows, the speed level for some voyages have been decreased in order to reduce the fuel consumption. As observed in laden voyage 6, the speed level is reduced by approximately 50%, which corresponds to a fuel cost/CO_2 emission reduction of 73,9%.

Compared to the first solution (medium time windows), several of the ten first laden voyages are assigned the same vessels and the same speed level which results in no changes in the fuel costs and CO_2 emissions. A common feature of these laden voyages is that the durations are long together with medium and high speed levels, which indicates that the distances are long. In these laden voyages speed reductions are not possible despite the wider time windows. In other instances, like laden voyage 5 and 6, the vessel allocation changes and speed level reductions results in lower fuel costs and CO_2 emissions of 36,4%

and 41,6% respectively.

With the tight time windows, it was presented how laden voyage 1 experienced increased fuel cost because of the need to sail with a high speed level. With wider time windows, the vessel is able to choose medium speed level, and thereby the fuel costs decreases compared to the base situation.

In the month as a whole, all the vessels in the joint fleet are utilized, which means that this solution implies total collaboration. Three ballast sailings are conducted, displayed in Table 7.8. All of these are conducted with very low or low speed levels. This is explained by the fact that with wider time windows, there is more flexibility in both the pickup and delivery. This facilitates choosing lower speed levels in the ballast sailings in order to reduce the fuel consumption and thereby both fuel costs and CO_2 emissions.

From *	**To ***	**Vessel Name**	**Speed (kn)**	**Fuel Cost (USD)**	**CO_2 (kg)**
3	49	Waikiki	4	3 708	29
4	51	Eagle Brasilia	2	364	3
13	41	Hera	6	6 305	41

Table 7.8: Ballast sailings, model 1 wider time windows
* represents the voyage number of the laden voyage.

In Figure 7.4 an overview of the movements of the four selected vessels is presented. None of the four selected vessels are among the vessels that are assigned ballast sailings in this solution, and thereby the map only displays laden voyages from the ports of the different laden voyages that the selected vessels are assigned to.

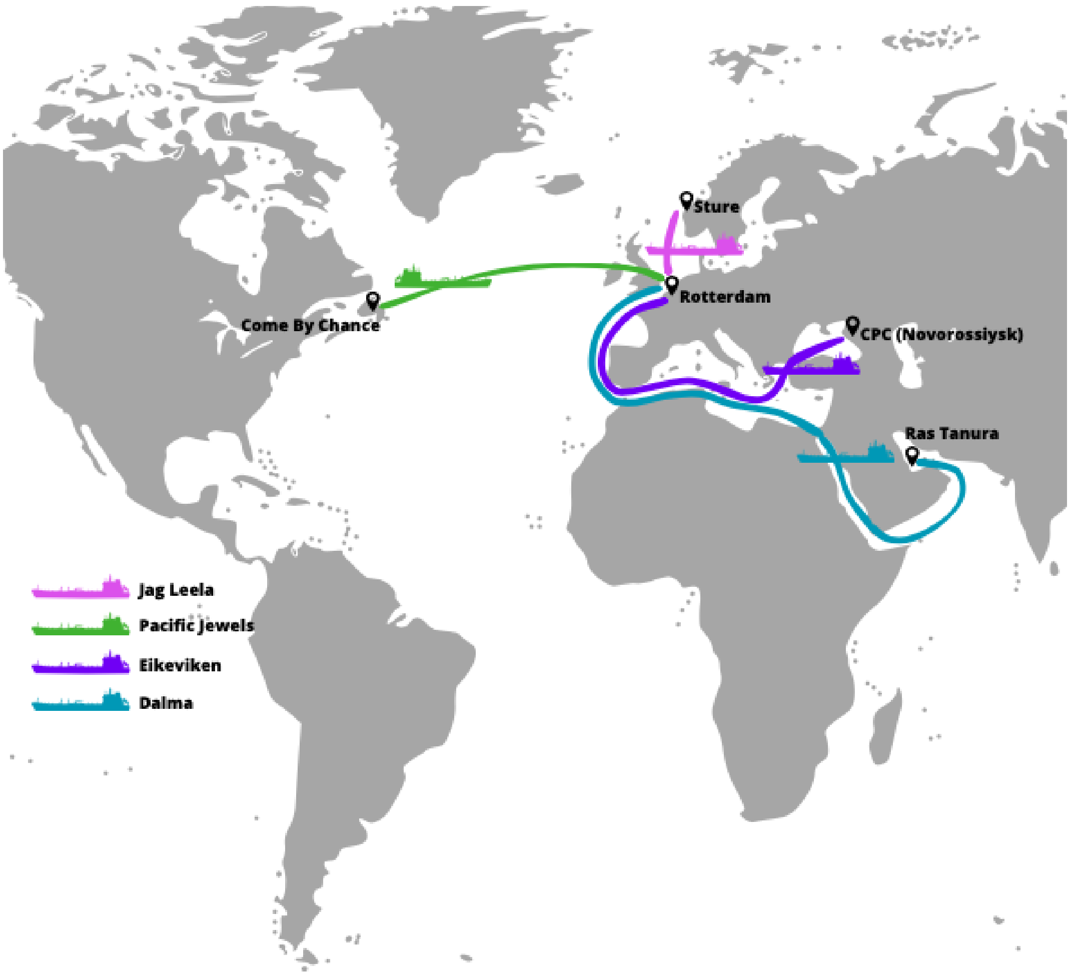

Figure 7.4: Overview of laden voyages of selected vessels, model 1 wider time windows

7.3 Summary of Results

In Table 7.9, the results from the different runs are summarized.

	Model 1			**Model 2**
	Tight Time Windows	**Medium Time Windows**	**Wide Time Windows**	**Medium Time Windows**
Total Fuel Cost (USD)	6 388 670	5 092 300	4 815 600	5 188 294
Total CO_2 Emissions (kg)	50 003	39 856	37 690	40 607
Percentage Reduction in Fuel Cost/ Emissions	10,46%	28,02%	32,16%	27,5%

Table 7.9: Summary of results

The initial running of model 1, with time windows of three days for pickup and two days for delivery, resulted in a fuel cost reduction of 28,02% compared to the base situation. Tighter time windows resulted in a reduction of 10,46%, while wider time windows resulted in 32,16%. Model 2 also represents a significant reduction, however model 1 performs better in terms of total fuel cost reduction. In addition, as discussed in Section 7.1.3, the solution provided by model 2 is less desirable compared to model 1 from a collaborational point of view.

One important observation when summarizing the results is the sensitivity of changes in the time windows. The results indicate that the vessel allocation and choice of speed levels are more sensitive towards tighter time windows than wider time windows. Wider time windows allow for more flexibility, and the changes in cost reduction indicates that a change of one day causes substantial effects when increasing from the tight scenario to the medium scenario. At the same time, the changes are not as substantial when increasing from the medium scenario to the wide.

8 Discussion

In this chapter, some managerial considerations related to the collaboration are discussed. The chapter continues with a discussion of the assumptions and limitations of our models, while the last section highlights suggestions for further research.

8.1 Managerial Considerations

In this thesis we have shown how establishing total collaboration in terms of gathering all the commercial operators in the grand coalition can reduce total fuel costs and CO_2 emissions substantially. However, some managerial considerations need to be evaluated in order for the collaboration to work in practice. Forming large coalitions can impose some managerial complexities, and as Guajardo and Rönnqvist (2015) points out, it is important to consider whether the savings overwhelm these complexities. A crucial prerequisite for the total collaboration suggested in our models is that all the commercial operators need to approve and engage in the grand coalition. One way to facilitate this approval is to ensure that the costs, revenues and CO_2 emissions are allocated in a fair manner. However, the perception of what is a fair allocation can be different among the different commercial operators, and as a group they will have to agree about the allocation criteria. Another consideration is that the process of managing the grand coalition and implementing the optimization models will involve some administrative costs. These costs need to be assessed and compared to the administrative costs that the individual commercial operators experience when operating by themselves.

Implementing the collaboration in practice involves some requirements from each individual operator in terms of integrating the new vessel allocation with their existing planning and decision processes. The vessels that only carry out one laden voyage is assumed to have completed their contribution in the planning period when that voyage is completed. What happens before the vessels first laden voyage, and after the last laden voyage is without the scope of the models. In these time periods, the vessel will be available for other voyages (outside of the collaboration) assigned by the commercial operators. In order for the models to be implemented in practice, they need to be integrated with the commercial operators other planning tools such that the vessels are available for the laden voyages they are assigned to be carrying out. When the models are integrated with other planning tools, the commercial operator can facilitate the use of the vessels for other purposes outside of the assigned laden voyages. This feature also relates to ballast sailings because the vessels will need to conduct a ballast sailing to the load port of the first assigned laden voyage (unless there is a demand for a delivery to the port in question). This also needs to be integrated in the planning process when implementing the models.

8.2 Assumptions and Limitations

In this thesis, we have developed models for solving the problem of minimizing fuel costs and CO_2 emissions by collaboration. The results indicate considerable reductions related to the base situation. However, a master thesis is limited when it comes to the scope of the thesis and time. In this section, we will highlight some of the assumptions and limitations in our models.

The linearization of the relationship between speed and fuel consumption is a crucial part of the models. Our choices related to this linearization creates some limitations because it is assumed that the vessels only can sail with distinct speed levels of 2, 4, 6, 8, 10, 12, 14 and 16 knots. Particularly in long sailing distances, the difference in the number of sailing days required when changing the speed by two knots will be significant. The choice of speed level is thereby less flexible compared to continuous speed, which relates to the fact that the models does not allow violations of the time windows.

The models only consider ballast sailings when a vessel is assigned to multiple laden voyages. In addition, a ballast sailing will only be facilitated from the discharge port of a predefined laden voyage. In practice, like observed in the base situation, ballast sailings will be conducted from other ports as well as the predefined discharge ports.

Some simplifications are made related to the fuel consumption and measures of costs and emissions. Fuel consumption is assumed to be determined solely by vessel specific characteristics and speed level. In terms of costs, the fuel costs are assumed to be the only cost parameter in the model. Regarding emissions, only the CO_2 emissions are considered. Fuel consumption is assumed to be the determining factor for both the fuel costs and the CO_2 emissions. These simplifications are made in order to reduce the complexity of the model.

8.3 Future Research

There are several possibilities of further developing different characteristics that may improve our models. In this section, some lines for future research are highlighted.

One way of developing the models further would be to consider the choice of speed levels in a way where the choice of speed is facilitated to be continuous. This could imply formulating a nonlinear model. It would be interesting to observe how such choices would affect the potential reductions in fuel costs and CO_2 emissions from the collaborational point of view.

Another line for future research would be to address the simplifications related to fuel consumption, costs, and emissions in order to improve the measures of costs and emissions. In terms of fuel consumption, one additional determinator to consider could be weather conditions. Weather conditions, especially prevailing wind, and waves, has significant influence on the fuel consumption (Bialystocki and Konovessis, 2016). By incorporating such factors related to fuel consumption, a more realistic measure will be obtained. In terms of costs, it would be interesting to examine how incorporating other types of costs in the models would affect the reductions in the proposed solutions. Other types of costs to include could be cargo-handling costs, berth costs and crew costs. In addition, measuring other types of emissions would be a way of extending the problem that increases the focus on greenhouse gas emissions. Addressing these simplifications would be interesting in terms of the assessment of how collaborating by joining the fleet of vessels and the speed level choices affects the total costs and emissions.

Expanding our models by defining solution algorithms/heuristics in order to solve larger instances of the problem in a reasonable amount of time is another field of future work. As presented in the literature review, including such solution algorithms or heuristics are common in the field of formulating optimization models for solving problems related to among others fleet deployment and speed optimization.

In this thesis we have defined total collaboration as the scenario where all the commercial operators engage in the grand coalition. Assessing the coalition structure differently would be an interesting scope for future work. As Guajardo and Rönnqvist (2015) points out, it may be better to facilitate different sub-coalitions rather than forming the grand coalition.

It would be interesting to examine how the fuel cost and CO_2 emission savings would be affected if the model facilitated the formation of sub-coalitions, and whether such sub-coalitions could improve the solutions. The size of such sub-coalitions would be an interesting feature to explore, as Guajardo and Rönnqvist (2015) points out how a certain number of members in the coalition will achieve the most savings.

9 Conclusion

In this thesis we have studied how collaboration between shipping companies can reduce the fuel costs and CO_2 emissions resulting from a sequence of pickup and deliveries with time windows by exploring the optimal vessel allocation and speed levels.

To solve this problem two optimization models are formulated as mixed integer linear problems. The first model (model 1) minimizes the total fuel costs of both the laden voyages and the ballast sailings, while the other model (model 2) minimizes the fuel cost of only the laden voyages. Collaboration is defined in terms of a collaborative decision of vessel allocation and speed levels where the shipping companies join their fleets of vessels and the requested deliveries. The main determinator of fuel costs is assumed to be the fuel consumption, which in our models depends on the speed level and vessel characteristics. The fuel consumption per time can be expressed as a cubic function of speed, and this relationship is linearized in order to formulate linear optimization models. This linearization is done by defining distinct speed levels and estimating a unique fuel consumption parameter for each speed level as well as each vessel in the fleet.

In the thesis we conduct a computational study where a dataset obtained from Signal Ocean is used in order to implement and test the models. The results show that all runs with both models produce solutions where collaboration implies reductions of both fuel costs and CO_2 emissions. Reductions are due to changes in the vessel allocation and choice of speed levels. The greatest reductions are observed from model 1, which minimizes the total fuel costs. Various time windows are implemented in different runs of model 1, which show that the resulting reductions changes. By implementing both tighter and wider time windows, we show that the effects on the fuel cost and CO_2 emission reductions when collaborating are more sensitive towards tighter time windows than wider time windows. Based on these results, we conclude that collaboration between shipping companies in terms of optimizing vessel allocation and speed levels in a sequence of pickup and deliveries with time windows implies reductions in fuel costs and CO_2 emissions.

References

Alvarez, J. F. (2009). Joint routing and deployment of a fleet of container vessels. *Maritime Economics & Logistics*, 11:186–208. https://doi.org/10.1057/mel.2009.5.

Andersson, H., Christiansen, M., and Fagerholt, K. (2011). The maritime pickup and delivery problem with time windows and split loads. *INFOR: Information Systems and Operational Research*, 49(2):79–91. https://doi.org/10.3138/infor.49.2.079.

Andersson, H., Fagerholt, K., and Hobbesland, K. (2015). Integrated maritime fleet deployment and speed optimization: Case study from roro shipping. *Computers & Operations Research*, 55:233–240. https://doi.org/10.1016/j.cor.2014.03.017.

Bialystocki, N. and Konovessis, D. (2016). On the estimation of ship's fuel consumption and speed curve: A statistical approach. *Journal of Ocean Engineering and Science*, 1(2):157–166. https://doi.org/10.1016/j.joes.2016.02.001.

Clarksons Research (n.d.a). *Shipping Intelligence Network*. Clarksons Research Portal. https://sin.clarksons.net/.

Clarksons Research (n.d.b). *World Fleet Register*. Clarksons Research Portal. https://www.clarksons.net/wfr/.

Corbett, J. J., Wang, H., and Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, 14(8):593–598. https://doi.org/10.1016/j.trd.2009.08.005.

Fagerholt, K., Johnsen, T. A., and Lindstad, H. (2009). Fleet deployment in liner shipping: a case study. *Maritime Policy & Management*, 36(5):397–409. https://doi.org/10.1080/03088830903187143.

Gelareh, S. and Meng, Q. (2010). A novel modeling approach for the fleet deployment problem within a short-term planning horizon. *Transportation Research Part E: Logistics and Transportation Review*, 46(1):76–89. https://doi.org/10.1016/j.tre.2009.06.004.

Guajardo, M. and Rönnqvist, M. (2015). Operations research models for coalition structure in collaborative logistics. *European Journal of Operational Research*, 240(1):147–159. https://doi.org/10.1016/j.ejor.2014.06.015.

IMO (2021). *Fourth IMO GHG Study 2020. Full Report.* International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.

IMO (n.d.). *IMO's work to cut GHG emissions from ships.* International Maritime Organization. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx.

King, A. (2022). *Emissions-free sailing is full steam ahead for ocean-going shipping.* Horizon, The EU Research and Innovation Magazine. https://ec.europa.eu/research-and-innovation/en/horizon-magazine/emissions-free-sailing-full-steam-ahead-ocean-going-shipping. Published on September 06, 2022.

Lau, H. C. and Liang, Z. (2002). Pickup and delivery with time windows: Algorithms and test case generation. *International Journal on Artificial Intelligence Tools*, 11(03):455–472. https://doi.org/10.1142/S0218213002000988.

Lee, E., Nam, H., and Song, D.-W. (2012). Defining maritime logistics and its value in Maritime Logistics. In Song, D-W. and Panayides, P.M. (Eds.), *Maritime logistics: a complete guide to effective shipping and port management* (p. 9-19). Kogan Page.

Lei, L., Fan, C., Boile, M., and Theofanis, S. (2008). Collaborative vs. non-collaborative container-vessel scheduling. *Transportation Research Part E: Logistics and Transportation Review*, 44(3):504–520. https://doi.org/10.1016/j.tre.2006.12.002.

Liu, X., Wang, D., Yin, Y., and Cheng, T. (2023). Robust optimization for the electric vehicle pickup and delivery problem with time windows and uncertain demands. *Computers & Operations Research*, 151:106119. https://doi.org/10.1016/j.cor.2022.106119.

Lyridis, D. V. and Zacharioudakis, P. (2012). Liquid bulk shipping. In Talley, W. K. (Ed.), *The Blackwell Companion To Maritime Economics* (p. 205-229). John Wiley & Sons, Incorporated.

Norstad, I., Fagerholt, K., and Laporte, G. (2011). Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C: Emerging Technologies*, 19(5):853–865. https://doi.org/10.1016/j.trc.2010.05.001.

Pasha, J., Dulebenets, M. A., Fathollahi-Fard, A. M., Tian, G., Lau, Y.-y., Singh, P., and Liang, B. (2021). An integrated optimization method for tactical-level planning in liner shipping with heterogeneous ship fleet and environmental considerations. *Advanced Engineering Informatics*, 48:101299. https://doi.org/10.1016/j.aei.2021.101299.

Psaraftis, H. N. (2012). Market-based measures for greenhouse gas emissions from ships: a review. *WMU Journal of Maritime Affairs*, 11:211–232. https://doi.org/10.1007/s13437-012-0030-5.

Psaraftis, H. N. and Kontovas, C. A. (2014). Ship speed optimization: Concepts, models and combined speed-routing scenarios. *Transportation Research Part C: Emerging Technologies*, 44:52–69. https://doi.org/10.1016/j.trc.2014.03.001.

Qiu, X., Wong, E. Y., and Lam, J. S. L. (2018). Evaluating economic and environmental value of liner vessel sharing along the maritime silk road. *Maritime Policy & Management*, 45(3):336–350. https://doi.org/10.1080/03088839.2018.1437285.

Ritchie, H. and Roser, M. (2020). *Greenhouse gas emissions.* Our World in Data. https://ourworldindata.org/greenhouse-gas-emissions.

Ship & Bunker News Team (2021). *Bunker Price Comparison: HSFO in 2019 vs VLSFO in 2020.* Ship & Bunker. https://shipandbunker.com/news/world/446768-bunker-price-comparison-hsfo-in-2019-vs-vlsfo-in-2020. Published on January 01, 2021.

Stopford, M. (2008). *Maritime economics 3e.* Routledge.

UNCTAD (2022). *Review of Maritime Transport 2022, Navigating stormy waters.* United Nations. https://unctad.org/publication/review-maritime-transport-2022.

Wang, K., Li, J., Huang, L., Ma, R., Jiang, X., Yuan, Y., Mwero, N. A., Negenborn, R. R., Sun, P., and Yan, X. (2020). A novel method for joint optimization of the sailing route and speed considering multiple environmental factors for more energy efficient shipping. *Ocean Engineering*, 216:107591. https://doi.org/10.1016/j.oceaneng.2020.107591.

Wang, S. and Meng, Q. (2012). Liner ship fleet deployment with container transshipment operations. *Transportation Research Part E: Logistics and Transportation Review*, 48(2):470–484. https://doi.org/10.1016/j.tre.2011.10.011.

Wang, X., Norstad, I., Fagerholt, K., and Christiansen, M. (2019). Green Tramp Shipping Routing and Scheduling: Effects of Market-Based Measures on CO2 Reduction. In H. N. Psaraftis (Ed.), *Sustainable Shipping: A Cross-Disciplinary View* (pp. 285-305). Springer International Publishing.