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Bunker Fuel Management Strategy of IMO 2020 Fuel Alternatives

by

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“And all I ask is a tall ship and a star to steer her by.”

– John Masefield

Vivat!

Abstract

Sulphur 2020, or IMO 2020 as more popularly known, is the regulation to limit sulphur emission to 0.5%. The regulation was proposed by IMO and will be enforced on 1st of January 2020. Many stakeholders, including liner shipping companies, voiced their concern about the disruption that it would bring to the industry, as the companies must face the uncertainties of choices among three fuel alternatives to comply with the cap. The choices are HFO with scrubbers, MGO and LNG. These choices of fuel alternatives would significantly alter the operations of the liner vessel, specifically to the bunker fuel cost of a liner service. Moreover, as the threat over environmental impact regarding carbon emission, proposal has already been agreed by the member states of IMO to reduce CO2 emission from maritime by 50% in 2050, hence making the choice of fuel alternatives in IMO 2020 becomes more complicated as CO2 emission has to be considered as well. This thesis aims to find and study the optimal tactical decision of bunker fuel management strategy of each fuel alternatives.

The methodology used by this thesis is based on the joint optimization of three different components of bunker fuel management strategy, which are the optimal choices of bunkering ports, optimal bunkering amounts, and optimal sailing speed adjustments. These three components are jointly optimized to obtain the most optimal tactical decision of bunker fuel management strategy. The equation by Ronen (1982) is used to calculate the relation between fuel consumption and speed, in which the coefficient of fuel consumption is only valid for speed on a certain size. Then we use historical price and estimation to obtain fuel prices on each alternative. This thesis then composes tactical planning of bunker fuel management strategy for a single service route of a liner shipping companies which is simulated to use three different fuel alternatives using mixed-integer nonlinear programming to solve the optimization. This thesis considers three different scenarios to be simulated on the route, which are relaxing of the port arrival time windows and total voyage times, changing the price of the fuel and increasing the fuel tank capacity.

The thesis finds several insights gained from the optimal strategies of each fuel alternatives; (1) Bunkering times of all three fuel alternatives depicts similarities, as all the current fuel tanks simulated in this study have a similar sailing range. (2) Bunkering amounts in bunkering port is affected by bunker fuel prices, quantity discount purchase and fuel requirements from the sailing distance, in which the quantity of the purchase is affected by the fuel tank capacity. (3) Increasing the tank capacity results in the decrease in total costs, as there are more capacities in the tank to purchase a larger amount of bunker fuel to obtain quantity discount. (4) Due to a difference in the density of each fuel, the increase in the fuel tank capacity results in different bunkering times between fuel oil and LNG. (5) The choice of bunkering ports is majorly affected by the price differences between ports along the service route, as different price change scenarios also change the optimal bunkering ports. However, the choice of bunkering ports is constrained by the fuel requirements over the sailing range. (6) The choice of bunkering ports differs between fuel oil and LNG as bunkering facilities for LNG are not available on every port. (7) Sailing speed is mainly affected by the port arrival time windows, which ultimately affect the bunker cost. Relaxing the port arrival time windows results in a reduced average sailing speed, thus results also in a reduced total bunker cost. (8) Bunker fuel consumption affects the total CO_2 emission. Combined with its emission per gram fuel, LNG consumes the least fuel, thus emits the least CO_2, meanwhile HFO with scrubber consume the most fuel and emits the most CO_2. (9) Relaxing total voyage time as to further reduce average sailing speed could be used as a strategy to further reduce CO2 emission. The amount of reduced speed to reach the emission target depends on the CO2 emission of each fuel alternative.

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List of Abbreviations

International Maritime Organization	IMO
United Nations Conference on Trade and Development	UNCTAD
Heavy Fuel Oil	HFO
Marine Gas Oil	MGO
Liquified Natural Gas	LNG
Low-Sulphur Fuel Oil	LSFO
Ozone Depleting Substances	ODS
Volatile Organic Compounds	VOC
Emission Control Area	ECA
The Technique for Order of Preference by Similarity to Ideal Solution	TOPSIS
Gas Infrastructure Europe	GIE
Compagnie Maritime d'Affrètement - Compagnie Générale Maritime	CMA CGM
Energy Information Administration	EIA
PricewaterhouseCoopers	PwC
Environmental Protection Agency	EPA
Advanced Interactive Multidimensional Modeling System	AIMMS
United States of America	USA
Boston Consulting Group	BCG
Million British Thermal Units	MMBtu
International Council on Clean Transportation	ICCT
Twenty Foot Equivalent Unit	TEU

1. Introduction

Maritime transportation is a major driver in world trade that carries 10.7 billion tons of goods around the world with 17.1% of seaborne trade carried by container ships (UNCTAD, 2018). Despite being considered as an inevitable part of global economy, shipping industry releases a significant amount of air pollutants resulted from vessel's combustion system, harming the ecosystem. In 2017, maritime shipping sector contributes 2.2%, 15%, and 13% of the worlds' total CO_2, NO_x, and SO_x emissions, respectively (Clear Seas Centre for Responsible Marine Shipping, 2019). Albeit shipping industry is considered efficient environmentally (Fagerholt et al., 2015), many aspects need to be regulated to achieve sustainable shipping.

International Maritime Organization has been actively involved in an effort of reducing the environmentally damaging effects of shipping. Take for example the Annex VI to MARPOL. This regulation aims to control emissions from sea-based shipping such as sulphur oxides (SOx), nitrogen oxides (NOx), ozone depleting substances (ODS), volatile organic compounds (VOC), and shipboard incineration. This regulation has been enforced since 2005. The SOx limits have been gradually regulated and reduced since 2005, as shown in the revised version of Annex VI in 2008. This revised version lead to a further reduction on sulphur limits to 0.1% by 2015 for all ship sailing within Emission Control Area (ECA) and to 0.5% by 2020 globally. The latter will be enforced subject to a research in 2018 to confirm the availability of alternative fuels that are compliant to sulphur limit. Otherwise, the implementation of 0.5% sulphur cap could be postponed to 2025. Fortunately, and unfortunately to some stakeholders, the research proved that the supply of the alternative fuels will be ready by the year 2020. Therefore, the upcoming regulation will be effectively enforced in 1st of January 2020.

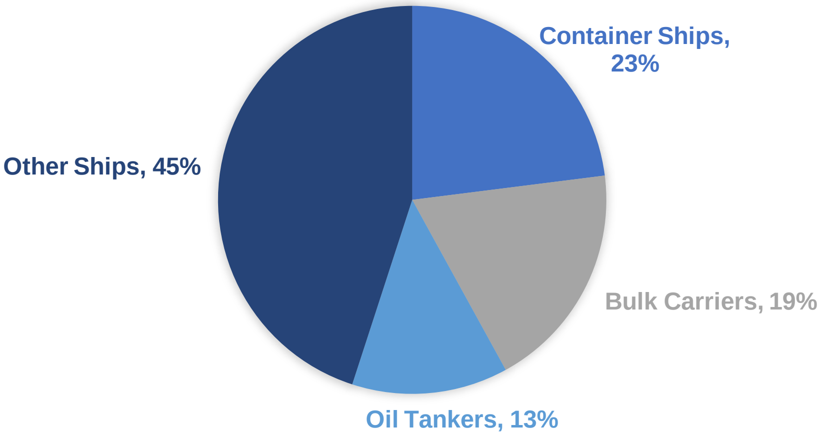

Figure 1. Share of Marine CO_2 equivalent Emissions by Ship Type
Source: ICCT (2017)

This IMO regulation is dubbed as one of the disruptive forces and many stakeholders in maritime transport react rather strongly, especially in the industry of container shipping. The reaction mainly comes from the rising cost of shipping caused by higher bunker cost. The concern about the uncertainty of availability of the bunker fuels also has been questioned by the stakeholders as it could affect the service (Poskus, 2018 and Billing et al., 2018). Feasible solutions to the upcoming IMO regulation regarding the rising cost and fuel availability are still being discussed by stakeholders, practitioners and researchers. IMO indicated that there would be three favourable fuel options for achieving 0.5% sulphur limit, i.e. installing scrubber system, utilising ultra-low-sulphur fuel oil, specifically marine gas oil (MGO), and utilising liquified natural gas (LNG) fuel.

Moreover, IMO, through Marine Environment Protection Committee has reached an agreement with member state delegates on 22 October 2018 on initial strategy for CO_2 emissions reduction from ships by 50% by 2050 and to begin the reduction as soon as possible. The initial strategy also includes reducing carbon emission per unit of transport work completed (IMO, 2018). Although the initial strategy is just a set of goals and no legal restrictions on CO_2 emission has been placed, it is wise for shipping companies to continuously adapt the operations management of the vessel to reduce the carbon emission as soon as possible.

1.1. *Problem Definition*

Bunker fuel cost is a major part of the operational cost of a ship. Given the regulation that will be imposed by IMO in 2020, the choice of fuel alternatives, namely HFO with scrubber, MGO and LNG will greatly affect not only the operational cost, but also the emissions of the fuel. Additionally, initiatives relating to reduce CO_2 emission by 50% in 2050 has been ratified agreed by member state delegates. As shipping companies are continuously trying to reduce the cost and the emissions, bunker fuel management strategy is vital to the operations management of shipping companies. Bunker fuel management strategy will not only impact the fuel consumption of the vessel, but also to the environmental issue that follows, namely the greenhouse gasses emission. Bunker fuel management strategy of three different fuel alternatives on a liner route will differ to one another. Each bunker fuel management strategy will be affected not only by fuel prices of each fuel alternatives, but also in the availability of bunker location on the shipping route. Moreover, the price of the fuel will also differ from port to port. The choice of alternative fuels then can be compared from the perspective of bunker fuel management strategy.

1.2. *Objectives and Research Question*

Consequently, the objectives of this thesis are to simulate vessels with three fuel alternatives following a shipping route, to optimize the bunker fuel management strategies and to compare and study the optimal strategies of each fuel alternatives. The bunkering strategies mentioned before include the selection of bunker ports, the amount of bunkering on each bunker ports and adjusting the speeds of the vessel on each leg in the route, as the three components are interrelated, thus should be optimized jointly to obtain the optimal bunker fuel management strategy. The vessel is simulated on an Asia-Europe route and optimized based on the fuel cost and CO_2 emission over several scenarios.

From the problems and objectives mentioned above, this thesis tries to answer the following main research question:

What are the optimal bunker fuel management strategies (cost-wise and emission-wise) on each fuel alternatives?

This thesis also tries to answer the following sub-research questions that supports and further improve the main research question:

1. *How the port arrival time windows and total voyage time affect bunker fuel management strategies?*
2. *How the changes in fuel prices bunker fuel management strategies?*
3. *How the increase in fuel tank capacity affect bunker fuel management strategies?*
4. *How the different fuel alternatives can be compared in terms of bunker fuel management strategy, both cost-wise and carbon emission-wise?*

1.3. *Thesis Structure*

To answer the research question, this thesis is organized as follows. In the second chapter, this thesis briefly reviews the decision-making levels of liner shipping and the position of bunker fuel management strategy in said decision-making levels. This thesis also reviews relevant literatures and development related to bunker fuel management strategy. This chapter also reviews three fuel alternatives proposed by IMO and further reviews relevant information of the alternatives related to bunker fuel management strategy. Lastly, this chapter discusses three methods of bunkering for maritime transportation. In the third chapter, this thesis discusses methodology, including research design and problem formulation of bunker fuel management strategy with its assumption, mathematical model, and error values. In the fourth chapter, the data required for the simulation are discussed including the choice of several parameters and its assumptions. This chapter also discusses the scenarios that are simulated in this thesis.

In the fifth chapter, the results of the optimization from each scenario are presented. This chapter mainly tries answers the main research question. The first to third sub-research questions are discussed in this part. This chapter also discusses the comparison of the alternatives, thus answering sub-research question 4. Finally, the conclusion, summary, contribution and future improvement are presented in the sixth chapter.

2. Literature Review

This chapter's objective is to review current literatures on bunker fuel management strategy and to obtain relevant information related to it. This chapter begins in Section 2.1. with a discussion on bunker fuel management strategy, specifically on speed adjustments and refueling strategies, and the research related to it are discussed. Then, research on joint optimization on refueling strategies, including bunker port selection and refueling amount, and speed adjustment are also discussed. On Section 2.2., this study continues on decision-making levels and the position of bunker fuel management strategy, in which include three components such as speed optimization, port bunkering choice and the amount to bunker. On Section 2.3., the discussion reviews the literature on fuel consumption regarding the sailing speed of a vessel and the size of the vessel. Then on Section 2.4., this chapter reviews the fuel alternatives of IMO 2020 regulation, namely HFO with scrubber, MGO, and LNG and the relation to its specific fuel consumption and greenhouse gasses emission. This chapter also touches slightly on the overview LNG supply chain. Section 2.5. discusses the methods that are available for bunkering. Lastly, Section 2.6. summarizes the literature review chapter with relevant information and research results that are used in this thesis.

2.1. Bunker Fuel Management Strategy

As written in chapter 1, bunker fuel management strategy concerns on three components, namely, sailing speed adjustments, bunkering amounts and ports bunker selection. Many researches have reviewed the bunker fuel management strategy, mainly on the specific components.

2.1.1. Sailing Speed Adjustments

Sailing speed adjustments is a way to manage a voyage, specifically to manage the bunker consumption, in order to achieve a certain target, usually relating to cost optimization, profit maximization, service reliability, emission control and many more. Fagerholt et al. (2010) optimized the sailing speed based on the cost constrained by port time windows. The vessel was also constrained to achieve the service level of 100%. The model that was developed uses a different method, in which the problem is tackled as a shortest route problem and arrival times are discretized. Wang and Meng (2012) developed a speed optimization problem in container routing and transshipment of a global liner shipping company. The problem was formulated in mixed-integer nonlinear model and was approximated by an algorithm called outer-approximation. Alvares (2009), proposed a model to solve optimal routing and deployment of a fleet of container vessels, which is related to speed adjustments by using a nonlinear mixed integer programming problem. The model considered different cost, revenue and operating properties of 120 ports of call.

Doudnikoff and Lacoste (2014) optimized the speed of a voyage in an emission-controlled area and outside emission-controlled area in order to calculate the cost-optimal voyage by also maintaining the service frequency without adding any vessel to the route. The paper solved the problem by using a combinatorial optimization model. This paper found that by differentiating the speed, the total cost was decreased but CO_2 emission was increased in a similar manner. Speed optimization is often used to solve delay recovery problem. Qi and Song (2012) build a model to minimize the emission by adjusting the speed in the condition of delays. The model was run under the assumption of uncertain port times. In Wang and Meng (2012), the uncertainties were not only on port times, but also sailing times. The model proposed the solution in the form of a tradeoff between round trip duration and fuel cost in respect to the speed adjustments. Kim et al. (2016) optimized the ship's speed to minimize the total fuel consumption subjected to multiple port arrival time windows using non-linear mixed integer programming.

In Du, Meng, and Wang (2015), fuel consumption under uncertain weather conditions was minimized using a robust planning method. Mulder and Dekker (2019) considered the problem of a ship delay optimal recovery policy with buffer time allocation in a development timetable and a decision to manage delays during operation, in which the decisions include adjusting sailing speed, skipping a port and extreme action used to bound delays. The discrete stochastic decision problems, both short- and long-term decisions were solved by using mixed integer programming. The existing liner shipping route cost was optimized up to 28.9% by optimizing the buffer time distribution.

2.1.2. Refueling strategies

Another component of bunker fuel management strategy that is not so often discussed is refueling strategies. Refueling strategies consist of the choice of where to bunker and the amount of bunkering, mainly affected by the differences in price on each port. The amount of research specific to refueling strategies of a vessel is limited if compared to research regarding speed adjustment. Although refueling strategies can be perceived as an inventory management problem, in which the fuel consumption is analogous to the demand of goods and refueling decision is analogous to purchasing decision to the supplier. In this literature review, however, we only focus on the refueling strategies of a vessel.

Wang, Yeo and Adolf (2014) developed a model on the choice of port bunker constrained to an uncertain ship arrival to the port using a method called Fuzzy-Delphi-TOPSIS method by scaling the data from literature, questionnaires, and actual data. Besbes and Savin (2009) also developed a model of route and refueling optimization by using a method called random dynamic programming. The model optimized the profit in liner and tramp shipping which was differentiated by the problem. The cost of liner shipping was optimized by the refueling strategy subject to random fuel prices and limited fuel capacity. Meanwhile the cost of tramp shipping was optimized by the refueling strategy subject to route selection, which adds the complexity to the problem. Sheng et al. (2015) optimized the refueling strategies constrained with the uncertainties of price and fuel consumption by using inventory strategy solved by an effective dynamic (s,S) policy, which is a minimum (s)/ maximum (S) policy. Ghosh et al. (2015) examined the service contract with known parameters between liner and fuel supplier and try to optimize the refueling strategy subject to the observed spot price. Wang and Meng (2015) consider the optimization of ship cost, cargo inventory cost and ship operation cost in Asia-Europe liner route using mixed nonlinear programming model.

2.1.3. Joint Refueling and Speed Adjustments Strategies

Jointly optimizing refueling strategies and speed adjustments can further optimize the cost incurred in the voyage. The research on joint optimization on speed adjustments and refueling strategies of bunker fuel management strategy, however, is also limited if compared to research on speed adjustments. Ronen (2011) stipulated the importance of reducing the sailing speed on the operating cost, specifically on fuel cost under the change of fuel prices. The study discusses the speed optimization problem and refueling strategies regarding service frequency and the number of vessels that are deployed. The study devised a cost model to analyze the trade-off between speed reduction, and service frequency and adding the number of vessels to the service. Yao, Ng and Lee (2012), considered a different price across different ports and proposed a bunker fuel management strategy to find optimal bunkering ports and bunkering amounts. The paper also considered the speed adjustments constrained to the arrival time windows in ports. Subjected by constraints above, the objective of this paper is to minimize the bunkering cost and revenue loss due to the bunker weight.

Many papers were influenced by Yao, Ng and Lee (2012). In Sheng, Lee, and Chew (2014), the objective of minimizing bunkering cost and revenue loss due to bunker weight is extended by adding the element of uncertainty in fuel consumption and fuel prices. This paper also added the objective of minimizing the holding cost of bunker fuel. The work of Aydin, Lee and Mansouri (2016), was also influenced by Yao, Ng and Lee (2012), in which they extended the work by adding the uncertainties in service times and time windows at ports by using dynamic programming model to optimize the speed. Furthermore, the paper added the option to choose ports that were not a part of the service schedule. The objective was still similar to the previous work, which to minimize the cost of sailing, but the model used non-linear relation between ship sailing speed and fuel consumption. Kim (2014), considered a bunker fuel management strategy for a container ship to minimize various cost components, which were fuel consumption, ship time (chartering cost of the ship and the value of the container) and carbon tax. The model, however, did not consider the arrival time windows, thus leaving the speed adjustments restricted only to the fuel cost. Wang and Chen (2017), discussed a similar problem, in which the objective was to optimize fuel costs and carbon emissions costs of a liner by considering sailing speeds, bunkering amounts, bunkering selection and the number of ships deployed in the specific route. The proposed model was applied into Asia-Europe service route.

2.2. *Decision-making Levels*

The type of shipping operations has since been transformed by containerized shipping. Lawrence (1972) describe three main operations in containerized shipping, namely industrial shipping, tramp shipping and liner shipping. In industrial shipping, the vessel that is used to ship the goods is also controlled by the cargo owner. The cargo owner aims to minimize the cost of transporting the good by controlling the said vessel. In tramp shipping, however, the cargo owner does not control the vessel. In order to maximize the profit, the vessel is controlled by the ship owner and so does the cargo selection that is transported by the said vessel. Lastly, in liner shipping, the ship owner or shipping liner company publishes the shipping service route that forms a round trip with a certain service frequency and port of calls. The regularity of the service is used to attract cargo. Furthermore, the liner ship has to keep sailing according to its published schedule, whether the ship is on full capacity or not.

Based on the characteristics listed above, Pesenti (1995) formulated three decision-making levels of a liner shipping to minimize the cost and to keep the schedule reliable. The three decision-making levels are strategic, tactical and operational. At the strategic level, the decisions are made to impact the company in the longer term, typically in two to five years. The type of decision such as ship fleet size, the choice of the ship, alliance strategies and network design are classified as a strategic decision. At the tactical level, decisions are made in the medium term, usually in the span of two to twelve months and to impact the company in same durations. The decisions such as frequency of its services, fleet deployment, sailing speeds of the ships and schedule design are classified as a tactical decision. Lastly, at the operational level, decisions are made on the weekly or even daily basis. Decisions such as cargo booking, cargo routing, and ship or cargo rescheduling in case of unexpected events are classified as an operational decision (Meng, Wang, Andersson and Thun, 2014). The decisions made on strategic level are impacting the decisions on the tactical level and so on. Fleet size and mix of a shipping liner company are a necessary input for the fleet deployment and routing of the cargo and/or vessel.

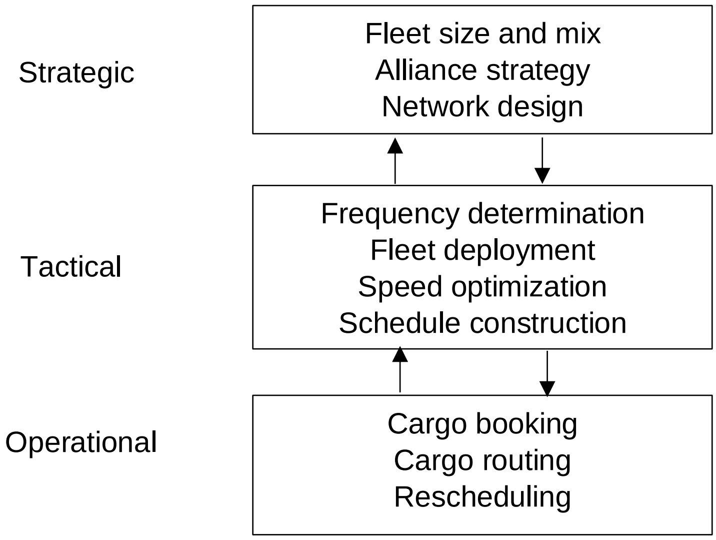

Figure 2. Decision Level Classification source: Meng, Wang, Andersson and Thun (2014)

There are differences in the classification on many studies. For example, liner shipping network design is classified as strategic planning by Meng, Wang, Andersson and Thun (2014), but in Agarwal & Ergun (2008), network design is classified as tactical decision. However, in many studies (Meng, Wang, Andersson and Thun, 2014; Fagerholt et al,, 2015; Brouer et al., 2017), speed optimization, which is a part of bunker fuel management strategy, is categorized as a decision on tactical level, as it is a decision that aims to answer the derived problem from network design and fleet size and mix, which is categorized on strategic level. Furthermore, the decision on where to bunker and how much to bunker, which are also a part of bunker fuel management strategy, are also categorized as a decision on tactical level. The decision on where to bunker and how much to bunker are also trying to solve the derived problem from network design and fleet and size mix (Fagerholt et al., 2015; Brouer et al., 2017). Thus, this thesis considers bunker fuel management strategy as a decision on a tactical level.

2.3. Fuel Consumption

Although fuel consumption is affected by many components, including weather (Bialystocki and Konovessis, 2016), hull coating (Edalat and Barzandeh, 2017) and propeller roughness (Mosaad, 1988). This thesis mainly discusses the researches on fuel consumption in relation to ship's speed and size, which analogous to the displacement of the ship, as both sailing speed and ship size are considered as a main factor in determining fuel consumption. There are two main differences among the researches on fuel consumption (Mersin et al., 2017), one is when the researches consider the weight, in which analogous of the displacement of the ship to the water and sailing speed as a variable, and the other is which the researches that only consider the sailing speed as the variable to the fuel consumption. To generalize the equation, the latter considers the weight of the ship as a coefficient which differs from ship size to ship size in respect to the fuel consumption at design speed. It is important to be noted that both formulas are valid on any speed between the minimal speed of the speed and the maximal speed specific to each ship (Brouer et al., 2014).

Barras (2004) proposed a formula for fuel consumption of a ship as a function of sailing speed and displacement of the ship. The fuel consumption (F) the ship is proportional to the fuel specific coefficient relating to the motor of the ship (a), actual sailing speed of the ship (V) and the displacement of the ship ($\triangledown$).

$$F = a\ (V)^3\ \nabla^{2/3} \tag{1}$$

As mentioned, the formula can be used to calculate the fuel consumption that varies by the ship speed and ship weight. This is particularly accurate when the weight of the cargo varies between the legs of the route and needs to be taken into account to the total weight of the ship.

Ronen (1982) proposed a formula for fuel consumption of a ship as a function of sailing speed. The fuel consumption (*F)* the ship is proportional to the fuel consumption at design speed times (F_0) actual sailing speed of the ship (*V*) divided by the design speed of the ship (V_0) to the power of three.

$$F = \left(\frac{V}{V_0}\right)^3\ F_0 \tag{2}$$

As the weight of the ship does not act as a variable in this formula, it is important to be noted that the fuel consumption at design speed is measured at the weight of the ship during the average load. Many researches have used Ronen's formula to obtain optimal sailing speed subjected to different constraints. (Corbett et al., 2010; Meng and Wang, 2012; Ronen, 2011; and Mulder and Dekker, 2018). However, there are limited researches that provide empirical data to prove Ronen's formula. Wang and Meng (2012) proved the formula by using the data of a containership of 3000 TEU size to 8000 TEU size. However, the empirical study did not consider the design speed into account. The objective of the empirical study was to find the value of coefficient a and b based on the data of many ship size.

$$F = a\ (V)^{\ b} \tag{3}$$

From the results, there were a variation in the power with respect to the ship size. However, Wang and Meng (2012) argued that the formula provided by Ronen (1982) is a good approximation, in a condition if not enough historical data that can be used to obtain empirical relation. Once there is enough data, one should obtain the accurate bunker consumption function on the basis of Ronen's formula.

Table 1. Empirical Results of Fuel Consumption in Relation to Speed from Wang and Meng (2012)

Parameters	**3000 - TEU SG - JKT**	**3000 - TEU SG - KS**	**5000 - TEU HK - SG**	**8000 - TEU YT - LA**	**8000 - TEU TK - XM**
a	0.014	0.010	0.004	0.011	0.037
b	2.892	3.002	3.314	3.118	2.709
R^2	0.964	0.960	0.977	0.993	0.990
Adjusted R^2	0.962	0.958	0.976	0.993	0.990

Source: Wang and Meng (2012)

Yao, Ng and Lee (2012) also tried to empirically obtain the relation between sailing speed based on Ronen's formula. Based on the data they acquired, they arrived at the formula provided below.

$$F = k1\ (V)^3 + k2 \tag{4}$$

The coefficient *k1* and *k2* differ with the ship size. Yao, Ng and Lee (2012) used decent amount of data points, in which one data point contained one ship speed and one fuel consumption. The results from the empirical study are provided below.

Table 2. Empirical Results of Fuel Consumption in Relation to Speed from Yao et al.(2012)

Size (TEU)	k1	k2	Number of Data Points	Speed Interval (knots)
0–1000	0.004476	6.17	73	(10.5,16.5)
1001 – 2000	0.004595	16.42	65	(12.5,19.5)
2001 – 3000	0.004501	29.28	51	(13.5,21)
3001 – 4000	0.006754	37.23	82	(14.5,21.5)
4001 – 5000	0.006732	55.84	193	(15,24)
5001 – 6000	0.007297	71.4	170	(14,24)
6000+	0.006705	87.71	53	(18,25)

Source: Yao, Ng and Lee (2012)

The conclusion from this empirical study is similar to the conclusion from Wang and Meng (2012). The equation provided from Ronen (1982) is a good approximation as long as there is no historical data of the specific ship type and size that can be regressed to obtain more accurate relation. Brouer et al. (2014) provided six generalized vessel class from 500 APM-Maersk ships, complete with its particulars, including design speed fuel consumption at the design speed which is shown in Table3.

Table 3. Vessel Particulars from Maersk Fleet List

Vessel Class	Size (TEU)	Fuel Consumption (tons/day)	Design Speed (knots)	Speed Interval (knots)
Feeder 900	900	18.8	12	10, 14
Feeder 1600	1,600	23.7	14	10, 17
Panamax 2400	2,400	52.5	18	12, 19
Panamax 4800	4,800	57.4	16	12, 22
Post Panamax	8,400	82.2	16.5	11, 23
Super Panamax	15,000	126.9	17	10, 22

2.4. Fuel Alternatives of IMO 2020 Regulation

As briefly mentioned in Chapter 1, IMO proposed three main alternatives to comply with the sulphur cap in 2020. This Section discusses the general information on each alternatives and bunker management related information, namely the fuel consumption of each alternatives in reference to HFO in normal operation and the greenhouse gasses emission of each alternative.

2.4.1. HFO with Scrubber

HFO itself is a residual fuel from a distillation and cracking process of crude oil. HFO is contaminated by several matters, for example aromatics, sulphur and nitrogen. The lack of processing of HFO has made the production cost the cheapest compared to other fuel. The quality of HFO may differ according to the quality of the crude oil. For standardization of the quality, HFO is usually blended to marine gas oil or marine diesel oil. Scrubber is a cleaning device attached in the exhaust system designed to process the exhaust gas with additive materials, such as freshwater, seawater and chemicals (Panasiuk, Lebedevas, and

Cesnauskis, 2014). The sulphur content from the treated exhaust gas is reduced to the set amount. This method allows shipowners and operators to comply with IMO regulation without changing the fuel into fuel with a higher price because of its low sulphur content (Catlin, 2018). However, in the consideration of other environmental damage, the scrubber system does not reduce the emission of CO_2, thus making it as dirty as HFO during normal operation without scrubber.

There are two types of scrubber which are wet scrubber and dry scrubber. Dry scrubber uses chemical to clean the exhaust gas and does not use any kind of water. Wet scrubber on the other hand, use water in addition to the chemicals. There are three types of wet scrubber, which are closed loop, open loop and hybrid. Open loop scrubber is when sea water is pumped from the sea to the scrubber and then returned to the sea. Closed loop is when the fresh water and chemicals are used. The wash water is not discharged to the sea, but rather kept in the ballast tank, which could be costly if compared to open loop. Although open loop system is cheaper, it is important to be noted that some area is considered to be sensitive to the waste from the wash water, thus the usage of open loop system could pose a danger to local waters. Hybrid scrubber is capable of using both types, which open loop is used on the open sea and closed loop is used on ports or any emission-controlled area (Panasiuk, Lebedevas, and Cesnauskis, 2014).

Installing scrubber might be cost efficient for shipowners and operators alike. As mentioned above, by installing scrubber ship owner does not need to change the bunker fuel, thus maintaining an almost similar price as using HFO in normal operation. The availability of the bunkering facilities of HFO is also not an issue, since HFO has been widely used as a maritime fuel. Despite this, many experts have voiced their concern about the future availability of HFO due to the shifted demand from HFO to MGO. Due to the possibility of decreased supply of HFO, many experts believe that the price differences of HFO and MGO would not be significant enough to choose scrubber (Billing et al., 2018). Furthermore, hesitation may arise as scrubber technology is rather unproven and future regulation may render the technology useless. For HFO with scrubbers, it is stated by Van Rynbach et al. (2018) that the fuel consumption of HFO with scrubber is 1,5%-3% higher than without using scrubber because of the needs of additional fuel to operates the scrubber system, with open loop system is on the high end of the consumption and the closed loop on the low end, while fuel consumption of the hybrid systems depends on the usage of both system.

2.4.2. MGO

Low-Sulphur Fuel Oil (LSFO) is categorized as a fuel oil with relatively low viscosity and low density, thus making the ignition properties relatively better than heavier fuel (Shell, 2018). Marine gas oil (MGO) is classified as such. MGO is a choice for many companies, among them is Maersk, which has secured deals to provide low-sulphur fuel source with many refineries (Cosgrove, 2019). Compared to other alternatives, the benefit of MGO is clear from the perspective of capital cost as switching to MGO requires no retrofitting. According to Billing, Fitsgibbon, and Shankar (2018), MGO would most likely be the popular choice for the initial phase of IMO 2020 implementation because the bunker fuel for ships could be switched to use MGO with relatively less modifications compared to the other fuel, making the investment cost of conversion to a minimum. Furthermore, bunkering facilities of MGO is the same as HFO (Jiang, Kronbak and Christensen, 2014). Thus, there is no issue on the availability from the bunkering facilities side.

However, MGO needs further refining from crude oil, thus making it much more expensive. In May 2018, the differences in prices between HFO and MGO reached $261.5 per metric ton and predicted to increase once the demand for MGO starts to rise in 2020. (Wood Mackenzie, 2018). The limited hydrotreating facility that would limit the supply would also likely to hike the MGO price (Grimmer, 2018). Although, many main bunkers are saying its readiness to provide a steady supply to anticipate the demand in 2020. Despite more processing is needed to distillate MGO, MGO has a 5% higher lower heat value compared to HFO, thus MGO consumption is 5% less than HFO in normal operating conditions (Van Rynbach et al, 2018). As per data from IMO (2014), MGO emits more CO_2, albeit not in significant amount, if compared to HFO.

2.4.3. LNG

LNG being another one of the alternatives has been chosen by several shipping companies, albeit not as popular as previous alternatives. CMA CGM has ordered 9 LNG-fuelled Ultra Large Container Vessel (ULCV) that will be delivered in late 2019 and late 2020 (Bergman, 2018). Although there are benefits in choosing LNG mainly for cleaner fuel and cheaper price over other fuels (Balcombe et al., 2018), there are only 33 LNG bunkers in operation worldwide (SEA LNG, 2019) and majorly centralized in West Europe (Berti, 2018). The investment in port LNG infrastructure, mainly LNG bunker, that can support international trade may also be a significant barrier for the usage of LNG as an alternative fuel, thus the number of LNG bunker are limited compared to conventional and other alternative fuels. But, as stakeholders are getting ready to prepare for the sulphur cap, it is believed that due to rising demand of LNG, among other factors, that the number of LNG bunker facilities worldwide will grow (Schinas and Butler, 2016), although, the facilities would most likely not grow as much as the demand.

The uncertainty over LNG availability can be mitigated by arranging a long-term contract with LNG suppliers. This method could also prevent a general shortage in the world by making it less uncertain. Considered as a clean fuel, LNG produces no sulphur and any particulate matter, and emit much less nitrogen oxide emission (IMO, 2017). It also emits less carbon compared to other alternatives, which makes it almost future proof towards forthcoming regulations. Furthermore, LNG is a more efficient fossil fuel among all three. LNG has 13% higher heating value compared to HFO. Despite the higher heating value, the energy efficiency relative to volume is low compared to other fuel, thus LNG has the need of larger tank if used as fuel for vessel. LNG has two times the volume if compared to fuel oil (Wang and Notteboom, 2014). The price of LNG is also favourable to the operational cost of a ship, as supported by the history of LNG price in Henry Hub gas, which is the world’s cheapest LNG trading place, is consistently less expensive than HFO. Furthermore, in Japan LNG, although the price of LNG is consistently higher than HFO, it is consistently and significantly less than MGO. This is partly due to LNG being cheaper to produce, making it the cheapest fuel among the alternatives (Elgohary et al., 2015).

2.4.3.1 LNG Supply Chain

LNG is delivered from the point of production to the end customers through multiple way. This includes extraction of natural gas, treatment, liquefaction, shipping, receiving and distribution to the end customers. As this thesis’ interest lies in the usage of LNG as a fuel, it is important to not that this thesis only concerns the end customers that use LNG as a transportation fuel, specifically LNG fuelled ship. There are two categories of the process in LNG supply chain (Brinkhof, 2013), which are upstream process and downstream process. The upstream process starts with the extraction and production of natural gas, to the process of liquefaction. Liquefaction is an adjustments process of the natural gas to make it compatible to low temperature, for the needs of transportation (Brinkhof, 2013). The need of transporting natural gas arises from the place where it has no natural gas production and as it is not always possible to transport the gas by the means of pipeline network, it is necessary to liquify the natural gas so that it can be transported by the means of shipping (Jarlsby, 2008). The liquefied form of natural gas then is stored in cryogenic tank until it is ready to be transported. Eventually, the LNG is transported from LNG export terminal near the production location to the LNG import terminal near the demand location.

The downstream process of LNG supply chain starts from the import LNG terminal. This terminal usually built to receive and store a large amount of LNG. From here, LNG is distributed to the end-users, in this case LNG fuelled vessel. This process is called bunkering. However, as it is not always possible to bunker the LNG to the LNG fuelled vessel from the LNG terminal by using feeder vessel and truck, it is necessary to build small scale and medium scale of LNG infrastructure as the next point of distribution of LNG. Small scale and medium scale of LNG infrastructure act as an intermediate point to the end users such as maritime transport (PwC, 2013).

2.4.4. Summary of Alternatives

Provided below is the summary of the fuel alternatives. The energy content and fuel consumption compared to HFO in normal operation are stated inTable3.

Table 4. Fuel Consumption of Each Alternative

	Fuel Type: HFO 380 with scrubber	Fuel Type: MGO-0.5%	Fuel Type: LNG
Energy Content	**40,500 kJ/kg**	**42,700 kJ/kg**	**49,000 kJ/kg**
Fuel Consumption (compared to HFO in normal operation)	**1.5% - 3% higher**	**5% lower**	**13% lower**

source: Van Rynbach (2018), Shipandbunker.com (2019) and Elgohary et al. (2015)

As briefly mentioned above, apart from fuel consumption of each alternatives, each fuel also differs in greenhouse gasses emission, provided in Table 5 are the greenhouse gasses emissions of each fuel. As can be seen, the emission of each fuel alternatives can be calculated from the amount of fuel consumption. In this thesis, however, only CO_2 emission and CO_2 emission equivalent are calculated. The amount of CO_2 emitted from each fuel alternatives depends on the amount of carbon on each fuel molecule (Garaniya, 2009). HFO and MGO, which the hydrocarbon structures are similar to each other, have similar CO_2 emission factor, meanwhile LNG, which is composed as a different hydrocarbon structure, has a different CO_2 emission factor. Although it is acknowledged that the regulation of IMO 2020 was made specifically to control Sulphur emission, this thesis does not study the emission of Sulphur. All fuel alternatives listed in this study are all compliant to the Sulphur cap of 0.5% set in IMO 2020, thus there would be no significant difference in between the three alternatives. This thesis also does not study the emission of Nitrogen Oxide (NO_x) due to technology already exists to tackle the emission (Kokkinos, 2017) such as selective catalytic reduction (SCR). The technologies would not notably affect the fuel consumption (Azzara, Rutherford & Wang, 2014) hence also would not notably affect the bunker fuel cost. Therefore, as far as emissions are concerned, it is recognized that LNG has the least emission per gram fuel in every type of emission, as provided in Table 4. As for LNG, there is a probability of a CH_4 (methane) slip in the vessel that use LNG as fuel, thus it is necessary to take into consideration. Although the probability of the methane slip can be decreased or even be removed completely, depending on the type of the engine (Ushakov, Stenersen and Einang, 2019). According to EPA (2019), greenhouse gasses emission from 1 gram of methane is equivalent to 25 grams of CO_2.

Table 5. Emission Factor of Each Alternatives

Emission (in gram per gram fuel)	Fuel Type: HFO 380 with scrubber	Fuel Type: MGO-0.5%	Fuel Type: LNG
SO_x	0.05	0.05	0
CO_2	3.114	3.206	2.750
CH_4 (Methane)	~0	~0	0.051 (equals to 1.25 gram of CO2)
NO_x	0.083	0.083	0.01

Source: IMO, 2014

2.5. Bunkering Methods

Bunkering methods of HFO, MGO and LNG share some similarities. However, the differences may lie in the availability of the bunkering infrastructure in the port, such as bunker storage or nearby LNG terminal. The difference in the method could affect the bunker price as each method has a different cost. Generally, IMO (2016), define three most common methods of bunkering, which are ship to ship bunkering, shore to ship bunkering and lastly truck to ship bunkering.

Truck to ship bunkering

Truck to ship bunkering is the method of supplying fuel by using trucks. This method is known to be the slowest because of the small capacity of one truck and the transport rate, but offer the greatest flexibility of all (Kokkinos, 2017). The bunkering process uses a hose from the fuel truck parked on the quay where the ship is berthed. Depending on the size of the vessel, bunkering using this method could be quite costly (Faber et al., 2017). Furthermore, large quantities bunkering using truck to ship method is not advisable (Wang and Notteboom, 2014).

Shore to Ship

In this bunkering process, the fuel is delivered directly from the tank by a pipeline connection. The distance from the tank to the berthed vessel is critical to this operation. This method offers the fastest transport rate and the biggest capacity as it is only constrained by the size of the tank on the shore. However, this method is the least flexible from the three depending on the port because of the tank locations to the berth and could be the costliest, depends mainly on the length of the pipe, according to Faber et al. (2017)

Ship to ship bunkering

As the name suggests, this process is done by a bunker vessel, such as barge or pontoon, which is connected to the vessel that needs to be fuelled. To save time, this process can be performed while in the process of loading and unloading cargo. The transport rate and the capacity of bunkering depend on the size of the feeder vessel, but it is generally faster than the truck to ship bunkering while offering the flexibility to the services as well. The bunker vessel is supplied by the nearest LNG terminal or LNG storage. This method is commonly used for medium to large sea going vessel as it is the cheapest method out of three (Faber et al., 2017).

By the reason of cost, flexibility and more importantly, as it most commonly used by large sea-going vessel, this thesis considers ship to ship bunkering as the method that is simulated. The additional cost of this bunkering method depends on the size of the vessel and the distance between LNG terminal or storage and targeted vessel, in which could range from 6% to 16% from the import price of LNG (details provided in appendix 2).

2.6. Chapter Summary

In this chapter, some of the researches regarding decision-making levels, bunker fuel management, fuel consumption, fuel alternatives of IMO 2020 regulation, and bunkering method are discussed. In Section 2.1., All of the research, whether it is related to speed adjustments, refueling strategies or the joint optimization between both components, have the objective of minimizing the fuel-related cost of the voyage. Some models incorporate uncertainties that can be solved by using robust model, some others incorporate deterministic settings that can be solved by using deterministic model. This research is specifically using the paper by Yao, Ng and Lee (2012) as a reference as the complexities and the problem subjected to the objective is similar. As written above, the study done by Yao, Ng and Lee (2012) considered the bunker fuel management strategy on the usage of one type of fuel only, which was heavy fuel oil. This thesis aims to expand the study done by Yao, Ng and Lee (2012) by adding different type of fuel to the simulation and also considers the emission caused by each fuel. The problem formulation is further discussed in chapter 3.1.

In Section 2.2., decision-making levels are briefly discussed, and the conclusion is that bunker fuel management strategy lies within the tactical decision level because it tries to answer the problem derived from the decision made in strategic level. In Section 2.3. researches on fuel consumption in regard to weight and speed are discussed. It is concluded that the formula proposed by Barras (2004), is more accurate if the weight of the cargo is taken into account. However, if the weight of the cargo is not being taken into account, then the formula proposed by Ronen (1982) is reasonably accurate, as proven by Wang and Meng (2012), and Yao, Ng and Lee (2012). In general, it is accepted that speed has a proportional relation to the power of three to fuel consumption.

In Section 2.4., fuel alternatives of IMO 2020 are discussed. General information such as the intrinsic cost of production and fuel efficiency relating to the fuel alternatives are given. General overview of the LNG supply chain is also discussed in this Section. Furthermore, each fuel has different fuel consumption and emission which are used in this thesis. Section 2.5 discusses the process of each bunkering methods and the cost relating to said methods. From Faber et al. (2017), the method of ship to ship is most commonly applied for sea-going ship and usually the cheapest out of the three. By that reason, this method of bunkering is used on this thesis. Lastly on Section 2.6., bunkering methods is discussed, which gives general overview of the process of the bunkering, which includes the cost and flexibility.

3. Methodology

This chapter aims to discuss the methodology of the thesis to further explain the problem definition written in chapter 1. Research design is discussed in chapter 3.1 to show the structure of the study and further explanation of the problem formulations including the limitations and assumptions. Then the mathematical model of bunker fuel management strategy is discussed in chapter 3.2, in which includes the objective function, constraints and the piecewise linearization to solve non-linear constraint. Lastly, Section 3.3. contains the summary of this chapter.

3.1. Research Design and Problem Formulation

This thesis considers a tactical decision level of bunker fuel management strategy in a shipping liner service in which the aim is to minimize the bunker fuel cost and to minimize the greenhouse gasses emission. It is considered as tactical decision level; thus, the result of the optimization can be used to plan an optimal practice for a whole service route which lasts approximately more than two months. This thesis considers a round trip of a service route in a shipping liner service that is served by one specific ship that is predetermined in the previous tactical decision. As it is known that bunker fuel cost and carbon gasses emission are mainly affected by the fuel consumption of the ship, in which is related to the ship speed and the bunker fuel prices in each port.

Scenarios are considered in this thesis to study the effect of main factors on the shipping industry. Three main scenarios that simulated are the relaxing of port arrival time windows, the change in bunker fuel prices on the ports along the service route, and the increase in fuel tank capacity. The results of the optimal bunker fuel management strategy in each scenario are then discussed.

Thus, this thesis aims to minimize the bunker fuel cost and the greenhouse gasses emission on the tactical planning level by optimizing the bunker fuel management strategies simulated on three main scenarios and to study the optimal strategy. The components of bunker fuel management strategy including the speed, bunkering amounts and bunkering ports selection of each leg of the route. Optimizing the bunker fuel. This thesis also considers quantity price discounts for bunker fuel as larger purchase yields in cheaper logistic cost and the practice of applying quantity price discounts are commonly applied in liner companies as stated in Yao, Ng and Lee (2012), Weng (1995), Hu and Munson (2002), and Zhou (2007).

This thesis is optimizing the bunker fuel management strategy by using mixed-integer nonlinear programming solved by OpenSolver as a programming interface. OpenSolver is developed and improved by Mason (2012) as an extension of Excel's built in solver.

In this thesis, the service route and the number of port of calls of a liner shipping service are known. The ship specifications such as minimum and maximum speed, design speed, fuel consumption at design speed, and tank size are known. The specifications on each fuel alternative such as energy content, bunker fuel prices and greenhouse gasses emission are known. Moreover, the time arrival window on each port and the total voyage time of one vessel in the service are also known. Entry time, unloading time, loading time, idle time and exit time, which are compiled into port time is assumed to be known for simplicity. Furthermore, the canal passage time is simplified by including the passage time into the port time of the previous port before the canal. Even though it is known that there is different type of costs incurred on shipping liner services such as capital costs, operational costs (other than bunker fuel cost), port charges, administration costs, terminal costs, and many others. These types of costs are considered as constants because the costs fall outside the scope that is relating to the focus of this thesis, which is the bunker fuel costs.

It is important to be noted that the model is general, in a sense that it can be applied to any vessel, any fuel and any shipping route, as long as the data requirements for the model are fulfilled.

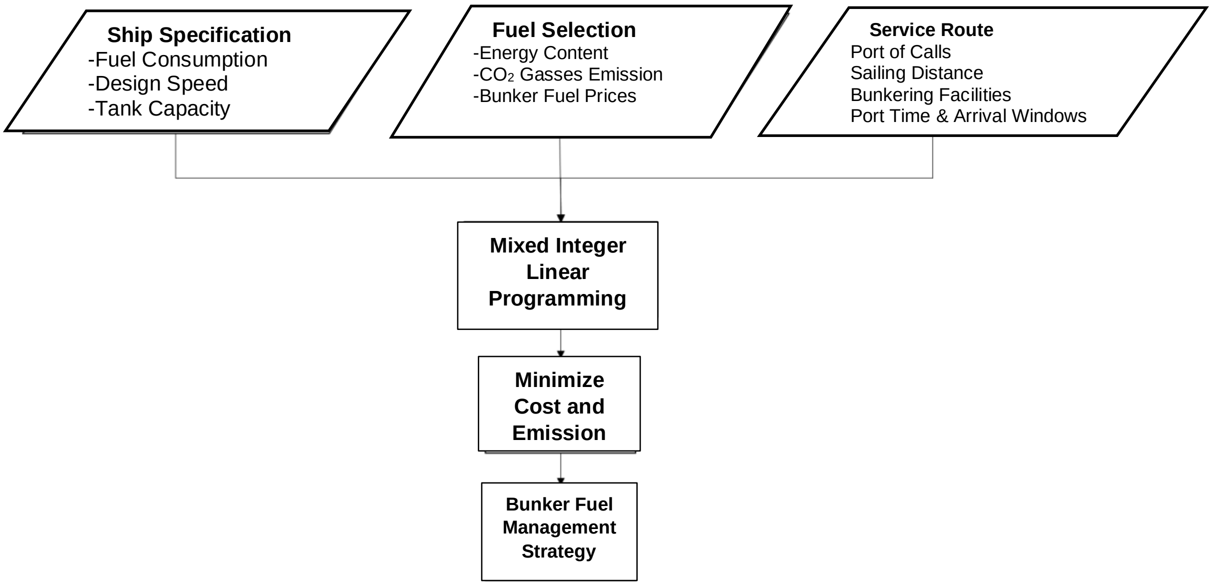

Figure 3. Research Design

3.2. Mathematical Model

This Section provides the notations, the mathematical model of mixed integer non-linear programming in which later linearized, and lastly the solution for the non-linearities in the model by using piecewise linearization.

Notations

The notations used in this thesis are:

Indices

i:	ports of call, with 1 as the first indices, indicating first port and 8 as the last indices, indicating second to last port.
j:	ports of call directly after port i, with 2 as the first indices, indicating the second port and 9 as the last indices, indicating the last port.
k:	piecewise bunkering indices

Parameters

n:	port calls
D_{ij}:	distance between port i and port j (nm)
w:	bunker capacity of a ship (tons)
q:	number of bunkering facilities
F_0:	fuel consumption rate at a design speed (tons/day)
e_i:	earliest arrival time in port i (h)
l_i:	latest arrival time in port i (h)
w:	bunker fuel capacity of a vessel (tons)
V_{min}:	minimum ship speed (knots)
V_{max}:	maximum ship speed (knots)
$V_{d:}$	design speed (knots)
G:	emission of fuel (tons)
P_i^1:	price of bunker fuel at port i ($/ton)

P_i^2, P_i^3:	Quantity discount price of bunker fuel at port i, with $P_i^2 = 0.95\, P_i^1,\;\; P_i^3 = 0.90\, P_i^1$ ($/ton)

Decision variables

V_{ij}:	sailing speed between port i and port j (knots)
S_i:	bunker fuel order-up-to-level (ton)
B_i:	binary decision variable; =1, bunkering at port i; = 0, does not bunker at port i
$x_i^k;\; k = 1, 2, 3, 4$:	decision variables for piecewise bunkering and piecewise cost function at port i
$z_i^k;\; k = 1, 2, 3$:	decision variables for piecewise bunkering and piecewise cost function at port i

Dependent variables

I_i:	bunker fuel inventory when arriving at port i (tons)
C_i:	cost of bunkering at port i ($)
F_{ij}:	fuel consumption rate between port i and port j(tons/day)
A_i:	arrival time in port I (h)
G_{ij}:	emission of fuel between port i and port j (tons)

The quantity discounts increase per 1000 tons purchase of bunker fuel. Thus, the cost structure from the quantity purchase is as written below:

$$C_i = \begin{cases} P_i^1\,(\mathrm{Si} - \mathrm{li}) & 0 < \mathrm{Si} - \mathrm{li} \leq 1000 \\ P_i^1\,(\mathrm{Si} - \mathrm{li}) + \; P_i^2\,(\mathrm{Si} - \mathrm{li} - 1000) & 1000 < \mathrm{Si} - \mathrm{li} \leq 2000 \\ P_i^1\,(1000) + \; P_i^2\,(1000) + \; P_i^2\,(\mathrm{Si} - \mathrm{li} - 2000) & 2000 < \mathrm{Si} - \mathrm{li} \leq 3000 \end{cases}$$

Mathematical Model:

The mathematical model for a bunker fuel management strategy is:

Minimum cost objective function

$$min \sum_i^n C_i \qquad (5)$$

Subjected to

$$Ci = x_i^1 0 \; + \; x_i^2 1000\; P_i^1 + \; x_i^3(1000\; P_i^1 + 1000\; P_i^2) + x_i^4\; (1000\; P_i^1 \; + \; 1000\; P_i^2 + (\mathrm{w} - 2000) P_i^3) \qquad \mathrm{i} = 1,..,\mathrm{n} - 1 (6)$$

$$S_i - L_i = \; x_i^1\; 0 + \; x_i^2\; 1000 + \; x_i^3\; 2000 + \; x_i^4\; w \qquad \mathrm{i} = 1,..,\mathrm{n} - 1 (7)$$

$$x_i^1 \leq z_i^1 \qquad \mathrm{i} = 1,..,\mathrm{n} - 1 (8)$$

$$x_i^j \leq z_i^{j-1} + \; z_i^j \qquad \text{j = 2,3; } \mathrm{i} = 1,..,\mathrm{n} - 1 (9)$$

$$x_i^4 \leq z_i^3 \qquad \mathrm{i} = 1,..,\mathrm{n} - 1 (10)$$

$$x_i^1 + \; x_i^2 + \; x_i^3 + \; x_i^4 = 1 \qquad \mathrm{i} = 1,..,\mathrm{n} - 1 (11)$$

$$z_i^1 + z_i^2 + z_i^3 = 1 \qquad i = 1,..,n-1 \quad (12)$$

$$G_{i,i+1} = (S_i - L_{i+1})\ x\ G; \qquad i = 1,..,n-1 \quad (13)$$

$$\sum_i^{n-1} Bi \leq q \qquad (14)$$

$$L_i = S_{i-1} - F_{i,i+1}\left(\frac{d_{i,i+1}}{24V_{i,i+1}}\right); \qquad \forall i \qquad (15)$$

$$S_i - L_i \geq 10\%\ w \qquad i = 1,..,n-1 \quad (16)$$

$$S_i - L_i \leq w \qquad i = 1,..,n-1 \quad (17)$$

$$\mathrm{L_i} \geq 5\%\ \mathrm{w}; \qquad \forall i \qquad (18)$$

$$\mathrm{S_i} \leq \mathrm{w}; \qquad i = 1,..,n-1 \quad (19)$$

$$\mathrm{F_{i,i+1}} = \mathrm{F_0}\left(\frac{\mathrm{V_{ij}}}{\mathrm{V_d}}\right)^3 \qquad i = 1,..,n-1 \quad (20)$$

$$\mathrm{V_{min}} \leq \mathrm{V_{i,i+1}} \leq \mathrm{V_{max}} \qquad i = 1,..,n-1 \quad (21)$$

$$\mathrm{A_{i+1}} = \mathrm{A_i} + \left(\frac{\mathrm{D_{i,i+1}}}{\mathrm{V_{i,i+1}}}\right) \qquad i = 1,..,n-1 \quad (22)$$

$$\mathrm{e_i} \leq \mathrm{A_i} \leq \mathrm{l_i} \qquad \forall i \qquad (23)$$

$$\mathrm{A_1} = 0 \qquad (24)$$

$$\mathrm{Bi} = 0 \text{ or } 1 \qquad \forall i \qquad (25)$$

$$x_i^j \geq 0 \qquad j = 1,2,3,4;\ i = 1,..,n-1 \qquad (26)$$

$$z_i^j = 1 \text{ or } 0 \qquad j = 1,2,3;\quad i = 1,..,n-1 \qquad (27)$$

Description

The problem is optimized by using mixed-integer non-linear programming. The objective is to minimize the total cost incurred by bunker fuel as written in equation (5). Each fuel alternatives differ in price in each port (Pi), emission (G), and fuel consumption on design speed (F_0). Each fuel alternatives also differ in the number of bunkering facilities that are available along the route (q). Each alternative is simulated on three separate mixed-integer linear programming, using identical constraints. Note that in this thesis we only consider the cost and the emission incurred by bunker fuel usage when sailing. The other costs and source of emissions are assumed to be constant. The cost of bunker fuel purchase is shown in constraints (6). As can be seen, the discount price structure is depicted here. The discount price structure is used identically on each fuel alternative. The discount price structure is set arbitrarily. Constraint (7) is the structure of bunker purchase based on piecewise bunkering. Constrains (8) – (12) are the constraint necessary for piecewise bunkering. The emission caused by fuel usage is shown in constraints (13). Constraints (14) restricts the maximum number of bunkering times, thus can be used to limit the number of bunkering facilities along the route. Constraints (15) is the fuel inventory when arriving at port i. Constraints (16) restricts the amount of minimum bunkering to a certain percentage of the bunker tank capacity of a vessel. The amount is set arbitrarily to 10% of the capacity of the tank. Constraints (17) restricts the amount of maximum bunkering to the bunker fuel capacity of a vessel. Constraints (18) ensures the bunker fuel inventory in the ship has a certain safety stock to ensure ship does not run out of fuel, which is set to 5% of the capacity of the tank. Constraints (19) ensures the order-up-to-level does not exceed bunker fuel capacity.

Constraints (20) depicts the relation between speed and fuel consumption. In this thesis, we use the formula provided by Ronen (1982) as this study do not considers changes in the weight of the ship caused by the change in cargo. The design speed of the ship and the coefficient F_0 are provided in chapter 4.1.1. Constraints (21) restricts the speed of the vessel to stay within certain interval. Constraints (22) is the time flow constraint. Constraints (23) is the arrival time windows constraints. Constraints (24) depicts the arrival time at the starting port. Constraints (25) is the binary constraints of bunkering decision variable. Constraints (26) is non-negativity constrain for piecewise bunkering variable. Constraints (27) is the binary constraints for piecewise bunkering variable decision variable

Model Solution

As can be seen, non-linearities still exist within the constraints (10), (15) and (17). To solve this, this study defines:

$$M_{ij} = 1/V_{ij} \qquad \forall \mathrm{i} \qquad (29)$$

As a result, constraints (10), (15), (16), and (17) are respectively modified to:

$$L_i = S_{i-1} - F_{i,i+1}\left(\frac{d_{i,i+1}}{24}\right)(M_{i,i+1}); \qquad \forall \mathrm{i} \qquad (30)$$

$$\mathrm{F_{i,i+1}} = \mathrm{F_0}\left(\frac{1}{\mathrm{M_{i,i+1}\ x\ V_d}}\right)^3 \qquad \mathrm{i} = 1,..,\mathrm{n}-1 \quad (31)$$

$$\mathrm{V_{min}} \leq \frac{1}{\mathrm{M_{i,i+1}}} \leq \mathrm{V_{max}} \qquad \mathrm{i} = 1,..,\mathrm{n}-1 \quad (32)$$

$$\mathrm{A_{i+1}} = \mathrm{A_i} + (\mathrm{D_{i,i+1}\ x\ M_{i,i+1}}) \qquad \mathrm{i} = 1,..,\mathrm{n}-1 \quad (33)$$

Combining constraints (30) and (31), we get:

$$L_i = S_{i-1} - \frac{F_0\ x\ d_{i,i+1}}{24\ V_{\mathrm{d}}^3}\left(\frac{1}{M_{\mathrm{i,i+1}}^2}\right); \qquad \forall \mathrm{i} \qquad (34)$$

Variable $\left(\frac{1}{M_{\mathrm{i,i+1}}^2}\right)$ is the only non-linearity left in the equation. In this thesis, the non-linearity of Variable $\left(\frac{1}{M_{\mathrm{i,i+1}}^2}\right)$ is approximated using piecewise linearization of $\mathrm{M_{i,i+1}}$, then the mixed-integer linear programming is solved using solver.

Piecewise Linearization

Consider the $\left(\frac{1}{M_{\mathrm{i,i+1}}^2}\right)$ as a non-linear function to be approximated. Figure 4 illustrates that the curve can be divided into many pieces that are approximated by straight lines. The points from each straight line are called breakpoints. This approximation is called piecewise linearization. The method is mathematically expressed as λ – formulation (AIMMS, 2018).

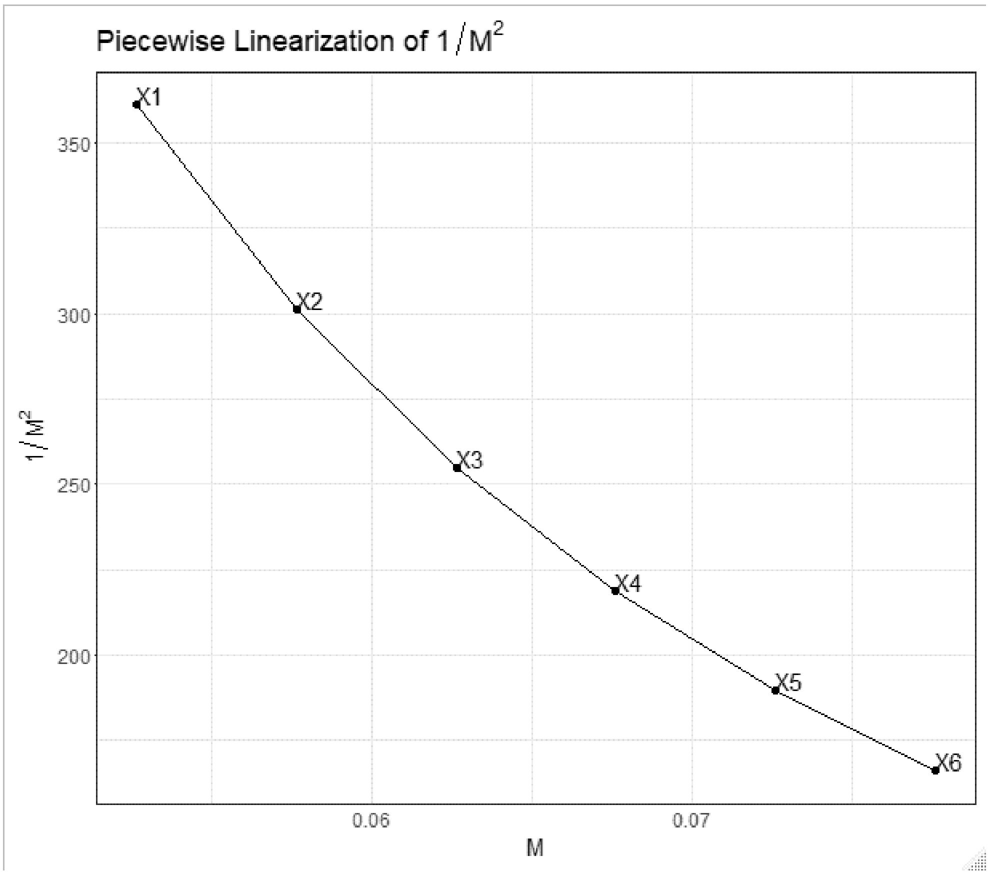

Figure 4. Illustration for piecewise linearization of 1/M^2

Consider the X1, X2, X3, X4, X5, and X6 as 6 breakpoints along the x-axis in figure 4, and let f(X1), f(X2), f(X3), f(X4), f(X5), and f(X6) as a function values of the breakpoints. Let $\lambda_1, \lambda_2, \lambda_3$ λ_4 λ_5 and λ_6 as a decision variable such as that their sum is 1. Thus, the piecewise linearization of $\left(\frac{1}{M^2_{i,i+1}}\right)$ can be written as:

$$\lambda_1 \, f(X1) + \lambda_2 \, f(X2) + \lambda_3 \, f(X3) + \lambda_4 \, f(X4) + \lambda_5 \, f(X5) + \lambda_6 \, f(X6) = f(x) = \frac{1}{M^2_{i,i+1}} \quad (27)$$

$$\lambda_1 \, (x1) + \lambda_2 \, (x2) + \lambda_3 \, (x3) + \lambda_4 \, (x4) + \lambda_5 \, (x5) + \lambda_6 \, (x6) = x \quad (28)$$

$$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 = 1 \quad (29)$$

Therefore, to solve the piecewise linearization of $\frac{1}{M^2_{i,i+1}}$, $M_{i,i+1}$ is discretized and is obtained through solving the binary variables attached to it. there are 1820 discretized value of $M_{i,i+1}$ with the increment of 0.0003 to be used in approximating $\frac{1}{M^2_{i,i+1}}$.

To obtain the maximum error value of the approximation, consider $\frac{1}{M^2_{1,2}}$ as written in equation (27) and $M_{1,2}$ as written in equation (28), here we define:

$$\lambda_1 \, (x1) + \lambda_2 \, (x2) = M_{1,2} \quad (30)$$

$$\lambda_1 f(\mathrm{x1}) + \lambda_2 f(\mathrm{x2}) = \frac{1}{M_{\mathrm{i,i+1}}^2} \tag{31}$$

From the range of 0.045454545 to 0.099754545, this study uses the value of x1 = 0.045454545 and x2 = 0.045754545, and the value of $f(\mathrm{x1})$ is 484 and $f(\mathrm{x2})$ is 477.6738971 as these values hold the maximum error value.

Table 6. Sample of error values of linear approximation

λ_1	λ_2	$\mathrm{M}_{1,2}$	Approximation of $\frac{1}{M_{\mathrm{i,i+1}}^2}$	Actual value of $\frac{1}{M_{\mathrm{i,i+1}}^2}$	Error value
0.9999	0.0001	0.045454575	483.9993674	483.9993611	0.00000627
0.9998	0.0002	0.045454605	483.9987348	483.9987222	0.00001254
0.5000	0.5000	0.045604545	480.8369485	480.821343	0.01560555
0.0001	0.9999	0.045754515	477.6745297	477.6745235	0.00000621

The result of approximation is provided below in Table 6. As can be seen from the fourth row, the maximum absolute error is 0.01560555. The branch and bound tolerance of this model is set to be 0% as it includes binary variables. The computational time of this model is 22.17 seconds.

3.3. Chapter Summary

In this chapter, methodology of this thesis is discussed. Research design and problem formulation are discussed in Section 3.1. This Section gives a more thorough explanation on the problem of minimizing the bunker fuel cost and the greenhouse gasses emission by jointly optimizing the speed, bunkering amounts and bunkering ports selection of each leg of the route and provides a general viewpoint on how the research is done in figure 3. This problem is solved using OpenSolver, linear programming interface developed by Mason (2012). This Section also gives the explanation on the assumptions that are used in the study. As stated, this model is general and can be used on another vessel and route as long as the data requirements are satisfied. Section 3.2 translate the problem into mathematical formulations of mixed-integer nonlinear programming. This Section also discusses the technique to solve the non-linear constraint by using piecewise linearization. This Section also discusses maximum absolute error value of the approximation of $\frac{1}{M_{\mathrm{i,i+1}}^2}$.

4. Data Description and Scenarios

This chapter discusses the data that are used in this thesis and also scenarios of the simulation. In Section 4.1., the data that are used is discussed, including the assumption and the sources. The Section is divided into three based on the data type, which are ship specification, fuel selection and service route. In chapter 4.2, scenarios that are simulated in this thesis are discussed.

4.1. Data Description

As written above, The Section is divided into three based on the data type: (1) ship specification, which discusses the chosen ship that is simulated along with its specification, including fuel consumption, design speed and tank capacity; (2) fuel selection, which discusses the energy content of each fuel alternatives along with its specific greenhouse gasses emission, fuel density, fuel consumption rate and bunker fuel prices; and (3) service route which discusses the list of port calls with the details associated with the ports, and bunkering facilities for the fuels on each port.

4.1.1. Ship Specifications

The ship that is chosen is MV Sajir that is delivered in 2014. The ship has the capacity of 14,993 TEU, classified as a Super Panamax vessel. The ship is owned by United Arab Shipping and operated by Hapag-Lloyd with the base of operation located in Hamburg. Currently the ship is operating on HFO-burning engine but is scheduled to be retrofitted to use LNG as a fuel in 2020. The ship will enter 90 docking days and will be ready to operate as usual (Hapag Lloyd, 2019).

The retrofit that will be done by MAN Energy Solutions at the Chinese Hudong shipyard will change the 4500 m^3 tank capacity of fuel oil to 6700 m^3 tank capacity of LNG fuel along with the change in the engine from oil-burning MAN B&W 9S90ME-C engine to a dual-fuel MAN B&W ME- Gas Injection engine. Converted to metric tons, the tank capacity for HFO and the change in the gas storage system will occupy an area equivalent to approximately 350 TEU. Fuel consumption is not provided in ship particulars; thus, this study uses the data of fuel consumption from Brouer et al. (2014). The ship has a design speed of 17 knots and the ship has a fuel consumption on the design speed of 126.9 metric ton of fuel per day. As mentioned in Section 2.3, the equation from Ronen (1982) works on a certain speed interval specific to the vessel. This has a drawback, however, as this value of fuel consumption may only be accurate to a certain degree, as this is a generalization of a fuel consumption on super Panamax Vessel class. In this vessel, the interval is between max speed of 22 knots and minimum speed of 10 knots (Clarkson Research, 2019).

As briefly mentioned in Section 2.3, the probability of methane slip depends on the type of the engine. There are three type of different gas engine. The difference lies in the combustion characteristics that result in the gas emission profile. The three types of gas engine are as follow: lean burn spark ignited engines, low pressure dual fuel engines and high-pressure dual fuel engines. The two first gas engines, due to the low-pressure injection before compression, still emit methane from methane slip. On the other hand, methane slip is removed completely in the high-pressure dual fuel engine with the high-pressure injection during combustion. MAN B&W ME- Gas Injection engine is the type of that is categorized as high-pressure dual fuel engines, thus does not emit any methane (Ushakov, Stenersen and Einang, 2018).

Moreover, MV Sajir is assumed to use hybrid scrubber system in this thesis, as the route that is used in this thesis contains some area that restricts the discharge of wash water, such as Belgium and China (Gard, 2019). Thus, the fuel consumption of using HFO with hybrid system scrubber that is used in this thesis is 2% higher than normal HFO operations. MV Sajir is chosen because for this thesis because of the retrofitting to LNG that will be done to the ship, thus allowing a fair comparison of the usage of three different fuel alternatives set by IMO in 2020. However, this thesis acknowledges that the usage of three different fuel is based on the assumption of different fuel consumption rate provided in Section 4.1.2. In the current reality, the ship has only been using HFO as fuel on normal operations without scrubber. Thus, the exact data of each specific fuel alternatives consumption cannot be obtained. The summary of the ship particulars that is used in this thesis can be seen on Table 7.

Table 7. Ship Particulars Data

Name	**Size (TEU)**	**Design Speed (Knot)**	**Speed Range (Knots)**	**Fuel Consumptions (Tons/day)**	**Oil Tank Capacity (m^3)**	**LNG Tank Capacity (m^3)**
MV Sajir	14,993	*17*	*10 – 22*	*126.9*	*4,500*	*6,700*

Source: Clarkson Research (2019) and Brouer et al. (2014)

4.1.2. Fuel Specifications

As already summarized in Section 2.4, the fuel specifications that are used are the fuel consumption rate of each fuel alternative, the emission of each fuel alternative and fuel prices. As mentioned before, in this thesis, MV Sajir is assumed to choose HFO with hybrid system scrubber, thus the fuel consumption is 2% higher compared to HFO in normal operation. As also mentioned before, the gas engine that MV Sajir is using in this thesis is categorized as high-pressure dual fuel engine which removes the methane slip completely. Bunker prices of HFO, MGO and LNG that are used in this thesis are obtained from projected prices for prices in 2020 from another study (Kokkinos, 2017 and Faber et al., 2017). However, while the price is an important element in bunker fuel management strategy, it is important to be noted that the accuracy of the forecasted average price does not affect the bunker fuel management strategy, rather the differences of bunker fuel prices that does affect the bunker fuel management strategy. Furthermore, bunker fuel prices are volatile. Thus, rather than depending on the forecast for analysis, this thesis uses several price scenarios that are explained in Section 4.2.2. The price projection here is then used as a baseline scenario only. For baseline scenarios, the fuel prices of HFO, MGO and LNG in all of the port of calls in this thesis are set to the global average of price projection of each fuel alternatives.

As HFO and MGO prices are strongly correlated to the price of crude oil, the prices of both fuels are calculated from the historic differences between each fuel price and Brent prices. Based on Shipandbunker (2019), the prices of HFO and MGO over the period of 09 August 2016 to 06 August 2019 have been respectively 18.7% lower and 30% higher on average, compared to Brent prices. Furthermore, according to the forecast of World Bank Commodities Price Forecast (2019), the price of crude oil in 2020 is forecasted to reach $80 per barrel ($553.6 per metric ton). Thus, based on the historical price differences the price of HFO and MGO that are used in this thesis are respectively $450.07 per metric ton and $719.68 per metric ton. The density is also provided to calculate the tank capacity of the ship in tons. In this thesis, the price of LNG is estimated as, to the author effort and knowledge, actual prices are not available for public use. The lack of published LNG bunker price is due to the small numbers of LNG fueled vessel; thus, the bunker prices are agreed based on a contract and the information regarding the prices are private to the shipowners or operators and the bunkering companies (Faber et al., 2017). The price for LNG is calculated as a function of import price, supply cost of LNG and bunkering cost (Jarlsby, 2008).

$$LNG\ Bunker\ Fuel\ Price = Gas\ Import\ Price + Supply\ Cost + Bunkering\ Cost \tag{32}$$

Import price is the market price of natural gas, measured in three different market, which are USA, Europe and Asia. Supply cost is the cost of LNG distribution from the source to the LNG terminal and bunkering cost is the cost of bunkering from the LNG terminal to the customer. The forecasted average price of LNG in 2020 from three different area (USA, Europe and Asia) by World Bank Commodities Forecast (2019) are $6.75 per MMBtu ($348.975 per metric ton). LNG logistics and bunkering estimated at $3.0/MMBtu ($155.1 per metric ton) by

Braemar (2018). Furthermore, it is assumed that the cost of bunkering using ship to ship method is \$0.5/MMBtu (\$25.85 per metric ton) Thus, bunker price for LNG that is used in this thesis is \$529.925 per metric ton.

Table 8. Fuel Specification Data

	Fuel Type: HFO 380 with hybrid system scrubber	**Fuel Type: MGO-0.5%**	**Fuel Type: LNG**
Density (ton/m³)	0.991	0.860	0.43
Fuel Tank Capacity of MV Sajir (Tons)	4459	3870	2881
Fuel Consumption Rate (compared to HFO in normal operation)	2% higher	5% lower	13% lower
Fuel Consumption on Design Speed (Tons/day)	129.438	120.555	110.40
Bunker Fuel Price in Baseline Scenario (\$/ton)	450.07	719.68	529.92
CO_2 Emission (gram/gram fuel)	3.114	3.206	2.750

Source: Van Rynbach (2018), and IMO (2014)

4.1.3. Service Route

Table 9. Far East 4 (FE 4) Hapag Lloyd Service Route Details

Port of Calls	**CNSHA**	**FRLEH**	**NLRTM**	**DEHAM**	**BEANR**	**GBSOU**	**CNYTN**	**CNNGB**	**CNSHA**
Distance from Previous Port (nm)	-	10229	260	303	391	252	9475	916	87
Earliest Arrival (days)	0	26	28	31	35	37	63	66	70.5
Scheduled Arrival	0	27	29	32	36	38	64	67	71
Latest Arrival (days)	0	27.5	30	33	36.5	39	64.5	68	72
Scheduled Departure (days)	0	28	31	35	37	40	65	70	-
Port Time (days)	2.5 + 0.66 (Suez Time)	0.5	1.5	2.5	0.5	1.5 + 0.66 (Suez Time)	0.5	2.5	2.5
LNG Bunkering Facilities (2019)	Yes	No	Yes	No	Yes	No	No	Yes	Yes

Source: Hapag Llyod (2019), seadistance.org (2019), GIE (2018), Bunkerspot (2019) and Lloydlist (2019)

Provided on Table 9 are the details on the service route provided by Hapag Lloyd named Far East 4. Far East 4 Service Route is a route that provides weekly service from Hapag Lloyd. This route is chosen to be simulated in this thesis, as it is also the route that is serviced by MV Sajir. The westbound route contains the ports of call of Shanghai, Le Havre, Rotterdam and Hamburg, while the eastbound route contains the ports of call of As can be seen, the details that are inputted to the simulation are distance from previous port, the scheduled arrival with the time arrival windows, the scheduled departure, port time and lastly the availability of bunkering facilities. All the details provided in Table 9 are published by Hapag Lloyd and many other sources. In this thesis, however, port times are not published by the route operator, thus port times are assumed to be scheduled departure day minus scheduled arrival day minus half days. For example, the scheduled arrival in Le Havre is at day 27 and the scheduled departure is at day 28, thus the port time is 28 – 27 - 0.5 = 0.5 port time days.

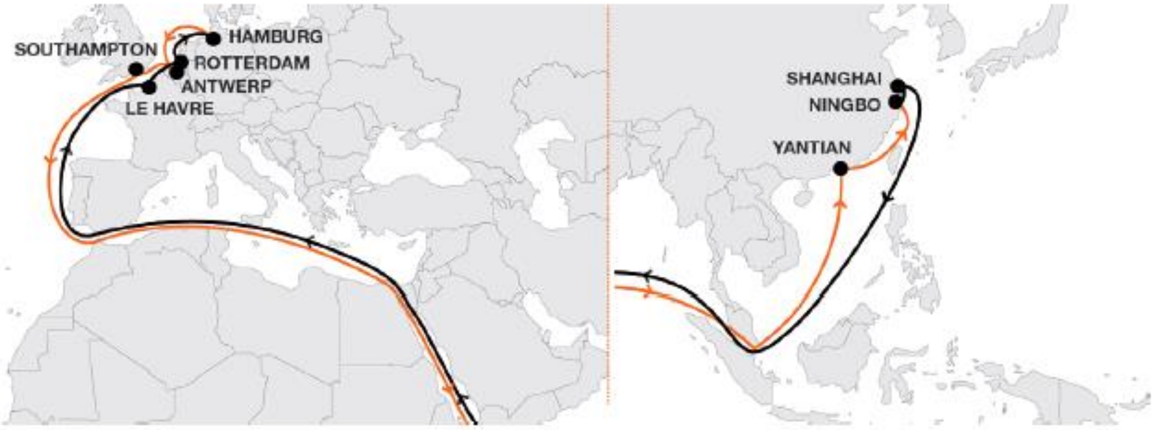

Figure 5. Far East 4 Service Route
(Source: Hapag Lloyd, 2019)

The availability of LNG bunkering facilities is published by Gas LNG Europe (2018), including planned facilities. It is important to be noted that this thesis only considers the bunkering methods of ship to ship that are capable to support large sea going vessel as it is the most common method of bunkering, and the cheapest method to boot. The ports that are considered with bunkering facilities are either already have bunkering facilities capable to bunker large container vessel or have the plan to develop its own LNG bunkering facilities. This aspect is important as is it used to ensure that the operation of ship to ship bunkering would be approved in the said ports. The ports are also must within the economic distance from nearest LNG terminal or storage. Economic distance defined by Danish Maritime Authority (2011) as 100 nm from nearest LNG terminal or storage. Thus, in the baseline scenario, only Rotterdam, Antwerp, Shanghai and Ningbo are assumed to have such facilities.

Bunkering facilities in Port of Rotterdam have since been operational since 2014 (Port of Rotterdam, 2014) and have since been giving nine licenses to provide LNG bunker fuel for sea going vessel. Port of Shanghai with its own LNG terminal eyes to open LNG bunkering facilities in 2020 (Bunkerspot, 2019). This is also the case for Port of Ningbo which could be supplied by Zhoushan LNG terminal close by (Lloydlist, 2019). Currently, small-scale LNG bunkering facilities are operational in the port of Antwerp which at the moment can only bunker small sea-going vessel and inland vessel which are provided by the method of ship to ship and truck to ship. For large sea-going vessel, Antwerp could be supplied by bunkering vessel from the nearest LNG terminal, which is Zeebrugge. LNG bunkering facilities in Hamburg also currently can only provide to the small sea-going vessel and inland vessel. However, the closest LNG terminal from port of Hamburg is Port of Rotterdam, thus making it less economical than other ports, thus making the Port of Hamburg is not considered to have bunkering facilities in this thesis. However, Port authority in port of Hamburg planned to build a much closer LNG terminal in Brunsbüttel to supply the demand in the area, including the demand of bunkering in the port of Hamburg. As per the data from Gas LNG Europe (2018), there is no plan on developing LNG bunkering facilities in Le Havre and Southampton. Also, as far as the knowledge of the author, there is no plan to build LNG bunkering facilities in

Yantian either. Bunkering facilities of other fuel are available in every port of calls in this route as published by Bunkerworld (2019).

4.2. Scenarios

As written above, different scenarios are simulated to observe the effect on the optimal bunker fuel management strategy, namely its effect on cost and emission, and also its effect on the change in speed, bunkering amounts and bunkering port selection. First, in the baseline scenario, the ship is simulated with time windows which are provided in Table 7, using baseline bunker fuel prices and ship's current fuel tank capacity which both provided in Table 8. Furthermore, at the start of the service route, the ship's fuel is set to 5% of the total tank capacity of the ship. There are three scenarios that are simulated in this thesis, namely relaxing the time arrival windows and voyage time, changing the price of the fuel, changing the tank capacity. On each scenario, this thesis provides the hypotheses on what would happen given the change in the scenario.

4.2.1. Relaxing the Port Time Arrival Windows and Voyage Time

Liner shipping operates similarly to public transport services with its published schedule (Christiansen et al., 2013). The designed schedule has to consider the availability of the ports as ports tend to provide services for several liner shipping companies. This made the designed schedule dependent on the time arrival windows provided by each port to the shipping liner company. Thus, having port arrival windows are a common practice in the liner services to restrict the arrival time of the vessel. In this scenario, this thesis compares three situations: (1) using the given port time arrival windows, in which the ship arrival time must be within the port time arrival windows; (2) relaxing the port time arrival windows, in which the total voyage time of the service route is still the same as the given schedule; and (3) when the time windows are relaxed and total voyage time is optimized to achieve the target of 50% reduction of CO_2 emission. In the last two situations, this thesis assumes that there is no penalty incurred to the shipping liner company for the change in arrival time and total voyage time.

Provided below are the hypotheses for this scenario.

Hypothesis 1: *The sailing speed on each leg would even out towards the average speed of the whole voyage in both when the port time arrival windows and total voyage time are relaxed.*

Hypothesis 2: *The cost and the emission of the sailing would be decreased as there are no constraints towards the time of arrival on each port.*

4.2.2. Changing the Price of the Fuel

The high market uncertainty that is caused by the IMO 2020 will surely have an effect on the price of IMO 2020 compliant fuel. Many studies have studied the effect of the uncertainty towards the price changes of each fuel alternative. BCG (2019) says in the study that, the changes in the price are affected by the decreased demand on HFO, increased demand in both LNG and MGO. Moreover, the changes in the price are also affected by the increased supply of each fuel alternative on each bunkering port. As already mentioned in chapter 4.1.3, rather than depending on the forecast, this thesis considers scenarios to analyze the bunker fuel management strategy.

Table 10. Fuel Prices Scenarios

		CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB
HFO	Increasing ($)	414.06	423.03	432.07	441.07	459.07	468.07	477.07	486.08
	Decreasing ($)	486.08	477.07	468.07	459.07	441.07	432.07	423.07	414.06
	Increasing – Decreasing ($)	432.07	441.06	459.07	468.07	468.07	459.07	441.07	432.07
	Decreasing Increasing ($)	468.07	459.07	441.06	432.07	432.07	441.07	459.07	468.07
MGO	Increasing ($)	662.11	676.50	690.89	705.29	734.07	748.47	676.50	777.25
	Decreasing ($)	777.25	762.86	748.47	734.07	705.29	690.89	676.50	662.11
	Increasing – Decreasing ($)	690.89	705.29	734.07	748.47	748.47	734.07	705.29	690.89
	Decreasing Increasing ($)	748.47	734.07	705.29	690.89	690.89	705.29	734.07	748.47
LNG	Increasing ($)	528.79	-	529.36	-	530.49	-	-	531.06
	Decreasing ($)	531.06	-	530.49	-	529.36	-	-	511.08
	Increasing – Decreasing ($)	511.08	-	529.93	-	529.93	-	-	511.08
	Decreasing Increasing ($)	548.77	-	529.93	-	529.93	-	-	548.77

This thesis study the evolution of bunker prices along the ports that provide bunkering facilities (for LNG, it is Rotterdam, Antwerp, Ningbo and Shanghai). This thesis considers six scenarios, in which the first four of the scenarios are hypothetical prices to observe the optimal bunker fuel management strategy in response to the change in price, and the last two scenarios are current and estimated fuel prices on each port. The first is increasing price along the service route, the second is decreasing price along the service route, the third is increasing then decreasing, the fourth is decreasing then increasing, the fifth scenario is simulated based on the bunker fuel price differences on each port on the current time. In the first four scenarios, the average prices in all ports are set the same to the bunker fuel price in baseline scenario. The price scenarios are provided in Table 10. The bunker fuel prices of MGO and HFO on different ports are obtained from Bunkerworld (2019). The different prices on each port is provided in the Table 11.

Table 11. Bunkering price of each bunker fuel and distance to the nearest LNG terminal

Port Code	**CNSHA**	**FRLEH**	**NLRTM**	**DEHAM**	**BEANR**	**GBSOU**	**CNYTN**	**CNNGB**
Price of HFO ($ per ton)	488	351	346	362	347	398	498	495
Price of MGO ($ per ton)	676	569	556	583	557	620	680	678
Price of LNG ($ per ton)	560.63	**-**	483.91	**-** (487.94 if supplied by LNG terminal in Brunsbüttel)	493.76	**-**	**-**	564.46
Distance to Nearest LNG Terminal or Storage (nm)	0	142	0	303 (36 from planned facility in Brunsbüttel.)	87	175	16	26

Source: Bunkerworld (2019), GIE (2018) and Faber et al. (2017)

In this thesis, the price of LNG on each port is calculated on the natural gas import price, distribution price and the ship to ship bunkering cost which is delivered from the nearest LNG terminal or storage. To simplify the calculation, the cost of bunkering using ship to ship method depends on the size of the bunker vessel itself and the distance from the nearest LNG terminal or storage. Faber et al. (2017) stipulate that there is 6%-10% bunkering cost from its import prices for bunker vessel that has the capacity of 10,000 m^3. The percentage range of 6%-10% depends on the distance of the LNG terminal or storage to the vessel, with the minimum of 0 nm (LNG terminal is in the same port) and the maximum of 100 nm.

The price of LNG in Rotterdam is based on natural gas import price which is based on Europe's natural gas prices plus the cost of ship to ship bunkering delivered from Rotterdam's LNG terminal. Based on World Bank Commodities Forecast (2019), the price of Europe's natural gas in 2019 is $6 per MMBtu ($310.2 per ton). The supply cost is assumed to be the same as baseline scenario at $3 per MMBtu ($155.1 per ton) and the bunkering cost is 6% of the natural gas import price, which at $0.36 per MMBtu ($18.61 per ton). The price of LNG in Antwerp is based on natural gas import price which is based on Europe's natural gas prices plus the cost of ship to ship bunkering delivered from Zeebruge LNG terminal. Using the same import price as Rotterdam, the price of Europe's natural gas in 2019 is $6 per MMBtu ($310.2 per ton). The supply cost is assumed to be the same as baseline scenario at $3 per MMBtu ($155.1 per ton) and the bunkering cost is 9.5% of the natural gas import price, which at $0.36 per MMBtu ($29.469 per ton).

The price of LNG in Ningbo is based on natural gas import price which is based on Japan's natural gas prices plus the cost of ship to ship bunkering delivered from Zhoushan LNG terminal. Based on World Bank Commodities Forecast (2019), the price of Japan's natural gas in 2019 is $7.4 per MMBtu ($382.2 per ton). The supply cost is assumed to be the same as baseline scenario at $3 per MMBtu ($155.1 per ton) and the bunkering cost is 7% of the natural gas import price, which at $0.44 per MMBtu ($26.95 per ton). The price of LNG in Shanghai is based on natural gas import price which is based on Japan's natural gas prices plus the cost of ship to ship bunkering delivered from Shanghai's LNG terminal. The price of Japan's natural gas in 2019 is $7.4 per MMBtu ($382.2 per ton). The supply cost is assumed to be the same as baseline scenario at $3 per MMBtu ($155.1 per ton) and the bunkering cost is 6% of the natural gas import price, which is at $0.51 per MMBtu ($22.95 per ton).

Furthermore, in the sixth scenario, port of Hamburg is assumed to have LNG bunkering facilities and supplied by the planned LNG terminal in Brunsbüttel (GIE, 2018). Thus, in sixth scenario, the price of LNG in Hamburg is based on natural gas import price which is based on Europe's natural gas prices plus the cost of ship to ship bunkering delivered from Brunsbüttel LNG terminal. Using the same import price as Rotterdam, the price of Europe's natural gas in 2019 is $6 per MMBtu ($310.2 per ton). The supply cost is assumed to be the same as baseline scenario at $3 per MMBtu ($155.1 per ton) and the bunkering cost is 7.3% of the natural gas import price, which at $0.43 per MMBtu ($22.43 per ton). This thesis then studies the effect on the addition of port of Hamburg as LNG bunkering ports with its price differences to the service route.

Provided below are the hypotheses for this scenario.

Hypothesis 3: *Bunkering strategy would differ in each scenario. The cheapest port would not always be the optimal bunkering port.*

Hypothesis 4: *The optimal speed on each leg would not be affected by the change in price. The average speed on the service route would stay the same as in the baseline scenario constrained with time arrival windows.*

4.2.3. Increasing the Capacity of the Fuel Tank

This thesis also considers the effect of the size of the fuel tank towards the optimal bunker fuel management strategy. The size of the fuel tank will surely affect the optimal bunker fuel management strategy to the benefit of the ship as the ship will have more fuel left in the tank to choose the cheapest bunkering ports and purchase a larger amount of bunker fuel to acquire quantity discount. However, the change in the size tank affects the ability of the ship to carry more containers. This condition is especially true in LNG fueled container ship as LNG tanks take up considerable space. In this scenario, this thesis aims to calculate the trade-off between the decrease in revenue caused by the reduction of carrying capacity of a vessel. According to reports by Hapag- Lloyd (2019) The conversion to LNG of the vessel MV Sajir simulated in this thesis, from 4500 m^3 heavy fuel oil tank to 6700 m^3 LNG tank will cost 350 TEU of the carrying capacity of the ship. Thus, based on that assumption, this scenario simulates that the increase of 2200 m^3 in the size of tank from the baseline scenario. The increase in tank capacity will result in a decrease of 350 TEU of carrying capacity in the vessel on any fuel alternatives. This scenario uses the same fuel prices as in baseline scenario. This scenario compares two situations: one when the market is strong thus the ship is almost fully utilized, the loss of 1 TEU is assumed to be 500$ net loss, and another when the market is weak thus the ship is under-utilized, thus there is no loss over the decrease in cargo carrying capacity.

Provided below are the hypotheses for this scenario.

Hypothesis 5: *The increase in tank capacity would reduce the cost of the voyage, however, it would not offset the loss incurred by the decrease in carrying capacity.*

Hypothesis 6: *There would be decreases in bunkering times in all fuel alternatives.*

4.3. Chapter Summary

In this chapter, data and scenarios that are used in this thesis are discussed. In Section 4.1.1., Ship specifications used in this simulation are discussed. MV Sajir is the vessel that is simulated in this thesis. The particulars of MV Sajir such as tank capacity, engine type and fuel consumption provide the constraints for this simulation. In Section 4.1.2., fuel specifications of the three alternatives are discussed. The details that are used in this thesis are densities, fuel consumption rates, and bunker fuel prices and greenhouse gasses emission. The forecasted prices of HFO and MGO are calculated based on historical prices of both fuels to Brent price. On the other hand, due to the lack of data available on LNG bunker price, the LNG bunker price is calculated by using the method from Jarlsby (2008), in which the cost function of bunker price is composed of the gas import price and LNG supply cost.

In Section 4.1.3., the characteristics in the service route are discussed which are distance from the previous port, arrival time windows, scheduled departure, port time and the availability of LNG bunkering facilities. Apart from port time, the data are provided from various sources. Port times of each port are assumed to be calculated as follow: scheduled departure day minus scheduled arrival day plus half days. Furthermore, the consideration of the availability of LNG bunkering facilities is based on the current or planned bunkering facilities of the port, and its economic distance from the nearest LNG terminal.

In Section 4.2., scenarios that are simulated in this thesis are discussed. This Section also provides hypotheses for each scenario. In Section 4.2.1., this thesis considers the relaxation of arrival time windows and total voyage time. The purpose of this scenario is to study the speed on each leg and the average speed on the service route in relation to service windows. This scenario also studies the effect of time windows on the total cost and emission. Moreover, this scenario also aims to study the bunker fuel management strategy in the case of relaxing the voyage time to reduce CO_2 emission by 50%. In Section 4.2.2., this thesis considers the evolution of prices on the ports along route. The purpose of this scenario is to study the price sensitivity to the bunker fuel management strategy. This scenario also considers the current prices on different ports to simulate condition that is similar to reality. In Section 4.2.3., this thesis considers the change in tank capacity. This scenario considers optimal strategy from the trade-off between the profit loss and the change in flexibility of bunkering from the change in capacity.

5. Results, Analysis and Discussion

This chapter provides the results, analysis and discussion of the simulation and optimal bunker fuel management strategies on each fuel alternative on each scenario described in Section 4.2. This chapter also compares the optimal bunker fuel management strategy on each fuel alternative, namely HFO with scrubber, MGO and LNG. This chapter is divided into five Sections, in which the first four Sections are for the discussion on the baseline scenario and each scenario, with a comparison on each fuel alternative. Lastly, summary is provided in Section 5.5.

5.2. Baseline Scenario

As mentioned in chapter 4.2, in the baseline scenario, the ship is simulated with time windows (Table 7 in chapter 4.1.1), using baseline bunker fuel prices and ship's current fuel tank capacity (Table 8 in chapter 4.1.2.).

Table 12. Optimal bunker strategy of each fuel alternative on the baseline scenario.

	HFO with Scrubber			**MGO**		
Port of Calls	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	4236	15.88	1,783,378	3676	15.88	2,489,265
FRLEH	-	11.17	-	-	11.17	-
NLRTM	-	11.17	-	-	11.17	-
DEHAM	-	11.17	-	-	11.17	-
BEANR	1519	11.17	672,223	1606	11.17	1,134,302
GBSOU	-	15.28	-	-	15.28	-
CNYTN	-	15.25	-	-	15.25	-
CNNGB	-	10.02	-	-	10.02	-
Total	**5755**		**2,455,601**	**5282**		**3,623,567**

	LNG		
Port of Calls	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	2528	15.88	1,285,256
FRLEH	-	11.17	-
NLRTM	-	11.17	-
DEHAM	-	11.17	-
BEANR	2309	11.17	1,181,150
GBSOU	-	15.28	-
CNYTN	-	15.25	-
CNNGB	-	10.02	-
Total	**4838**		**2,466,407**

Provided in the Table 12 is the results of the baseline scenario of the ship using each alternative. As can be seen, on the ship with 4,500 m^3 tank capacity for oil fuel and 6,700 m^3 tank capacity for LNG, the ship is able to bunker only twice along the service route, once on Shanghai and once on Antwerp, which in this case both ports has LNG bunkering facilities. The bunkering port choice depicts the combination of quantity discount purchase and the ship needs to bunker once on westbound route and once on eastbound route. This also shows that all three fuels with its specific fuel tank capacity with have similar sailing range. The speed values of each bunker fuel alternatives do not differ with each other. Furthermore, the ship speed values for each fuel alternatives are varied between each leg, with speed on a certain leg is faster than the other. This is further discussed in next section. The average speed of the whole route is 15.31 knots. The average speed value and the bunker cost that entails can be used as a factor if the liner company wants reduces the bunker costs by increasing the number of vessels to keep the regular weekly service.

In regard to each bunker fuel prices and fuel consumption rate, the total bunkering amounts and bunker fuel cost differ from each other. HFO with scrubber has the cheapest bunker fuel cost among the other three. On the contrary, MGO has the most expensive bunker fuel cost. In spite of the unit bunker fuel price of LNG differs significantly from the unit bunker fuel price of HFO ($529.72 per ton compared to $450.7 per ton), the total bunker fuel cost of LNG and HFO with scrubber does not differ significantly. This is because the difference of energy content of each fuel alternative, which translates to fuel consumption rate of each fuel alternative, could offset the difference in bunker fuel price. This is also shown in the total bunkering amounts of each fuel. The simulated ship that uses HFO with scrubber, which has the least energy content per ton, consumes the most fuel out other three fuel alternative 5755 tons. On the contrary, the simulated ship that uses LNG, which has the most energy content per ton, consumes fewest fuel out of other three fuel alternative, in the amount of 4838 tons (15% lower than HFO with scrubber). MGO consumption ranked on the second, with 5282 tons (8% lower than HFO with scrubber). Based on fuel consumption and the fuel prices on baseline scenario, the bunker cost of HFO with scrubber is proven to be the cheapest from other alternatives in the amount of $2,455,601. MGO has the most expensive bunker cost, in the amount of $3,623,567 (47% higher than HFO with scrubber). Lastly LNG is ranked in the second, in the amount of $2,466,407 (0.4% higher than HFO with scrubber)

What is also different from the oil fuel and LNG is that the bunker fuel purchase amount on each port along the service route. On both HFO with scrubber and MGO, the bunker fuel purchase amount on the port of Shanghai reach the maximum capacity of the fuel tank. The next bunker fuel purchase on port of Antwerp decrease significantly, as the ship still has enough fuel left in the tank to reach the last port of calls on the service route. On LNG, however, the bunker fuel purchase amount on port of Shanghai does not reach the maximum capacity of the fuel tank. The bunker fuel purchase amount is just enough to reach the next port on which the ship makes another purchase (the details of full detail on bunker fuel management strategy on each fuel alternatives is provided in Appendix 5 - 32). The LNG fueled ship then makes another bunker fuel purchase that is just enough to reach the last port of calls on the service route. This occurs because there are less bunkering-available ports for LNG fueled ship to bunker. This caused the ship to consider the distance to the next bunkering available ports and make an optimal decision based on that factor. This is also caused by the discount price structure used in this study.

As written in Section 3.2., the discount price decrease on each 1000 tons purchase. The discount price stops increasing after the purchase of 2000 tons. The ship simulated in this study that uses HFO with scrubber and MGO have significantly larger tank, thus allowing more bunker fuel purchases after 2000 tons. The much-discounted price from large bunker fuel purchase on port of Shanghai counteracts the less discount price from small bunker fuel purchase on port of Antwerp. On LNG, as the price discount from maximum purchase amount on port of Shanghai does not offset the less discount price from the smaller purchase on port of Antwerp, the optimal bunkering strategy is to get the most of price discount on both port of Shanghai and port of Antwerp.

Table 13. CO2 emissions on each fuel alternative.

	HFO with Scrubber			MGO		
Port of Calls	**Ship Speed (Knots)**	**CO_2 Emission Until Next Port (Tons)**	**CO_2 Emission per Distance (Ton/nm)**	**Ship Speed (Knots)**	**CO_2 Emission Until Next Port (Tons)**	**CO_2 Emission per Distance (Ton/nm**
CNSHA	15.88	8953.20	0.88	15.88	8460.70	0.83
FRLEH	11.17	112.45	0.43	11.17	106.26	0.41
NLRTM	11.17	131.05	0.43	11.17	123.86	0.41
DEHAM	11.17	169.11	0.43	11.17	159.81	0.41
BEANR	11.17	109.02	0.43	11.17	102.99	0.41
GBSOU	15.28	7678.52	0.81	15.28	7256.14	0.77
CNYTN	15.25	739.35	0.81	15.25	698.68	0.76
CNNGB	10.02	30.33	0.35	10.02	28.66	0.33
Total		**17,923**			**16937.11**	

LNG

Port of Calls	**Ship Speed (Knots)**	**CO_2 Emission Until Next Port (Tons)**	**CO_2 Emission per Distance (Ton/nm)**
CNSHA	15.88	6646.17	0.65
FRLEH	11.17	83.49	0.32
NLRTM	11.17	97.28	0.32
DEHAM	11.17	125.53	0.32
BEANR	11.17	80.91	0.32
GBSOU	15.28	5699.94	0.60
CNYTN	15.25	548.84	0.60
CNNGB	10.02	22.51	0.26
Total		**13,304**	

Provided in Table 13 is the greenhouse gasses emission from the ship on this service route using each fuel alternatives. It is established in equation by Ronen (1982) that faster sailing speed means higher bunker fuel consumption, hence resulting in higher CO_2 emission. As in line with HFO's CO_2 emission per ton and adding to the fact that ship that uses HFO with scrubber consumes the most fuel, HFO with scrubber emits the most of CO_2 in total. The total bunker fuel consumption and the total amounts of CO_2 emission of MGO are ranked in the middle among all three (6% less than HFO with scrubber). LNG, which its CO_2 emission per ton and total bunker fuel consumption are the fewest, emits the least CO_2 among the three alternatives (25% less than HFO with scrubber). Also, the ship emits more CO_2 per nautical miles on several legs of the route than other. This is caused by the different sailing speed on each leg. Faster speed consumes more fuel, thus emits more CO_2 compared to the lower speed.

5.2. Relaxing the Port Arrival Time Windows and Voyage Time

This thesis analyzes the impact of port arrival time windows on the optimal bunker fuel management strategy by relaxing the port arrival time windows. As mentioned in Section 4.2.1., the service route on relaxed port arrival time windows still has the same total voyage time. Provided below in Table 14,15 and 16 are the optimal bunker strategy of each fuel alternative with and without port arrival time windows.

Table 14. Optimal bunker strategies of HFO with scrubber, with and without port arrival time windows

HFO with Scrubber

	With Time Windows			Without Time Windows		
Port of Calls	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	4236.05	15.88	1,783,378	4236.05	15.18	1,783,378
FRLEH	-	11.17	-	-	15.18	-
NLRTM	-	11.17	-	-	15.18	-
DEHAM	-	11.17	-	-	15.12	-
BEANR	1519	11.17	672,223	1385.98	15.12	615,104
GBSOU	-	15.28	-	-	15.17	-
CNYTN	-	15.25	-	-	15.18	-
CNNGB	-	10.02	-	-	15.18	-
Total	**5755**		**2,455,601**	**5622**		**2,398,481**

Table 15. Optimal bunker strategies of MGO with and without port arrival time windows

MGO

	With Time Windows			Without Time Windows		
Port of Calls	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	3676.5	15.88	2,489,265	3676.5	15.17	2,489,265
FRLEH	-	11.17	-	-	15.18	-
NLRTM	-	11.17	-	-	15.18	-
DEHAM	-	11.17	-	-	15.12	-
BEANR	1606.44	11.17	1,134,302	1483.8	15.12	1,050,467
GBSOU	-	15.28	-	-	15.18	-
CNYTN	-	15.25	-	-	15.18	-
CNNGB	-	10.02	-	-	15.12	-
Total	**5282**		**3,623,567**	**5160**		**3,539,732**

Table 16. Optimal bunker strategies of LNG with and without port arrival time windows

LNG

	With Time Windows			Without Time Windows		
Port of Calls	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Ship Speed to the Next Port (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	2528.17	15.88	1,285,256	2736.95	15.17	1,384,829
FRLEH	-	11.17	-	-	15.18	-
NLRTM	-	11.17	-	-	15.18	-
DEHAM	-	11.17	-	-	15.12	-
BEANR	2309.89	11.17	1,181,150	1988.82	15.12	1,027,724
GBSOU	-	15.28	-	-	15.18	-
CNYTN	-	15.25	-	-	15.18	-
CNNGB	-	10.02	-	-	15.18	-
Total	**4838**		**2,466,407**	**4725**		**2,412,553**

This thesis finds that the optimal bunker fuel cost decrease in all three fuel alternatives when the time windows are relaxed. The bunker fuel cost of HFO with scrubber decreased by 2.31%, the bunker fuel cost of MGO decreased by 2.31%, and the bunker fuel cost LNG decreased by 2.33%. The relaxed port arrival time windows depict the full benefits to the ship as it can adjust the sailing speed for the whole route without being constrained by port arrival time windows while keeping total voyage time unaltered. The decreased bunker cost comes from the decrease in bunker purchase which is the result of the decreased average speed of the whole voyage. For all three fuel alternatives, the average speed decreased from 15.31 knots to 15.17 knots. Furthermore, by relaxing the port time arrival windows, the sailing speed on certain legs of the route such as Le Havre – Rotterdam, Rotterdam – Hamburg, Hamburg – Antwerp, and Antwerp – Southampton evens out to the average of the whole voyage.

Additionally, the purchase amount of LNG differs when the port time arrival windows are relaxed. The purchase amount in the port of Shanghai reaches the maximum capacity of the tank as opposed to the purchase amount with port arrival time windows. In relaxed port arrival time windows, the price discount from maximum purchase amount on port of Shanghai offset the less discounted price from the smaller purchase on port of Antwerp. Thus, the optimal bunkering strategy is to get the most of price discount on port of Shanghai rather than port of Antwerp.

Table 17. Comparison of arrival times with and without port arrival time windows.

			HFO with Scrubber		**MGO**		**LNG**	
Port of Calls	**Earliest Arrival (days)**	**Latest Arrival (days)**	**Arrival Times with time windows (days)**	**Arrival Times without time windows (days)**	**Arrival Times with time windows (days)**	**Arrival Times without time windows (days)**	**Arrival Times with time windows (days)**	**Arrival Times without time windows (days)**
CNSHA	26	27.5	27.50	28.74	27.50	28.76	27.50	28.76
FRLEH	28	31	28.97	29.95	28.97	29.98	28.97	29.98
NLRTM	31	33	31.60	32.28	31.60	32.31	31.60	32.31
DEHAM	35	38	35.56	35.86	35.56	35.88	35.56	35.89
BEANR	37	40	37.00	37.05	37.00	37.08	37.00	37.08
GBSOU	63	65	65.00	65.25	65.00	65.25	65.00	65.25
CNYTN	66	68	68.00	68.26	68.00	68.26	68.00	68.26
CNNGB	70	72	70.86	71.00	70.86	71.00	70.86	71.00

As can be observed in Table 17, the change in the sailing speed on certain legs of the route resulting in the change in arrival times. The arrival times without current time windows could be used to determine the new cost-efficient time windows. In this scenario, however, there are no significant differences in both average sailing speed of the whole service route and sailing speed on each leg between three fuel alternatives, thus resulting in no significant differences on arrival time.

Table 18. CO_2 emission comparison

Fuel Alternatives	CO_2 emission (tons)	Change from HFO in normal operation
HFO in normal operation	17,316	-
HFO with scrubber – time windows	17,923	4%
HFO with scrubber – relaxed time windows	17,507	1%
HFO with scrubber – optimized total voyage time and relaxed time windows	8,657	-50%
MGO – time windows	16,937	-2%
MGO – relaxed time windows	16,543	-4%
MGO – optimized total voyage time and relaxed time windows	8,657	-50%
LNG – time windows	13,304	-23%
LNG – relaxed time windows	12,995	-25%
LNG – optimized total voyage time and relaxed time windows	8,657	-50%

Subsequently, the CO_2 emission in arrival times without port arrival time windows is decreased in the same ratio as the decrease in bunker consumption (Table 18). If compared to HFO in normal operation, apart from HFO with scrubber, all fuel alternatives show a reduction in CO_2 emissions. Furthermore, significant CO_2 emission reduction of 23% can be achieved by choosing LNG on a route with a relaxed time windows. This still falls short to the target of 50% CO_2 emission reduction from HFO with normal operations. Thus, to achieve the target, this study considers bunker fuel management strategy when the total voyage time is relaxed to the 50% reduction in CO_2 emission in each fuel alternative, as provided in Table 19.

Table 19. Optimal bunker strategy of each fuel alternative to achieve emission reduction

	HFO with Scrubber				MGO			
Port of Calls	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**	**Arrival Time (Days)**	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**	**Arrival Time (Days)**
CNSHA	2780	10.60	1,193,719	40.88	2699	10.98	1,856,262	39.50
FRLEH	-	10.60	-	42.41	-	10.98	-	40.99
NLRTM	-	10.60	-	45.10	-	10.95	-	43.64
DEHAM	-	10.56	-	49.14	-	10.95	-	47.63
BEANR	-	10.56	-	50.63	-	10.95	-	49.09
GBSOU	-	10.60	-	90.06	-	10.98	-	87.21
CNYTN	-	10.60	-	94.16	-	10.95	-	91.19
CNNGB	-	10.56	-	97.01	-	10.95	-	94.02
Total	**2780**		1,193,719		2699		1,856,262	

	LNG			
Port of Calls	**Bunkering amounts (Tons)**	**Ship Speed (Knots)**	**Bunker Fuel Cost ($)**	**Arrival Time (Days)**
CNSHA	2736	12.39	1,384,829	35.07
FRLEH	-	12.37	-	36.45
NLRTM	-	12.37	-	38.97
DEHAM	-	12.41	-	42.78
BEANR	407	12.37	215,758	44.13
GBSOU	-	12.37	-	78.22
CNYTN	-	12.37	-	81.81
CNNGB	-	12.41	-	84.60
Total	**3114**		**1,600,587**	

When total voyage time is relaxed, there is bound to be a decrease in average sailing speed, thus, significantly reducing the bunker consumption, which also leads to decreases in bunker costs (51% on HFO with scrubber, 48% on MGO and 35% on LNG). Moreover, as the fuel consumptions decrease, both HFO with scrubber and MGO only bunker once during the trip. However, the most interesting part is the reduction of average sailing speed in each fuel alternative. As HFO with scrubber emits CO_2 the most, the average sailing speed is also reduced the most (from 15.31 knots to 10.59 knots). The average sailing speed in LNG is reduced the least (from 15.31 to 12.38), as LNG also emits CO_2 the least.

The total voyage time of each fuel alternatives is increased in which the amounts depends on the decrease in average sailing speed time. As can be seen, HFO with scrubbers gains 26.01 days added to the original total voyage time, MGO gains 23.02 days added to the original total voyage time and LNG gains 13.60 days added to the original voyage time. The increase in total voyage will relate to the revenue gained by the shipping liner and will lead to a different optimal fleet deployment on the service route, hence making the choice of fuel alternative became more important. The reduction in sailing speed and increase in total voyage time if each fuel alternative could be used as a reference to the strategy of reducing the CO_2 emission in this service route.

5.3. Changing the Price of the Fuel

Secondly, this thesis considers the impact of the change in bunker fuel price. As written in Section 4.2.2., this thesis considers six scenarios: (1) Increase in prices along the service route in the bunkering ports, (2) decrease in prices along the service route in the bunkering ports, (3) increase then decrease in prices, (4) decrease then increase in prices, (5) using the actual bunker fuel price data for fuel oil and estimation data for LNG; and (6) adding Hamburg as LNG bunkering port. As mentioned before, the average prices in all ports are set the same to the bunker fuel price in baseline scenario in the scenario of increasing price, decreasing price, increasing then decreasing, and decreasing then increasing.

Table 20. Optimal bunkering strategies for different pricing scenarios.

	Increasing Price		**Decreasing Price**	
Fuel Alternatives	**Choice of Bunkering Ports**	**Bunkering amounts (tons) and Total Cost ($)**	**Choice of Bunkering Ports**	**Bunkering amounts (tons) and Total Cost ($)**
HFO with scrubber	Shanghai; Le Havre	4236; 1519 $2,272,541	Shanghai; Southampton	3042; 2712 $2,523,753
MGO	Shanghai; Le Havre	3676; 1606 $3,356,368	Shanghai; Southampton	2792; 2490 $3,722,243
LNG	Shanghai; Rotterdam	2736; 2101 $2,462,299	Shanghai; Antwerp	2528; 2309 $2,467,889

	Increasing then Decreasing		**Decreasing then Increasing**	
Fuel Alternatives	**Choice of Bunkering Ports**	**Bunkering amounts (tons) and Total Cost ($)**	**Choice of Bunkering Ports**	**Bunkering amounts (tons) and Total Cost ($)**
HFO with scrubber	Shanghai; Le Havre	4236;1519 $2,370,802	Shanghai; Hamburg	2951; 2804 $2,468,824
MGO	Shanghai; Le Havre	2639; 2643 $3,528,629	Shanghai; Hamburg	2708; 2574 $3,641,269
LNG	Shanghai; Antwerp	2736, 2101 $2,417,168	Shanghai; Rotterdam	2446; 2391 $2,510,726

The optimal results for scenario 1 to scenario 4 are presented in Table 20. As shown in the table, different prices scenarios can result in different bunker fuel management strategy. In general, the choices of bunkering ports are majorly affected by the price differences between ports, but there are several instances where the choice of bunkering ports are limited by the fuel requirements over the sailing distance. In scenario (1), the ship chooses to bunker in the first two ports which are Shanghai and Le Havre in HFO with scrubber and MGO, and in Shanghai and Rotterdam in LNG. Furthermore, as the cheapest bunker fuel prices are on the first port, the bunkering amounts on the first bunkering ports reach the maximum capacity of the fuel tank. As the price increase in the next port, the bunkering amounts is much less than the first bunkering port. This is true in all the fuels. The total bunkering cost on this scenario is in the lowest among all four scenarios. In scenario (2), as there are decremental changes in fuel price, the choice of bunkering ports falls into port of Shanghai and port of Southampton for HFO with Scrubber and MGO, and port of Shanghai and port of Antwerp.

Furthermore, in all three fuel alternatives, the purchase amount in the first bunkering port is just enough until the next cheaper port, if not the cheapest port. The choice of bunkering does not fall on the cheapest port due to fuel required to reach the cheapest port and the large quantity discount purchase. The total bunker fuel cost is the most expensive among all scenarios. In scenario (3), the choice of bunkering ports and bunkering amounts is akin to scenario (1). However, since the incremental change of the bunker fuel price is higher than the scenario (1), the total bunker fuel cost in this scenario is the second cheapest among all four others. Lastly in scenario (4), the choice of bunkering ports and bunkering amounts is also the same, but to the scenario (2). For the same reason as in scenario (3), the decremental change of the bunker fuel price is higher than the scenario (2), hence making scenario (4) is the second most expensive out of four others.

There is not much of a difference in the bunker fuel management strategy between the three fuel alternatives. As mentioned above, the purchasing amount of all three fuels are similar, relative to its tank capacity. Although there is a difference between fuel oil and LNG, as the bunkering facilities for LNG are not available on every port. Thus, the choice of bunkering ports in the ship differs a bit between HFO with scrubber and MGO, and LNG. The price evolution in all four scenarios does not affect the bunkering times in the service route. The large bunker purchase discount is more optimal than bunkering more than twice in which the cheapest ports are chosen.

Table 21. Optimal speeds for different pricing scenarios.

		Increasing Price	Decreasing Price	Increasing then Decreasing	Decreasing then Increasing
Fuel Alternatives	**Ports**	**Sailing Speed (Knots)**	**Sailing Speed (Knots)**	**Sailing Speed (Knots)**	**Sailing Speed (Knots)**
HFO with scrubber	**CNSHA**	15.88	15.88	15.88	15.88
	FRLEH	11.17	11.17	11.17	11.02
	NLRTM	11.17	11.17	11.17	11.02
	DEHAM	11.17	11.17	11.17	11.29
	BEANR	11.17	11.17	11.17	11.32
	GBSOU	15.28	15.28	15.28	15.28
	CNYTN	15.25	15.25	15.25	15.25
	CNNGB	10.02	10.02	10.02	10.02
	Average Speed (Knots)	15.31	15.31	15.31	15.31
MGO	**CNSHA**	15.88	15.88	15.88	15.88
	FRLEH	11.17	11.17	11.17	11.02
	NLRTM	11.17	11.17	11.17	11.02
	DEHAM	11.17	11.17	11.17	11.29
	BEANR	11.17	11.17	11.17	11.32
	GBSOU	15.28	15.28	15.28	15.28
	CNYTN	15.25	15.25	15.25	15.25
	CNNGB	10.02	10.02	10.02	10.02
	Average Speed (Knots)	15.31	15.31	15.31	15.31
LNG	**CNSHA**	15.88	15.88	15.88	15.88
	FRLEH	11.17	11.17	11.17	11.06
	NLRTM	11.17	11.17	11.17	11.20
	DEHAM	11.17	11.17	11.17	11.20
	BEANR	11.17	11.17	11.17	11.18
	GBSOU	15.28	15.28	15.28	15.28
	CNYTN	15.25	15.25	15.25	15.25
	CNNGB	10.02	10.02	10.02	10.02
	Average Speed (Knots)	15.31	15.31	15.31	15.31

Table 21 provides information on the sailing speed on each price evolution scenario. There are slight differences in speed in each leg in scenario (4). However, the average sailing speed does not change, and the value is the same as the average sailing speed in the baseline scenario. This is because the speed is mainly affected by the port arrival time windows. By limiting the arrival time, the choice of the sailing speed on the specific leg is also limited. It can be concluded that the choice of bunkering ports is mainly affected by the bunker fuel prices on each port and the sailing speed is mainly affected by port arrival time windows. Furthermore, as CO_2 emission is affected by bunker consumption, which in this scenario, bunker consumptions do not differ significantly from baseline scenario, thus CO_2 emission is not affected by the change in bunker fuel price.

Table 22. Optimal bunkering strategies for the current price.

	HFO with Scrubber		MGO		LNG	
Port of Calls	**Bunker Fuel Price ($)**	**Bunkering amounts (Ton)**	**Bunker Fuel Price ($)**	**Bunkering amounts (Ton)**	**Bunker Fuel Price ($)**	**Bunkering amounts (Ton)**
CNSHA	488	2905.32	676	2669.07	560.63	2445.02
FRLEH	351	-	569	-	-	-
NLRTM	346	2851.41	556	2614.17	483.91	2393.19
DEHAM	362	-	583	-	-	-
BEANR	347	-	557	-	493.76	-
GBSOU	398	-	620	-	-	-
CNYTN	498	-	680	-	-	-
CNNGB	495	-	678	-	564.46	-
Total Bunker Fuel Cost ($)	2,289,051		3,116,797		2,432,639	

In scenario 5, this thesis studies the optimal bunker fuel management strategy according to the current bunker fuel prices on each port as provided in Table 22. As expected, the optimal bunker fuel management strategy chooses the cheapest ports, which in all fuel alternatives, falls into port of Shanghai and port of Rotterdam. Still, even in this scenario, the bunkering times do not change.

Table 23. Optimal bunkering strategy of LNG with port of Hamburg as an added bunkering choice.

Port of Calls	**Bunker Fuel Price ($)**	**Bunkering amounts (Ton)**	**Ship Speed (Knots)**	**Fuel Consumption (Ton)**	**Bunker Fuel Cost ($)**
CNSHA	560.63	2445.023	15.88	2416.79	1,317,772
FRLEH	-	-	10.77	28.24	-
NLRTM	483.91	2393.19	11.28	36.10	1,114,867
DEHAM	487.94	-	11.28	46.58	-
BEANR	493.76	-	11.28	30.05	-
GBSOU	-	-	15.28	2072.71	-
CNYTN	-	-	15.25	199.58	-
CNNGB	564.46	-	10.02	8.19	-
Total				**4838**	**$** 2,432,639

In scenario 6, port of Hamburg is added to the bunkering port choice, to simulate the added terminal in Brunsbüttel. From the optimal bunker fuel management strategy shown in Table 23, port Hamburg is not chosen as bunkering ports due to as the same as in the previous scenarios, the most optimal bunkering times is twice along the service route and Rotterdam being the cheapest port in Europe.

5.4. Increasing the Capacity of the Fuel Tank

Table 24. Optimal bunkering strategies of HFO with scrubber at different fuel tank capacity.

HFO with Scrubber

	Current Tank (4500 m^3)			**Increased Tank (6700 m^3)**		
Port of Calls	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	4236.05	15.88	1,783,378	5755.62	15.88	2,398,902
FRLEH	-	11.17	-	-	11.17	-
NLRTM	-	11.17	-	-	11.17	-
DEHAM	-	11.17	-	-	11.17	-
BEANR	1519	11.17	672,223	-	11.17	-
GBSOU	-	15.28	-	-	15.28	-
CNYTN	-	15.25	-	-	15.25	-
CNNGB	-	10.02	-	-	10.02	-
Total	**5755.62**		**2,455,601**	**5755.62**		**$2,398,902**
					Revenue Loss:	**+$175,000**
						$2,573,902
	Cost differences without revenue loss: -$46,698 **Cost differences with revenue loss: $128,301**					

Lastly, this study considers the change in tank capacity. As mentioned in Section 4.2.3., this scenario considers the case without and with revenue loss of $175,000. Table 24 shows two optimal bunkering strategies for HFO with scrubber, each for different tank capacity. In the increased tank capacity, the bunkering purchase in the first port, although not to the full capacity of the tank, is enough for the whole service route. If bunkering once is desired by the ship operator, this bunkering amount can be used as a reference in order to avoid the excess amount of space in tank capacity. It can be seen that in the case of increased tank, there is no difference in the bunkering amounts from the baseline scenario due to no difference in sailing speed. Thus, the amount of CO_2 emitted does not differ from the baseline scenario. In the case without revenue loss, there is a decrease in bunker cost of $46,698 (-2%). This is due to the larger quantity purchase discount allowed by the increased tank capacity. However, in the case of revenue loss, there is a cost increase in bunker cost in the amount of $128,301 (5%).

Table 25. Optimal bunkering strategies of MGO at different fuel tank capacity.

	MGO					
	Current Tank (4500 m^3)			Increased Tank (6700 m^3)		
Port of Calls	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	3676.5	15.88	2,489,265	5282.94	15.88	3,529,777
FRLEH	-	11.17	-	-	11.17	-
NLRTM	-	11.17	-	-	11.17	-
DEHAM	-	11.17	-	-	11.17	-
BEANR	1606.44	11.17	1,134,302	-	11.17	-
GBSOU	-	15.28	-	-	15.28	-
CNYTN	-	15.25	-	-	15.25	-
CNNGB	-	10.02	-	-	10.02	-
Total	**5282.94**		**3,623,567**	**5282.94**		**$3,529,777**
					Revenue Loss:	**+$175,000**
						$3,704,777
	Cost differences without revenue loss: -$93,790 **Cost differences with revenue loss: $81,209**					

Table 25 shows the two optimal bunkering strategies for MGO, also for each different tank capacity. The same bunkering strategy as HFO with scrubber also occurs in MGO. The bunkering purchase in the first port is enough for the whole service route. The purchase amount also does not reach the maximum capacity of the tank, which shows the excess amount of space in tank capacity. Similar to HFO with scrubber, there is no change in sailing speed and bunkering amounts the increased tank, hence no difference in CO_2 emission as well. In the case without revenue loss, there is a decrease in bunker cost of $93,790 (-2.5%) from the baseline scenario. The decrease in bunkering cost is larger than in HFO with scrubber, as the price of MGO is significantly more expensive. The significant differences from prices do not offset the revenue loss, however. The total cost is still larger than in baseline scenario, in the amount of $81,209 (2.2%).

Table 26. Optimal bunkering strategies of LNG at different fuel tank capacity.

	LNG					
	Current Tank (6700 m^3)			Increased Tank (7900 m^3)		
Port of Calls	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**	**Bunkering amounts (Ton)**	**Sailing Speed (Knots)**	**Bunker Fuel Cost ($)**
CNSHA	2528.17	15.88	1,285,256	3635.65	15.88	1,813,448
FRLEH	-	11.17	-	-	11.17	-
NLRTM	-	11.17	-	-	11.17	-
DEHAM	-	11.17	-	-	11.17	-
BEANR	2309.89	11.17	1,181,150	1202.41	11.17	631,825
GBSOU	-	15.28	-	-	15.28	-
CNYTN	-	15.25	-	-	15.25	-
CNNGB	-	10.02	-	-	10.02	-
Total	**4838.06**		**2,466,407**	**4838.06**		**2,445,274**
					Revenue Loss	**+ 175,000**
						2,620,274
	Cost differences without revenue loss: -$21,132 **Cost differences with revenue loss: $153,867**					

Table 26 shows the two optimal bunkering strategies for LNG for each different tank capacity. There is an apparent difference if compared to HFO with scrubber and MGO. The bunkering purchase in the first port is not enough for the whole service route. Thus, the ship still needs to bunker twice on the service route. This is because of the density of LNG is notably smaller than the other two fuels, which resulting in the low energy content per volume. LNG has the lowest energy content per volume among the fuel alternatives, so the increase of 2200 m^3 in the capacity of the tank does not suffice for the fuel requirement of the whole service route. The purchase amount in the first port reaches the maximum capacity of the tank to obtain maximum quantity discount. The ship then purchases much lower amount of bunker fuel in the next port to reach the end of service route. Same as the other fuels, while using LNG, there is also no change in sailing speed and bunkering amounts in the increased tank. There is a decrease of $21,132 (-1%) from baseline scenario in bunker cost in the case without revenue loss. The decrease in bunkering cost is smaller if compared to two other fuel alternatives because of the quantity discount purchase is smaller. Furthermore, In the scenario of revenue loss, there is an added cost of $153,867 (6%) from the baseline scenario.

5.5. Chapter Summary

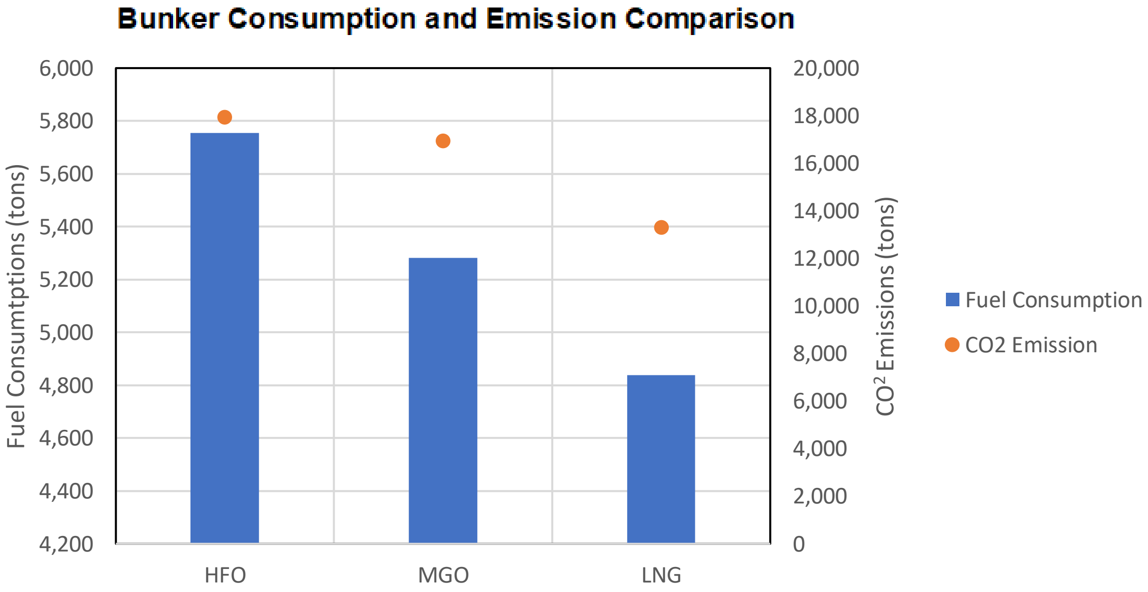

Figure 6. Bunker Fuel Consumption and CO_2 emission in Baseline Scenario

Results, analysis and discussion of the simulations of bunker fuel management strategy on three fuel alternatives is provided in this chapter. Bolded word are intended to point the reader to the prove for the hypotheses stated in Section 4. In Section 5.1., the baseline scenario is simulated. All three fuel alternatives show similar result in term of bunkering times and bunkering port choices. The ship on all three fuel alternatives bunkers twice along the service route and chooses port of Shanghai and port of Antwerp as bunkering ports. **The bunkering times and are affected by the size of the tank, meanwhile the choices of bunkering ports and the bunkering amounts are affected by quantity purchase discount and the need of fuel before the sailing legs to the west and the east.** Furthermore, the total bunkering amounts on each fuel alternative differs because of the different fuel consumption rate, in which LNG has the smallest amounts of bunkering amounts and HFO has the largest amounts of bunkering. The total CO_2 emission is affected by total bunker consumption and specific CO_2 emission per ton fuel. HFO with scrubber emit the most of CO_2 meanwhile LNG emits the least.

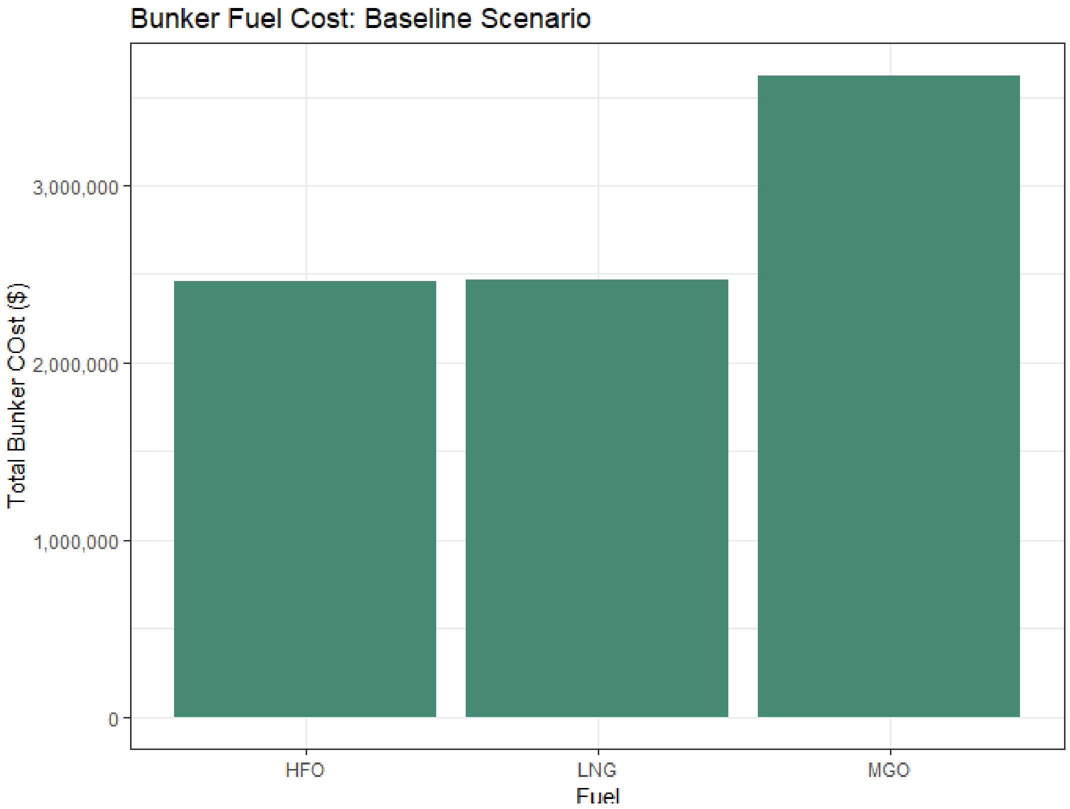

Figure 7. Bunker Fuel Cost in Baseline Scenario

Bunkering amounts and bunker fuel prices then directly affect the bunker fuel cost of every fuel alternatives. This thesis finds that HFO with scrubber has the cheapest bunker fuel cost, LNG is ranked on the second (0.4% more expensive), and MFO is ranked on the last (47% more expensive). **However, for LNG, bunkering amounts and the choices of bunkering ports are also affected by the availability of LNG bunkering facilities.**

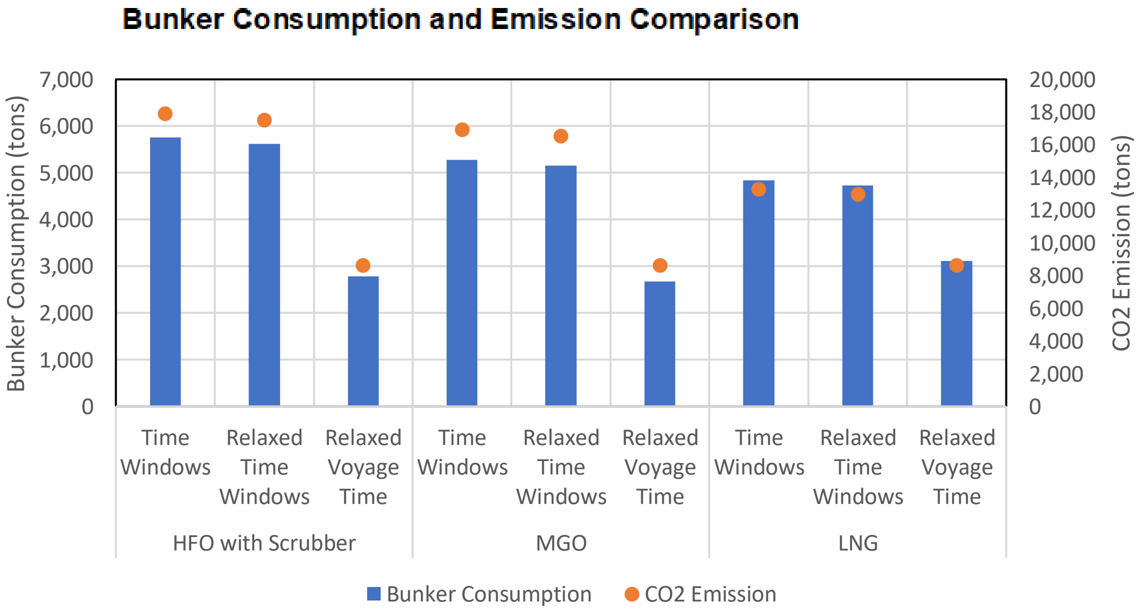

Figure 8. Bunker consumptions; with and without time windows, and relaxed voyage time

In Section 5.2, bunker fuel management strategies in the scenario of relaxing the port arrival time windows are presented. **This study finds that the total bunker fuel costs decrease on all three fuel alternatives caused by the decrease in bunker consumption** (2.36% decrease on HFO with scrubber, 2.31% decrease on MGO, and 2.18% decrease in LNG). Furthermore, the purchasing amount of LNG in the first port differs as the decrease in bunker consumption affect the large quantity purchase. **The decrease in bunker consumption is affected by the decrease in average sailing speed for the whole voyage** (from 15.31 knots to 15.17 knots). **Hence, proving the second hypothesis. The sailing speed on several legs of the route even out to the average sailing speed of the whole route. This study also finds that, there is no notable difference in both average sailing speed and sailing speed on each leg among all three fuel alternatives. This statement proves the first hypothesis.** The decrease in CO_2 is in the same ratio as the decrease in bunker consumption. Lastly, this study considers the relaxing of total voyage time to achieve 50% reduction in CO_2 emission. Each fuel alternative reduces its average speed by a significant amount. The reduction of sailing speed depends on CO_2 emission of each fuel, in which HFO with scrubber, the highest CO_2 emitter, reduces the sailing speed the most (from 15.31 knots to 10.59 knots), meanwhile LNG, the lowest CO_2 emitter, reduces the sailing speed the least (from 15.31 knots to 12.38 knots). **The reduction of sailing speed could be used as an extra strategy for shipowners and ship operators to reduce CO_2, in addition to choosing fuel alternatives relaxing port arrival times.**

In Section 5.3, the simulation result of changing the price of the fuel is shown. Different changes in fuel prices on the port of calls along the service route result in different optimal bunker fuel management strategies. **In general, ship tries to choose the cheapest bunkering port, but still constrained to the fuel requirements to reach the cheapest port, but this is not always the case, as bunkering ports are affected by quantity purchase discount and the need of fuel for sailing. This proves the third hypothesis**.

The change in fuel price does not affect the bunkering times as it is affected by fuel tank capacity and large quantity purchase discount. Relating to the fourth hypothesis, **the average sailing speed for the whole service route does not affected by the change in price, although there are slight differences of sailing speed on a couple of sailing legs. The statement does not fully prove the fourth hypothesis**, as there are differences in sailing speed on each sailing legs, albeit not significant. Furthermore, this study considers the current bunker fuel prices that are different on each port. The choices of bunkering port based on the current bunker fuel prices fall to port of Shanghai and port of Rotterdam. In LNG, this also does not change, even after port of Hamburg is added as a port with LNG bunkering facilities.

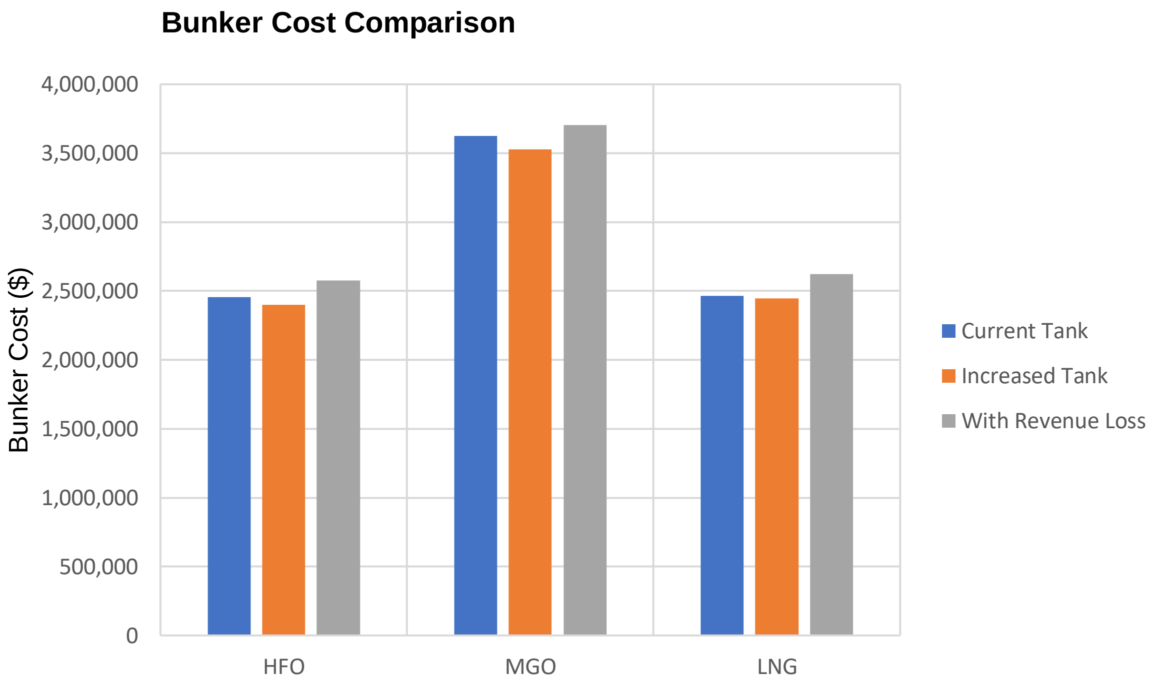

Figure 9. Bunker Cost Comparison of Different Tank Capacity

Lastly, Section 5.4. provides simulation result of increasing the capacity of the fuel tank. **The increase in the capacity of the tank provides the space for larger bunker fuel purchase, thus making it possible to obtain a larger quantity discount and resulting in reduction in bunker fuel cost. However, if revenue loss is taken into account, the reductions in bunker fuel cost do not offset the said loss.** Therefore**, hypothesis 5 can be accepted.** The decrease in bunker fuel cost in HFO with scrubber is in the percentage of 2% without revenue loss, but after considering revenue loss, the cost increase in the percentage of 5%. **Furthermore, there is a change in bunkering times from twice to once on the whole service route.** In MGO, however, the decrease in bunker cost is larger, in the percentage of 2.5% without revenue loss. The total cost is still larger when revenue loss is considered, in the percentage of 2.2%. **The bunkering times in MGO also change from twice to once**. In LNG, there is a decrease also in the percentage of 1% without revenue loss. The cost increase if revenue loss is considered in the amount of 6%. The decrease is smaller than the other fuel alternatives, **because the bunkering times does not change as the fuel tank capacity still does not suffice for the whole service route**. Due to this**, hypothesis 6 cannot be accepted** as not all fuel alternatives is bunkering once. LNG still needs to bunker twice.

6. Conclusion

The regulation to limit sulphur emission to 0.5% by IMO that will be enforced in 1st of January 2020, is feared by many stakeholders, including liner shipping companies, to be disruptive to the shipping industry. There are three fuel alternatives to be chosen by liner shipping companies, namely, HFO with scrubbers, MGO and LNG. The choices of IMO 2020-compliant fuel alternatives would affect the operations of the liner vessel, more specifically to the bunker fuel cost of a liner service. Additionally, initiative has already been agreed by the member states to reduce CO_2 emission from maritime by 50% in 2050, thus making the choice of fuel alternatives in IMO 2020 becomes more complicated as CO_2 emission has to be considered as well. Relating to the issue of bunker fuel cost and CO_2 emission by liner shipping companies, this thesis aims to answer the main research question: "What are the optimal bunker fuel management strategies (cost-wise and emission-wise) on each fuel alternatives?".

This thesis aims to minimize the bunker fuel cost and the carbon gasses emission by optimizing the bunker fuel management strategy, and to compare and study the optimal strategy of the three fuel alternatives. The scope of this study is to optimize the bunker fuel management strategy of a vessel named MV Sajir, which is servicing Far East 4 route, operated by Hapag Lloyd. The ship is chosen based on the recent development on the vessel on which the vessel will be retrofitted in 2020 to use LNG fuel. A comparison study of three fuel alternatives would be best suited for a vessel that currently fueled by fuel oil and will be using LNG in the future. Note that the service route in this study is a weekly liner service with a detailed total voyage time and port arrival time windows.

This study first finds the classification of bunker fuel management strategy on decision-making levels based on literatures. It is concluded that bunker fuel management strategy is categorized as a tactical level decision. The optimal solution from tactical decision, in this case can be used as consideration for planning a whole voyage in one service route. This study then finds the literature regarding fuel consumption. This study decided to use equation provided by Ronan (1982) to calculate fuel consumption. This study also considers the type of bunkering method, which is affecting the fuel price estimation of LNG. This study decides to simulate ship to ship method of bunkering, as it is the most common, most flexible and cheapest method of bunkering. This study then develops tactical planning of bunker fuel management strategy for a shipping liner service route which is simulated to use three different fuel alternatives of IMO 2020. This bunker fuel management strategy includes optimal bunkering ports, optimal bunkering amounts and optimal speed adjustments on each leg of the service route. This study considers three different scenarios to be simulated on the route, which is relaxing of the port arrival time windows and total voyage time, changing the price of the fuel and increasing the fuel tank capacity.

From the result of the study, provided below are some key insights.

(1) Bunkering times of all three fuel alternatives depict similarities, as all the current fuel tanks simulated in this study have a similar sailing range.
(2) Bunkering amounts in bunkering port is affected by bunker fuel prices, quantity discount purchase and fuel requirements from the sailing distance, in which the quantity of the purchase is affected by the fuel tank capacity.
(3) Increasing the tank capacity results in the decrease in total costs, as there are more capacities in the tank to purchase a larger amount of bunker fuel to obtain quantity discount.
(4) Due to a difference in the density of each fuel, the increase in the fuel tank capacity results in different bunkering times between fuel oil and LNG.
(5) The choice of bunkering ports is majorly affected by the price differences between ports along the service route, as different price change scenarios change the optimal bunkering ports. However, the choice of bunkering ports is constrained by the fuel requirements over the sailing range.

(6) The choice of bunkering ports differs between fuel oil and LNG as bunkering facilities for LNG are not available on every port.
(7) Sailing speed is mainly affected by the port arrival time windows, which ultimately affect the bunker cost. Relaxing the port arrival time windows results in a reduced average sailing speed, thus results also in a reduced total bunker cost.
(8) Bunker fuel consumption affects the total CO_2 emission. Combined with its emission per gram fuel, LNG consumes the least fuel, thus emits the least CO_2, meanwhile HFO with scrubber consume the most fuel and emits the most CO_2.
(9) Relaxing total voyage time to further reduce average sailing speed could be used as a strategy to further reduce CO_2 emission. The amount of reduced speed to reach the emission target depends on the CO_2 emission of each fuel alternative.

In conclusion, the answer to the main research question comprised of different bunkering amounts, bunkering port selection, and speed adjustments, depending on which scenario it is simulated. The optimal bunker fuel management strategies are affected by the insights provided above. The first sub-research question is answered on insight (7) and (9), the second sub-research question is answered on insight (5), the third sub-research question is answered on insight (3), and lastly the fourth sub-research question is answered on insight (1), (4), (6), (8) and (9).

This thesis provides some comprehensions relating IMO 2020 alternative fuels from a bunker fuel management strategy perspective. The insights from this perspective can be used to compare and used as a consideration when making a choice of fuel to comply with the regulation. The method of optimizing bunker fuel management strategy that is used in this study can also be used in a different route and on a different ship, as the input to ship specifications and service route can be changed.

This thesis acknowledges its limitations, in which one of them is the uncertainty over the fuel prices is set rather deterministically. As one of the main worries of many stakeholders over supply of the fuel alternatives. Further research may use a stochastic model to solve uncertainty of supply over the fuel prices. Additionally, after the implementation of the regulations when the prices of fuels could be more easily forecasted more accurately due to less uncertainty, the bunker fuel management strategy could be extended to operational level by including bunker fuel price forecasting model on each bunkering port to obtain more accurate bunker cost in a service route. This research provides the reference for lowering the average sailing speed on this route to achieve 50% reduction in CO_2 emission. Future research may add another factor into consideration when lowering the sailing speed, such as the loss of revenue from the decrease in total voyage time and optimal vessel deployment configuration.

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Appendix

Appendix 1. Port of Calls

Port Code	Port Name	Country
CNSHA	Port of Shanghai	China
FRLEH	Port of Le Havre	France
NLRTM	Port of Rotterdam	The Netherlands
DEHAM	Port of Hamburg	Germany
BEANR	Port of Antwerp	Belgium
GBSOU	Port of Southampton	United Kingdom
CNYTN	Port of Yantian	China
CNNGB	Port of Ningbo	China

Appendix 2. Ship to Ship Bunker Cost

Bunkering Method	Size of the bunker vessel (m^3)	% cost from LNG import price
Ship to Ship Bunkering	500	13-16
	1,000	11-15
	2,000	13
	3,000	8-16
	10,000	6-10

According to Faber et al. (2017), ship to ship bunkering cost varies by vessel size and distance from LNG terminal. Provided in appendix 2 are the varying cost from LNG import price of various vessel sizes. The cost arising from the transporting LNG from LNG terminal is also provided in the value of % of LNG import price. The lower bound of the percentage is when the bunker vessel does not have to sail from LNG terminal (0 nm sailing), meanwhile the upper bound is when the bunker vessel has to sail from LNG terminal (100 nm sailing).

Appendix 3. HFO and MGO prices relative to Brent Prices

Date	HFO prices	Brent prices	MGO prices	HFO-Brent Price Differences ($)	MGO - Brent Price Differences ($)	HFO-Brent Price Differences (%)	MGO-Brent Price Differences (%)
09/Aug/16	254.7	278.6	475	-23.9	196.4	-8.58%	70.50%
23/Aug/16	251.5	272.77	471	-21.27	198.23	-7.80%	72.67%
06/Sep/16	253.5	358.58	464	-105.08	105.42	-29.30%	29.40%
20/Sep/16	253.25	349.05	458.25	-95.8	109.2	-27.45%	31.28%
04/Oct/16	268.5	386.78	481.75	-118.28	94.97	-30.58%	24.55%
18/Oct/16	283.25	292.88	500	-9.63	207.12	-3.29%	70.72%
01/Nov/16	275.5	357.67	491.5	-82.17	133.83	-22.97%	37.42%
15/Nov/16	264.25	352.33	468.25	-88.08	115.92	-25.00%	32.90%
29/Nov/16	286.5	364.64	475.25	-78.14	110.61	-21.43%	30.33%
13/Dec/16	322.5	412.72	517.75	-90.22	105.03	-21.86%	25.45%
27/Dec/16	330.75	322.85	522.75	7.9	199.9	2.45%	61.92%
10/Jan/17	335.25	409.41	532.25	-74.16	122.84	-18.11%	30.00%

Date	HFO prices	Brent prices	MGO prices	HFO-Brent Price Differences ($)	MGO - Brent Price Differences ($)	HFO-Brent Price Differences (%)	MGO-Brent Price Differences (%)
24/Jan/17	331.5	416.11	529	-84.61	112.89	-20.33%	27.13%
07/Feb/17	323.5	414.9	530.5	-91.4	115.6	-22.03%	27.86%
21/Feb/17	326	423	531.7	-97	108.7	-22.93%	25.70%
07/Mar/17	322.75	410.54	527.75	-87.79	117.21	-21.38%	28.55%
21/Mar/17	297.75	382.75	507.25	-85	124.5	-22.21%	32.53%
04/Apr/17	307.25	408.62	515	-101.37	106.38	-24.81%	26.03%
18/Apr/17	347.24	405.94	527	-58.7	121.06	-14.46%	29.82%
02/May/17	305.25	381.21	509.75	-75.96	128.54	-19.93%	33.72%
16/May/17	310	391.3	505	-81.3	113.7	-20.78%	29.06%
30/May/17	309.75	384.59	505.25	-74.84	120.66	-19.46%	31.37%
13/Jun/17	299.75	360.24	488.75	-60.49	128.51	-16.79%	35.67%
27/Jun/17	295.25	353.95	478.5	-58.7	124.55	-16.58%	35.19%
11/Jul/17	298.25	358.65	486.75	-60.4	128.1	-16.84%	35.72%
25/Jul/17	312	391.6	504.5	-79.6	112.9	-20.33%	28.83%
08/Aug/17	318	394.72	514.5	-76.72	119.78	-19.44%	30.35%
22/Aug/17	312.75	393.33	511.5	-80.58	118.17	-20.49%	30.04%
05/Sep/17	322.25	405.04	538.25	-82.79	133.21	-20.44%	32.89%
19/Sep/17	335.5	419.53	539.24	-84.03	119.71	-20.03%	28.53%
03/Oct/17	339	420.93	553	-81.93	132.07	-19.46%	31.38%
17/Oct/17	344.25	436.85	554.25	-92.6	117.4	-21.20%	26.87%
31/Oct/17	359.75	458.8	566.5	-99.05	107.7	-21.59%	23.47%
14/Nov/17	376.5	467.16	585.25	-90.66	118.09	-19.41%	25.28%
28/Nov/17	374	475.18	592.25	-101.18	117.07	-21.29%	24.64%
12/Dec/17	371.75	473.56	582.5	-101.81	108.94	-21.50%	23.00%
26/Dec/17	382	502.78	592.5	-120.78	89.72	-24.02%	17.84%
09/Jan/18	390	519.65	617	-129.65	97.35	-24.95%	18.73%
23/Jan/18	393.5	528.94	633.5	-135.44	104.56	-25.61%	19.77%
06/Feb/18	388.25	497.96	634.25	-109.71	136.29	-22.03%	27.37%
20/Feb/18	379.5	491.33	611.5	-111.83	120.17	-22.76%	24.46%
06/Mar/18	373.5	484.94	609.25	-111.44	124.31	-22.98%	25.63%
20/Mar/18	376.25	515.39	621	-139.14	105.61	-27.00%	20.49%
03/Apr/18	380.25	512.6	638.25	-132.35	125.65	-25.82%	24.51%
17/Apr/18	396.25	546.15	658.75	-149.9	112.6	-27.45%	20.62%
01/May/18	412.75	551.53	679.25	-138.78	127.72	-25.16%	23.16%
15/May/18	445.75	590.58	699.25	-144.83	108.67	-24.52%	18.40%
29/May/18	444	575.63	701.25	-131.63	125.62	-22.87%	21.82%
12/Jun/18	448.75	574.61	697	-125.86	122.39	-21.90%	21.30%
26/Jun/18	450.25	579.55	681	-129.3	101.45	-22.31%	17.50%
10/Jul/18	467.25	573.26	701	-106.01	127.74	-18.49%	22.28%
24/Jul/18	454.75	554.85	684.25	-100.1	129.4	-18.04%	23.32%
07/Aug/18	458.75	553.19	693	-94.44	139.81	-17.07%	25.27%
21/Aug/18	450	555	693.75	-105	138.75	-18.92%	25.00%
04/Sep/18	461	585.23	722	-124.23	136.77	-21.23%	23.37%

Date	HFO prices	Brent prices	MGO prices	HFO-Brent Price Differences ($)	MGO - Brent Price Differences ($)	HFO-Brent Price Differences (%)	MGO-Brent Price Differences (%)
18/Sep/18	462.25	596.49	721.24	-134.24	124.75	-22.50%	20.91%
02/Oct/18	498.5	644.15	758.25	-145.65	114.1	-22.61%	17.71%
16/Oct/18	499.5	608.12	761	-108.62	152.88	-17.86%	25.14%
30/Oct/18	498	569.95	748.5	-71.95	178.55	-12.62%	31.33%
13/Nov/18	467.5	495.44	708.5	-27.94	213.06	-5.64%	43.00%
27/Nov/18	430	449.43	645.25	-19.43	195.82	-4.32%	43.57%
11/Dec/18	412.25	453.12	617.5	-40.87	164.38	-9.02%	36.28%
25/Dec/18	365.5	394.5	587.5	-29	193	-7.35%	48.92%
08/Jan/19	380.75	452.4	597	-71.65	144.6	-15.84%	31.96%
22/Jan/19	397.5	461.74	622.5	-64.24	160.76	-13.91%	34.82%
05/Feb/19	411.5	469.38	633.75	-57.88	164.37	-12.33%	35.02%
19/Feb/19	432.25	502.74	654	-70.49	151.26	-14.02%	30.09%
05/Mar/19	436	496.42	658.25	-60.42	161.83	-12.17%	32.60%
19/Mar/19	435.25	512.45	654.25	-77.2	141.8	-15.06%	27.67%
02/Apr/19	435.25	522.62	658.75	-87.37	136.13	-16.72%	26.05%
16/Apr/19	437.25	539.68	670.24	-102.43	130.56	-18.98%	24.19%
30/Apr/19	445.5	545.85	669	-100.35	123.15	-18.38%	22.56%
14/May/19	418.25	539	672.75	-120.75	133.75	-22.40%	24.81%
28/May/19	413	525.44	661	-112.44	135.56	-21.40%	25.80%
11/Jun/19	392.25	460.31	618.5	-68.06	158.19	-14.79%	34.37%
25/Jun/19	403	495.74	627	-92.74	131.26	-18.71%	26.48%
09/Jul/19	432	493.97	634	-61.97	140.03	-12.55%	28.35%
23/Jul/19	430.5	478.19	635.5	-47.69	157.31	-9.97%	32.90%
06/Aug/19	397	433.62	617.25	-36.62	183.63	-8.45%	42.35%
Average						**-18.7%**	**30%**

Appendix 4. Brent and Natural Gas Prices

Year	Brent ($/bbl)	LNG Japan ($/MMBtu)	NG Europe ($/MMBtu)	NG US ($/MMBtu)	Brent ($/ton)	LNG Japan ($/ton)	NG Europe ($/ton)	NG US ($/ton)
2015	50.75	10.9	6.8	2.6	362.74	563.53	351.56	134.42
2016	42.81	7.4	4.6	2.5	305.98	382.58	237.82	129.25
2017	52.81	8.6	5.7	3	377.46	444.62	294.69	155.1
2018	68.35	10.7	7.7	3.2	488.53	553.19	398.09	165.44
2019	66	7.4	6	2.8	471.74	382.58	310.2	144.76
2020	65	7.5	6	2.9	464.59	387.75	310.2	149.93
2021	65.48	7.6	6.1	3	468.02	392.92	315.37	155.1
2022	65.97	7.7	6.2	3.1	471.52	398.09	320.54	160.27
2023	66.46	7.8	6.3	3.2	475.02	403.26	325.71	165.44
2024	66.96	7.9	6.4	3.3	478.60	408.43	330.88	170.61

Appendix 5. LNG: Baseline Scenario

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	255.43	225.07	189.70	144.05	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2672.22	255.43	225.07	189.70	2453.94	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2528.17	0.00	0.00	0.00	2309.89	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 6. LNG: Relaxed Time Windows

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	676.68	620.55	555.13	471.48	2406.38	360.60	162.83	144.05
Order Up to Level (tons)	2881.00	676.68	620.55	555.13	2460.29	2406.38	360.60	162.83	144.05
Bunkering Amount (tons)	2736.95	0.00	0.00	0.00	1988.82	0.00	0.00	0.00	0.00
Speed (knots)	15.17	15.18	15.18	15.12	15.12	15.18	15.18	15.18	

Appendix 7. LNG: Relaxed Total Voyage Time

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	1410.92	1373.69	1330.29	1273.87	1644.93	287.80	156.60	144.05
Order Up to Level (tons)	2881.00	1410.92	1373.69	1330.29	1681.02	1644.93	287.80	156.60	144.05
Bunkering Amount (tons)	2736.95	0.00	0.00	0.00	407.15	0.00	0.00	0.00	0.00
Speed (knots)	12.39	12.37	12.37	12.41	12.37	12.37	12.37	12.41	

Appendix 8. LNG: Increasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	464.21	433.85	2499.59	2453.94	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2881.00	464.21	2534.96	2499.59	2453.94	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2736.95	0.00	2101.11	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 9. LNG: Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	464.21	433.85	398.48	352.83	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2881.00	464.21	433.85	398.48	2453.94	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2736.95	0.00	0.00	0.00	2101.11	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 10. LNG: Increasing - Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	173.80	144.05	2499.97	2454.02	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2590.59	173.80	2535.58	2499.97	2454.02	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2446.54	0.00	2391.53	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 11. LNG: Decreasing - Increasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	172.29	144.05	2501.15	2454.57	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2589.07	172.29	2537.24	2501.15	2454.57	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2445.02	0.00	2393.19	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	10.77	11.28	11.28	11.28	15.28	15.25	10.02	

Appendix 12. LNG: Current Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	172.29	144.05	2501.15	2454.57	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2589.07	172.29	2537.24	2501.15	2454.57	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2445.02	0.00	2393.19	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	10.77	11.28	11.28	11.28	15.28	15.25	10.02	

Appendix 13. LNG Current Price with Hamburg

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	144.05	172.29	144.05	2501.15	2454.57	2424.52	351.81	152.24	144.05
Order Up to Level (tons)	2589.07	172.29	2537.24	2501.15	2454.57	2424.52	351.81	152.24	144.05
Bunkering Amount (tons)	2445.02	0.00	2393.19	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	10.77	11.28	11.28	11.28	15.28	15.25	10.02	

Appendix 14. LNG: Increased Tank

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	191.35	1410.21	1379.86	1344.48	1298.83	2471.82	399.11	199.54	191.35
Order Up to Level (tons)	3827.00	1410.21	1379.86	1344.48	2501.25	2471.82	399.11	199.54	191.35
Bunkering Amount (tons)	3635.65	0.00	0.00	0.00	1202.41	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 15. HFO Baseline Scenario

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	1583.86	1547.74	1505.66	1451.36	2935.92	470.12	232.69	222.95
Order Up to Level (tons)	4459.00	1583.86	1547.74	1505.66	2970.93	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	4236.05	0.00	0.00	0.00	1519.58	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 16. HFO: Relaxed Time Windows

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	1831.56	1764.78	1686.96	1587.44	2909.29	480.57	245.30	222.95
Order Up to Level (tons)	4459.00	1831.56	1764.78	1686.96	2973.43	2909.29	480.57	245.30	222.95
Bunkering Amount (tons)	4236.05	0.00	0.00	0.00	1385.99	0.00	0.00	0.00	0.00
Speed (knots)	15.18	15.18	15.18	15.12	15.12	15.17	15.18	15.18	

Appendix 17. HFO: Relaxed Voyage Time

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	1704.83	1671.82	1633.36	1584.05	1552.26	350.19	233.92	222.95
Order Up to Level (tons)	3003.28	1704.83	1671.82	1633.36	1584.05	1552.26	350.19	233.92	222.95
Bunkering Amount (tons)	2780.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	10.60	10.60	10.60	10.56	10.56	10.60	10.60	10.56	

Appendix 18. HFO: Increasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	1583.86	3067.32	3025.24	2970.93	2935.92	470.12	232.69	222.95
Order Up to Level (tons)	4459.00	3103.43	3067.32	3025.24	2970.93	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	4236.05	1519.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 19. HFO: Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	390.46	354.35	312.26	257.96	222.95	470.12	232.69	222.95
Order Up to Level (tons)	3265.60	390.46	354.35	312.26	257.96	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	3042.65	0.00	0.00	0.00	0.00	2712.97	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 20. HFO: Increasing - Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	1583.86	3067.32	3025.24	2970.93	2935.92	470.12	232.69	222.95
Order Up to Level (tons)	4459.00	3103.43	3067.32	3025.24	2970.93	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	4236.05	1519.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 21. HFO: Decreasing - Increasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	299.09	263.93	222.95	2971.88	2935.92	470.12	232.69	222.95
Order Up to Level (tons)	3174.23	299.09	263.93	3027.37	2971.88	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	2951.28	0.00	0.00	2804.42	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.02	11.02	11.29	11.32	15.28	15.25	10.02	

Appendix 22.. HFO: Current Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	222.95	253.13	222.95	3029.96	2972.62	2935.92	470.12	232.69	222.95
Order Up to Level (tons)	3128.28	253.13	3074.37	3029.96	2972.62	2935.92	470.12	232.69	222.95
Bunkering Amount (tons)	2905.33	0.00	2851.42	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	10.21	11.47	11.47	11.43	15.28	15.25	10.02	

Appendix 23. HFO: Increased Tank

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	331.99	3212.47	3176.36	3134.27	3079.96	3044.96	579.15	341.72	331.98
Order Up to Level (tons)	6087.61	3212.47	3176.36	3134.27	3079.96	3044.96	579.15	341.72	331.98
Bunkering Amount (tons)	5755.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 24. MGO: Baseline Scenario

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	1230.98	1197.83	1159.20	1109.35	2683.67	420.37	202.44	193.50
Order Up to Level (tons)	3870.00	1230.98	1197.83	1159.20	2715.79	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	3676.50	0.00	0.00	0.00	1606.44	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 25. MGO: Relaxed Time Windows

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	1462.80	1401.50	1330.07	1238.72	2663.67	429.77	213.82	193.50
Order Up to Level (tons)	3870.00	1462.80	1401.50	1330.07	2722.55	2663.67	429.77	213.82	193.50
Bunkering Amount (tons)	3676.50	0.00	0.00	0.00	1483.82	0.00	0.00	0.00	0.00
Speed (knots)	15.17	15.18	15.18	15.12	15.12	15.18	15.18	15.12	

Appendix 26. MGO: Relaxed Voyage Time

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	1632.84	1600.78	1563.66	1515.76	1484.89	316.38	204.16	193.50
Order Up to Level (tons)	2892.71	1632.84	1600.78	1563.66	1515.76	1484.89	316.38	204.16	193.50
Bunkering Amount (tons)	2699.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	10.98	10.98	10.95	10.95	10.95	10.98	10.95	10.95	

Appendix 27. MGO: Increasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	1230.98	2804.28	2765.64	2715.79	2683.67	420.37	202.44	193.50
Order Up to Level (tons)	3870.00	2837.42	2804.28	2765.64	2715.79	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	3676.50	1606.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 28. MGO: Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	347.25	314.11	275.47	225.63	193.50	420.37	202.44	193.50
Order Up to Level (tons)	2986.27	347.25	314.11	275.47	225.63	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	2792.77	0.00	0.00	0.00	0.00	2490.17	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 29. MGO: Increasing - Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	193.50	2804.28	2765.64	2715.79	2683.67	420.37	202.44	193.50
Order Up to Level (tons)	2832.52	2837.42	2804.28	2765.64	2715.79	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	2639.02	2643.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	

Appendix 30. MGO: Increasing – Decreasing Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	263.39	231.11	193.50	2716.67	2683.67	420.37	202.44	193.50
Order Up to Level (tons)	2902.41	263.39	231.11	2767.61	2716.67	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	2708.91	0.00	0.00	2574.11	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.02	11.02	11.29	11.32	15.28	15.25	10.02	

Appendix 31. MGO: Actual Price

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	193.50	223.55	193.50	2767.99	2716.67	2683.67	420.37	202.44	193.50
Order Up to Level (tons)	2862.57	223.55	2807.68	2767.99	2716.67	2683.67	420.37	202.44	193.50
Bunkering Amount (tons)	2669.07	0.00	2614.18	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	10.63	11.32	11.33	11.32	15.28	15.25	10.02	

Appendix 32. MGO: Increased Tank

	CNSHA	FRLEH	NLRTM	DEHAM	BEANR	GBSOU	CNYTN	CNNGB	CNSHA
Fuel Inventory (tons)	288.10	2932.02	2898.88	2860.24	2810.39	2778.27	514.97	297.04	288.10
Order Up to Level (tons)	5571.04	2932.02	2898.88	2860.24	2810.39	2778.27	514.97	297.04	288.10
Bunkering Amount (tons)	5282.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Speed (knots)	15.88	11.17	11.17	11.17	11.17	15.28	15.25	10.02	