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Maritime Routing Optimization in LNG Bunkering

by

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~This is for Aaron and Tresy~

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Abstract

Since the IMO 2020 global sulphur limit, there is a promising growth on the adoption of LNG as shipping fuel. LNG is considered as one of the most preferred ship's fuel alternatives because of its technical maturity and its availability. The main challenge in the current adoption phase is to secure the utilization of LNG bunker, however the *chicken-and-egg* dilemma between ship owners and fuel providers has been slowing down the development of the LNG bunkering infrastructures. Ship-to-Ship (STS) transfer method is argued to be one key in unlocking the infrastructure development while it has already been considered to be an efficient operation when there is a far distance from bunker source to the receiving ship. In that sense, by arranging an optimum bunkering supply plan, the aim to promote the utilization of LNG as shipping fuel can be achieved while also improving the efficiency of supply.

Motivated by that purpose, this thesis puts forward the objective to determine the optimal plan of fleet composition and the routing of LNG Bunker Vessels (LNGBVs) to fulfil the growing demand of LNG bunkering in the Port of Rotterdam (PoR). A mathematical model which comprehends several theoretical foundations is developed to formulate the problem into a vehicle routing problem. Experiments using scenarios are done and the analysed results conclude two determining factors of the problem as 1) Bunkering Volume and 2) Length of Bunkering Time Window. The bunkering volume affects the choice of fleet while the length of time window affects the routing and scheduling.

The optimal plan of route, schedule, and fleet composition for LNG bunkering in the Port of Rotterdam is determined for various scenarios. Moreover, in the experiments we observed two important findings. Firstly, a high proportion of bunkering time in the time window leads to a higher penalty cost particularly when this proportion is higher than 0.4. Secondly, the ratio of total capacity per total demand impacts the level of the fixed cost. While a higher total demand can lower this ratio, it turns out it can maintain the fixed cost under 5% of total costs. The current existing LNG bunkering fleet in PoR, which only consists of one dedicated vessel with a medium capacity, is evaluated. In that extent, it is certain that it can only serve tasks that is smaller than its capacity, so it can be a disadvantage in terms of securing the demand from the current growing size of LNG bunker. On the other hand, the current capacity is high enough to serve the small market at this moment optimally, especially when the total capacity takes not more than 0.8 of the total demand and when there are sufficient large time windows.

This thesis also discusses further: the model and result findings applicability, dealing with uncertainties, approaching longer term planning, and makes a contribution to enhance LNG bunkering utilization. This thesis contributes primarily in the model development of successfully combining several models of VRP to a tailored model for LNG bunkering maritime transport problem. On the other hand, this thesis is limited to a deterministic setting and to the scope of tactical level of transportation problem which only applies for a short-term planning.

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List of Abbreviations

Abbreviation	Remarks
LNG	Liquefied Natural Gas
TTS STS PTS	Truck-to-Ship, Ship-to-Ship, Port (Terminal)-to-Ship
PoR	The Port of Rotterdam
LNGBV	LNG Bunkering Vessel
IMO	International Maritime Organization
GHG	Green House Gasses
HVO	Hydrotreated Vegetable Oil
EC	European Commission
EMSA	European Maritime Safety Agency
TEU	Twenty-foot Equivalent Unit
HVRP	Heterogeneous Vehicle Routing Problem
FSMVRPTW	Fleet Size and Mix Vehicle Routing Problem with Time Windows
AIMMS	Advanced Interactive Multidimensional Modelling System, a mathematical modelling tool
LoA	Length overall
AIS	Automatic Identification System
AFI	Alternative Fuel Insight
MIP	Mixed Integer Programming
CMA CGM	Compagnie Maritime d'Affrètement and Compagnie Générale Maritime, which translated as "Maritime Freighting Company" and "General Maritime Company".

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Chapter 1 Introduction

1.1 Background

Liquefied Natural Gas (LNG) is the most preferred shipping fuel alternatives that currently has the highest availability and technical maturity among the other fuel alternatives, however, the limited availability of bunkering infrastructure and its high capital expenditure are reported as the two main barriers for the low utilization of LNG as ships' fuel (DNV GL, 2019b). In that sense, it can be argued that there are still two key remarks before the widespread uptake of LNG can take place, which are to increase the availability of infrastructures as well as to lower the capital expenditure. Therefore, securing the LNG bunker utilization is one of the biggest challenges, especially in the current phase of LNG adoption (Ngai, 2018).

LNG bunkering development is another classic *chicken-and-egg* dilemma between ship owners and fuel providers. Ship owners are not confident to invest in LNG before the bunkering infrastructure is as convenient as the existing fuel infrastructure, while on the other hand the LNG bunkering (infrastructure) providers need to be assured by a secured demand (Faber, et al., 2017). Fortunately, some efforts have already taken place to boost the utilization of LNG as shipping fuel, not only the physical development such as: bunkering stations, portable tanks, trucks' common manifold, but also in the intangible side such as a promoting regulation for LNG bunker, incentive schemes, and also contractual models.

EMSA (2018) discussed that the set of LNG bunkering infrastructure depends on its delivery method which follow this three common types: Port(Terminal)-to-Ship (PTS), Truck-to-Ship (TTS), and Ship-to-Ship (STS). Lagarrigue,V. & Herniary, J. (2018) argued that STS is a key element in unlocking the LNG bunkering infrastructure development. In line to that, Olainyi & Gerlitz (2019) designed a typical LNG bunkering contract model that considers using bunkering vessels and/or barges as the supply mode in the case of far distance between the terminal (source of bunker) and the receiving ship with the aim to decrease logistic time and costs while increase the coverage by serving local demand. In the extent of costs, Stenersen (2008) argued two considerations for the LNG fuel price as: (1) the ship owner's competitive position should not be weakened relative to other fuels, and (2) the LNG seller should be able to recover his costs of supply.

The IMO 2020 global sulphur limit (2019) promotes a faster adoption of LNG as ships' fuel. Since its introduction, the orderbook of LNG fuelled ships has increase significantly. A study of DNV GL estimated that it will reach 500 ships in 2020 with 121 ships had already operated in 2019 (Nilsen, 2019). From that point, the demand of LNG Bunkering shows a relatively higher growth than its development on the supply side. In that case, the current limited number of infrastructures may then impact the supply costs of LNG bunker while also potentially incur opportunity costs on the users' side. The growing size of LNG-fuelled ships demand a higher volume size and bunkering rate which can be served more efficiently via STS using LNG bunkering vessels (LNGBVs) or barges. In that sense, an optimum bunker supply plan can lead to a more efficient operation which potentially increases the utilization of LNG bunkering and to promote the adoption of LNG.

The Port of Rotterdam (PoR) is one of the largest global bunker hubs and a fast-growing LNG bunkering port (Port of Rotterdam, 2020d). PoR promotes the ideal and efficient way for ships-bunkering by allowing simultaneous bunkering for sea-going ships during cargo operation at terminals. They also provide buoys, dolphins, and public quays within the port to facilitate STS transfer, besides that PoR has already run mature IT systems that also support the bunkering process, from the *TimetoBunker* to port calls optimization system. There is a significant growth of the LNG bunker sales, for around 723% in average, reported from 2016-2019 (Port of Rotterdam, 2020g). However, currently there are only three LNGBVs operated in PoR area (World Maritime News, 2020) with only one vessel stationed in Rotterdam.

The increase in global orderbooks of large LNG fuelled ships certainly will bring potential LNG bunker demand to PoR. In order to serve the demand, how does the STS bunker supply operation fill the infrastructure gap while maintain the competitiveness of LNG as ships' fuel? Or specifically in other words: how does the STS bunkering improve the utilization of LNG bunker in terms of time and the cost of supply?

As a start, the supply process of LNG bunker / or the LNG bunkering can basically be seen as a transportation problem, the objection of which aims to minimize total costs. In this case, beside the transportation costs, opportunity costs may arise in relation to any delay of LNG bunkering from the time window of cargo operation at terminals. As previously mentioned, the lateness issue is important to be addressed, as it affects the competitiveness of LNG and the choice of bunkering. In a simple sense, the opportunity costs simply act as a penalty for not fulfilling the demand at the right time and the right place. Finally, in strategic and/or tactical level of transportation problem, the fleet mix – size and number of vessels – decision with optimal routing of LNGBVs shall be determined to achieve the efficient LNG Bunkering.

1.2 Research Questions and Objective

From the described issues, facts, and reasonings, this thesis puts forward the following main research question:

What is the optimum fleet mix and route plan of LNGBVs to fulfil the potential LNG bunkering demand in the Port of Rotterdam?

In addressing this problem, we formulated the following sub questions:

1. What is the optimal plan of route, schedule, and fleet composition for LNG bunkering in the Port of Rotterdam?
2. What are the determining factors of the bunkering transportation problem?
3. How does the time windows impact the optimal plan and what will be the cost?
4. How does the size and the number of tasks impact the optimal plan?
5. How can the existing fleet fulfil the potential LNG fuel demand in the Port of Rotterdam in terms of time and cost?

From the research questions, the objective of this research is to determine the optimal tactical plan of fleet mix and the routing of LNGBVs to fulfil the growing demand of LNG bunkering in the Port of Rotterdam. This research also aims to evaluate the optimal plan of fleet and routes under the current conditions and in adapting to some changes of factors.

1.3 Thesis Structure

This thesis is structured into eight chapters:

Chapter 1 introduces the background and the motivation of the research, expresses the research questions, defines the objective of the research, and also outlines the report. In Chapter 2, set of literatures are reviewed to explain the context of the research and relate some points in literatures with the research question.

Chapter 3 describes the problem in a more specific context. This chapter also comprehends some theoretical foundations to formulate and model the problem. This chapter describes the methodology in approaching the problem and the way to answer the research questions. Chapter 4 describes all the data, information, and the related assumptions used in and as the scope of the thesis. All the described data and information are then primarily utilized in the scenario development in the next chapter.

Chapter 5 discusses the scenarios as the case study and implements the model to find the optimal solution. This chapter also explains the solutions and briefly describes the findings. Chapter 6 analyses the results of the experiment and describes the findings to infer some general insight from the results.

Furthermore, Chapter 7 discusses the results and the model performances in the context of several real application topics specially to gain better understanding and well answered the research questions. Finally, Chapter 8 gives concluding remarks of the research, answers the research question, and recommends some area of development for future research.

Chapter 2 Literature Review

In this chapter, set of literatures and previous studies are reviewed to provide an update on LNG as shipping fuel, explain the context of LNG Bunkering and its characteristics in the Port of Rotterdam, and to give underlying perspectives for the research questions.

2.1 LNG as shipping fuel

Shipping or maritime transportation is by far the most energy efficient of transport mode in terms of joules / tonne-kilometre, while consumes about 2% of the world's energy which mostly for international cargo shipping (DNV GL, 2019a). The introduction of the IMO (2019) global sulphur-emissions restriction persuade governments to place the regulation by 2020 with a long run target of 50% CO_2 reduction by 2050. So far the efforts to reduce the emissions came in a combination of energy efficiency improvement and alternative fuels utilization, which were completely measured in Bouman, et al. (2017) as a mixture of ship design improvement (hull design, materials, coatings, air lubrication, ballast water reduction, etc), power & propulsion system improvement, alternative fuels & energy sources, and to operational improvement (speed optimization, capacity utilization, voyage optimization, etc.).

To meet the ambitious GHG-reduction goals of IMO, it can be argued that along with the other type of efforts, the adoption of new and alternative fuels in shipping plays a key role (DNV GL, 2019b). Currently, there are some developed energy alternatives considered for shipping such as HVO, LNG, hydrogen, and biofuels, in which LNG is preferred based on quite many aspects. The next section amplifies the reasons why LNG has advantages, and also explain the barriers especially in the supply side.

2.1.1 LNG as ships' fuel alternatives

Many studies conclude that LNG as ship's fuel is proven and can be an available solution for reducing GHG. The positive supports came from many aspects, such as technology, fuel availability, infrastructures, regulations, incentive environmental gains, and cost effectiveness (DNV GL, 2019b) EMSA (Guidance on LNG Bunkering to Port Authorities and Administrations, 2018) (Faber, et al., 2017). The study of DNV GL (2019b) well resumed all of the important aspects as in the following figure:

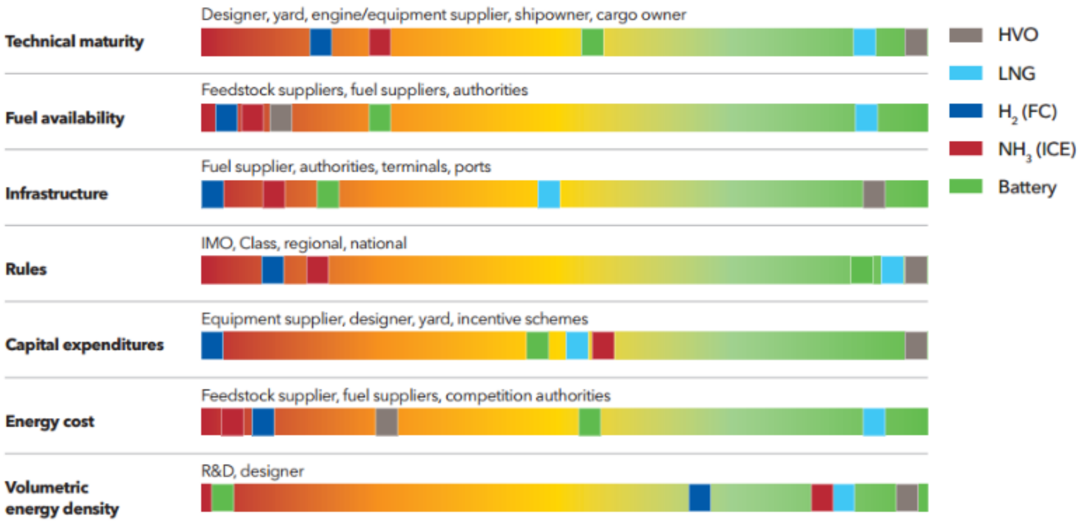

Figure 1 The Alternative Maritime Fuel Barrier Dashboard, Source: (DNV GL, 2019b)

It can be seen that LNG ranks among all the other traditional fuel alternative in resolving the barriers. The technical maturity is one indicated by the current implementation of dual-fuel engines and the methane slip elimination feature in modern engines (DNV GL, 2015). Besides that, the increasing natural gas resources, the fact that the energy content of LNG is comparable to diesel fuels, and the reducible volume of LNG are indications to its maturity in the aspects of fuel availability, energy cost, and volumetric energy density (EMSA (2018)). On the regulatory side, LNG has gained a great attention for the implementation, for example the European Commission's (EC) communication on clean power for transport identifies LNG could reduce oil dependence of maritime transport while reducing pollutants, also the EU's Directive 2014/94/EU on the deployment of alternative fuels infrastructure requires refuelling points for LNG availability in 2025 (Faber, et al., 2017). On the other hand, the infrastructure aspect shows the relatively low availability of bunkering infrastructures and the high capital investment still has not fully supported by incentive schemes (in equipment, shipyard, port incentives, etc).

Focussing on the supply infrastructure, LNG bunkering is another classic *chicken-and-egg* dilemma between ship owners and fuel providers. Ship owners are not willing to invest in LNG ships before LNG bunkering infrastructures is as convenient as the existing fuel bunker infrastructures, while on the other hand the LNG bunkering (infrastructure) providers will not invest unless they are assured by the secured demand (Faber, et al., 2017). However, it is believed that it is important to expand LNG bunkering infrastructures (DNV GL, 2015) and securing the LNG bunker utilization is one of the biggest challenges (Ngai, 2018).

2.1.2 LNG value chain in brief

Along its value chain, from natural gas resource to the end customers, LNG run into different shapes and move in different supply designs which depend on the variety end customers' requirement. EMSA (2018) simplified the LNG value chain as in the following figure:

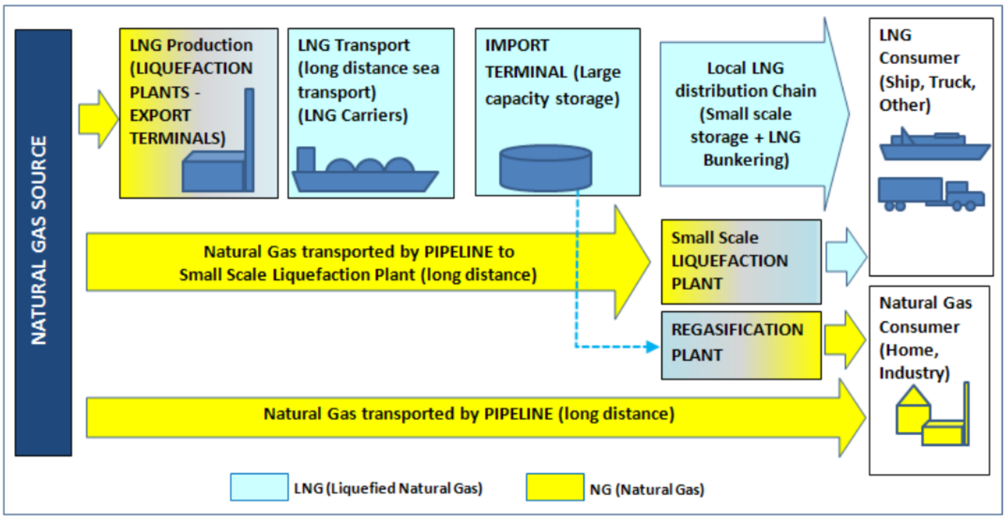

Figure 2 LNG Value Chain, Source: (European Maritime Safety Agency (EMSA), 2018)

Three main points can be taken from the explanation in EMSA (2018), first is that the important consideration in designing an LNG chain which the more interfaces – liquefaction, regasification, distribution links and modes – the more likely the LNG have an accidental or operational releases which may harm the environment. in line with that, it is important to have safety awareness in lots of interfaces. Finally, the LNG chain can be contained in a boundary of port. In that case, different stakeholders may be included especially that provide the services for supply, transport, storage, and also bunkering. A well-established regulatory framework and control must take place to ensure safety.

In the context of the scale of LNG chain, practically, it is divided into 2 categories which are:

Table 1 The different scale of LNG development

Category	**LNG storage typical capacities**	**Description**
Large Scale LNG	> 100,000 m^3	EMSA (2018) defined that a large-scale LNG operation typically includes: - Production trains with capacity between 1 and 6 MTPA (million metric tonnes per annum), and its sequential large liquefaction sites which located in coastal areas. - LNG carriers with capacities ranging 120,000 m^3 (54,000 tonnes) up to 267,000 m^3 (120,000 tonnes). - LNG hubs as the receiving terminals typically with capacity > 120,000 m^3 which also function as export / import terminals.
Medium to Small Scale LNG	≤ 100,000 m^3	The small-scale LNG operation includes: - LNG terminals up to 100,000 m^3 in size which previously known as the medium size term (EMSA (2018)) which supplied with small-scale LNG carriers (1,000 m^3 – 40,000 m^3) - Small-scale LNG also comprises the LNG distribution to small regasification units for small users. - LNG bunkering is included as a small-scale LNG (Clarksons, 2019) with the source that can be either from large-scale terminals or the medium scale terminals.

2.1.3 LNG Bunkering

As mentioned previously, LNG bunkering can be considered as a small-scale LNG supply chain and can be briefly represented by the following figure:

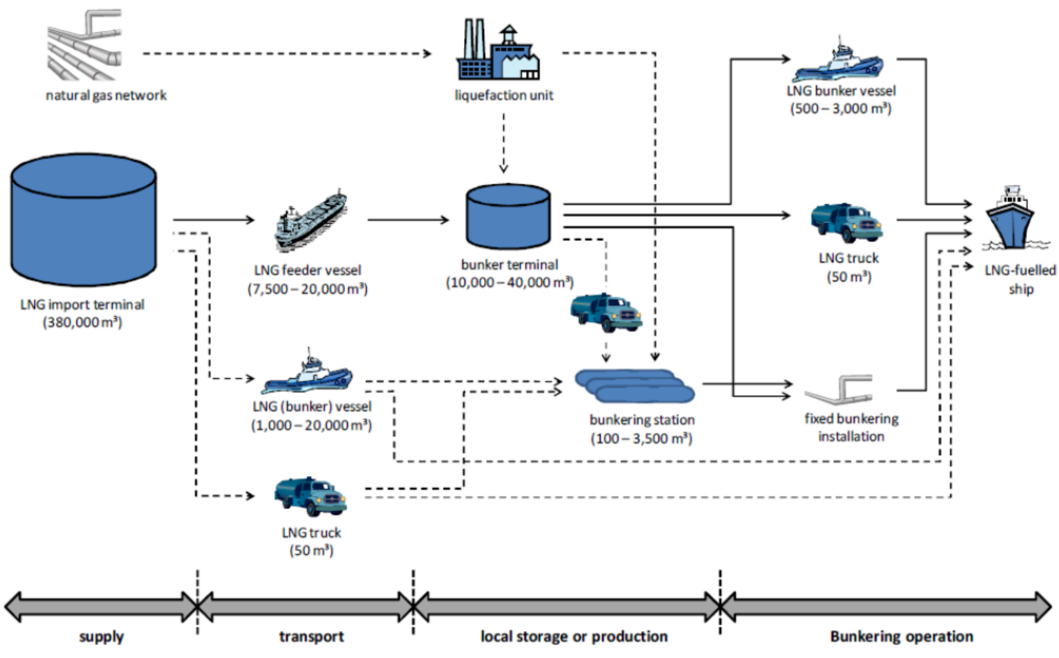

Figure 3 Different supply routes for LNG Bunkering, Source: EMSA (2018)

EMSA (2018, p. 43) also defined LNG bunkering as: *"…a particular type of operation where LNG fuel is transferred from a given distribution source to an LNG fuelled ship."* or in short as how the LNG is delivered to the receiving vessel. The operation involves different stakeholders, from the receiving ships, LNG terminal, port authority, safety personnel, up to policy and administrative personnel.

LNG bunkering supply infrastructure, as stipulated in EMSA (Guidance on LNG Bunkering to Port Authorities and Administrations, 2018), can be divided according to the delivery method of bunkering which involves a sequence or combination of infrastructures such as: storage / tank terminals, trucks, barges, vessels, and pipelines. EMSA (Guidance on LNG Bunkering to Port Authorities and Administrations, 2018) compiled three types of LNG bunkering as: Shore-to-Ship / Port-to-Ship (PTS), Truck-to-Ship (TTS), and Ship-to-Ship (STS) which described as in the following table:

Table 2 LNG Bunkering modes, Source: EMSA (2018)

Method	Typical volume and rates	Remarks
Truck-to-Ship (TTS)	Volume: 50-100 m^3 Rates: 40-60 m^3/h	- LNG truck(s) is connected to the receiving ship on the quayside using a flexible hose - have the advantages in operational flexibility, adaptive to different situation, enable point-to-point delivery. - Limited in: flow rates, volumes, movement in the quayside of the terminal, congested roads to the destination point.
Ship-to-ship (STS)	Volume: 100-20,000 m^3 Rates: 500-1,100 m^3/h	- LNG (bunker) vessel is connected to the receiving vessels that moored on the opposite side of the quay / buoys / dolphins. - STS has the advantage in: simultaneous operation and does not interfere with cargo operation, favourable by ships with short port turnaround time, larger capacity than TTS - Some source mentioned that it basically covers all types of ships and sizes as argued in DMA (2012, pp. 82, 187). - Some disadvantages are: high investment costs, port limitations, impacting life cycle costs
Terminal (Port)-to-Ship (PTS)	Volume: 500-20,000 m^3 Rates: 1,000-2,000 m^3/h	- LNG fuelled ship is bunkered from small LNG storage unit or from import/export terminal. - PTS is good for a long-term stable demand and also has the possibility of higher rates. - However, some limitations exist such as the geographical limitations, far and timely distance, and also difficult in investing and develop contracts.

As can be found in today's operation, mostly LNG is done via TTS mode for supporting vessels such as tugs, pilot boat, and also other vessels like RO-RO and ferries which has only small bunkering quantity. On the other hand, the IMO regulation promotes faster adoption in LNG and emerges LNG fuelled ships in bigger sizes, for example an 15,000 TEU containers. Therefore, while Ngai (2018) argues that in the early years of LNG adoption securing the LNG bunker utilization is one of the biggest challenges and Lagarrigue,V. & Herniary, J. (2018) argued that STS is a key element in unlocking the infrastructure development.

2.2 Development of LNG as fuel

On the demand side, the IMO 2020 global sulphur limit (2019) promotes faster adoption of LNG as ships' fuel. Since then, the growing demand and the increase in orderbooks of LNG fuelled ship improve significantly. A study of DNV GL estimates that it probably has reach 500 ships including LNG carriers in 2020 (Nilsen, 2019) from the previous 121 LNG fuelled ships in operation. For the orderbooks, the uptake of LNG as a fuel is increasing and growing more diverse in terms of vessel type, which around two thirds is non LNG carriers that includes Aframaxes, Post-Panamax containerships, and also retrofits for dual-fuel VLCC (Clarksons, 2019, p. 54).

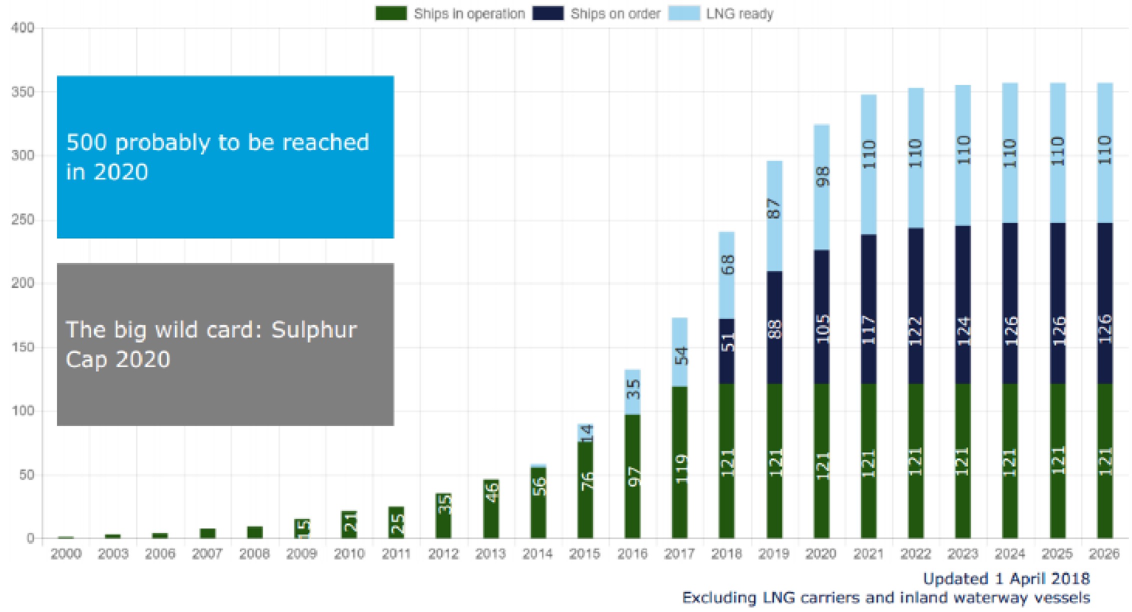

Figure 4 The Yearly development of LNG fuelled ships, Source: (Nilsen, 2019)

On the supply infrastructures side, currently there are 132 ports with bunkering facilities, either existing or planned, with limited facilities' availability by region (Clarksons, 2019). The coverage is wide within Northwest Europe and developing in the Mediterranean and East Asia while elsewhere the development still grows more slowly (Clarksons, 2019). Therefore, it can be argued that the infrastructure growth is relatively slow which may limit the operation area of LNG fuelled ships and holds the adoption of LNG.

From the previous point, the growing demand of LNG Bunkering is relatively higher than its development on the supply side. The current limited number of infrastructures on several port may impact the supply cost of LNG bunker with also potentially incur opportunity costs on the users' side. While, in line with that, Stenersen (2008) argued two considerations for the price of LNG as fuel which are: (1) the ship owner's competitive position should not be weaken relative to other fuels, and (2) the LNG seller should be able to recover his costs of supply.

As also mentioned in previous section, the growing size of LNG-fuelled ships demand a higher volume and bunkering rate which can be served more efficiently via STS using LNG bunkering vessels (LNGBVs) or barges as the only current viable option. In that sense, an optimum plan of LNGBVs can lead to a more efficient supply which increase utilization of LNG as ships' fuel and ultimately to promote the adoption of LNG.

2.3 LNG bunkering in the Port of Rotterdam

The Port of Rotterdam (PoR) is one of the largest global bunker hubs and a fast-growing LNG bunkering port (Port of Rotterdam, 2020d). PoR promotes the ideal and efficient way for ships-bunkering by allowing simultaneous bunkering for sea-going ships during cargo operation at terminals. They also provide buoys, dolphins, and public quays within the port area to facilitate STS transfer, and especially there is one set of dolphins which has the priority for LNG transhipment.

PoR also advances in IT systems that support bunkering, from *TimetoBunker*, Navigation, and port calls optimization system. Bunkering digital pre-notification is enabled which information are shared with interested parties including Harbour Master to Customs (Port of Rotterdam, 2020j), that creates a single submission procedure while also beneficial fo better bunkering planning. On the regulation side, there are some incentives scheme for using LNG as fuels in PoR, such as the green award discount, environmental ship index discount, special rates for waste fee, etc (Port of Rotterdam, 2020b).

The growing LNG bunkering infrastructures in PoR is reflected by the development of the import terminal, LNG bunkering vessels and barges, pipelines, LNG trucks, and several small regasification points. Gate Terminal is the only import terminal in PoR which has the capacity of 180,000 m^3 that is also completed with liquefaction and regasification facilities. It serves European LNG pipeline networks, reloading to ships, LNG vessels, and tank trucks. They have three jetties with one dedicated jetty for reloading LNG bunkering vessels (Port of Rotterdam, 2020g). Currently there are only three licensed LNGBVs to operate in PoR area, which are Shell's Cardissa (6,500 m^3), Titan LNG Flex Fueller (4x370 m^3), Anthony Veder-Sirius Shipping's Coralius (5,800 m^3) (World Maritime News, 2020). Yet, there is only one vessel that is stationed in the port, which is Cardissa that is fully in cooperation with the Gate Terminal.

Besides that, there is an exponential growth of the LNG bunker sales reported from 2016-2019 (Port of Rotterdam, 2020g), which in average of 723% per year. Begins with only 100 metric tons in 2016 and 1,500 in 2017, the total sales continue to increase to 9,483 in 2018 until 31,944 metric tons in 2019 or around 70,600 m^3 and currently in Q1 2020 it has already reaches 15,710 metric tons or around 34,700 m^3 (Port of Rotterdam, 2020g).

On the contrary, as previously mentioned, there is only one dedicated bunkering vessel in the port which also serves the North Sea market. In such gap between the growing demand and the resources, there is a high potential in low availability of bunkering modes which may impact the utilization and the uptake of LNG as fuel in the port. As introduced in the previous section, this issue of serving a growing demand with limited resource can be accommodated with an optimal supply planning that also considers the LNG competitiveness as fuel with an ultimate purpose to promote the adoption of LNG as ships' fuel.

2.4 Previous similar studies

As introduced in the previous chapter and sections, this thesis puts forward the optimization of LNG bunkering maritime transport. As far as the author's knowledge, there is limited number of studies in the area of bunkering transport moreover that specific the scope inside a port area. However, there are lots of research in LNG supply chain optimization and more abundantly in vehicle routing and scheduling problem and other sea transportation problems. The following contributions are of interest.

Bittante, et al. (2018) develops a mathematical model as decision support for tactical aspect of LNG logistic chains design and focus on maritime transportation for small-scale LNG supply chain. They utilize multiple journeys from multiple supply sources and receiving ports, and a set of heterogeneous fleet. They also implement a Mixed Integer Linear Programming (MILP) to find the optimum routes and applied it in a case study of maritime routing optimization in the area of Caribbean Islands.

Fagerholt (2001) conducts a research in ship routing and scheduling optimization that considered as a multi ship pickup and delivery problem with soft time windows (m-PDPSTW). The research describes a new optimisation approach for the m-PDPSTW problem, in the case of ocean shipping. Therefore, the research not only deals with the optimal route, as the previous study, but also adds the scheduling aspect in sea transport. Furthermore, it also considers 'soft' time windows than the usual 'hard' time windows that enable a service outside the time window with a penalty scheme. The research developed a mathematical model with the applied optimisation algorithm.

An earlier study conducted by Ferland & Michelon (1988) also deals with vehicles transportation scheduling problem with the emphasize in multiple vehicle types. This study shows the vehicle scheduling problem with time windows that is extended to the multiple vehicle types problem. It is a network design research with scheduling in a more theoretical and general case of transportation. The research also described the heuristics method and the exact optimisation methods to approach the formulated problem.

Huang, et al. (2019) studies the Feeder Vehicle Routing Problem (FVRP) as one extension of the Vehicle Routing Problem (VRP) which enables customers to be served by different vehicle delivery characteristics (trucks and motorcycles). The study models when to establish the tour of additional vehicle, the motorcycle, and when it is needed to complement the truck's tour with an addition of the condition for motorcycle to load at the truck location. The research used the ant colony optimization as the approach to find the optimal routes.

To some extent, it can be referred that although the study on bunkering transportation problem inside a port area is still very limited, yet it has a lot of similarities with the work in the area of network design, vehicle routing and scheduling, and other transportation or operational researches. In that case, a review on the related studies is important, in which to note that a contextual adaptation is needed in the process of developing the models. It can be reflected from the previous studies that:

- While there is an increased interest in small-scale LNG, a Mixed Integer Programming (MIP) can be used as a decision support on the tactical aspect in designing its logistics chain.
- Bunkering problem is a close match to the Vehicle Routing Problem (VRP) which has being studied for a minimum of thirty years. It has many extensive features to help make a well-formulated bunkering transportation problem, from adding scheduling aspect or the time window, enabling the 'soft' time window, and to modelling an additional tours or vehicles.

Chapter 3 Problem formulation and Methodology

This chapter describes the problem which has been introduced in the first chapter, and comprehends some theoretical foundations to model the problem, then briefly describes the research methods to approach the problem and answer the research questions. This chapter is put in order starting from problem description, problem formulation with a brief theoretical groundwork, thesis model development, and the research methodology to approach, solve, evaluate, and analyse the outcomes of the study.

3.1 Problem description

As introduced in the first section, STS bunkering is one key to improve the current LNG bunker utilization and to fill the LNG bunker supply infrastructure gap. Parameters such as the availability of bunkering vessels, the supply capacity, and the LNG bunker supply costs are crucial to maintain LNG competitiveness in the timely bunkering market. An optimum plan of STS bunkering supply operation is important to serve the current growing size of LNG bunker demand in the low development LNG bunker infrastructure.

The bunker supply problem can be basically seen as a transportation problem. The basic model of transportation problem is to serve demand in a set of locations from the source with a fleet of vehicles. In this case, the demand comes from LNG-fuelled ships as the receiving ships, LNG terminal acts as the depot or the source of supply, and the fleet of LNGBVs is the vehicles to supply the LNG from the depot to the demand location.

There are several unique characteristics in bunker sea-transportation, especially when it is operated within the port area. Firstly, while bunkering process itself is considered as a non-value-adding activity, the operation inside the port area is a timely operation. High traffic and congestion at terminals are several reasons that a time-efficient operation is important. Secondly, bunkering operation cannot be partially served, or in other words one receiving ship can only be bunkered by one bunkering vessel. Although it is not flexible, but it actually is a simple supply operation. Thirdly, different than any land-based transportations, sea transportation inside the port area is simpler in terms of the vehicle routing. As the port route and traffic are highly regulated, there is a predetermined path among terminals which can be considered as a line between sequence of locations.

The bunkering tactical and operational plan particularly decides on the size of bunkering vessels, number of bunkering vessels, the route assignment, and the schedule of the bunkering vessel. Those decision variables are evaluated in terms of cost of supply. So finally, the thesis optimizes the supply costs of LNG bunker by determining the fleet size and mix decision, the routing, and the schedule of LNG Bunkering Vessels (LNGBVs)

3.2 Problem formulation

This thesis makes use of the vehicle routing problem (VRP) as basic problem and applies the extensions to decide on the fleet composition which known as Heterogeneous VRP (HVRP), specifically decides for unlimited capacitated fleet setting or the Fleet Size and Mix decision (FSMVRP), and considers Time Windows constraints (VRPTW). A mathematical model is used to find the optimal solution to the set of scenarios, and later the results are analysed to find insights and general inferences to answer the research questions.

3.2.1 Vehicle Routing Problem

The classical Vehicle Routing Problem (VRP) aims to determine an optimal routing plan of a homogeneous fleet of vehicles to serve a set of customers, in the condition that: the fleet start and end at a depot, and each customer is visited only once by one fleet (Koç, Bektas, Jabali, & Laporte, 2016). The VRP can be extended to specific problems, in which it has many variants. In the case to determine fleet composition, the term Heterogeneous VRP (HVRP) is known. HVRP can be classified into two categories whether it considers a limited or unlimited fleet of capacitated vehicles (Koç, Bektas, Jabali, & Laporte, 2016). The Fleet Size and Mix VRP is then used to define the optimal composition of unlimited fleets, on the opposite the Heterogeneous Fixed Fleet VRP (HFVRP) is used if the fleets are fixed to a predetermined fleet.

This thesis aims to obtain the optimal number of capacitated LNG bunkering vessels to fulfil the demand of LNG bunker in the port. The number of receiving ships act as the set of customers while the LNG loading terminal is the depot. The optimal routing plan of LNGBVs then can be determined to efficiently serve the LNG bunker demand inside the port area.

3.2.2 Fleet Size and Mix Vehicle Routing Problem

The classical FSMVRP simultaneously determines the composition and routing of heterogeneous fleet of vehicles in order to serve pre-determined customers with known demand from a central depot (Liu & Shen, 1999). The objective of FSMVRP is basically the same as VRP which is to minimizes fixed costs and routing costs, however it is in the situation when the number of vehicles is to be determined. The same constraints as in the VRP are followed in FSMVRP which are: routes begin and ends at the depot, customers can be served only once, and the capacity constraint for each route.

3.2.3 Fleet Size and Mix Vehicle Routing Problem with Time Windows

The Fleet Size and Mix Vehicle Routing Problem with Time Windows (FSMVRPTW) is the FSMVRP that consider the time window constraint. Every customer must be served without violating the time window. There are two types of time windows; which are the hard time window and the soft time window. In the hard time window, the demand must be served within the time window, otherwise it cannot be served at all. On the other hand, in the soft time window, demand can be served outside the time window with some appropriate penalties or so-called inconvenience costs.

This thesis follows the FSMVRPTW with soft time windows since these following conditions must be considered, which are:

- This thesis decides on the optimal size and number of vessels or the fleet size & mix decision (FSM).
- Bunkering process is to assign bunkering vessels to routes of demand in different locations from one depot (VRP).
- Bunkering process is ideally and efficiently done simultaneous with the cargo operation during the berth time in a terminal, so that time window must be considered (TW).
- The bunkering can still be held outside the time window at the terminal by moving to a buoys / dolphins / public quay (soft time window).

However, some unique conditions for bunkering which is not explained in the theoretical model are also important to be considered which are:

- The LNGBVs do not start from the depot, but they stationed to a particular place within the port area which may take time to travel and to load at the depot.

- In practice, bunker notification is placed before ship arrive, for maximum 72, 48, 24, 12, 6 to 3 hours prior to the process.
- A bunkering vessel cannot wait at the customer location before the customer or the receiving vessel arrive at the location. In this case, there is only a late penalty for bunkering process but there is no penalty for arrived too early to the location since it is not possible.

3.3 Mathematical Model Formulation:

As previously described, this thesis makes use of the vehicle routing problem (VRP) as basic and applies the extensions to decide on the fleet composition which known as Heterogeneous VRP (HVRP) and specifically decides for unlimited capacitated fleet setting or the Fleet Size and Mix decision (FSMVRP), and considers Time Windows constraint (VRPTW).

The concept of FSMVRPTW uses locations and fleet of vehicles as the main sets of variables. It is then can be modelled as a mixed integer programming (MIP). The mathematical model is developed by adapt several existing models which will be described along in the following section. The model then furtherly developed to match the unique conditions of bunkering supply process. The model is then implemented to approach and solve the developed scenarios. For the implementation purpose, the mathematical program is run using an optimization software package.

We formulate the problem in terms of (bunkering) vessels which have to serve (= supply LNG) to customers (vessels to be supplied) on given berth locations. The vessels start fully loaded at a given depot from where they also can be resupplied. The following section explain the mathematical model starting from the list of all variables and the parameters, continue with the objective function description and then completed with the explanation of all constraints.

3.3.1 Model Variables and Parameters

Sets

$N = set\ of\ berth\ locations = \{0 \ldots n\}, \quad index\ i, j, h$

$V = set\ of\ vessels = \{1 \ldots v\} \quad , \quad index\ k$

Decision variables

$x_{ij}^k = \begin{cases} 1, & if\ vessel\ k\ travels\ directly\ from\ customer\ i\ to\ j \\ 0, & otherwise \end{cases}$

$y_i^k = \begin{cases} 1, & if\ vessel\ k\ serve\ customer\ i \\ 0, & otherwise \end{cases}$

$z_{ij}^k = \begin{cases} 1, & if\ vessel\ k\ travels\ directly\ in\ a\ 2nd\ tour\ from\ customer\ i\ to\ j \\ 0, & otherwise \end{cases}$

$p_i^k = arrival\ time\ at\ customer\ i\ for\ vessel\ k$

$u_i^k = \begin{cases} 1, & if\ vessel\ k\ is\ late\ at\ customer\ i \\ 0, & otherwise \end{cases}$

$r_i \quad = cumulative\ demand\ that\ a\ vessel\ has\ served\ after\ reach\ i\ (demand\ at\ i\ is\ included)$

$p_0^k \ = ready\ time\ of\ vessel\ k\ /\ finished\ loading\ time\ at\ the\ depot$

$p"_0^k = 2nd\ tour\ start\ time\ for\ vehicle\ k\ /\ after\ reloading\ at\ the\ depot$

$g_k \ = end\ time\ of\ first\ tour\ of\ vessel\ k$

Data and Parameters

c_{ij}^k = $cost\ of\ using\ vessel\ k\ to\ serve\ i\ and\ j$

f_k = $fixed\ acquisition\ cost\ of\ vessel\ k\ (f_1, < f_2 < \cdots < f_v)$

a_i = $earliest\ start\ time\ or\ start\ of\ time\ window\ at\ i$

b_i = $latest\ start\ time\ or\ the\ end\ of\ time\ window\ at\ i$

s_i = $service\ time\ at\ customer\ i$

t_{ij} = $travel\ time\ from\ i\ to\ j$

l_k = $loading\ time\ at\ depot\ for\ vehicle\ k$

ST = $travel\ time\ from\ bunkering\ vessels\ station\ to\ depot\ (= 45\ mins)$

d_i = $demand\ at\ customer\ location\ i$

q_k = $capacity\ of\ vessel\ k\ (q_1 < q_2 < \cdots < q_v)$

μ_i = $predetermined\ penalty\ cost\ for\ serving\ customer\ i\ late$

M = $large\ number$

3.3.2 Mathematical Modelling

Objective function:

The objective is to minimize cost that consists of three parts: fixed acquisition cost of the vessels, the routing cost in terms of daily operational costs and loading costs, and also the penalty cost for any late deliveries. The cost structure itself can be found in section 4.4.

The objective mainly follows the classical FSMVRP objective as derived from Golden, et al. (1984) with the penalty cost model in Koskosidis, et al. (1992). The penalty is configured from a variable term into a fixed cost term per its late occurrences and the index *k* is added since every vehicle is scheduled individually with its own lateness

$$\min \sum_{k \in V} \sum_{j \in N: j > 0} f_k\, x_{0j}^k + \sum_{k \in V} \sum_{i \in N} \sum_{j \in N} c_{ij}^k (x_{ij}^k + z_{ij}^k) + \sum_{k \in V} \sum_{i \in N} u_i^k \mu_i \qquad (1)$$

Subject to:

Customers visit constraints

$$\sum_{i \in N} (x_{ij}^k + z_{ij}^k) = y_j^k, \qquad \forall\ (j \in N)\ \forall\ (k \in V) \qquad (2)$$

$$\sum_{j \in N} (x_{ij}^k + z_{ij}^k) = y_i^k, \qquad \forall\ (i \in N)\ \forall\ (k \in V) \qquad (3)$$

$$\sum_{k \in V} y_i^k = 1, \qquad \forall\ (i \in N: i > 0) \qquad (4)$$

Flow conservation constraints:

$$\sum_{i \in N} x_{ih}^k - \sum_{j \in N} x_{hj}^k = 0, \qquad \forall\ (h \in N: h > 0)\ \forall\ (k \in V) \qquad (5)$$

$$\sum_{i \in N} z_{ih}^k - \sum_{j \in N} z_{hj}^k = 0, \qquad \forall\ (h \in N: h > 0)\ \forall\ (k \in V) \qquad (6)$$

Constraints (2)-(6) are the classical VRP constraints on developing routes that guarantee customers visit rule and a balance flow. Constraints (2)-(4) make sure that each customer can only be visited once with only one vessel. The constraints are adapted from Koskosidis, et al. (1992) and Ferland & Michelon (1988) with the addition of z_{ij}^{k} as the variable to accommodate second tour. The second tour is adapted from the idea of additional vehicles from Huang, et al. (2019) that enables the same vehicle to be used in more than one route. On the other hand, the constraints (5)-(6) make sure a balance flow for every route that also guarantee the vessels start and end at the depot (Golden, Assad, Levy, & Gheysens, 1984) (Calvete, Gale, Oliveros, & Sanchez-Valverde, 2007).

Second tour activation constraint

$$\sum_{i,j\in N} z_{ij}^{k} \le n \sum_{i,j\in N} x_{ij}^{k}, \qquad \forall\,(k \in V) \tag{7}$$

Since one bunkering vessel can be assigned to more than one route, it allows a second tour for the fleet. Constraint (7) regulates that the second tour can only be activated only if the first tour has already activated.

Time window constraints

$$p_j^k + M(1 - x_{ij}^k - z_{ij}^k) \ge a_j\,, \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{8}$$

$$p_j^k - M(1 - x_{ij}^k - z_{ij}^k) \le b_j + M\left(u_j^k\right), \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{9}$$

Vessels' schedule feasibility constraints

$$p_j^k - p_i^k + M\left(1 - x_{ij}^k - z_{ij}^k\right) \ge\ s_i + t_{ij}\,, \qquad \forall\,\left((i,j) \in N: (i,j) > 0\right)\forall\ (k \in V) \tag{10}$$

$$p_j^k - p_i^k - M\left(1 - x_{ij}^k - z_{ij}^k\right) \le\ s_i + t_{ij}, \qquad \forall\,\left((i,j) \in N: (i,j) > 0\right)\forall\ (k \in V) \tag{11}$$

Schedule feasibility constraints for 1st-tour

$$p_0^k = l_k + ST \tag{12}$$

$$p_j^k - p_0^k + M\left(1 - x_{0j}^k\right) \ge\ t_{0j}\,, \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{13}$$

$$p_j^k - p_0^k - M\left(1 - x_{0j}^k\right) \le\ t_{0j}\,, \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{14}$$

$$g_k - p_i^k + M\left(1 - x_{i0}^k\right) \ge\ s_i + t_{i0}\,, \qquad \forall\,(i \in N: i > 0)\,\forall\ (k \in V) \tag{15}$$

$$g_k - p_i^k - M\left(1 - x_{i0}^k\right) \le\ s_i + t_{i0}\,, \qquad \forall\,(i \in N: i > 0)\,\forall\ (k \in V) \tag{16}$$

Schedule feasibility constraints for 2nd-tour

$$p''^k_0 = g_k + l_k \tag{17}$$

$$p_j^k - p''^k_0 + M\left(1 - z_{0j}^k\right) \ge\ t_{0j}\,, \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{18}$$

$$p_j^k - p''^k_0 - M\left(1 - z_{0j}^k\right) \le\ t_{0j}\,, \qquad \forall\,(j \in N: j > 0)\,\forall\,(k \in V) \tag{19}$$

Constraints (8)-(19) are the time windows and scheduling constraints adapted from Koskosidis, et al. (1992) and Calvete, et al. (2007). Additional configurations to the previous model are added. Firstly, is the addition of vehicle index *k* to note that every vessel has its own scheduling, so that each vessel has its own arrival time or in other words the arrival time is not independent of the vehicle types. Secondly, are the constraints for 1st and 2nd tour schedule feasibility.

The basic constraints for scheduling can be found in constraints (8)-(11). Constraints (8)-(9) guarantee that arrival time of any vessels are placed within the time window of the tasks' earliest start and latest start. Constraint (9) is modified to model the late arrival by adding the variable u_j^k. Besides that, constraints (10)-(11) guarantee the feasibility of the schedule and also define the arrival time by the bunkering time and travel time. The large number (M) enables the link for two decision variables x_{ij}^k and p_i^k, that also relates that a vessel will be scheduled in the particular route only if the route is activated.

Besides that, constrains (12)-(19) expand the schedule feasibility constrains. They regulate the schedule in first tour (constrain 12-16) and the schedule in the second tour (constraint 17-19). Both schedules are linked using parameters g_k and $p"_0^k$ that make sure the second tour schedule is done after finishing the first tour and reload the vessel at the depot. It is also noted that p_0^k is not the arrival time of vessel *k* to the depot but the ready time of the vessel after finished loading at the depot. The same also applies for $p"_0^k$ is the ready time for the second tour after reloading at the depot.

Capacity and Demand constraints

$$r_0 = 0 \tag{20}$$

$$r_j \geq r_i + d_j - M\left(1 - \sum_k x_{ij}^k\right), \qquad \forall\,(i \in N)\;\forall\,(j \in N: j > 0) \tag{21}$$

$$r_j \geq r_i + d_j - M\left(1 - \sum_k z_{ij}^k\right), \qquad \forall\,(i \in N)\;\forall\,(j \in N: j > 0) \tag{22}$$

$$r_j \leq \sum_{k \in V} q_k y_j^k, \quad \forall\,(j \in N: j > 0) \tag{23}$$

The demand constraints (20)-(23) follow the idea of classical FSMVRP model (Golden, Assad, Levy, & Gheysens, 1984) which use cumulative demand in the route including first and second tour. Ultimately the demand constrains are used in constrain (23) which regulates the total demand on each route to not exceed the assigned vessel's capacity.

Binary and Non-Negativity Constraints

$$x_{ij}^k \in \{0,1\}, y_i^k \in \{0,1\}, \qquad \forall\,(i \in N)\;\forall\,(j \in N)\;\forall\,(k \in V) \tag{24}$$

$$z_{ij}^k \in \{0,1\}, u_i^k \in \{0,1\}, \;\; p_i^k \geq 0$$

Finally, constraint (24) defines the binary variables and the non-negative variables. The vessel assignment and route assignment variables x_{ij}^k , y_i^k, and z_{ij}^k are binary, while the arrival time p_i^k is a non-negative variable.

3.4 Research Methodology

This section briefly describes the steps on how the research is conducted. The research is conducted through 6 different steps, which are:

a. Literature Review
   This step has been done in Chapter 2, in which set of literature reviews on LNG as shipping fuel to LNG Bunkering is conducted to have an update on the current issues and to find where the possible improvement areas which then used as the background of the study as introduced in Chapter 1. In addition to that, previous relevant studies are also reviewed to obtain insight on formulating and approaching the problem. Ultimately it is also to define the objective of the study.
b. Model development
   This step has been discussed in this Chapter, which a study on the theoretical model and its extensions is conducted to formulate the problem. A mathematical model is then developed to describe the problem in a quantitative way and to make clear the boundary of the problem and also on how to approach and solve the problem.
c. Scenario development
   Secondary data and information are gathered to prepare a case study for the model implementation. Generic data, publicly available data, secondary data, and reasonable assumptions are used to develop scenarios. Nested scenarios are developed to conduct experimental research by controlling the parameters and identify the behaviour of the model. This step will be discussed in the next chapters (Chapter 4 and 5).
d. Model implementation
   An optimization software tool, AIMMS, is used to implement the model to the developed scenarios. Apart from calculating the results, the tool also has a role in the verification of the model. Besides that, manual calculation is also done as another additional verification to the model. The optimization will be conducted within Chapter 5.
e. Results Analysis
   The result analysis is conducted to find insight and other important findings in order to make general inferences. Other than that, it also used to identify the determining factors of the problem together with the relation among the variables. The analysis will be done in Chapter 6.
f. Discussion
   The insights and important findings are furtherly discussed in several views to answer the research question In addition to that, some aspects such as validity, uncertainties, projections, up to economics are also discussed not only to better answer the research questions but also to provide additional knowledge. This step will be conducted in Chapter 7.

Chapter 4 Scope and Data Description

This chapter describes data, information, and the related assumptions used in the thesis. The data used in this research are secondary data compiled from a set of literatures, researches, companies' websites, international organization reports, and other publicly available information and data. The data, thereafter, are used to specify the scope and parameters which are formulated in the previous chapter. The data provided in this chapter are used in the scenario development later in the next chapter.

4.1 Port Area

For the purpose of this thesis, the problem is scoped into Port of Rotterdam (PoR) area. Following the information in Port of Rotterdam (Ship-To-Ship Transfers, 2020h), the port area is divided into 5 main areas as in the following figure:

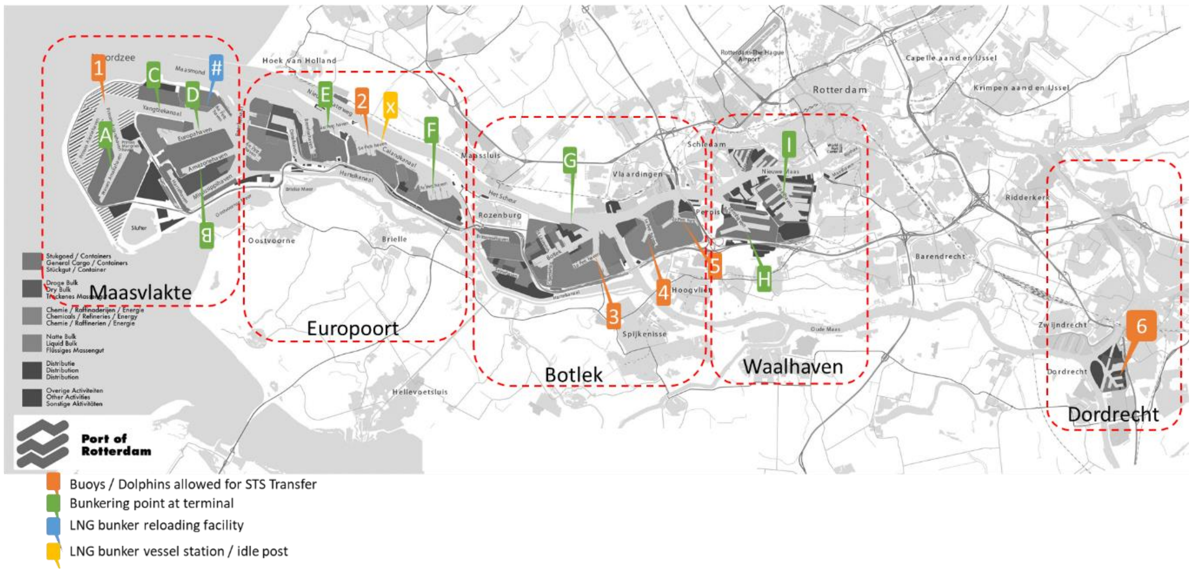

Figure 5 Port Area Divisions, Source: Author based on Port of Rotterdam (2020h)

The locations on each area, as shown in the figure, are specified as the berth locations including loading and bunkering points. While the focus of the thesis is only to STS LNG bunkering operation and only for sea-going vessels whose bunker sales are reported (Port of Rotterdam, 2020g), so that the points in the above figure represent all the allowed location for STS bunkering (Port of Rotterdam, 2020h).

- The green lettered points (A-I) represent terminals in which STS bunkering activities are done during cargo operations.
- The orange numbered points (1-6) represent buoys / dolphins / public quays location that are allowed for STS bunkering for sea-going ships. They can act as demand locations and moreover these points are used as the off-terminal locations for bunkering in case the time window is not met. In that case, the ship will move from the terminal to any nearby buoys/dolphins/quays to be served outside the time window and for the purpose of this thesis the travel time to the any of these locations will be ignored.
- The blue point (#) represents reloading facility for LNG bunkering vessels.
- The yellow point (x) is the current station for LNG bunkering vessels.

The following table lists the name of the area of the mentioned points:

Table 3 Location Names List, Source: Author's based on (Port of Rotterdam, 2020c)

Area	Location	Berth	Terminal
Maasvlakte	A	Prinses Amaliahaven	RWG, APMT
	1	STS Dolphins no. 90-91	
	C	Yangtzekanaal	ECT, Euromax
	#	8e Petroleumhaven	Gate Terminal
	D	Europahaven	ECT, APM
	B	Amazonehaven	ECT
Europoort	E	4e petroleumhaven	Shell
	2	STS Dolphins no. 78-84	
	F	7e Petroleumhaven	Vopak, MET, Lyondell
Botlek	G	1e Werkhaven	Steinweg, Vopak, Verolme
	3	STS Buoys no. 61	
	4	STS Buoys no. 51-52	
	5	STS Buoys no. 50	
Waalhaven	H	Prins Willem Alexanderhaven	ECT, RST
	I	Waalhaven	Uniport, Steinweg
Dordrecht	6	Julianahaven	TTD

In maritime routing problem, terminal location nodes are simply can be illustrated as sequential points. The following figure illustrates the distance and travel time between locations in simple sequential nodes:

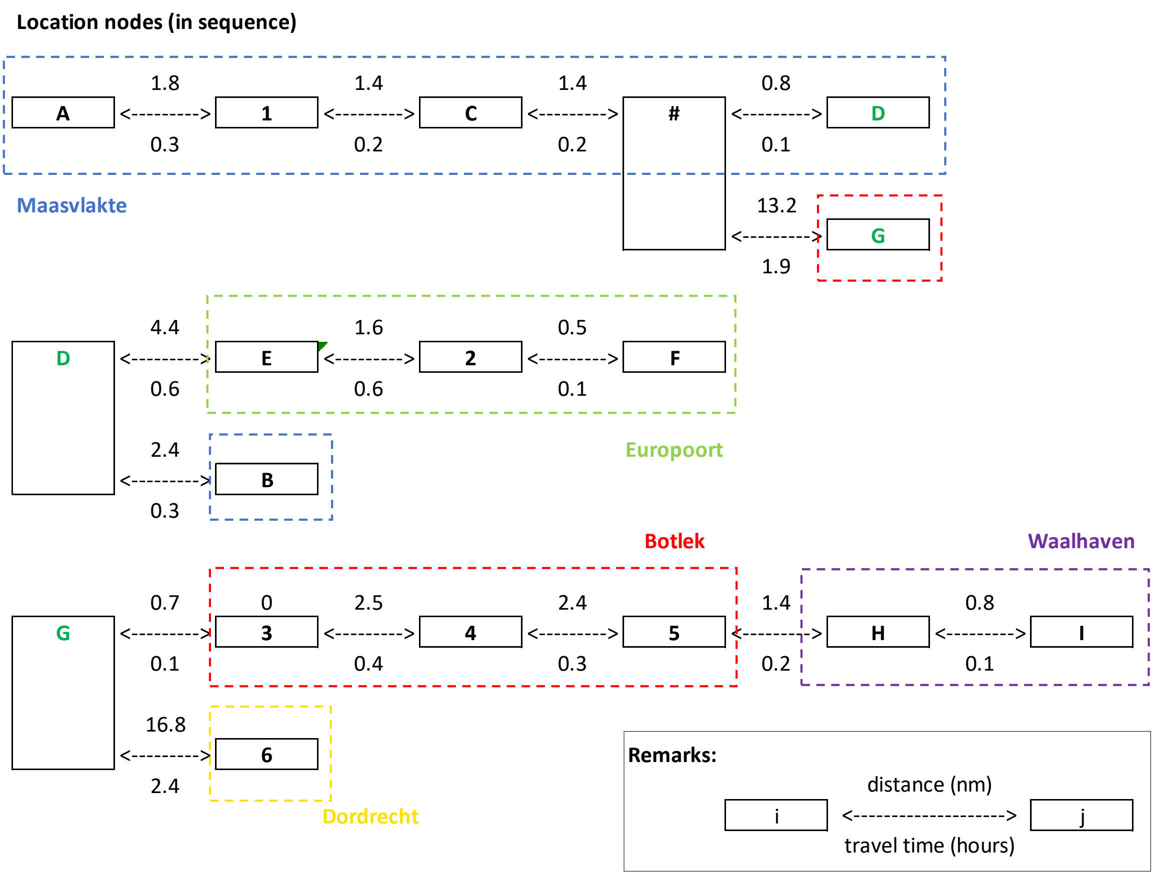

Figure 6 Simplified DIstance and Travel Time Matrix, Source: Author's based on (Port of Rotterdam, 2020e), (Sea-Seek, 2020), (Sea-DIstances.org, 2020)

The distance between the nodes was measured manually using the tool provided in (Sea-Seek, 2020) following the inland routes between terminals as defined in the Navigate Platform (Port of Rotterdam, 2020e). From then, the travel time is calculated by dividing the distances with the maximum allowed speed in the Port of Rotterdam for inland movement which is 13 km/h or equal to 7 knots. The travel time calculation was also checked by comparing with the measurement provided in (Sea-DIstances.org, 2020).

The defined berth locations then also define the limit of the area of this thesis. So that, despite the spread of LNG bunker market in the North Sea, this thesis will only look into the Port of Rotterdam area in order to obtain detailed understanding on specific operational issues by having focus to improve the utilization of LNG bunker in this particular port. The defined points are considered to adequately represent the location of most terminals, buoys, dolphins, and public quays which act as the bunkering locations that served by the LNGBVs. The following subsection describes the bunkering characteristics of the receiving ships and the LNGBVs used for this thesis.

4.2 LNG receiving ships and bunkering vessels characteristics

4.2.1 Generic Ship Types

In this research, generic ship types defined in EMSA (2018) are used for the solutions of the model, which are:

4.2.1.1 Receiving Ships

The receiving vessels in this case are the LNG-fuelled sea-going ships which are operated in the port. The generic types and their typical bunkering demand stipulated in EMSA (2018) are used, which are:

Table 4 Typical LNG bunkering per different generic ship type, Source: EMSA (2018)

Ship Type	Bunker Quantity (m^3)	Rate (m^3/hr)	Duration (hr)	Hose or arm diameter	Adequate Bunkering Mode
Service Vessels. Tugboats, Patrol Boats and Fishing Boats	50	60	0.8	2x2" or 1x3"	TTS
Small RO-RO and RO-Pax Vessel	400	400	1	2x4" or 1x6"	TTS/STS
Large Ro-Ro and Ro-Pax Vessels	800	400	2	2x4" or 1x6"	STS
Small cargo, container and freight vessels	2,000	1,000	2	2x8" or 1x12"	STS
Large freight vessels	4,000	1,000	4	2x8" or 1x12"	STS
Large Tankers, Bulk Carriers and Container Ships	10,000	2,500	4	2x10"	STS/PTS
Very Large Ships and Oil Tankers	20,000	3,000	7	2x12"	STS/PTS

4.2.1.2 LNG Bunkering Vessels

EMSA (2018) divided the typical size for LNG bunkering vessels into 2 ranges, which are:

- LNG (bunker) vessel
  Capacity : 1,000 - 20,000 m^3
  Loading point : from import terminal (380,000 m^3)

- LNG bunker vessel
  Capacity : 500-3,000 m^3
  Loading point : from small-scale terminal (10,000 - 40,000 m^3)

In line with the categories from EMSA, furthermore, this research follows 5 types of LNGBVs as the choice of bunkering vessels specified in Faber, et. al. (2017), which are: 1,000 m^3; 3,000 m^3; 4,000 m^3; 10,000 m^3, and 20,000 m^3.

4.2.1.3 Existing LNG bunker providers in the Port of Rotterdam

Currently there are four LNG bunker specialist licensed to operate in the port, in which there are three permanent LNG bunker vessels operating in Rotterdam (World Maritime News, 2020), which are: Shell's Cardissa (6,500 m^3), Titan LNG Flex Fueler (4 x 370 m^3), Anthony Veder-Sirius Shipping's Coralius (5,800 m^3). The general specifications for the three ships furthermore can be seen in the appendix.

It is noted that there is only one vessel, Cardissa, that stationed in the Port of Rotterdam, while the other two vessels are licensed to supply LNG bunker in the port but are not stationed in Rotterdam. The current LNG bunker supply with the existing vessel will later be assessed and be used as a comparison for the proposed solution.

4.3 LNG Bunkering Demand Projection

The research uses LNG Bunkering demand projection that is forecasted using the adoption rate of LNG developed by (Aronietis, Sys, van Hassel, & Vanelslander, 2016) combined with the historical (sea-going vessel) LNG bunker sales in PoR (Port of Rotterdam, 2020g).

Aronietis et.al. (2016) propose a forecasting method for LNG bunker volume at port level which categorized per ship types with each LNG adoption rate. They used historical evidence from set of literatures to determine the future characteristics of demand of LNG bunker. The historical evidences consider current technological evolution and innovation. They stipulated that the adoption rate of LNG follows a sigmoid function with lower adoption rate in initial years and saturation period in the final year (see figure 7).

They conclude different adoption rate and adoption possibility for different types of ships. They also used generic type of ships which is similar with the one defined in EMSA (2018), so that this thesis bundles up the vessel types in Aronietis et.al (2016) to the EMSA types. The following table shows the mentioned vessel type with its LNG adoption rate:

Table 5 LNG Adoption Rate per generic ships type, Source: Author's based on (Aronietis, Sys, van Hassel, & Vanelslander, 2016) & (European Maritime Safety Agency (EMSA), 2018)

Vessel Type	Criteria	Adoption rate	Possible adoption in 100 years
Service Vessels. Tugboats, Patrol Boats and Fishing Boats	-	Medium	50%
Small RO-RO and RO-Pax Vessel	< 180 m	Very High	100%
Large RO-RO and RO-Pax Vessels	> 180 m	Medium	70%
--include: Small general cargo	< 5000 DWT	High	90%
Large freight vessels			
--include: Large general cargo	> 5000 DWT	Medium	70%
Small cargo, container and freight vessels			
-- include: Small container vessels	< 2000 TEU	High	90%
-- include: Small tankers	< 25000 DWT	High	90%

Vessel Type	Criteria	Adoption rate	Possible adoption in 100 years
-- include: Small bulk carriers	< 35000 DWT	High	90%
Large Tankers, Bulk Carriers and Container Ships			
-- include: Large container	2,000 - 8,000 TEU	Low	20%
-- include: Large tanker	25,000 - 200,000 DWT	Low	20%
-- include: Large bulk carriers	> 35,000 DWT	Low	20%
Very Large Ships and Oil Tankers			
-- include: VLCC, ULCC, ULCV	> 200,000 DWT	Very Low	5%
Inland Ships	inland ships	Very Low	5%

The adoption rates are based on the estimations on twenty international experts including engine producers, academics, policy makers, and consultants (Aronietis, Sys, van Hassel, & Vanelslander, 2016). Aronietis et.al (2016) also assumed that in the long run defined as 100 years, every ship will reach its maximum level of saturation and when the 100-year timespan is changed the impact to the first 11 years is still minimal (see the following figure).

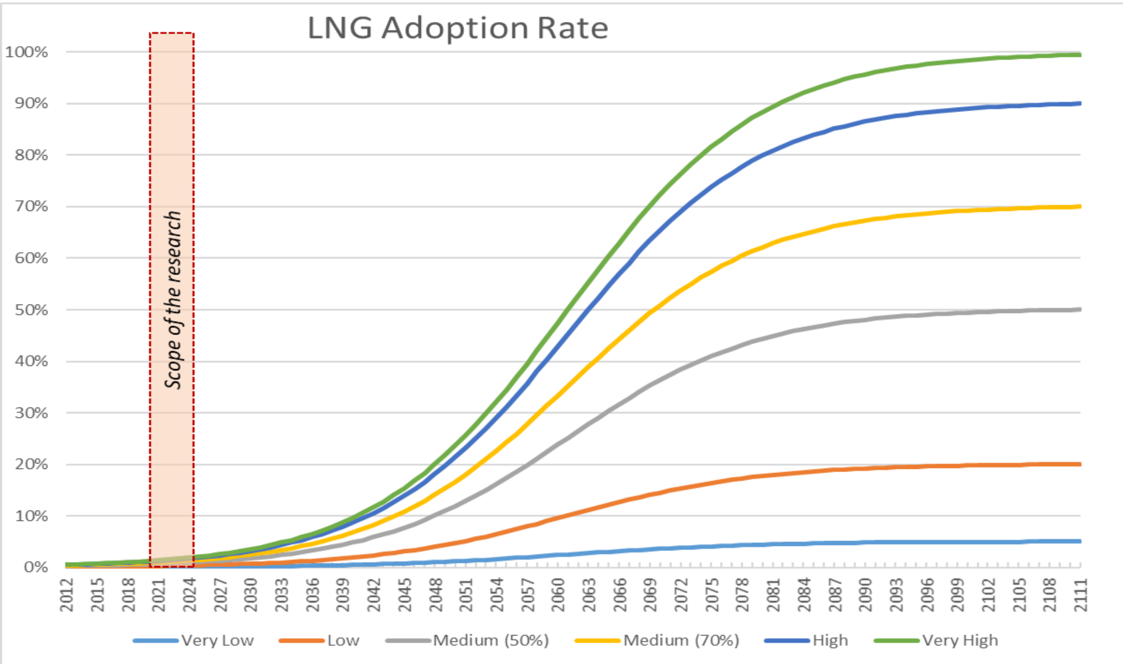

Figure 7 Possibility and Adoption Rate of LNG as Bunker per generic ship type, Source: Aronietis et.al. (2016)

Based on set of literature reviews, Aronietis et.al (2016) approximated the 2012-2025 global LNG adoption (as % share of LNG in total world consumption) with a sigmoid function $f(x) = \frac{x}{\sqrt[a]{b+x^2}}$ by varying the value of *a* and *b*, and obtained the values of a = 1.1623 and b = 0.9994 with the coefficient of determination R^2 = 0.71, from then it is distributed to each vessel types with a different predefined growth factors depend on its adoption rate.

From that point, using the same approach as in Aronietis et.al (2016), the historical data in the Port of Rotterdam as the basis to forecast. The adoption rates are compared with the historical LNG bunkering sales from 2016-2019, which can be seen from the following table. It can be noted that the actual growth rate is higher than the forecasted adoption rate. However, this thesis assumes the adoption rate defined in Aronietis et.al (2016) for 2020-2024 period that has a smoother growth than the historical growth.

Table 6 Comparison of LNG actual bunker sales rate and the adoption rate scenario, Source: Author's calculation based on Port of Rotterdam (2020), and Aronietis et.al. (2016)

Year	Actual Rate				Scenario Rate				
	Bunker Sales of LNG (in metric tons)*	**Bunker Sales of LNG (in cubic meters)****	**Total Bunker sales in cubic meters (incl. Fuel Oil, MGO, MDO, LNG)**	**% LNG adoption in PoR**	**Very Low**	**Low**	**Medium**	**High**	**Very High**
2015	-	-	10,539,611	-	0.04%	0.15%	0.52%	0.66%	0.74%
2016	100	221.00	10,049,779	0.002%	0.04%	0.16%	0.57%	0.74%	0.82%
2017	1,500	3,315.00	9,793,730	0.034%	0.05%	0.18%	0.64%	0.82%	0.91%
2018	9,483	20,957.43	9,402,093	0.223%	0.05%	0.20%	0.71%	0.91%	1.01%
2019	31,944	70,596.24	8,947,103	0.789%	0.06%	0.23%	0.79%	1.01%	1.12%
2020					0.06%	0.25%	0.88%	1.13%	1.25%
2021					0.07%	0.28%	0.97%	1.25%	1.38%
2022					0.08%	0.31%	1.08%	1.39%	1.54%
2023					0.09%	0.34%	1.20%	1.54%	1.71%
2024					0.10%	0.38%	1.33%	1.72%	1.90%
2025					0.11%	0.42%	1.48%	1.90%	2.11%

*Bunker Sales report in PoR (based on: Bunker notifications, TimetoBunker and bunker companies)

**assuming 1 MT LNG = 2.21 cbm

In addition to that, the port call composition data in PoR is adapted to the generic type of ships and complemented with each of the adoption rate. The following table shows the relation between the composition with the adoption rate on each generic vessel type.

Table 7 Port Call Composition, Source: Author's based on Port of Rotterdam (2020), EMSA (2018), Aronietis et.al. (2016)

No.	Vessel Type	Adequate Bunkering Mode	Adoption rate	PoR's GT Range	Total call	
A	Service Vessels. Tugboats, Patrol Boats and Fishing Boats	TTS	Medium	0-1,500	923	3%
B	Small Ro-RO and RO-Pax Vessel	TTS/STS	Very High		2,352	8%
C	Large Ro-Ro and Ro-Pax Vessels	STS	Medium	1,501-10,000	2,318	8%
	--Small general cargo		High		2,754	10%
D	Large freight vessels	STS			-	-
	--Large general cargo		Medium		2,974	11%
E	Small cargo, container and freight vessels	STS		10,001 - 50,000	-	-
	--Small container		High		4,541	16%
	--Small tanker		High		6,786	24%
	--Small bulk carriers		High		315	1%
F	Large Tankers, Bulk Carriers and Container Ships	STS/PTS		10,001 - 50,000 50,001 - 100,000 100,001 - 180,000 >180,001	-	-
	--Large container		Low		1,516	5%
	--Large tanker		Very Low		1,209	4%
	--Large bulk carriers		Low		862	3%
G	Very Large Ships and Oil Tankers	STS/PTS			-	-
	--VLCC, ULCC, ULCV		Very Low		1,473	5%
				Total Seagoing	28,023	100%
H	Inland Ships	TTS/STS	Very Low	Total Inland	110,000	-

Assuming that every vessel call brings potential LNG bunkering demand to the port, then considering the adoption rate and the port call composition, the demand for LNG bunkering are then estimated as in the following table.

Table 8 Forecasted Demand for LNG Bunkering, Source: Author's calculation

No.	Vessel Type	Adequate Bunkering Mode	Adoption rate	GT Range	Total call		Forecasted Demand (in m3) 2020	2021	2022	2023	2024
A	Service Vessels. Tugboats, Patrol Boats and Fishing Boats	TTS	Medium	0-1,500	923	3%	46.24	46.24	57.06	63.37	70.37
B	Small Ro-RO and RO-Pax Vessel	TTS/STS	Very High		2,352	8%	1,876.16	2,084.37	2,315.33	2,571.44	2,855.34
C	Large Ro-Ro and Ro-Pax Vessels	STS	Medium	1,501-10,000	2,318	8%	2,601.16	2,889.84	3,210.05	3,565.13	3,958.73
	--Small general cargo		High		2,754	10%	3,973.40	4,414.36	4,903.50	5,445.91	6,047.15
D	Large freight vessels	STS			-	-	-	-	-	-	-
	--Large general cargo		Medium		2,974	11%	16,686.48	18,538.33	20,592.50	22,870.34	25,395.29
E	Small cargo, container and freight vessels	STS		10,001 - 50,000	-	-	-	-	-	-	-
	--Small container		High		4,541	16%	16,379.09	18,196.83	20,213.16	22,449.03	24,927.47
	--Small tanker		High		6,786	24%	24,476.66	27,193.06	30,206.23	33,547.49	37,251.23
	--Small bulk carriers		High		315	1%	1,136.18	1,262.28	1,402.15	1,557.24	1,729.17
F	Large Tankers, Bulk Carriers and Container Ships	STS/PTS		10,001 - 50,000 50,001 - 100,000 100,001 - 180,000 >180,001	-	-	-	-	-	-	-
	--Large container		Low		1,516	5%	6,075.68	6,749.96	7,497.89	8,327.27	9,246.63
	--Large tanker		Very Low		1,209	4%	1,211.33	1,345.76	1,494.88	1,660.24	1,843.53
	--Large bulk carriers		Low		862	3%	3,454.64	3,838.04	4,263.31	4,734.90	5,257.65
G	Very Large Ships and Oil Tankers	STS/PTS			-	-	-	-	-	-	-
	--VLCC, ULCC, ULCV		Very Low		1,473	5%	2,951.67	3,279.25	3,642.61	4,045.54	4,492.18
				Total Seagoing	28,023	100%	-	-	-	-	-
H	Inland Ships	TTS/STS	Very Low	Total Inland	110,000	-	22,042.38	24,488.62	27,202.12	30,211.09	33,546.48
						TOTAL	102,911.07	114,326.93	127,000.80	141,049.00	156,621.21
						STS only	102,864.83	114,280.69	126,943.74	140,985.63	156,550.84
						STS only (Seagoing Vessel)	**80,822.45**	**89,792.07**	**99,741.61**	**110,774.54**	**123,004.36**
						Calls / week	**6**	**6 - 7**	**7 - 8**	**8 - 9**	**9 - 10**

Table 8 combines the information in table 7 with the projected rate in table 6. The projected demand in Table 8 is calculated by distributing the global demand in table 6 to each of the vessel's adoption rate and composition provided in Table 7. The estimated demand per vessel types is then summed up to yearly demand and provided in volume unit and in calls per week unit. Below is the projected potential demand converted in graph:

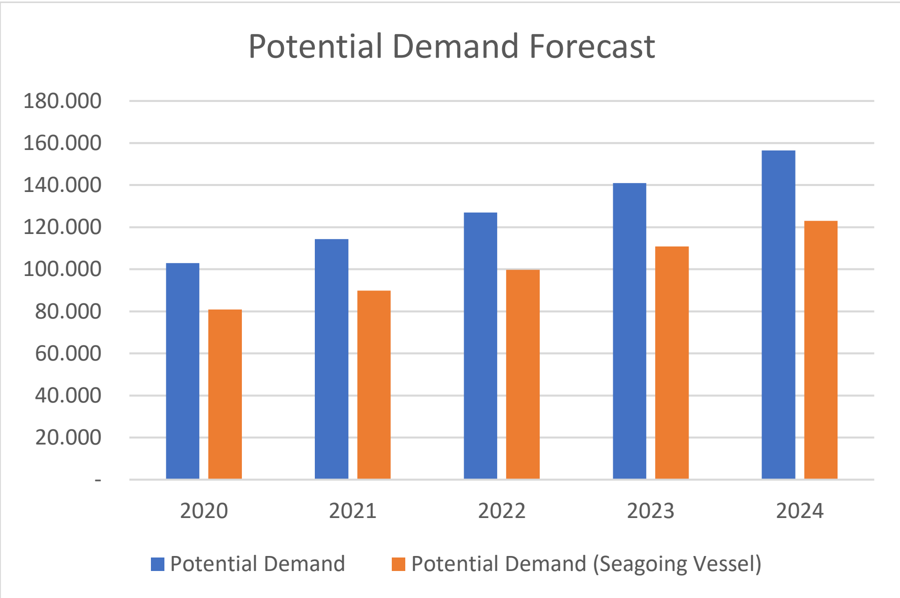

Figure 8 Potential LNG Bunkering Demand Forecast (based on previous table)

The projection will be used as a reference for the scenario development in the next chapter. The scenarios use the weekly calls projection for the demand to develop a more tactical plan as in line with the purpose of this thesis. Furthermore, the longer-term plan will then be discussed in Chapter 7. The next chapter specifies one of the important parameters for the model which is the supply costs.

4.4 Supply Cost Data

4.4.1 Investment, Transport, and Operational Costs

Practically around 80% of bunker suppliers and ship owners secure a long term sales / service contract to pre-determine the LNG bunker price and the volume of bunker (Erkmen, 2018), while the variability of the bunkering supply cost (including logistics, setup, and operational costs) is relatively high depending on fuel, distance and other technical conditions.

Several methods are considered to structure the price on LNG bunkering. Erkmen (2018) focuses on the terminal revenue side and suggests fixed cost compensation revenue and regasification tariff as part of the pricing while leaves the bunkering modes' cost for further research. Stenersen (2008) focus on supply logistics cost and market gas price as two main components in supplying LNG bunker, so that:

Cost of LNG supply = Market based gas price + Cost of supply logistics.

which the cost of supply logistics is divided as: Freight & Terminal Cost, and Bunkering operation costs.

Faber, et. al. (2017) specifically compile Ship-to-ship (STS) bunkering cost while discussed that STS method as the most suitable for basically all maritime vessels as the bunker volumes of or above 100 m^3 LNG.

Table 9 LNG Bunkering costs in STS scenario, Source: (Faber, et al., 2017)

Type of investment	Unit	Price
Investment costs LNG bunkering ships	EUR	
• 1,000 m^3		20 million
• 3,000 m^3		28 million
• 4,000 m^3		32 million
• 10,000 m^3		41 million
• 20,000 m^3		57 million
Operational costs LNG bunkering ships	EUR / year	
• 1,000 m^3		1.8 million
• 3,000 m^3		2.4 million
• 4,000 m^3		2.5 million
• 10,000 m^3		3.2 million
• 20,000 m^3		4.2 million
Transport cost*	EUR / t HFO	530 / t
LNG terminal take-out fee (Loading cost)	EUR	8 / m^3

*transport cost will be excluded since the supply operation is within a port area which has small distance than a sea-going trip, hence it will only count the travel time as the distance factor

Furthermore, Faber, et. al. (2017) explain the coverage of the cost of LNG bunkering in STS scenario as follows:

- Investment Costs: LNG bunkering equipment, bunkering vessels, license costs / safety measures / training of personnel, installation of quay.
- Operational costs: operational costs of bunker vessel
- LNG terminal take-out fee includes transhipment costs from import hub.

The research will assume no competition among other bunkering method for the demand especially when 2 or more modes can be done (TTS/STS situation), thus it will then use only

STS in such condition. Furthermore, the LNG price will be assumed to be uniform in Port of Rotterdam, so that the cost-related parameters only that provided in the previous table.

4.4.2 Penalty cost / Opportunity Cost

In line with the discussion in Stenersen (2008), LNG price as fuel should considers two main points, which are: (1) the ship owner's competitive position should not be weaken relative to other fuels, and (2) the LNG seller should be able to recover his costs of supply. The second point has already covered in the previous section, a penalty cost scheme is used to model the first point which to point-out the ships' fuel competitiveness.

The penalty cost applies when the bunkering cannot be done during the receiving ships' cargo operation in terminals. It is assumed that there will be no rejected demand, so if the bunkering request cannot be delivered within the time window, then the ship will deviate to a nearby buoy or dolphin and wait to be bunkered. The penalty cost represents the opportunity costs that occurred per occasion (per 24-hours of buoys rent period), and in this case is the aggregate cost of:

- Buoys, Dolphins, and Public Quays Dues
  Since the assumed condition that every bunkering demand will not be rejected then every bunkering activities outside the time window of cargo operation take place on any buoys / dolphins / public quays which incurs dues. The established tariff for Buoys, Dolphins, and Public Quays Dues are based on a rate of **€ 3.25 per vessel metre** or part thereof (overall length) per 24 hours period or part thereof (Port of Rotterdam, 2020b).

- Additional Pilotage Costs for berth shift
  As provided in Port Information Guide, basically pilotage is compulsory for all ships except for the holder of pilot exemption based on Decree on Pilot Exemption Certificate Holders Shipping Traffic Act (Port of Rotterdam, 2020f). In this thesis, it will be assumed that all of the ships do not have any exemptions for pilotage.

  Tariff for pilotage in the Rotterdam-Rijnmond Region consists of starting rate (S) as the fixed tariff for covering the fixed costs of Loodswezen, and route dependent tariff (T) which is variable depending on the duration and the operational area of pilotage (Loodswezen, 2020). There are 3 main voyages under the pilotage, which are: to and from pilot station, berth shift, and rendezvous voyages. Therefore, in the case of shifting from terminal to buoys/dolphins/public quays, the berth shift tariff shall be applied. The tariff depends on the actual reported draught and also the location origin and destination in the port area. The detailed tariffs are provided in appendix B.

- Additional Towage and Mooring Costs for berth shift
  Most of the sea-going cargo vessels' movement within the port area are obliged to be assisted by towage services and mooring services. As provided in tariff publication of Port of Rotterdam (2020i), commonly there are 3 towage service providers and 2 mooring service providers where each has its own terms and operational area. The assistances are needed for two main activities, which are assistance for: from river to berth or vice versa, and berth shifting. The towage rates depend on the vessels' length over all (LoA) while especially for shifting it also depends whether to shift at same quay, within same area, or from one area to another. In this case, the shifting tariffs scheme then applied and the detailed tariff are provided in appendix B.

- Idling Opportunity Cost
  Since the violation of time window, the vessels may be impacted from inefficiencies / idle during the charter period. In general sense, bunkering activity is considered as a non-value-added activity so that such opportunity cost occurred since no earnings will be gained during the period. In this case, the opportunity cost simply will be derived from each ship's operating cost per day referring to (Drewry, 2019). The operating cost is considered in daily unit to also consider shifting time (2x3 hours) and bunkering time.

In this research, all of the tariffs mentioned above are summed up as the penalty costs and summarized as in the following table:

Table 10 Penalty Cost Components per different generic ship types (Source: Author's calculation based on many sources)

No.	**Vessel Type**	**Buoys Dues**	**Pilotage**	**Towage**	**Mooring**	**Idle Cost**	**Total (€ / day)**
A	Service Vessels. Tugboats, Patrol Boats and Fishing Boats LoA: 6-48 m Avg Draught: 3 m	19.5	92	-	-	3,300	3,411
B	Small Ro-RO and RO-Pax Vessel LoA: 48-180 m Avg Draught: 6m	156	399	2,115	132	3,620	6,422
C	Large Ro-Ro and Ro-Pax Vessels LoA: >180 m Avg Draught: 14m	585	1,587	2,500	944	4,250	9,866
D	Large freight vessels LoA: 85-200 m Avg Draught: 4-**8** m	276	779	2,827	944	4,250	9,076
E	Small cargo, container and freight vessels LoA: 100-200 m Avg Draught:**4**-7 m	325	129	2,115	304	4,510	7,383
F	Large Tankers, Bulk Carriers and Container Ships LoA: 200-350 m Avg Draught: **8**-13 m	650	779	2,827	944	7,510	12,710
G	Very Large Ships and Oil Tankers LoA: > 350 m Avg Draught: > **14** m	1,138	1,587	6,292	4,227	8,700	21,944

This specific scheme of penalty is directly related to violation of time window which are furtherly defined and specified in the next section.

4.5 Time Window

The second parameters used in this research is time. The variables used as "window" openings for the bunkering process, which ideally for efficiency, bunkering must be done (start and end) inside cargo operations / or during laytime. These parameters directly relate to the occurrence of the penalty costs mentioned above.

Berth time

Berth time is defined as time a ship spend from berth to unberth, which include cargo operations. Secondary data are used for the research which is a full 1-month operation of sea-going vessels cargo operation at ECT Delta Terminal monitored via their online tracing system (Hutchison Ports - ECT Rotterdam, 2020). The data are as follows:

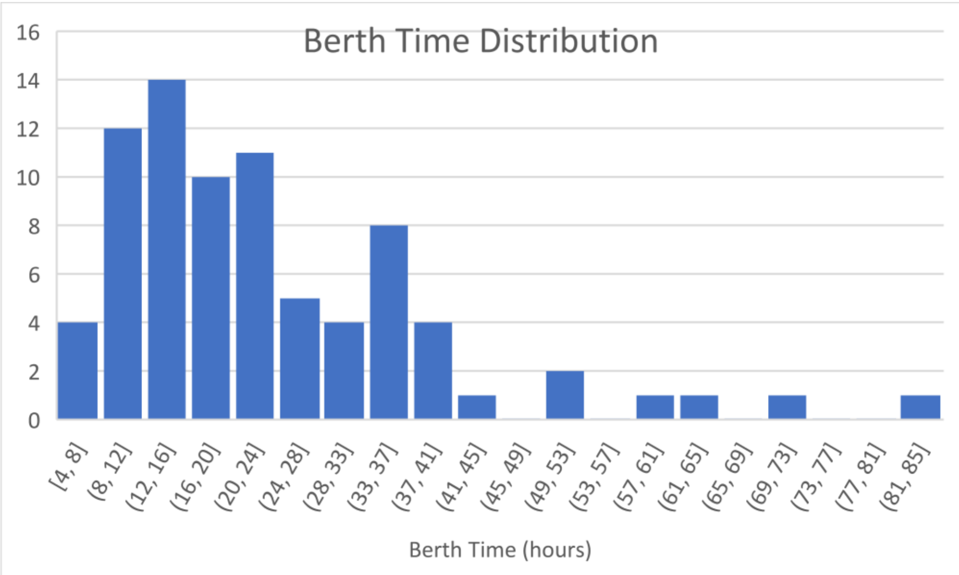

Figure 9 Berth Time Distribution Data, Source: Author's based on (Hutchison Ports - ECT Rotterdam, 2020)

The data are grouped into several 4-hours-ranges to represent the assumed typical tolerance of late / early berth time (+/- 2 hours). The research also assumes uniform distribution for each group which the centre of each column represents the most likely time. In addition, the following is the statistics of the data:

- Modes : 14 hours
- Average : 24 hours
- Standard Deviation : 15 hours
- Minimum – maximum : 4 hours – 85 hours

Bunkering time

Bunkering time follows the earlier mentioned standard bunkering time in EMSA (see table 4). This research also assumes the bunker quantity and rate as provided in the table. So that the bunkering time are deterministic and depends on the ship types, which are:

Table 11 Typical LNG Bunkering Time per ship type, Source: EMSA (2018)

Vessel Type	**Bunker Quantity (m^3)**	**Rate (m^3/hr)**	**Duration (hr)**	**Bunkering Mode**
Service Vessels. Tugboats, Patrol Boats and Fishing Boats	50	60	0.8	TTS*
Small RO-RO and RO-Pax Vessel	400	400	1	TTS/STS
Large Ro-Ro and Ro-Pax Vessels	800	400	2	STS
Small cargo, container and freight vessels	2,000	1,000	2	STS
Large freight vessels	4,000	1,000	4	STS
Large Tankers, Bulk Carriers and Container Ships	10,000	1,100	9	STS/PTS**
		2,500	4	
Very Large Ships and Oil Tankers	20,000	1,100	18	STS/PTS**
		3,000	7	

* will be excluded from this research

** only STS mode is considered which utilizes max rate of 1,100 m^3/hr

Bunkering preparation time is ranging from 0.5 hour to 1 hour (Faber, et al., 2017) and will be assumed to be already included on the bunkering time. Moreover, start operation time of the bunkering vessel from its idle station follows the stipulation of the pilotage procedure and from TimeToBunker pre-notification procedure which is for 72, 48, 24, 12, 6, to 3 hours prior the bunkering activity (Loodswezen, 2020) (Port of Rotterdam, 2020j). For the purpose of this research the shortest notification will be used as start time for LNGBVs which is 3 hours prior to the earliest bunkering task.

Chapter 5 Scenario Development and Optimization

This chapter develops and discusses the scenarios which are used as the case study for the thesis. The scenarios are also solved in this chapter using the optimization model that has been developed in Chapter 3. This chapter also explains the solutions which are gained from the model implementation, briefly describes the findings, and in the next chapters they are analysed and discussed extensively.

5.1 General Data and Information

Scenarios are developed to illustrate the problem and to better understand the model approach. The scenarios are defined as the number of bunkering tasks to be served by the fleet of bunkering vessels (LNGBVs) at a given time window (deterministic scenarios). The initial scenarios are adapted from the snapshots on today's operation of LNG bunkering in the PoR. From then, the later scenarios are developed to view the model's behaviour, and to identify determining factors and their relations.

The information and data used for scenario development are previously mentioned earlier in the previous chapter, such as locations in port area and travel time (4.1), receiving vessels and their bunkering characteristics (4.2), demand projection (4.3), LNGBVs related data and penalty scheme (4.4), and also the time window (4.5). Besides that, the following figure and tables briefly provide the data used as the general information for all of the scenarios in this section.

Table 12 Receiving Vessels Data

Vessel Type	Bunker Quantity (m^3)	Bunkering Duration (hrs)	Penalty Cost (€ / 24 hours)
Small RO-RO and RO-Pax Vessel	400	1	6,422
Large Ro-Ro and Ro-Pax Vessels	800	2	9,866
Small cargo, tanker, container and freight vessels	2,000	2	9,076
Large freight vessels	4,000	4	7,383
Large Tankers, Bulk Carriers and Container Ships	10,000	9	12,710
Very Large Ships and Oil Tankers	20,000	18	21,944

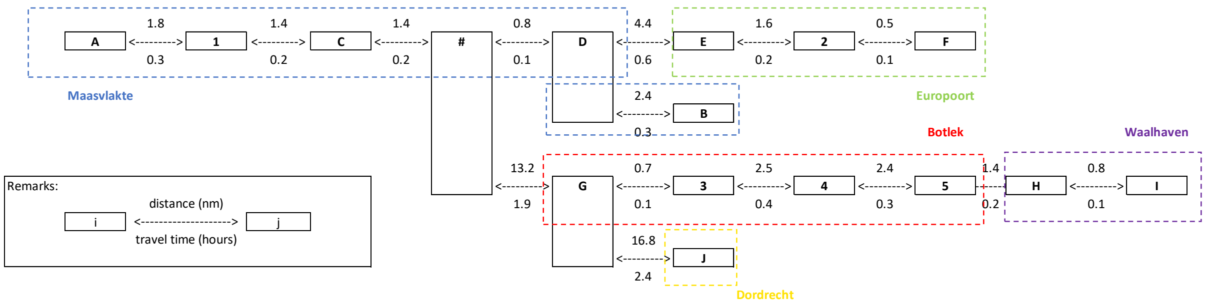

Figure 10 Locations Data (in sequence)

Table 13 LNGBV fleet options

k	Type	Fixed Acquisition Cost		Operational cost		loading cost from depot** (€)	Loading time** (hrs)
		in million €	Per day* (€)	Per Year (in million €)	Per day* (€)		
1	1,000 m^3	20	2,500	1.8	5,000	8,000	1
2	3,000 m^3	28	3,500	2.4	6,667	24,000	3
3	4,000 m^3	32	4,000	2.5	6,944	32,000	4
4	10,000 m^3	41	5,125	3.2	8,889	80,000	10
5	20,000 m^3	57	7,125	4.2	11,667	160,000	20

*assuming 25 years of ships' age with 40 docking days / year
* assuming 360 days / year for operational cost
**for fully loaded, with loading unit cost = 8 EUR/m^3

5.2 Scenario 1

5.2.1 Scenario 1 - Description

The first scenario is derived from the snapshot of July 1st 2020 in the Port of Rotterdam which captured from AIS map in the AFI Platform provided by DNV-GL (DNV GL, 2020) which had been monitored for the thesis from June 19th – July 18th 2020 combined with detailed ship information from (Marine Traffic, 2020). It is assumed that each LNG-fuelled vessel demanded bunkering during that period. The following shows the map of berth locations of the LNG-fuelled ships as the receiving vessels:

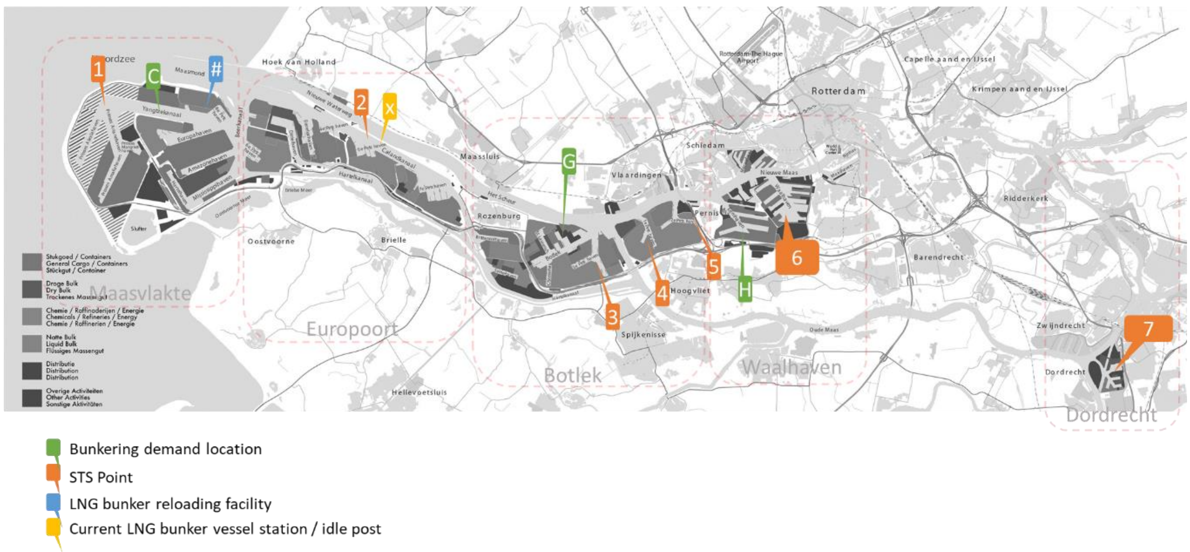

Figure 11 Scenario 1 Location Map

The green points labelled with alphabet shows the location of the terminal where the receiving vessels are berthed for doing cargo operation. The orange points labelled with numbers, as mentioned before, are the location of buoys / dolphins / public quays as the place where bunkering is done outside the time window. Finally, the blue point shows the location of loading terminal as the depot and the yellow point shows the current station of the bunkering vessel(s).

In this scenario, there are 3 demand locations / tasks which are located in C, G, and H. The following table describes each task's details:

Table 14 Scenario 1 data

Task location	Ship Types	ATA	ETD / ATD	Berth Time (hrs)	Bunkering Time (hrs)	Calculated time window: Earliest start (mins)	Latest Start (mins)	ETD (mins)
i, j					s_i	a_i	b_i	
C	Large Container	30/06/2020 17:39	01/07/2020 07:39	14	10	630	870	1470
G	Small Tanker	30/06/2020 10:09	01/07/2020 00:09	14	3	180	840	1020
H	Large Freight Vessel	01/07/2020 12:20	02/07/2020 02:20	14	4	1751	2351	2591

		In Date	**In minutes**
Earliest arrival (task G)	:	30/06/2020 10:09	180
Start operation time	:	30/06/2020 07:09	0

*Assumed as 3 hours prior to the earliest ship

5.2.2 Scenario 1 - solution and findings:

The scenario is run using AIMMS 4.74.4.5, modelled as Mixed-Integer Programming (MIP) and solved using linear optimization tools CPLEX 12.10. The program is completed normally after 64 iterations and the optimal solution achieved as the following:

Table 15 Scenario 1 Solution

		Location *(i,j)***	**#**	**C**	**G**	**H**	**Demand (q_i)**
Routing		#	0	1	1	0	-
		C	1	0	0	0	10,000
		G	0	0	0	1	2,000
		H	1	0	0	0	4,000
Scheduling	Arrival Time (p_i^k)	*k=1*	105*	-	-	-	
		k=2	225*	-	-	-	
		k=3	285*	-	-	-	
		k=4	645*	657	1922 (late)	2142	
			17:54*	18:06	15:27 +1 day	17:56 +1 day	
		k=5	1245*	-	-	-	
	Time Window	a_i	0	630	180	1751	
		b_i	0	870	840	2351	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue

Total Cost (€ per day)	**158,286**
• Fixed Acquisition Cost	5,125
• Variable Cost = Operational Cost + Loading Cost	145,778
• Penalty Cost	7,383

The solution table comes with 3 sections: routing, scheduling, and costs.

- There are 2 developed routes, which: #-C-# and #-G-H-#. The assigned bunkering vessel will start at the depot then to the first task in location C after that it goes back to the depot to reload. After that, the second tour starts from the depot consecutively to the tasks in G and H, then return back to the depot.

- For that particular routes, the 4th type of LNGBV (10,000 m^3) is used to serve all tasks.
  It starts at 07:09, which set as 0-minute point, to move from its station. It will arrive and finish loading at the depot in 645 minutes or at 17:54. It will continue the journey and scheduled to arrive:
  - at task C in 657 minutes or at 18:06,
  - at task G in 1,922 minutes or at 15:27 the next day (after reloading at the depot),
  - and at task H in 2,142 minutes or at 18:51 the next day.
  - Task G is the only task that is not served on time, so that it returns with a penalty cost. Task G has around 18 hours waiting time.
- The total cost for the solution is € 158,286 per day.

Findings from scenario 1:

It can be identified that one main factor of the fleet assignment is the bunkering quantity / volume with its required bunkering time. Since bunkering can only be served by one vessel or in other words it cannot be partly served by number of vessels, then the bunkering volume directly affect the size of the assigned vessel, for example: the feasible vessels for task C (10,000 m^3) are only k=4 or k=5 which capacity are 10,000 m^3 and 20,000m^3. In this case, the vessel k=4 is assigned which also can accommodate each task's quantity.

On the other hand, travel time has relatively small impact to the routing and scheduling arrangement, since mostly only take around 0-3 hours in one-way trip, except to one location Dordrecht (location 6) which takes 3-5 hours from any other locations. So accordingly, within the length of time window, bunkering time together with the loading/reloading time at depot take a bigger part in the schedule than the travel time. Apart from that, bunkering time is directly affected by the volume itself.

The main finding from this scenario is that bunkering volume is one main factor in the vessel assignment decision. Not only it affects the size of the choice of vessel, but its required bunkering time also takes a big part in its schedule. In that sense the ratio of bunkering time and the length of time window determines the schedule.

5.2.3 Model Verification - Manual Solving Step for Scenario 1:

The following section describes the manual solving steps for the problem based on the problem formulation. This section aims to show step-by-step approach to the problem not only to gain better understanding on how the program works but also to act as the verification of the developed program for this thesis. Stepwise the scenario is approached as the following:

- 1st step: time window calculation and conversion
  As the preparation step, the data regarding time windows are converted from date format into a number format (in minutes) and calculated to define the earliest and the latest start the time windows. Besides that, as previously mentioned, the start operation time or the 0-minute point is predefined as 3 hours prior to the first task which is at 30/06/2020 07:09.

Table 16 Scenario 1 Data - Manual Solving

							Calculated time window	
Berth Location / Task	Ship Types	ATA	ETD / ATD	Bunker-ing Time (hrs)	Bunker-ing Qty	Penalty Cost	Earliest start (min)	Latest start (min)
i, j				s_i	q_i	u_i	a_i	b_i
C	Large Container	30/06/2020 17:39	01/07/2020 17:39	10	10,000	12,710	630	870

Berth Location / Task	Ship Types	ATA	ETD / ATD	Bunker-ing Time (hrs)	Bunker-ing Qty	Penalty Cost	Calculated time window: Earliest start (min)	Calculated time window: Latest start (min)
i, j				s_i	q_i	u_i	a_i	b_i
G	Small Tanker	30/06/2020 10:09	01/07/2020 10:09	3	2,000	7,383	180	840
H	Large Freight Vessel	01/07/2020 12:20	02/07/2020 12:20	4	4,000	9,076	1751	2351

- 2nd step: define the feasible choice of LNGBV
  As the bunkering is done by one bunkering vessel for each receiving vessel, so the feasible vessel depends on the bunkering quantity

Table 17 Feasible Fleet Manual Calculation

		Feasible Fleet Choice				
		k=1	k=2	k=3	k=4	k=5
Task	Bunkering Quantity	1,000 m^3	3,000 m^3	4,000 m^3	10,000 m^3	20,000 m^3
C	10,000 m^3	-	-	-	1	1
G	2,000 m^3	-	1	1	1	1
H	4,000 m^3	-	-	1	1	1

- 3rd step: Determine feasible routes by schedule all feasible vessels and evaluate the cost
  Using each vessel's pre-calculated start operation time then we schedule all feasible vessels to the tasks. Each vessel is assigned and forward-scheduled to the nearest and currently open tasks (see appendix F). All possible routes are manually scheduled to evaluate the total cost. The following table resumes the feasible routes together with each total cost

Table 18 Scenario 1 - Manual Calculation Result

Vessel (k)	Type	Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	unmet demand
5	20,000m3	#-C-G-H-#	7,125	139,667	21,786	168,578	-
		#-G-C-H-#	7,125	139,667	21,786	168,578	-
		#-C-H-G-#	7,125	139,667	21,786	168,578	-
		#-G-H-C-#	7,125	139,667	21,786	168,578	-
4	10,000m3	#-C-#	5,125	88,889	-	94,014	6,000
		#-C-# + #-G-H-#	5,125	145,778	7,383	158,286	-
		#-C-# + #-H-G-#	5,125	145,778	7,383	158,286	-
3	4,000 m3	#-H-#	4,000	38,944	-	42,944	12,000
		#-G-#	4,000	22,944	-	26,944	14,000
		#-H-# + #-G-#	4,000	68,832	7,383	80,215	10,000
		#-G-# + #-H-#	4,000	68,832	-	72,832	10,000
2	3,000 m3	#-G-#	3,500	22,667	-	26,167	14,000
4 & 3		#-C-#	5,125	88,889	-		
		#-G-# + #-H-#	4,000	68,832	-	+	
			9,125	157,721	-	166,846	-

From the manual solving result, it can be identified that the cheapest cost to meet all the demand is by assigning the vessel k=4 to routes: #-C-# and #-G-H-# which is the same as the optimal solution run from the program. Besides that, one important finding is that apparently without any penalty the vessel k=5 might have the lowest cost in serving all the demand. However, since in this case all fleets are assumed to have the same start time so that the vessel k=5 has the latest ready time because of its lengthy loading time. In the next scenario the effect of the start time will furtherly described.

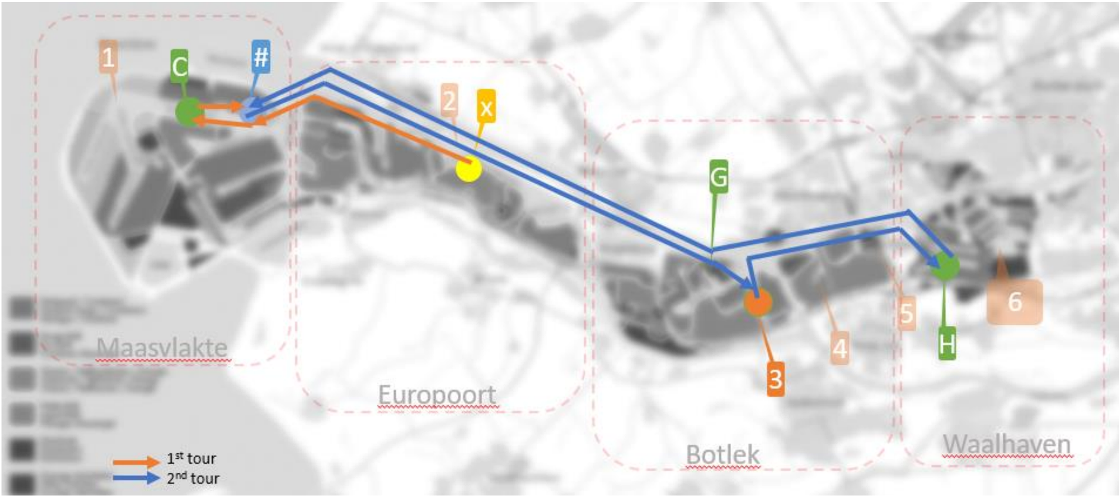

Figure 12 Optimal Route illustration for Scenario 1

5.3 Scenario 2

5.3.1 Scenario 2 - Description

Scenario 2 simulates on the smallest possible problem in the system from which it is then expanded to see the basic behaviour of the model in assigning vessels and finding its determination factors. Beside the expansion on the number of tasks, the change in time window is also simulated in this scenario. The general aspects of the scenario used here are the same as in other scenarios as mentioned earlier in the beginning of the subsection.

The following resumes the tasks data for the sub scenarios. In short (please see appendix for details), the following sums up the idea of scenario 2:

Table 19 Scenario 2 Resume

Sc.	**Tasks** (location | volume (m³))	**Remarks**
2a	A | 2,000;	• For each pair: A, C and G, H, same arrival time and time window length are used. • 2a, 2b, and 2c simulate the problem in a 14 hours' time window, while • 2d, and 2e simulate different time window from loose to the tightest window (bunkering time = berth time)
2b	A, C | 2,000; 2,000	
2c	A, C, G, H | 2,000; 2,000; 4,000; 4,000	
2d	A, C, G, H | 2,000; 2,000; 4,000; 4,000	
2e	A, C, G, H | 10,000; 10,000; 20,000; 20,000	

5.3.2 Scenario 2 – Details, Solution, and Findings

Scenario 2a

The first part of the 2nd scenario put only one task with small bunkering volume in one location with a loose time window, the following details the data for this scenario:

Table 20 Scenario 2a data

Berth Location / Task	Volume (m³)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180 and 630	900 and 1350

This scenario implements the model using AIMMS 4.74.4.5, modelled as Mixed-Integer Programming (MIP) and solved using linear optimization tools CPLEX 12.10. The program is completed normally and the optimal solution achieved as the following:

Table 21 Scenario 2a solutions

No.	Time Window (a_i –- b_i)	Assigned Vessels	Finished loading time at depot (p_0^k)	Arrival time at task A (p_1^k)	Total Cost
1	180 –- 900	k=2 (3,000 m^3)	225	264	26,167
2	630 –- 1350	k=4(10,000 m^3)	645	684	30,014

This scenario makes use of two different time windows, 180-900 and 630-1350. From the arrival time result, it can be seen that different fleet choice is used for each time window. For one 2,000 m^3 task, the vessel k=2 is used when the earliest start is 180 and k=4 is used when the earliest start is 630. It can be derived that the model prevents any waiting for the bunkering vessel and will choose the vessel which is ready in a time that is close to the opening of the task's window despite the cost.

Scenario 2b

In this scenario an identical task in a different location is added to scenario 2a.

Table 22 Scenario 2b data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180	900
C	2000	14	2	0.14	180	900

The scenario is also run using AIMMS 4.74.4.5, modelled as Mixed-Integer Programming (MIP) and solved using linear optimization tools CPLEX 12.10. The program is completed normally after 32 iterations and the optimal solution achieved as the following:

Table 23 Scenario 2b solution

Assigned Vessel	Route	Arrival time	Total Cost
k=3 (4,000 m^3)	#-C-A-#	At task C = 297	42,944
		At Task A = 444	

Form this scenario, it is quite obvious that the vessel with adequate capacity is assigned to both tasks. In this case, one 4,000 m^3 (k=3) vessel is used and since there is sufficient time window, both tasks are served on time. It can be derived from the solution that if there is enough time, the model will choose one vessel that served all tasks over assigning more vessels.

Scenario 2c

This scenario expands the previous scenario as follows:

Table 24 Scenario 2c data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180	900
C	2000	14	2	0.14	180	900
G	4000	14	4	0.28	1451	2051
H	4000	14	4	0.28	1451	2051

The optimal solution is achieved as the following:

Table 25 Scenario 2c solution

Assigned Vessel	Route	Late Task	Total Cost
k=4 (10,000 m^3)	2 tours: #-C-A-#-G-H-#	-	118,903

Same as in scenario 2b, assigning one vessel is preferred than assigning more. Moreover, even if the total demand (12,000 m^3) is more than the capacity of the chosen vessel (k=4, 10,000 m^3), this solution holds. It is also to note that since each demand is feasible to be served by the vessel. It can be concluded that certainly a second tour is preferred than adding more vessels which is more expensive.

Scenario 2d

This scenario simulates the previous tasks in a tighter time window, which in this case reduced step-by step from 14 hours of berth time to be the same as each task bunkering time. Or in other words, from $(s_i / TW) < 1$ to $(s_i / TW) = 1$ for each task.

Table 26 Scenario 2d data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	*14 to 2*	2	0.1 to 1	180	vary
C	2000	*14 to 2*	2	0.1 to 1	180	vary
G	4000	*14 to 4*	4	0.1 to 1	1451	vary
H	4000	*14 to 4*	4	0.1 to 1	1451	vary

The comparison of all results is resumed in the following table

Table 27 Scenario 2d results comparison

Si / TW	No. of late task	Assigned vessel (k)	Fixed Cost	Variable Cost	Penalty Cost	Total Cost
0.9 – 1	4	5	7,125	107,667	32,918	147,710
0.5 – 0.8	3	5	7,125	107,667	23,842	138,634
0.3 – 0.4	2	5	7,125	107,667	14,766	129,558
0.2	1	4 (2 tours)	5,125	113,778	7,383	126,286
0.1	0	4 (2 tours)	5,125	113,778	0	118,903 (= scenario 2c)

It can be derived from the solutions that in a condition where late is inevitable (when the time window is tight) the size of the assigned vessel is bigger to avoid reloading time for second tour which will require substantial time. However, late is preferred than adding another type of vessels with note that the penalty for small task is still less than the fixed and variable costs of more other vessels.

Scenario 2e

In addition to the previous scenario, the changes in time window then applied to different bunkering volume / bunkering time. In this case the volume in tasks A, C, G, H are upscaled to 10,000 m^3, 10,000 m^3, 20,000 m^3, and 20,000 m^3. Then to be short, the result is as follows:

Table 28 Scenario 2e results comparison

Si / TW	**No. of late task**	**Assigned vessel (k)**	**Fixed Cost**	**Variable Cost**	**Penalty Cost**	**Total Cost**
0.4 – 1	4	5 (3 tours)	7,125	515,001	69,308	591,434
0.39	2	4 (1 tour) and 5 (3 tours)	12,250	523,890	34,654	570,794
0.34 – 0.38	1	4 (1 tour) and 5 (3 tours)	12,250	523,890	12,710	548,850
0.32 – 0.33	0	4 (1 tour) and 5 (3 tours)	12,250	523,890	0	536,140
0.25 – 0.3	1	5 (3 tours)	7,125	515,001	12,710	534,836
0.21 – 0.24	0	5 (3 tours)	7,125	515,001	0	522,126
<0.21	*N/A*, since berth time is higher than 85 hours					

Similar to the previous result, the solutions in high demand condition show that late is occurred besides adding extra vessels. It is also to note that in this condition the fixed and variable cost for the feasible vessels are higher than in the small tasks condition. It is also identified that in this condition, the lengthy bunkering time impact the number of late tasks significantly at $(s_i/TW) > 0.38$.

5.4 Scenario 3

5.4.1 Scenario 3 - Description

In the third scenarios, scenario 1 is used as the basis and additional tasks will be added to the system in order to find the impact of number of tasks and the total demand to the number and the choice of assigned vessels. The general aspects of the scenario used here are the same as in other scenarios as mentioned earlier in the beginning of the subsection. This scenario is divided into 4 parts and briefly described as follows:

Scenario 3a: This scenario utilizes the varying arrival time as in Scenario 1 yet using the small tasks' volume (< 10,000 m^3). Besides that, it is simulated three times: in the second run an additional task in the farthest location (task 6) is added, and in the third run task 6 is not simultaneous with any other task.

Table 29 Scenario 3a data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A	2,000	14	2	630	1350
6	2,000	14	2	630 / 2000	1350 / 2720
C	2,000	14	2	180	900
G	4,000	14	4	1451	2051
H	4,000	14	4	1751	2351

Scenario 3b: This scenario doubles the number of tasks in the previous scenario with the same arrival time and time window / simultaneous.

Table 30 Scenario 3b data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A + B	2,000 + 2,000	14	2	630	1350
C + D	2,000 + 2,000	14	2	180	900
G + F	4,000 + 4,000	14	4	1451	2051
H + E	4,000 + 4,000	14	4	1751	2351

Scenario 3c: A high volume demand (10,000m3) is added to the initial scenario in location B.

Table 31 Scenario 3c data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
I			s_i	a_i	b_i
A	2,000	14	2	630	1350
C	2,000	14	2	180	900
B	10,000	14	9	630	1350

Scenario 3d: Task A from scenario 3c is upscaled to 10,000 m3 in this scenario.

Table 32 Scenario 3d data

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A	10,000	14	9	630	1350
C	4,000	14	2	180	900
B	10,000	14	9	630	1350

5.4.2 Scenario 3 – Solutions and Results Comparison

The results in scenario 3 are compared to each other in order to see the changes in fleet assignment impacted by total demand and the number of tasks. The following table summarizes the results in this scenario:

Table 33 Results Summary for Scenario 3

Sc.	**No. of Tasks**	**Highest Volume** (m^3)	**Total Demand** (m^3)	**Assigned Vessel** (k | capacity in m^3)		**Route**	**Late Task**	**Total Cost** (€ / day)
3a-i	4	4,000	12,000	k=4	10,000	#-A-C-# #-G-H-#	-	118,903
3a-ii	5	4,000	14,000	k=3	4,000	#-C-6-#	-	141,736
				k=5	20,000	#-A-G-H-#	-	
3a-iii	5	4,000	14,000	k=4	10,000	#-A-C-# #-G-H-6-#	-	134,903
3b	8	4,000	24,000	k=4	10,000	#-B-C-A-# #-F-E-# #-G-H-#	-	237,806
3c	3	10,000	14,000	k=3	4,000	#-C-#-A-#	-	143,902
				k=4	10,000	#-B-#	-	
3d	3	10,000	22,000	k=4	10,000	#-A-#	B (15hrs)	216,189
				k=5	20,000	#-C-B-#		

From scenario 3a, it can be identified that one vessel k=4 is assigned to serve all tasks, and two vessels (k=3 & k=5) are assigned when one simultaneous task in the farthest location is added. However, when the task in the farthest location is set to arrive in a different time period then the optimal solution is again by assigning only one vessel. The tasks in 3a then doubled so that we have 3b, surprisingly only one vessel (k=4) is assigned to serve all tasks in 3 tours. Finally, high volume tasks are then added as we have in 3c and 3d, which are assigned to two different vessels even the total capacity is way higher than the total demand.

From the solutions in the third scenarios, we can derive that:

- Similar as in scenario 2, assigning one vessel which has an adequate capacity for all tasks is preferred than adding more vessels with small capacity. It is also to note that it happens in a sufficient time window.
- However, additional vessels are considered when one of this two conditions are met:
    a. Sufficient time window to serve tasks on time.
    b. One or more tasks require a bigger bunkering vessel than the other tasks. It is found especially in 3c and 3d that an additional 10,000 m^3 demand is added to the current tasks of 2,000 m^3 and 4,000 m^3.
    c. Simultaneous tasks potentially cause late that is more expensive than adding extra vessels. This especially can be found in 3a-ii, 3c, and 3d where each simultaneous task may cause penalty, so that extra vessels were added to those situations. This is also to note that there is a sufficient time window to serve the tasks on time, otherwise assigning one vessel is preferred which we have already identified in scenario 2.

Chapter 6 Results Analysis

This chapter further analyses the experiment results in order to identify the determining factors of the model and how it can affect the performance of the bunker vessels. The findings from previous chapter are compared, analysed, and measured for any relations exist among the parameters and the variables. The insight and the results analyses are ultimately to well-answer the research questions.

6.1 Determining Factors and the Model Behaviours

The LNG bunkering supply process can basically be modelled as a transportation problem and specifically as an FSMVRPTW problem in terms of determining the optimum number of vessels and routes with scheduling constraints. Described in chapter 3, a mathematical programming formulation is used to model the problem quantitatively. Some advantages in using mathematical model is to have a precise and unambiguous way to approach the problem, and also to handle large sets of data, parameters, and variables along with their complex relations. More importantly, it can accurately make an investigation on the problem, predict, and control the solutions so that it also enables an equal comparison among several scenarios to simulate the different possible realities.

Model Behaviours

As developed in chapter 5, an experiment is conducted to gain insights on how the model determines the solution. Deterministic scenarios are developed and solved in chapter 5 and the optimum solutions of 1) Fleet size and mix, 2) routing of the fleet, and 3) schedule of fleet are achieved.

The following summarizes the observations on how the model works from the solutions of the scenarios:

- The model will choose the vessel that is immediately ready for the next open tasks.
  This behaviour is identified in the solution of scenario 2a, when a small 2,000 m^3 task is evidently assigned to two different vessels (with different capacity) depending on their availability to the nearest open task. In that case, in deciding the arrival time of vessels to any tasks, despite the costs, a vessel that is ready earlier on the open task is preferred than choosing another suitable vessel which are ready on the later time.
- Assigning one vessel to serve all tasks is preferred than adding more vessels.
  Regarding the extra cost that may occur by assigning one additional vessel, it is quite certain that when there is a sufficient time window, assigning one suitable vessel to all tasks is preferred. This behaviour is identified from the solutions in scenario 2b and 2c and even clearer in scenario 3b. In 3b, even when the total demand of all tasks is more than twice of the capacity, still (with the sufficient time window) it is only completed by a single vessel.
- Late is preferred over adding an extra vessel.
  Assigning one vessel late for many tasks is preferred over assigning extra vessel, such situation occurs especially when late is inevitable particularly in a situation of a series of tight time windows. The situation is found in scenario 2d and 2e, especially when the bunkering time takes more than half of the time window, one vessel with the highest capacity then serves all tasks in late.

Determining Factors

The deeper understanding of the model's behaviours narrows down some factors that affect the solutions for the bunkering transportation problem. Some main points arise to be the factors, such as: bunkering time, length of the time window, start time, and also the tasks' volume. Those factors affect the solutions in each different extension. Prior to specify the determining factors, the following summarizes the findings from the model implementation in the previous chapter completed with the corresponding scenario number:

Table 34 Findings from the Model Implementation

Sc.	Findings	Remarks
1	Bunkering volume (with the required bunkering time) is one main factor in determining the size of fleet.	Since the supply of bunker is ideally done by only one vessel which in other words it cannot be partly bunkered, then some level of capacity is necessarily needed to fulfil a certain bunkering quantity.
	Travel time relatively takes a small part in determining the route and schedule compared to bunkering and loading time.	Travel time from one location to another is relatively small for the case of bunkering inside port area, or specifically in Port of Rotterdam area. The whole operation time is then dominated with bunkering time and loading time at the depot.
2	Start time of the bunkering vessels affect the choice of fleet.	The model assigns a vessel to the closest opening task to its ready time. Since different size of vessel requires different loading time at the depot, then vessels finished loading time are different to each other. It has already defined that the bunkering vessel starting point is not in the depot, so it needs to be loaded first before ready to supply the bunker.
	Bunkering time proportion within the length of time window *(s_i / TW)* affects the choice of fleet and route.	In a loose time-window (s_i / *TW* < 0.4) smaller vessel with more tours is preferred, while in a tight window (s_i / *TW >0.4*) a bunkering vessel with high capacity is preferred to serve all tasks.
3	Bunkering volume and simultaneous task are the considerations to add more fleet.	Same as the first finding, bunkering volume determines the choice of fleet in terms of size, while simultaneous task which may cause several lateness also affecting the decision in adding extra vessel to serve the tasks on time.

The model constructs a solution by determining the main variables 1) Fleet size and mix, 2) routing of fleet, and 3) schedule of the fleet, in order to minimize total cost. The combined findings above helps to define the main parameters which act as determining factors for the model in developing a solution.

It can be argued that there are two determining factors as derived from the findings: 1) Bunkering Volume and 2) Length of Time Window which can be explained as follow:

1. Bunkering volume, or simply the receiving ship size, affects the choice of LNGBV fleet size and mix in the sense of:
   - The fleet capacity must be higher or equal to the highest task volume that may arrive to the system. Since one bunkering operation can only be done by one LNGBV, so for example if there is any 20,000 m^3 demand then a 20,000 m^3 LNGBV must be deployed.

- The variability of bunkering volume also impacts the fleet mix – vessels number with different capacity – decision.
- In addition, the bunkering time – which directly affected by the bunkering volume – takes relatively a bigger part than travel time in which its proportion in the time window length will also impact the choice of fleet and its routing.

2. Length of Time Window, or simply the Berth time of receiving vessels at the terminal highly affect the schedule of the fleet and also the optimum route. However, this parameter works together with other factors, which mainly are: bunkering time, the arrival time and terminal operation time, and the LNGBV's start operation time.
   - As mentioned in the previous point, the proportion of bunkering time to the length of time window impacts routing of the fleet. In that sense, with a constant bunkering time, the length of time window determines the proportion's ratio.
   - The ships' arrival time and the terminal operation time directly define the length of the window or when the ship can be bunkered in the earliest and the latest time.
   - The LNGBV start time form the station also determines when in the window that she will be ready to do bunkering or at how much remaining time she will be ready.

6.2 Analysis on the Impact of Bunkering Time Proportion to Supply Costs

As one of the determining factors, the bunkering volume, corresponds to the length of bunkering time which take the bigger part in the time window. The proportion of bunkering time in the time window *(s_i/TW)* describes how loose or tight is the opening of the window of the task. It impacts the fleet size and mix decision and also the developed routes. As obtained from scenarios 2d and 2e, the following graph illustrates the impact of the proportion *(s_i/TW)* to the supply cost or in this case the percentage of penalty cost to the total cost:

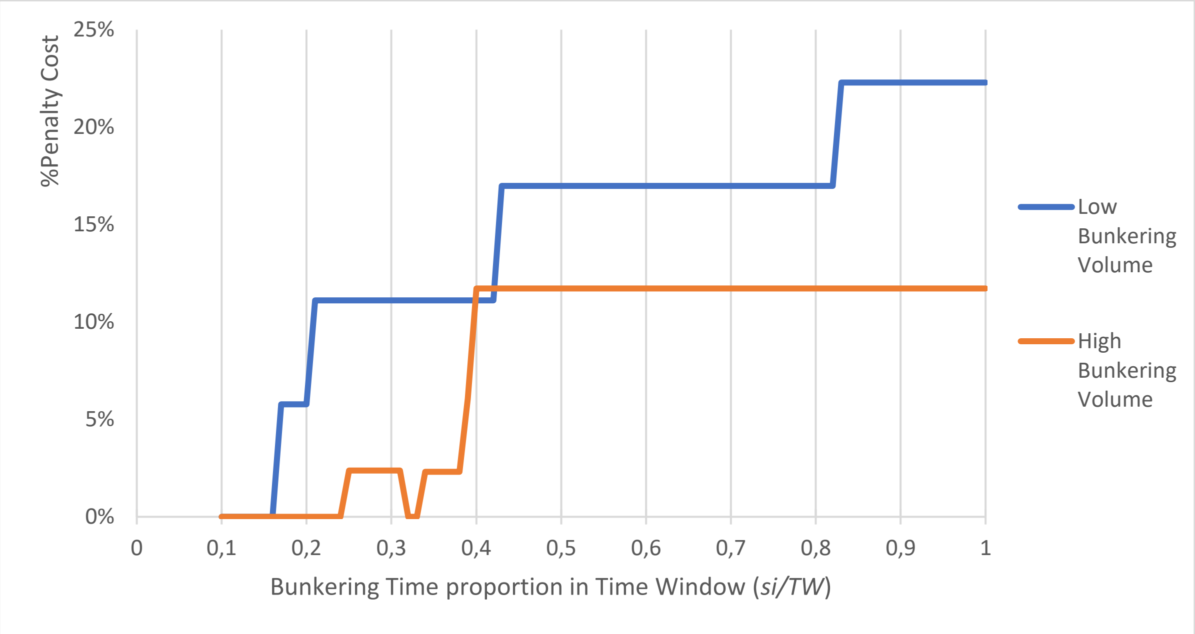

Figure 13 Bunkering time proportion vs % Penalty Cost

The figure identifies the relation between the bunkering time proportion with the percentage of penalty costs. It can be seen that the penalty cost gets higher when the time schedule is tight or when as the ratio approaches 1.0. Initially it is quite certain that in a tighter window and even when late task is certain, the penalty cost increases. However, as previously explained, the model will only assign one vessel with high capacity to serve all tasks in late. The possible explanation is that when late task is unavoidable, there is no need to assign more vessel in the fleet since the extra vessels will not eliminate the lateness and still cannot serve the tasks on time.

The impact is different depending on different settings. In a low bunkering volume situation or when each task is below 10,000 m^3, the penalty cost percentage increases gradually but can reach more than 20%. On the other hand, in a high-volume situation (when each task is more than or equal to 10,000m^3), the percentage of penalty cost is increased significantly at 0.4 and only can reach around 12% of the cost. It is also noted that in high-volume situation the variable cost itself will be a lot higher than in low-volume situation so that the proportion of penalty in this situation is only can reach around to the 12% level.

As a general principle, from the figure we can also define the sufficient level of *'spare time'* of any situation or to say how tight the windows are when facing any real scenarios as:

- In a low bunkering tasks' volume or in a short bunkering tasks situation, when the average bunkering time proportion is at around 0.8, all of the tasks will be served in late. In the range from 0.1 to 0.4, there is enough spare times to serve all tasks on time (or there is around a maximum of half of the tasks will be served late).
- In a high-volume situation or in a long bunkering time situation, when the average of bunkering time proportion is at 0.4, all of the tasks will be served in late. However same as in the low-volume situation there is enough spare times or there is around a maximum half of the number tasks will be served late in the range from 0.1 to 0.4.

6.3 Analysis on the Impact of Fleet Capacity to Supply Costs

One main decision of the model is to determine the number of vessels in the fleet. However, as previously described, to some extent the model prefers to only assign one or fewer vessels in serving the tasks. However as specifically derived from scenario 3, additional vessels are considered when:

a. There are sufficient time windows to serve the tasks on time, or in other words in the low ratio of bunkering time and time window *(s_i/TW).*
b. One or more tasks require a bigger bunkering vessel capacity than the other tasks.
c. Simultaneous tasks potentially causing late, especially when the total penalty is more than the cost of a particular adding vessel.

Taking those three considerations as a general rule of thumb, the following figure illustrates on how the number of vessels and the total capacity may impact the supply costs.

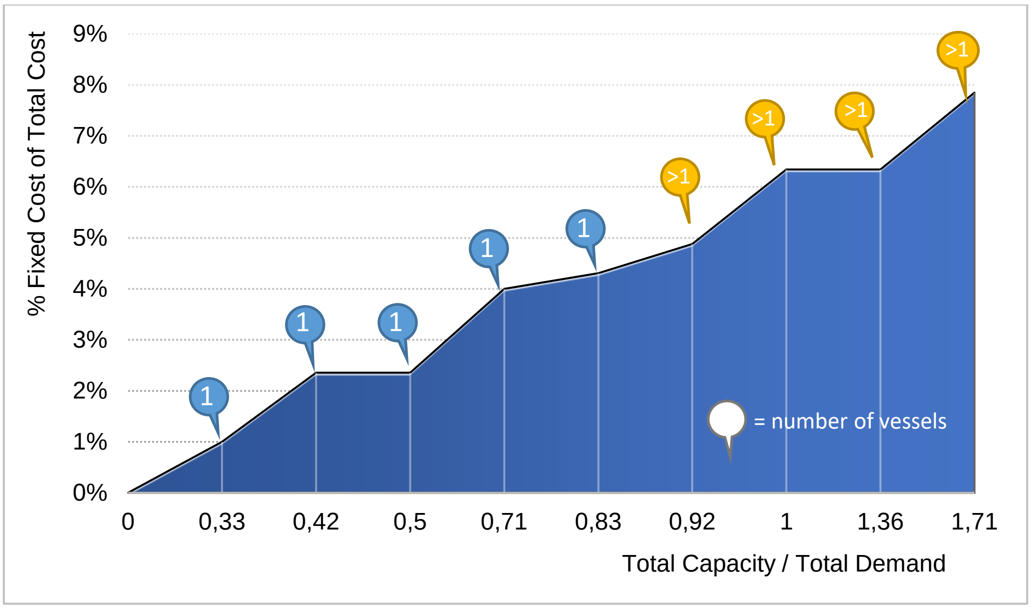

Figure 14 Total Capacity / Total Demand Ratio vs %Fixed Cost

The figure is basically gathered from all scenarios especially from the third scenario, it shows the relation between the ratio of total capacity per total demand and the percentage of fixed cost. The fixed cost equals to the acquisition cost or the capital cost per day which basically show the fleet composition. In that sense the higher the capacity means that there is an addition in number of bunkering ships or there can be a change in the size of the fleet. The figure also illustrates how the total capacity per total tasks volume affecting the costs.

The x-axis shows that the higher the fleet capacity the higher the ratio is (going to the right), on the other hand the higher the total demand is the smaller the ratio (going to the left). It also shows that the higher the capacity per demand ratio the higher the fixed cost. It is quite certain that in that situation the capital cost is high which resulting from the bigger vessel size and/or the number of vessels.

As previously described, the model prefers to assign one ship over adding extra vessels, that behaviour is also covered in the figure that there is only one vessel assigned from the range of 0.3 to 0.8. It can be said that in the low ratio or when the total demand is high, one vessel will serve all of the tasks. In this case, the higher total demand can also mean that there are few tasks with high volume or when there are a high number of tasks with small volumes. On the contrary, the additional vessel are instead considered to match the total demand (at range 0.9 to 1) and in some cases even caused excess capacity (at 1.71) in which they are likely to be decided to avoid late or penalty.

Chapter 7 Discussion

This chapter discusses the model development and implementation performance in the area of: model applicability, uncertainties, approaching longer term planning, the current condition in the Port of Rotterdam, and contribution to enhance LNG bunkering utilization. The discussion is to also touch and answer the research questions while also to give additional insight in a wider argument and understanding.

7.1 The Applicability of The Model and The Result Findings

This thesis models the LNG bunkering operation in the Port of Rotterdam as a Fleet Size and Mix Vehicle Routing Problem with Time Windows (FSMVRPTW). To implement the model, the thesis conducts some experiments to find insight on improving the LNG bunker supply process in order to achieve an efficient operation and to also enhance the LNG competitiveness as ship's fuel. Aligning the theoretical model and the results of the experiment to reality is certainly one challenge that requires further adaptation and make use of some practical knowledge. It is also noted that the limitation of the thesis may create a gap to the actual condition. However, to some extent the insight can be elaborated further to be a key on the optimal operation.

On one hand, the mathematical model as one of the biggest contributions of this thesis can be considered as a general model for the bunker supply operation, especially to its extension in determining fleet composition, routes, and schedule. Besides, its theoretical characteristics that encloses the problem and separates them from some external factors, eventually the model is applicable to other similar problems. Moreover, the model algorithm had also been verified in two ways, firstly using the AIMMS software and secondly by the manual calculation than can be found in the first scenario.

On the other hand, the general inferences from the experiment may contrast in a different application which are mainly identified in:

- It is inferred that, the travel time relatively takes a small part in determining routes and schedule compared to bunkering and loading time. Since the model is applied to the situation within a single port, travel time is not really significant compared to the bunkering time. However, when the model is applied to a wider area such as in the ARA Region (Amsterdam-Rotterdam-Antwerp) that consist of several port areas, then travel time can potentially takes a bigger part than before or even bigger than the bunkering time itself.
- From the point above it is also related to the findings on the bunkering proportion factor. In a situation when travel time takes the bigger part, the proportion of bunkering time to the time window may likely be less affecting the choice of fleet.

The experiment results from the thesis are yet beneficial to the user, one of which is for the LNG bunkering operators / transporters or the bunkering providers in general. it can be concluded that a better information lead to a better operation planning, which are indicated in the findings such as:

- As one of the determining factors, the length of time window is noted to be supported by ship's arrival time and terminal operation time parameters. So, a more accurate information of those parameters certainly will help in a better route and schedule planning of the fleet.

- The impact of the proportion of bunkering time to supply costs which is identified in section 6.2 provides a quick benchmark especially to define looseness or tightness of the time window. In this case, this finding acts as the necessary information to be considered in the supply plan.
- Another inference is the conditions to determine the moment when to assign additional vessel as can be found in section 6.3. It can be an example of information that is accurately needed to make a better planning. This can also be related to the reality that adding vessels can take a lot of time moreover when in the case of newbuilding.

7.2 Dealing with Uncertainties

Uncertainties in the Model

As discussed in the previous section, the limitations, scope, and assumptions that are used in this thesis set it apart from the real condition that deals with a lot of uncertainties. This thesis simulates the scenarios in the deterministic settings with some predefined parameters while also treats some parameters as given. In that sense, it is important to discuss where the uncertainties may occur, how likely it is to occur, and how it may affect the current result.

Lindley (2006) simply define uncertainty as a subjective presumption for matters under lack of full information. While he considers uncertainty as a subjective matter, he explains that the degree of uncertainty can be differ depending on who the subject is. In that sense the considerations on uncertainty is needed to approach, manage and recommend any action in the course of decision making.

The developed scenarios consider some parameters as given and deterministic, which are found in:

- Given arrival time of the receiving ships and simultaneous tasks on every scenario.
- Deterministic terminal time / ship's berth time.
- Deterministic travel times from/to terminal locations that ignores some uncertain aspects as weather condition, tides, any conditions under some period of time, congestions, technical difficulties for berthing, etc.
- Loading time at the depot is also assumed to be fixed and ignoring the schedule of the terminal and the availability of the jetty.
- Deterministic bunkering time, rate and bunkering volume.

Robust Optimization Experimental Calculation

The AIMMS software can be used to accommodate uncertainty without changing the model and explains three necessary steps to simulate the robust optimization, which are: 1) indicate the uncertain parameters, 2) indicate the adjustable variables as the consequence of the uncertain parameters, and 3) specify the region of possible realization of the uncertain parameters (Roelofs & Bisschop, 2019). Moreover, Anderson, et al. (2016, p. 430), defined one way to incorporate uncertain activity times by take into account the concept of optimistic, most probable, and pessimistic time estimates.

Considering both of the methods, then the following table determines the adjusted parameters and variables for the experiment in robust optimization.

Table 35 Uncertain parameter definition in the model

Uncertainty in	**Uncertain Parameters**	**Adjustable Variables**	**Uncertainty region**
Arrival Time and Terminal / Berth Time	Earliest Start *(a_i)*	• Arrival time (p_i^k) • 1st tour Start time (p_0^k) • 2nd tour start time (p''^k_0)	**Assuming uniform / box distribution for all uncertain parameters:* Optimistic ≤ most likely ≤ pessimistic time time time
	Latest Start *(b_i)*		
Loading time at depot	Loading time *(l_k)*		
Bunkering time	Bunkering Time *(s_i)*		

As defined in the previous table, all of the uncertain parameters correspond to the same variables, or it can be said that the variables – arrival time and start time – depend on the uncertain parameters. The experiment assumes all uncertain parameters to be uniformly distributed as follows:

- In line with section 4.5, the berth time is assumed to be uniformly distributed for every groups. As used in the scenarios, this thesis utilizes the most frequent berth time which lies in the range of 12-16 hours. In this case, the uncertainty region ranges +/- 2 hours from its most likely time which is 14 hours.
- For loading and bunkering time uncertainty, it is assumed that the current generic time as the most likely and the optimistic time. While it is also assumed that the pessimistic time considers 2 hours delay from the generic time. So that the uncertainty region is as follow: (Optimistic time) = (Bunkering time) ≤ (Bunkering time + 2 hours).

Then scenario 1, 2c, and 3b-d are re-simulated under the uncertain parameters. The scenarios are run using AIMMS 4.74.4.5, modelled as Mixed-Integer Programming (MIP) and solved using linear optimization tools CPLEX 12.10. The program is completed normally with more iterations and more solving time than in the deterministic setting. However, an integer solution for the robust counterpart cannot be achieved for all scenarios, so that the objective value of the original deterministic model can be used as performance measure with uncertain scenarios (Roelofs & Bisschop, 2019). And the different results are found as follow:

Table 36 Results under uncertain scenarios

Sc	Deterministic scenario			Uncertain scenario		
	Fleet choice	Late task	Total Costs	Fleet choice	Late task	Total Costs
1	k=4 (10,000 m^3)	1	159,979	k=4 (10,000 m^3) k=3 (4,000 m^3)	-	159,902
3c	k=4 (10,000 m^3) k=3 (4,000 m^3)	-	143,902	k=4 (10,000 m^3) k=2 (3,000 m^3)	-	142,848

Since there is not any existing integer solution in robust counterpart, so that the min-max result cannot be obtained. However, the uncertain scenarios surprisingly generate a slightly different result for scenario 1 and 3c. in this case, the 'adjustable' property on one of the variables becomes one factor. The adjustable 2nd tour start-time variable in the uncertain scenario 1 decide on an additional vessel. Same factor also applies on scenario 3c which create a change in the fleet composition.

The experimental calculation on the robust model briefly gives an illustration on some aspects that can be affected by uncertainties. The time uncertainties may generate more spare time or low ratio of bunkering time and time window, and also may increase likeliness of simultaneous tasks. One of both factors evidently acts as one condition for adding vessel as discussed in chapter 6.3, from which it can explain the difference of the results. In that case, since there is some adjustable 'flexibility' in 2nd tour start time, it causes the occurrence of one of those two factors.

7.3 Approaching the Longer-Term Demand

As mentioned in Chapter 4, the thesis adopts the work of Aronietis et.al. (2016) for projecting the LNG bunkering demand. In that chapter, we can find the use of LNG adoption rate as the method to forecast the long-term demand. However, this thesis only takes into account the projected weekly demand or the short-term demand since the main purpose is find the optimal supply plan in the operational or tactical level. It is also to note from chapter 3 that LNG bunkering transport problem with its timely characteristic is well formulated in the tactical level which only accommodates short to medium period.

It is clear that in the longer term the intention is to determine the optimal fleet composition which related to the future purchase / lease decision. When the intention of a company is to decide on purchasing / leasing fleet of vessels for the future then the FSMVRP becomes a mid-term (or long term) planning issue which the attributes such as demand, time windows, and others in a planning period are becoming highly uncertain (Liu & Shen, 1999). For the consequences, the optimal short-term plan may be quite useless while it is needed to be rescheduled and re-planned after some periods of time.

Liu & Shen (1999) argued that although the daily plan seems useless in the long term, however the linkage between the short-term and the mid to long term should not be ignored which is found in the idea as surrogate costs. A surrogate cost is a cost that is converted in different unit and used in two different cases. Liu & Shen (1999) also argued that the surrogate costs, for example, the fixed investment cost, is important to be included in the short term plan to keep the linkage to the longer term exists. In that sense, they also argued that for mid-term planning purpose, depreciation costs and tax can be included to the short-term planning. To some extent, the developed model can still handle the mid-term planning by simply utilizes different unit of time as the input data, such as aggregated demand and monthly time window with daily scheduling.

Therefore, it can be argued that considering the short-term routing and scheduling plan is important as a factor to help the longer-term planning or ultimately to determine the optimal fleet in the future. It seems quite obvious that managing the knowledge such as historical data, plans, and decisions is one key for a sustainable business. In that case, the findings from the scenarios' solutions can be used for a long-term planning especially by also considering the important factors such as the future bunkering volume, vessel size, LNG fuel adoption, future trade and port throughput.

7.4 Current LNG Bunkering Fleet in the Port of Rotterdam

As noted from chapter 2 and 4, there is only one dedicated vessel currently in the Port of Rotterdam, which is Shell's Cardissa with 6,500 m^3 tank capacity. As previously defined, the LNG bunkering characteristics come in the following typical volume: 50 m^3, 400 m^3, 800 m^3, 2,000 m^3, 4,000 m^3, 10,000 m^3, 20,000 m^3. In STS scheme, one ship is ideally bunkered with one vessel, therefore a 6,500 m^3 may only serve in maximum a 6,500 m^3 bunkering volume demand. In an instant, 10,000 m^3 and 20,000 m^3 bunkering demand characteristics may not be served with the current fleet.

In practice, the bunkering contract is not as simply as fulfilling incoming demand but also involving several service level agreements to be met. For example, the renowned newbuild 23,000 TEU CMA CGM Jacquess Saade as one of the largest LNG fuelled containerships (CMA CGM, 2019) is likely to have a 10,000 or even 20,000 m^3 bunkering demand. Short story, CMA CGM agreed on a bunkering contract with Total which provides them with one bunkering barge in port of Marseilles and a bunkering solution in port of Singapore (Total, 2017) and moreover in 2019 Total launched a LNG supply ship to supply the Jacquess Saade in Rotterdam (van Marle, 2019).

Spontaneously we can say that in terms of competition, the current fleet in Rotterdam cannot served the potential demand and turns out that it gave up the demand to another player outside the port. It is a fair matter to discuss that to some extent Shell may not target the large segment with their current fleet. However, as described in chapter 2, since the IMO 2020 introduction, there is a growing number of LNG adoption in large trading vessels which are likely to operate in Rotterdam as one of the main international trade hubs. Therefore, adding a bigger vessel can be very reasonable.

As concluded in chapter 6, bunkering volume is one of determining factors for the optimal plan for bunkering transport. In this case, by deciding to target the large ship market, as the CMA CGM example, an additional bunker vessel must be added to the fleet which then changes the current fleet plan. However, the decision to add vessel consequently impacts the ratio of Total Capacity per Total Demand to be higher in which it also impacts the supply cost by increase of its fixed cost as inferred from chapter 6.3.

On the other hand, one possible decision is to also keep with business as usual by using only one vessel. One advantage is that 6,500 m^3 is high enough to serve the small market, while as also inferred in chapter 6.3, a particular level of capacity can still optimally serve all smaller tasks at once until a certain level of total capacity / total demand ratio to around 0.8. However, it is also to note that it applies in a condition where there is sufficient time window otherwise it is likely can be a disadvantage. Such high demand seasonality can give numerous tasks in a period of time which will reduce the service level if there is no increase in capacity. Molina, et al. (2020) discussed a VRPTW problem in a limited number of resources, in which they argued that when such occasion arises some orders maybe postponed since the logistic costs gets too high. They also argued that the heterogeneous fleet which are incorporated by a company can be an advantage for a better adaptation to the demand.

Finally, it can be concluded that with the current fleet there is a trade-off of between high utilization and market coverage. With the current increase in bunkering size and the small task numbers, any bunkering providers can enter and thrive in different market segment with different competitiveness focus. Such factors as the ratio of capacity per total demand and the heterogeneous level in fleet can be considered to decide on which segment can be targeted.

7.5 Enhancing LNG bunkering competitiveness through optimal supply

The discussion in LNG utilization is a contrast topic from the previous optimisation discussion. To promote LNG adoption / utilization as ships' fuel is more an interest to the government and the port authority while the LNG bunkering service providers still require a level of profitability in return for their investment and operational costs. In that sense, it is important to discuss the trade-off between competitiveness of LNG among the other fuel and the competitiveness of LNG as fuel in terms of costs.

As described in chapter 4, defining cost of LNG supply is vary but it focusses on two aspects which are the LNG price and supply logistics costs which it also applies to bunker supply / bunkering. While putting aside the LNG price, the thesis incorporates the study from Faber, et. al. (Study on the Completion of an EU Framework on LNG-fuelled Ships and its Relevant Fuel Provision Infrastructure, 2017) which covers investment costs, operational costs, and loading costs. In addition to that opportunity costs are also considered as a penalty for not meeting the demand on time. Stand by the argument in Stenersen (2008) that LNG fuel price should considers two points: (1) the ship owner's competitive position should not be weaken relative to other fuels, and (2) the LNG seller should be able to recover his costs of supply. In that sense, the level of service can also support the willingness of ship owners to confidently adopt LNG as fuel.

As the main point of the thesis, an optimal plan to supply LNG bunker improves not only the efficiency of supply costs but also the service level in terms of on-time-delivery. Besides any other factors, the thesis measures the service level of bunkering by applying penalty scheme that comes from the opportunity costs from any late deliveries. Therefore, for the purpose of the study, we can limit the measurement of competitiveness by identifying the level of penalty costs in a different setting:

LNG bunkering competitiveness vs adding vessels in the fleet

In a pessimistic setting where the growth of LNG bunker is low and the size of bunkering is steady at previous years' level (dominated with ferries and small supporting ships), it is quite certain that without considering additional vessel the service level of delivery can be maintained even with only one vessel. However, in that situation the bunker providers will automatically serve for the broader market demand so then one challenge in supplying one particular area is lied on the travel time that implies to scheduling.

Oppositely in the optimistic setting where the growth of LNG adoption is promising not only in quantity but also in size, then adding vessels is a serious consideration to promote higher utilization of LNG as fuel. In that case:

- In a higher number of tasks especially simultaneous tasks then adding vessel can maintain the delivery time so that the opportunity costs can be kept to the lowest level.
- In a bigger bunkering volume tasks, adding vessel with a corresponding vessel size means to acquire the demand which certainly enhance LNG utilization as fuel. However, the downside is that the increase in costs will occur as the total capacity gets higher than the total demand. The LNG bunker providers need to recover the increase of costs by either balance the total capacity with other demand or probably tailor an incentive scheme in the contract or from the government for balancing the supply side.

LNG bunkering competitiveness vs Penalty costs

As described earlier, the higher the penalty costs mean to let occurrence of opportunity costs. The penalty will not impact the supply costs as it exists on the shipowners' side as the extra costs and also time to do bunkering outside the planned time window. In that sense keeping the service level promise to the client not only securing the demand but also securing the confidence level of any other shipowners to adopt LNG as fuel, thus the LNG bunkering utilization would increase.

LNG bunkering competitiveness vs LNG bunkering competition

Promoting LNG as ships' fuel can be economically complex, especially with the current few players since the relatively high barriers to entry. It can be said that the current situation is an oligopoly or to some extent a duopoly or even monopoly situation with still very low in competition. Assuming a promising growth in demand, the downside of the low competition situation is that there will be no tendency towards efficient operation or the price offered would be higher it should be.

In a low competition, it can be certain that an LNG bunkering provider takes as many tasks / demands as possible while spends as little costs as possible. In other words, from the performance aspect, the providers prefer high utilization of the vessel rather than consider the opportunity cost on the demand side. Without any attempts to level the competition, that situation certainly decrease the competitiveness of LNG as fuel.

On the other hand, when there is a high competition among LNG bunkering providers, efficient process of supply will be achieved to be able to serve many customers. In that situation, assuming a stable gas price, certainly LNG competitiveness as fuel will be improved. In that sense, to keep the LNG bunkering providers' competitive advantage, the utilization of LNG bunkering vessels can be in a low level to maintain the availability of their fleet. The downside is that, with higher ratio of total capacity per total demand, the fixed costs will also get higher which may reduce the profitability of the company.

It can be concluded that maintaining a good level of competition can improve the LNG bunker competitiveness while on the supply side it may reduce the profit. A regulatory framework becomes important to keep the service level high especially when there is a high barrier to entry the LNG bunker supply side and difficult to increase the competition level.

Chapter 8 Conclusion and Further Research

8.1 Conclusion

Since the introduction of IMO 2020 global sulphur limit, there is a promising growth of the adoption of LNG as shipping fuel. Utilizing LNG as ship's fuel is considered as one of the most preferred choice since its high technical maturity and availability. Securing LNG bunker is one of the biggest challenges, moreover the chicken-and-egg dilemma between shipowners and fuel providers slows down the development of LNG bunkering infrastructures. Ship-to-ship (STS) transfer method is considered as one key in unlocking the infrastructure development. Bunkering vessels and barges are also considered as the efficient modes when there is a far distance from bunker source to the receiving ships. In that sense, the optimum supply plan will eventually improve supply efficiency while promote utilization of LNG as shipping fuel. Motivated by that purpose, the thesis puts forward the main research question as: *What is the optimum fleet mix and route plan of LNGBVs to fulfil the potential LNG bunkering demand in the Port of Rotterdam?*

This thesis scopes the area of the research in the Port of Rotterdam with the objective to determine the optimal plan of fleet composition and route to fulfil the growing demand of LNG bunkering in the port. Set of literatures are reviewed in a relation to clarify the context of the thesis, to provide updates on the current issue, and to review the previous similar studies. The problem is furtherly specified in Chapter 3 which started by describing the STS bunkering problem as a tactical and operational transportation problem. Several theoretical foundations in vehicle routing are comprised to formulate the problem into a FSMVRPTW with considering special characteristics in LNG bunker supply. A mathematical formulation is developed to model the problem and to solve it quantitatively.

Further details for the data are described in Chapter 4, such as the description of location, generic ship and LNGBV types, demand, costs, and time window to the description of the general assumptions. An experiment using scenarios is conducted to approach the problem. Scenarios are developed to simulate several bunkering cases which are divided into three scenarios: the first scenario is derived from snapshots of current operation of LNG fuelled ships in the port, the second scenario simulates five different conditions with specific attention on the changes in time window, and the third scenario simulates four different conditions by adding number of tasks, volumes, and simultaneous tasks.

From the result analysis, the model behaviours are analysed to understand the model's decision-making process. Furthermore, the determining factors of the bunkering transportation are inferred as: 1) Bunkering Volume and 2) Length of Time Window. Besides that, the impact of bunkering time proportion and the ratio of total capacity per total demand are evaluated in terms of costs. Then the analysed results are discussed further in a several topics to answer the research questions as follow:

1. The optimal plan of route, schedule, and fleet composition for LNG bunkering in the Port of Rotterdam can instantly follow the result under Scenario 1 which derived from today's snapshot. The solution consists of fleet of one 10,000 m^3 LNGBV that served all tasks in 2 different routes by having 1 late task in plan. Moreover, it is also discussed that the planned late task with its penalty can work oppositely with the goal to enhance LNG bunkering competitiveness. In addition to that, the optimal plan has to be re-evaluated

considering any changes in situation and in the determining factors which then lead to the answer of the second research question.

2. The determining factors of the bunkering transportation problem are bunkering volume and length of time windows. In brief, the bunkering volume affects the choice of fleet while the length of time window affects the routing and scheduling. Furthermore, the impact of both factors answers the next two research questions.
3. The time windows impact the optimal plan in terms of route and schedule and lead to a higher percentage of penalty costs. The length of time window works together with four other factors especially with the proportion of bunkering time, which highly affects the schedule and the route of the vessel particularly at the ratio above 0.4.
4. The size and the number of tasks impact the bunkering volume and the total demand of the system. Since one bunkering should only be done by one vessel, so that the higher the task volume requires a certain higher capacity in terms of securing demand. In that sense, it then impacts the optimal plan in terms of fleet choice. Besides that, in a fixed level of capacity, the higher the total demand can lower the ratio of capacity per total demand that can keep the fixed costs under 5% of the total costs.
5. As there is only 1 dedicated vessel with 6,500 m^3 in the existing fleet of the Port of Rotterdam then in an instant it can only serve the tasks that lower than the capacity. Moreover, in the current growing size of LNG fuelled ships it can be a disadvantage in terms of attracting or securing demand on that size. On the other hand, the current capacity is high enough to serve the small market and can still be optimal in a general sense that the level of total capacity / total demand ratio only up to 0.8 with a note that there is a sufficient time window.

This thesis also discussed on: the applicability of the model and the result findings, dealing with uncertainties, approaching the longer-term planning, and the contribution to enhance LNG bunkering utilization with the intention to go further with the findings and the solution to reach the purpose to broaden the argument, knowledge, and to maintain the attention in the application to the real situation.

8.2 Contributions and Recommendations for Further Research

This thesis contributes primarily in the model development that adequately success combining several models of VRP to tailor a well-suited model for LNG bunkering maritime transport problem. The thesis also extends its experimental findings to general inferences and discussed them in a broad argument. However, the thesis also limited to a rather deterministic setting and with the scope of operational / tactical level of transportation plan.

Further research in stochastic optimization is recommended to implement the model in a more realistic situation. In addition to that, it is also recommended to develop the model which accommodate longer term of transportation planning. Another recommendation in the model implementation is that to implement this model in other similar case as an advanced verification of the model.

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Appendix

Appendix A - Distance and Travel time matrices

Distance Matrix

Distance (in nm)			Maasvlakte						Europoort			Botlek				Waalhaven		Dordrecht
			#	A	1	C	D	B	E	2	F	G	3	4	5	H	I	6
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maasvlakte	#	0	-	4.6	2.8	1.4	0.8	1.6	3.6	5.2	5.7	13.2	13.9	15	15.2	17.9	18.8	30
	A	1	4.6	-	1.8	3.2	4.5	6.2	8.2	9.8	10.3	17.8	18.5	19.6	19.8	22.5	23.4	34.6
	1	2	2.8	1.8	-	1.4	2.7	4.4	6.4	8	8.5	16	16.7	17.8	18	20.7	21.6	32.8
	C	3	1.4	3.2	1.4	-	1.3	3	5	6.6	7.1	14.6	15.3	16.4	16.6	19.3	20.2	31.4
	D	4	0.8	4.5	2.7	1.3	-	2.4	4.4	6	6.5	14	14.7	15.8	16	18.7	19.6	30.8
	B	5	1.6	6.2	4.4	3	2.4	-	5.2	6.8	7.3	14.8	15.5	16.6	16.8	19.5	20.4	31.6
Europoort	E	6	3.6	8.2	6.4	5	4.4	5.2	-	1.6	2.1	16.8	17.5	18.6	18.8	21.5	22.4	33.6
	2	7	5.2	9.8	8	6.6	6	6.8	1.6	-	0.5	18.4	19.1	20.2	20.4	23.1	24	35.2
	F	8	5.7	10.3	8.5	7.1	6.5	7.3	2.1	0.5	-	18.9	19.6	20.7	20.9	23.6	24.5	35.7
Botlek	G	9	13.2	17.8	16	14.6	14	14.8	16.8	18.4	18.9	-	0.7	1.8	2	4.7	5.6	16.8
	4	10	13.9	18.5	16.7	15.3	14.7	15.5	17.5	19.1	19.6	0.7	-	2.5	2.7	5.4	6.3	17.5
	5	11	15	19.6	17.8	16.4	15.8	16.6	18.6	20.2	20.7	1.8	2.5	-	2.4	3.8	4.6	18.6
	6	12	15.2	19.8	18	16.6	16	16.8	18.8	20.4	20.9	2	2.7	2.4	-	1.4	2.2	18.8
Waalhaven	H	13	17.9	22.5	20.7	19.3	18.7	19.5	21.5	23.1	23.6	4.7	5.4	3.8	1.4	-	0.8	21.5
	I	14	18.8	23.4	21.6	20.2	19.6	20.4	22.4	24	24.5	5.6	6.3	4.6	2.2	0.8	-	22.4
Dordrecht	8	15	30	34.6	32.8	31.4	30.8	31.6	33.6	35.2	35.7	16.8	17.5	18.6	18.8	21.5	22.4	-

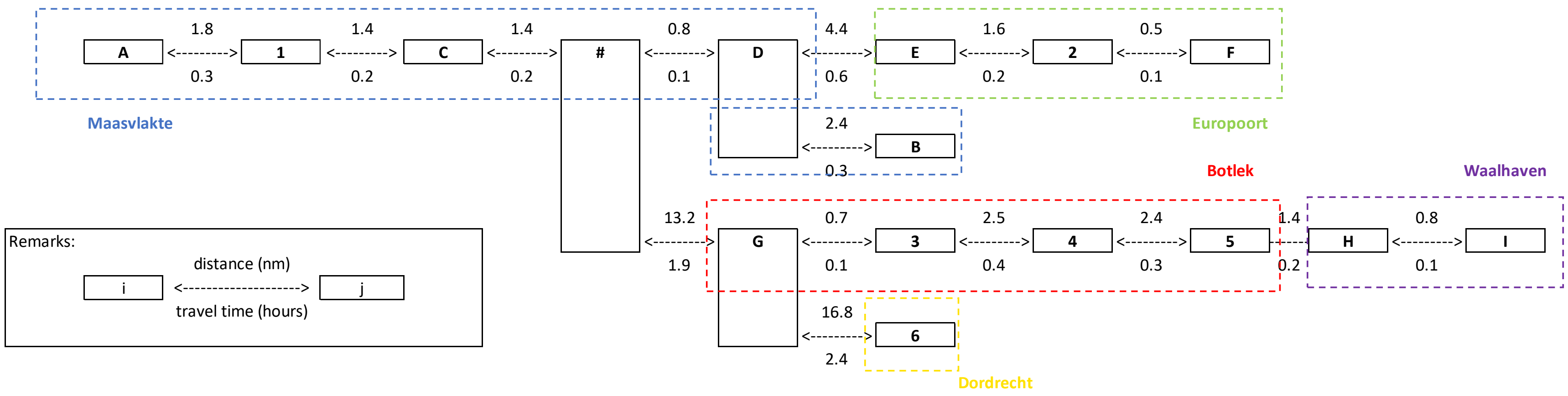
Travel Time Matrix

Travel time (in hrs)			Maasvlakte						Europoort			Botlek				Waalhaven		Dordrecht
			#	A	1	C	D	B	E	2	F	G	3	4	5	H	I	6
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maasvlakte	#	0	0.0	0.7	0.4	0.2	0.1	0.2	0.5	0.7	0.8	1.9	2.0	2.1	2.2	2.6	2.7	4.3
	A	1	0.7	0	0.3	0.5	0.6	0.9	1.2	1.4	1.5	2.5	2.6	2.8	2.8	3.2	3.3	4.9
	1	2	0.4	0.3	0.0	0.2	0.4	0.6	0.9	1.1	1.2	2.3	2.4	2.5	2.6	3.0	3.1	4.7
	C	3	0.2	0.5	0.2	0.0	0.2	0.4	0.7	0.9	1.0	2.1	2.2	2.3	2.4	2.8	2.9	4.5
	D	4	0.1	0.6	0.4	0.2	0.0	0.3	0.6	0.9	0.9	2.0	2.1	2.3	2.3	2.7	2.8	4.4
	B	5	0.2	0.9	0.6	0.4	0.3	0.0	0.7	1.0	1.0	2.1	2.2	2.4	2.4	2.8	2.9	4.5
Europoort	E	6	0.5	1.2	0.9	0.7	0.6	0.7	0.0	0.2	0.3	2.4	2.5	2.7	2.7	3.1	3.2	4.8
	2	7	0.7	1.4	1.1	0.9	0.9	1.0	0.2	0.0	0.1	2.6	2.7	2.9	2.9	3.3	3.4	5.0
	F	8	0.8	1.5	1.2	1.0	0.9	1.0	0.3	0.1	0.0	2.7	2.8	3.0	3.0	3.4	3.5	5.1
Botlek	G	9	1.9	2.5	2.3	2.1	2.0	2.1	2.4	2.6	2.7	0.0	0.1	0.3	0.3	0.7	0.8	2.4
	3	10	2.0	2.6	2.4	2.2	2.1	2.2	2.5	2.7	2.8	0.1	0.0	0.4	0.4	0.8	0.9	2.5
	4	11	2.1	2.8	2.5	2.3	2.3	2.4	2.7	2.9	3.0	0.3	0.4	0.0	0.3	0.5	0.7	2.7
	5	12	2.2	2.8	2.6	2.4	2.3	2.4	2.7	2.9	3.0	0.3	0.4	0.3	0.0	0.2	0.3	2.7
Waalhaven	H	13	2.6	3.2	3.0	2.8	2.7	2.8	3.1	3.3	3.4	0.7	0.8	0.5	0.2	0.0	0.1	3.1
	I	14	2.7	3.3	3.1	2.9	2.8	2.9	3.2	3.4	3.5	0.8	0.9	0.7	0.3	0.1	0.0	3.2
Dordrecht	6	15	4.3	4.9	4.7	4.5	4.4	4.5	4.8	5.0	5.1	2.4	2.5	2.7	2.7	3.1	3.2	0.0

Travel time **(in minutes)**			Maasvlakte						Europoort			Botlek				Waalhaven		Dordrecht
			#	A	1	C	D	B	E	2	F	G	3	4	5	H	I	6
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maasvlakte	#	0	0	39	24	12	7	14	31	45	49	113	119	129	130	153	161	257
	A	1	39	0	15	27	39	53	70	84	88	153	159	168	170	193	201	297
	1	2	24	15	0	12	23	38	55	69	73	137	143	153	154	177	185	281
	C	3	12	27	12	0	11	26	43	57	61	125	131	141	142	165	173	269
	D	4	7	39	23	11	0	21	38	51	56	120	126	135	137	160	168	264

Travel time **(in minutes)**			Maasvlakte						Europoort			Botlek				Waalhaven		Dordrecht
			#	A	1	C	D	B	E	2	F	G	3	4	5	H	I	6
			0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	B	5	14	53	38	26	21	0	45	58	63	127	133	142	144	167	175	271
Europoort	E	6	31	70	55	43	38	45	0	14	18	144	150	159	161	184	192	288
	2	7	45	84	69	57	51	58	14	0	4	158	164	173	175	198	206	302
	F	8	49	88	73	61	56	63	18	4	0	162	168	177	179	202	210	306
Botlek	G	9	113	153	137	125	120	127	144	158	162	0	6	15	17	40	48	144
	3	10	119	159	143	131	126	133	150	164	168	6	0	21	23	46	54	150
	4	11	129	168	153	141	135	142	159	173	177	15	21	0	21	33	39	159
	5	12	130	170	154	142	137	144	161	175	179	17	23	21	0	12	19	161
Waalhaven	H	13	153	193	177	165	160	167	184	198	202	40	46	33	12	0	7	184
	I	14	161	201	185	173	168	175	192	206	210	48	54	39	19	7	0	192
Dordrecht	6	15	257	297	281	269	264	271	288	302	306	144	150	159	161	184	192	0

Location Nodes in sequence



Appendix B – Pilotage, Towage, and Mooring Tariff

Pilotage Tariff for Berth Shift Voyage, Source: (Loodswezen, 2020, pp. 29-35) (1/2)

The matrix below explains the tariff structure for regular routes for region Rotterdam-Rijnmond. It shows which tariff table, which S tariff and which T tariff column will be charged.

Sea port area Rotterdam-Rijnmond incl. Scheveningen			RV	RVLNG	Sea	A	B	C	D	E	F	G	H	I	J
			Rendezvous	Rendezvous LNG		1e Maasvlakte	Europoort	Botlek	Waalhaven	Bolnes	Dordrecht	Moerdijk	Haringvliet	Scheveningen	2e Maasvlakte
						4	5	6	6	8	11	12	13	5	5
RV	Rendezvous		S-RV + TC15												
RVLNG	Rendezvous LNG			S-RV + TC10											
Sea					S-IN/OUT + TC4										
A	1e Maasvlakte	4	S-RV + TC15	S-RV + TC10	S-IN/OUT + TC4	S-BS + TC1									
B	Europoort	5	S-RV + TC16		S-IN/OUT + TC5	S-BS + TC2	S-BS + TC1								
C	Botlek	6			S-IN/OUT + TC6	S-BS + TC3	S-BS + TC4*	S-BS + TC1							
D	Waalhaven	6			S-IN/OUT + TC6	S-BS + TC3	S-BS + TC4*	S-BS + TC1	S-BS + TC1						
E	Bolnes	8			S-IN/OUT + TC8	S-BS + TC5	S-BS + TC6*	S-BS + TC3	S-BS + TC3	S-BS + TC1					
F	Dordrecht	11			S-IN/OUT + TC11	S-BS + TC8	S-BS + TC9*	S-BS + TC6	S-BS + TC6	S-BS + TC4	S-BS + TC1				
G	Moerdijk	12			S-IN/OUT + TC12	S-BS + TC9	S-BS + TC10*	S-BS + TC7	S-BS + TC7	S-BS + TC5	S-BS + TC2	S-BS + TC1			
H	Haringvliet	13			S-IN/OUT + TC13	S-BS + TC10	S-BS + TC11*	S-BS + TC8	S-BS + TC8	S-BS + TC6	S-BS + TC3	S-BS + TC2	S-BS + TC1		
I	Scheveningen	5			S-IN/OUT + TC5	S-BS + TC2	S-BS + TC1	S-BS + TC2	S-BS + TC2	S-BS + TC4	S-BS + TC7	S-BS + TC8	S-BS + TC9	S-BS + TC1	
J	2e Maasvlakte	5	S-RV + TC16		S-IN/OUT + TC5	S-BS + TC2	S-BS + TC3*	S-BS + TC4*	S-BS + TC4*	S-BS + TC6*	S-BS + TC9*	S-BS + TC10*	S-BS + TC11*	S-BS + TC1	S-BS + TC1

Explanation of colour scheme and used abbreviations:

- Rendezvous voyage
- Ingoing and outgoing voyages (Pilot Station)
- Berth Shift

S tariff = Start tariff
T tariff = Route dependent tariff
RV = Rendezvous voyages
IN/OUT = Ingoing and outgoing voyages (Pilot Station)
BS = Berth Shift voyages
TC = Tariff Column T tariff

* For berth shift voyages between tariff area Europoort (B) on the one hand, and Botlek (C), Waalhaven (D), Dordrecht (F) en Moerdijk (G) on the other hand, the regular route goes via the Separation buoy and the Lower Light (tariff area A), and the Nieuwe Waterweg. For berth shift voyages between tariff area 2nd Maasvlakte (J) and all other tariff areas, the regular route goes via tariff area 1st Maasvlakte (A). In both situations an additional tariff of two extra tariff columns will be charged, this is regarded as an A tariff, and charged as two times the financial difference between tariff columns 2 and 1 (based on art. 4.5.g of the Registered Pilots Market Supervision Decree).

Pilotage Tariff for Berth Shift Voyage, Source: (Loodswezen, 2020, pp. 29-35) (2/2)

BERTH SHIFT VOYAGES - *Pilotage tariffs decision ACM, 3 December 2019 - Pilotage tariffs are expressed in euro, exclusive of Dutch VAT*

Actual draught (in dm)	S-tariff (starting tariff) in €	T-tariff (route-dependent tariff) in €															
		A - J	B, G, H, I, J	C, D, E, J	C, D, F, I, J	E, G	E, F, H, J	G, I	F, H, I	F, G, I, J	G, H, J	H, J					
		TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 9	TC 10	TC 11	TC 12	TC 13	TC 14	TC 15	TC 16
≤27	**40**	35	43	49	56	62	70	77	84	91	97	105	111	120	127	133	141
28	**43**	38	46	52	59	67	74	82	89	97	104	111	120	128	134	142	149
29	**45**	41	48	56	62	72	79	87	94	103	109	120	127	135	142	151	157
30	**49**	43	50	59	67	76	84	93	100	109	117	127	134	143	151	159	168
37	**59**	51	62	73	83	93	104	114	125	135	145	155	167	176	187	197	208
38	**62**	54	66	78	87	98	109	121	132	143	153	165	176	186	197	210	219
39	**66**	57	70	82	92	104	117	127	139	151	161	173	186	196	209	221	230
40	**70**	59	73	86	96	109	123	133	145	158	168	181	196	206	219	232	241
60	**214**	185	223	260	296	333	371	407	445	482	519	556	593	630	667	704	740
61	**224**	193	233	272	311	349	389	426	466	505	544	582	621	660	699	737	776
62	**233**	203	244	284	324	366	406	447	487	528	568	608	649	690	731	771	811
63	**244**	212	254	296	339	381	423	466	508	550	593	636	678	720	763	805	847
64	**253**	221	264	309	353	397	442	486	530	573	618	662	706	749	794	838	882
75	**369**	320	384	449	512	577	640	704	769	833	897	961	1024	1089	1153	1217	1281
76	**379**	329	395	461	527	592	658	723	790	856	922	987	1052	1119	1185	1250	1317
77	**388**	337	406	473	541	608	676	743	811	878	946	1013	1081	1149	1217	1283	1352
78	**398**	346	415	485	554	624	692	762	831	900	969	1039	1108	1177	1247	1316	1385
79	**407**	354	424	495	566	637	708	779	850	920	992	1061	1133	1202	1274	1344	1415
80	**416**	363	434	505	579	651	723	795	868	939	1012	1084	1158	1229	1302	1374	1445
140	**851**	736	884	1032	1179	1327	1474	1620	1768	1916	2063	2210	2359	2506	2652	2799	2947
141	**861**	744	894	1043	1192	1342	1492	1638	1788	1936	2086	2236	2384	2535	2681	2831	2979
142	**870**	752	903	1054	1205	1357	1508	1655	1807	1958	2109	2261	2411	2562	2709	2861	3012
143	**881**	761	914	1065	1219	1372	1524	1673	1826	1979	2132	2285	2438	2591	2739	2892	3046
144	**887**	770	923	1078	1231	1385	1539	1692	1846	2000	2154	2309	2462	2616	2770	2924	3078
145	**896**	776	932	1088	1243	1398	1553	1708	1864	2019	2174	2329	2484	2640	2795	2951	3106

Towage and Mooring Tariffs, Source: (Port of Rotterdam, 2020i, p. 3)

HARBOUR TOWAGE SVITZER EUROMED B.V.

ROTTERDAM/EUROPOORT/MAASVLAKTE FROM THE RIVER TO OR FROM

A Berthing/Sailing Maasvlakte 1 or 2
B Berthing/Sailing Europoort area
C Berthing/Sailing Rotterdam area (i.e. Pernis, Botlek, Brittanie dock, Seine dock and Rotterdam City)
All Shifting within the same zone (additional surcharge of 25% mark up on tariff if within zone C / Rotterdam area)

REGULAR ASSISTANCE WITH MAXIMUM DURATION TIME OF 2 HOURS						(3 HOURS)
L.o.a. of vessels in meters (a)			A	B	C	All
<	-	164	1,529	1,639	2,076	2,115
164.01	-	175	1,700	1,809	2,246	2,384
175.01	-	187	1,832	1,941	2,379	2,500
187.01	-	212	2,235	2,344	2,781	2,827
212.01	-	236	2,478	2,587	3,023	3,173
236.01	-	260	2,801	2,910	3,347	3,452
260.01	-	285	3,152	3,261	3,698	3,945
285.01	-	309	3,424	3,533	4,165	4,667
309.01	-	334	3,727	3,836	4,584	5,083
334.01	-	358	3,925	4,035	4,815	5,223
358.01	-	383	4,084	4,193	5,018	5,664
383.01	-	>	4,297	4,406	5,396	6,292

(a) LOA as published at Vesseltracker.com as prima facie source

SURCHARGES

1 Additional time, waiting (in combination with an assistance): (for all vessel sizes) **2,100** per hour

2 Standby pushing per hour (minimum charge of two (2) hours): (for all vessel sizes) **1,050** per hour

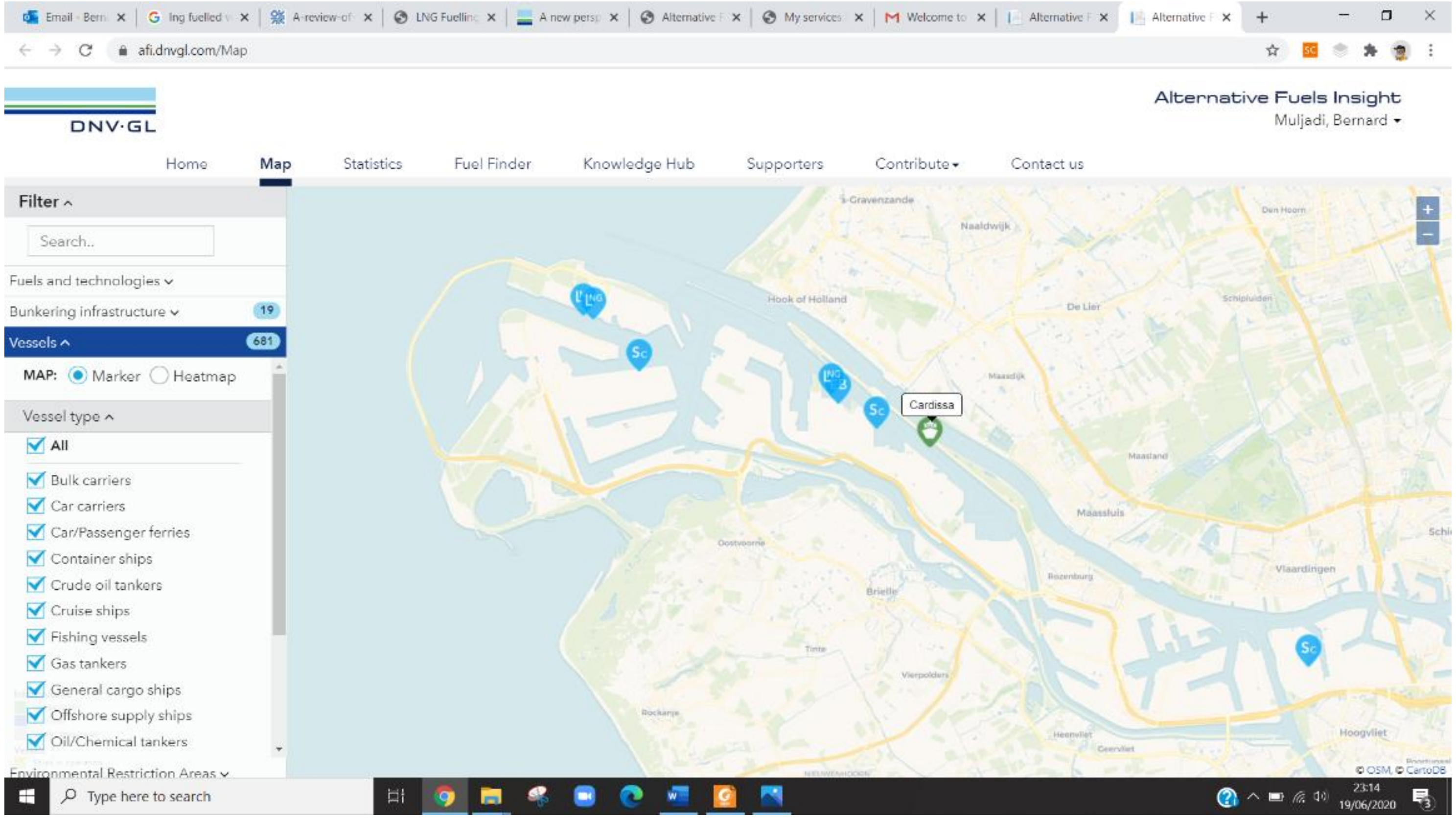
3 Dead ships surcharge 200% of the tariff will be charged.

4 Order/Cancellation/Postponement within two (2) hours of job commencement 50% of the tariff will be charged.

5 Order/Cancellation/Postponement within one (1) hour of job commencement 100% of the tariff will be charged.

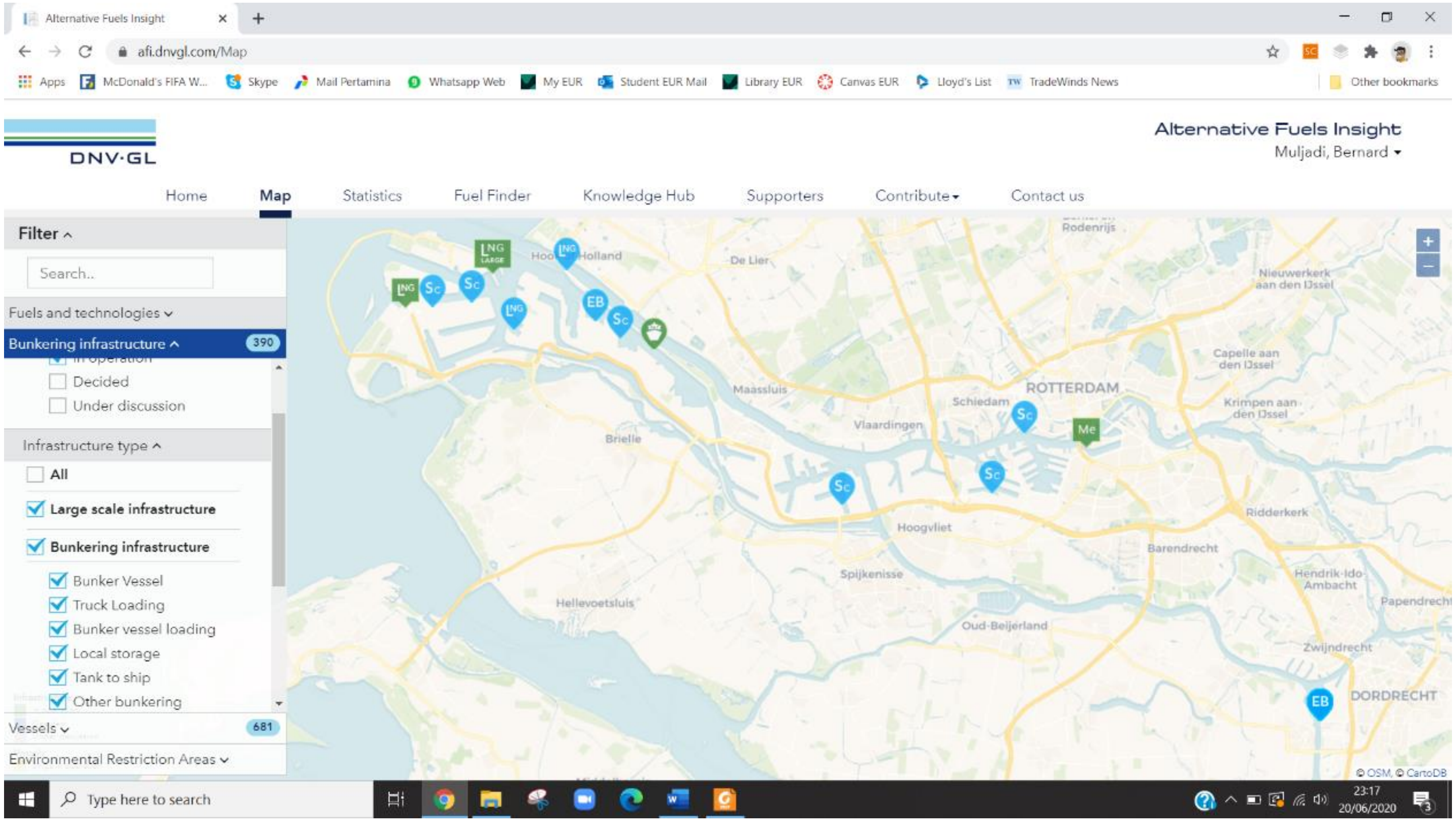
Appendix C – AIS Map Snapshots (DNV GL, 2020) (Marine Traffic, 2020)

Snapshot on 19/06/2020



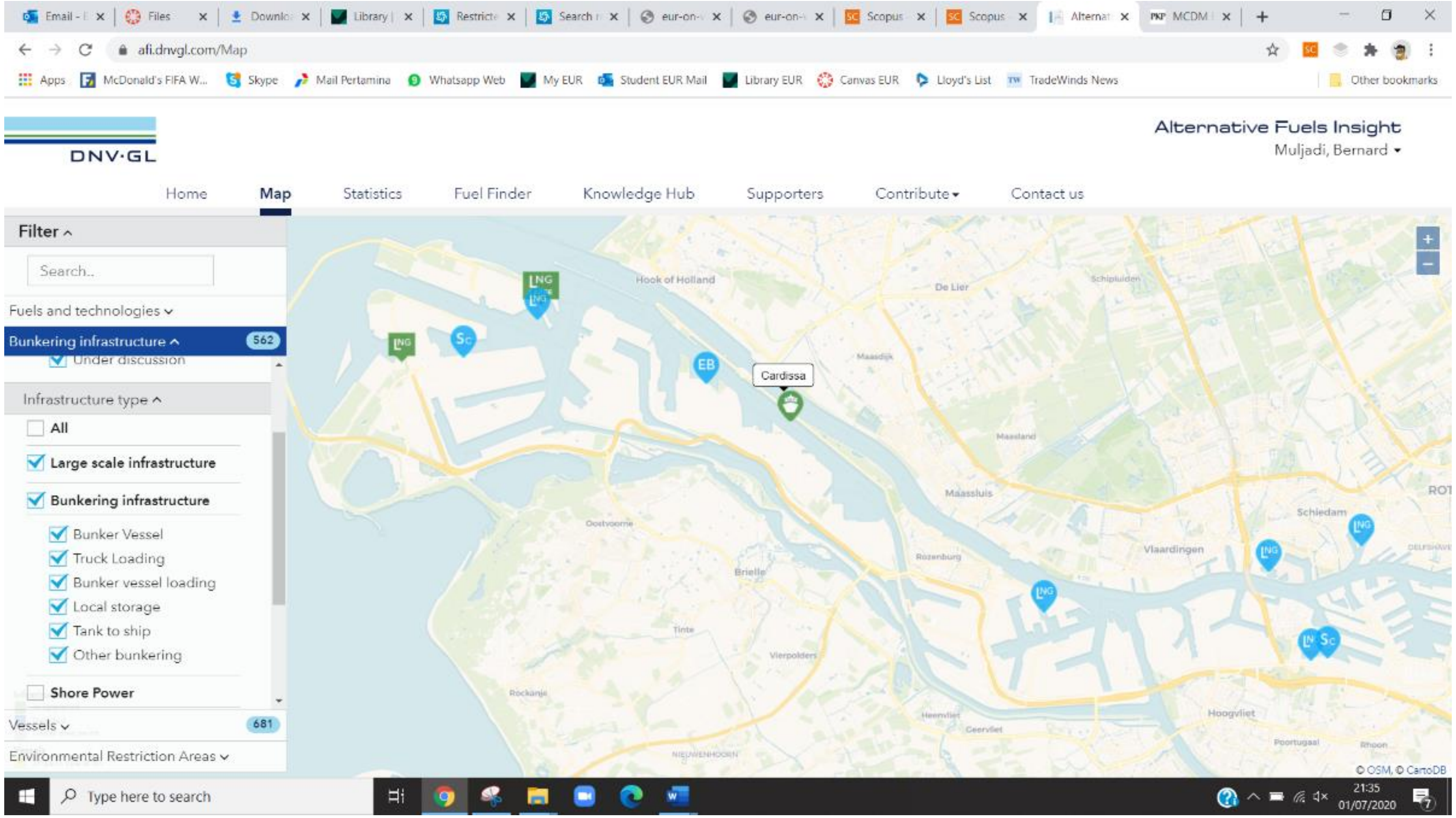
	Date taken	Ship Name	Ship Type	Origin	port	ATD	Current	Berth	ATA	Next Port		move from berth (manual check)	ATD	ETA / ATA	GT
LNG	19/06/2020	Taurus	Container ship	GR	Piraeus	-	Maasvlakte I	Euromax	18/06/2020 17:39	Piraeus	GR	-	-	27/06/2020 21:00	149,210
LNG	19/06/2020	Cosco Shipping Univer:	Container ship	-	-	-	Maasvlakte I	Euromax	-	Suez Canal	EG	19/06/2020 17:50	19/06/2020 20:59	27/06/2020 22:00	201,000
LNG	19/06/2020	NS Pride	Tanker (Oil, Chemical	-	-	-	Europoort	Shell (4e petrole	-	Vysotsk	RU	20/06/2020 08:30	20/06/2020 10:52	24/06/2020 20:00	25,467

Snapshot on 20/06/2020 – 21/06/2020



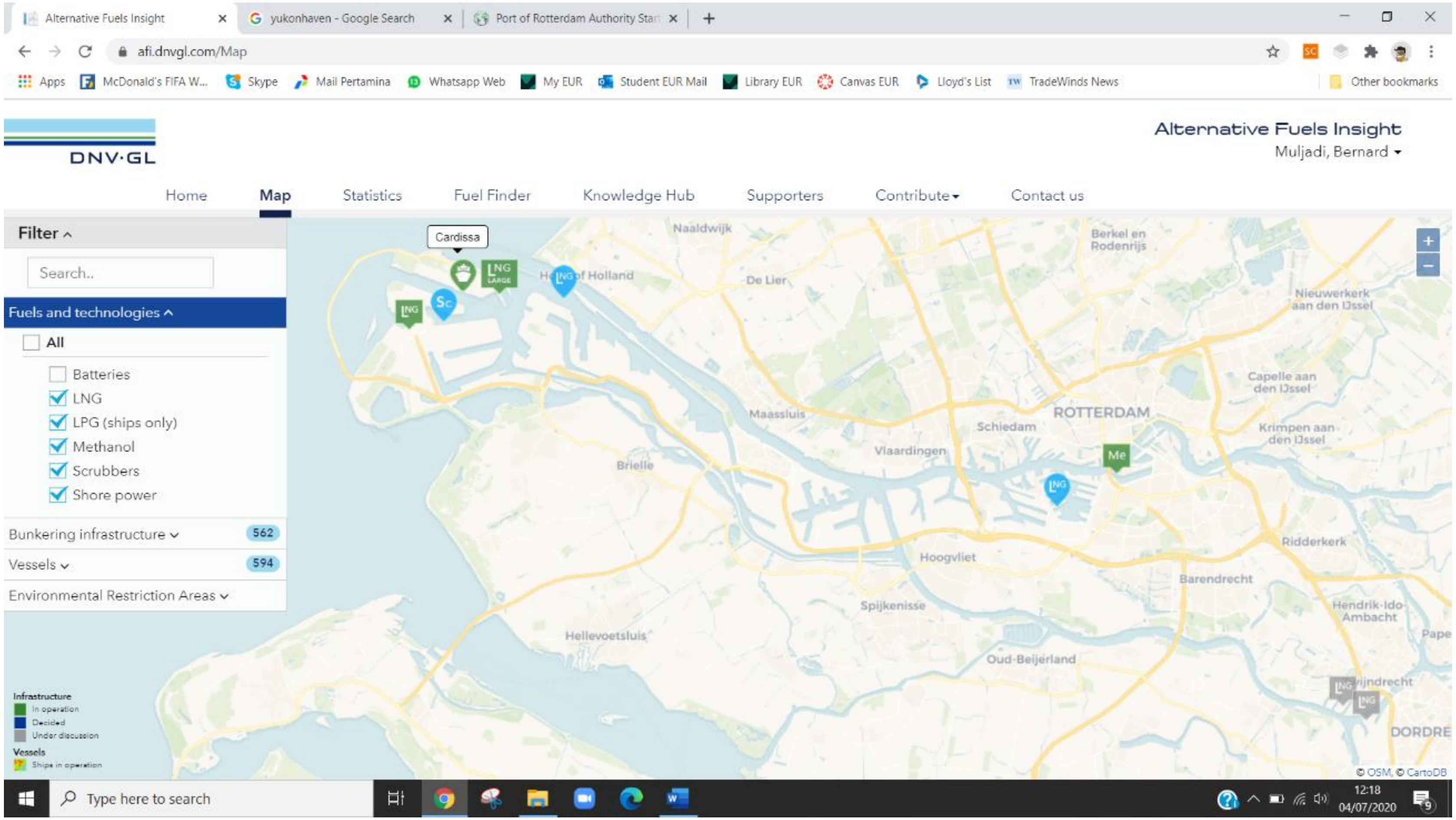
	Date taken	Ship Name	Ship Type	Origin	port	ATD	Current	Berth	ATA	Next Port		move from berth (manual check)	ATD	ETA / ATA	GT
LNG	20/06/2020	Valsinni	Tanker (Inland, Moto	NL	Dordrecht	20/06/2020 08:35	Europoort	6e petroleumha	20/06/2020 10:14	Dordrecht	NL	20/06/2020 15:40	20/06/2020 15:45	20/06/2020 18:40	-
LNG	20/06/2020	-	*Other activities*	-	-	-	Europoort	Breeddiep - Nieu	-	-	-	-	-	-	-
SC	20/06/2020	Santa Rita	Container ship	ES	Algeciras	17/06/2020 07:08	Maasvlakte I	Europahaven	20/06/2020 03:04	Thames LBP	GB	20/06/2020 23:48	21/06/2020 02:12	21/06/2020 08:00	85,676
SC	20/06/2020	MSC Anisha R	Container ship	BE	Antwerp	-	Maasvlakte I	Europahaven	20/06/2020 12:31	Bremerhave	DE	-	21/06/2020 00:13	21/06/2020 20:30	45,803
SC	20/06/2020	TORC	Tanker (Oil, Chemical	NL	Ijmuiden	19/06/2020 18:22	Botlek	3e petroleumha	20/06/2020 00:30	Gotteborg	SE	20/06/2020 20:10	20/06/2020 22:32	22/06/2020 22:00	8,391
SC	20/06/2020	ELBCARRIER	Container ship	-	-	-	Waalhaven	Pr. Margriethave	20/06/2020 16:08	Dublin	IE	21/06/2020 05:10	21/06/2020 07:24	22/06/2020 22:00	8,246

Snapshot on 01/07/2020



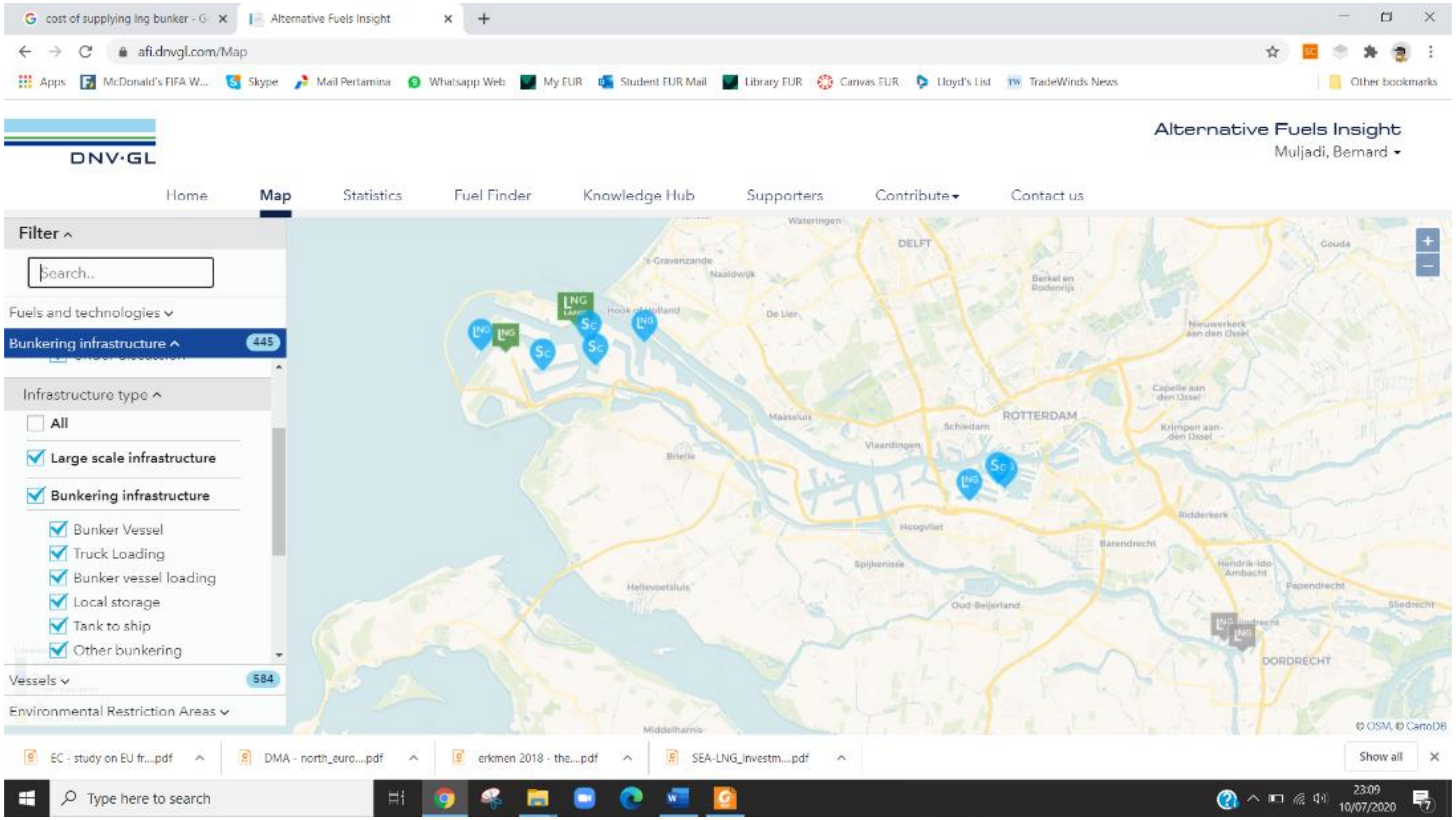
	Date take	Ship Name	Ship Type	Orig	port	ATD	Current	Berth	ATA	Next Por		move from berth (manual check)	ATD	ETA / ATA	GT
SC	01/07/2020	Elke	Container Ship				Maasvlakte I	Europahaven	29/06/2020 21:17	-	-	-	-	-	9,701
LNG	01/07/2020	Oraholm	Crude oil tankers	NL	Vondelling	28/06/2020 10:07	Botlek	Torontohaven (\	28/06/2020 10:09	-	-	-	-	-	3,709
LNG	01/07/2020	Deo Confidentes	Inland Cargo / Conta	NL	Vlissingen	30/06/2020 17:09	Waalhaven	Prins Willem-Ale	01/07/2020 03:52	-	-	-	-	-	-
SC	01/07/2020	Fenny I	Inland Container Ves	NL	Vondelling	01/07/2020 11:42	Waalhaven	Prins Willem-Ale	01/07/2020 11:47	-	-	-	-	-	-
LNG	01/07/2020	Scombrus	Gas Tanker / Trawler	NL	Schiedam	28/04/2020 09:50	Vlaardingen	Wiltonhaven	28/04/2020 09:53	-	-	-	-	-	4,025
LNG	01/07/2020	Amelie 2	*Other activities*	NL	Schiedam	01/07/2020 12:19	Waalhaven	Merwehaven	01/07/2020 12:20	Antwerp	BE	-	-	-	-

Snapshot on 04/07/2020



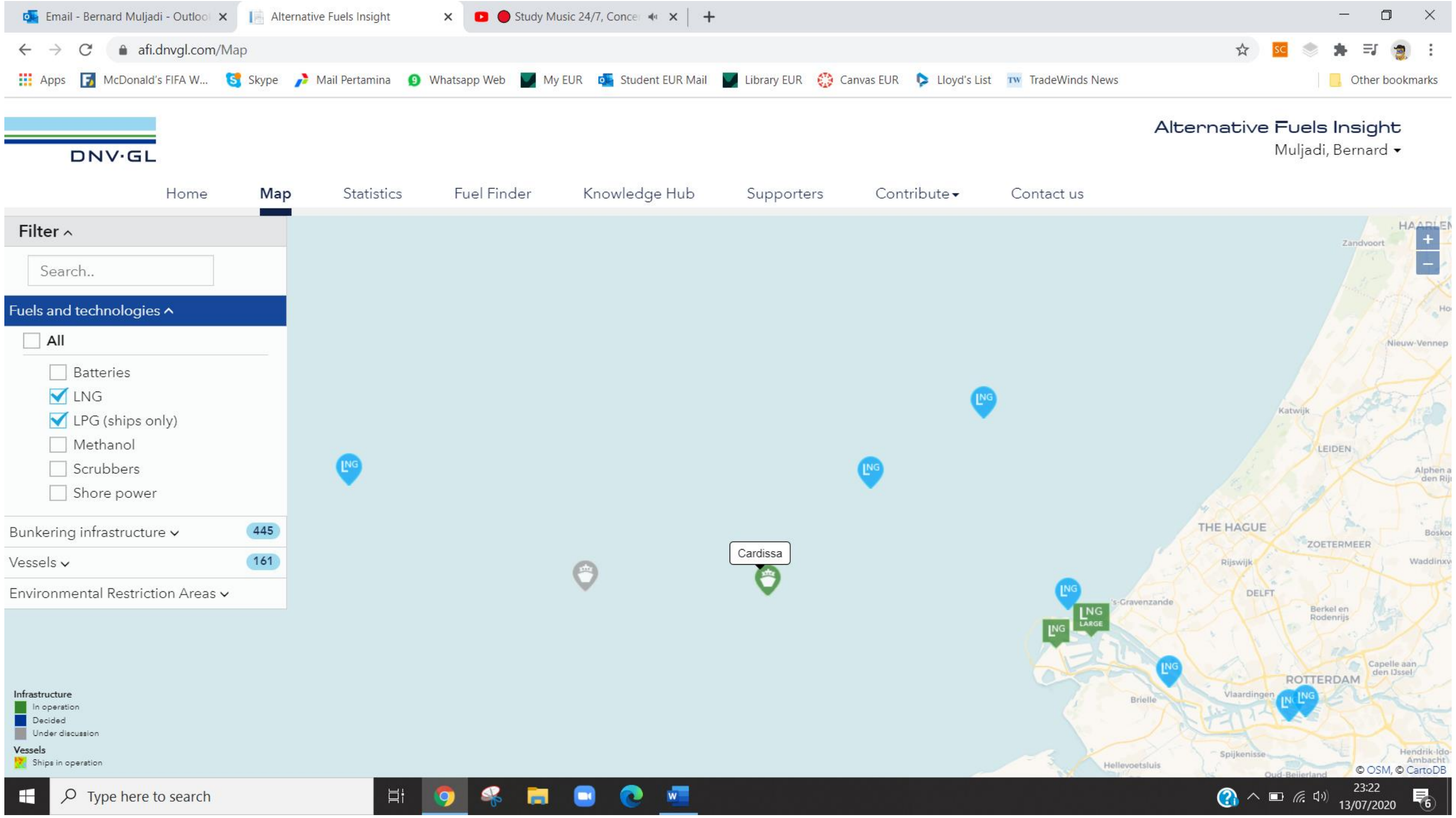
	Date take	Ship Name	Ship Type	Orig	port	ATD	Current	Berth	ATA	Next Por		move from berth (manual check)	ATD	ETA / ATA	GT
LNG	04/07/2020	Sefarina	LPG Tanker	NL	Schiedam	29/06/2020 14:18	Waalhaven	Ophemer	29/06/2020 14:25	-	-				2938
LNG	04/07/2020	-	*Other activities*	-	-	-	Europoort	Breeddiep - Nieu	-	-	-	-	-	-	-
SC	04/07/2020	Maersk Esmeraldas	Container ship	GB	Felixtowe	03/07/2020 20:24	Maasvlakte I	Europahaven	04/07/2020 06:46	-	-	-	-	-	141754

Snapshot on 10/7/2020



	Date take	Ship Name	Ship Type	Orig	port	ATD	Current	Berth	ATA	Next Por		move from berth (manual check)	ATD	ETA / ATA	GT
LNG	10/07/2020	Sajir	*Container ship*	-	-	-	Maasvlakte II	RWG	10/07/2020 20:21	*Suez Canal*	EG	-	-	-	153148
LNG	10/07/2020	-	*Other activities*	-	-	-	Europoort	Breeddiep - Nieu	-	-	-	-	-	-	-
SC	10/07/2020	Brunello	Tanker (Inland, Moto	NL	Botlek	10/07/2020 03:51	Europoort	6e petroleumha	10/07/2020 03:52	-	-	-	-	-	-
SC	10/07/2020	MSC Antalya	*Container ship*	NL	anchorage	10/07/2020 00:04	Maasvlakte I	Amazonehaven	10/07/2020 01:17	-	-	-	-	-	94402
LNG	10/07/2020	Containerships VI	*Container ship*	LT	Klaipeda	06/07/2020 10:07	Waalhaven	Prins Willem-Ale	10/07/2020 02:59	-	-	-	-	-	9953
SC	10/07/2020	BG Diamond	*Container ship*	-	-	-	Waalhaven	pier 7	03/07/2020 08:45	Europoort	NL	-	13/07/2020 05:00	-	12831
LNG	10/07/2020	Sefarina	LPG Tanker	NL	Schiedam	29/06/2020 14:18	Waalhaven	Ophemer	29/06/2020 14:25	-	-	-	-	-	2938

Snapshot on 13/07/2020



	Date take	Ship Name	Ship Type	Orig	port	ATD	Current	Berth	ATA	Next Por		move from berth (manual check)	ATD	ETA / ATA	GT
LNG	13/07/2020	*2 container ships at anchorage area*													
LNG	13/07/2020	Iguazu	*Dredger*	NL	Maasvlakte	10/07/2020 15:30	Maasvlakte	hook of holland	dredging	-	-	-	-	-	499
LNG	13/07/2020	Torm Gyda	Tanker (Oil, Chemical	-	-	-	Europoort	7e petroleumha	12/07/2020 11:25	La Pallice	FR	-	-	16/07/2020 13:00	23332
LNG	13/07/2020	Green Mountain	General Cargo	ES	Vigo	10/07/2020 16:51	Waalhaven	Eemhaven	13/07/2020 08:42	-	-	-	-	-	30469
LNG	13/07/2020	Sefarina	LPG Tanker	NL	Schiedam	29/06/2020 14:18	Waalhaven	Ophemer	29/06/2020 14:25	-	-	-	-	-	2938

Appendix D - Specifications of existing LNG bunkering vessels in Port of Rotterdam

As mentioned in World Maritime News (Port of Rotterdam Points to Rise in LNG Bunkering, 2020), currently there are three permanent LNG bunkering vessels operated in the Port of Rotterdam while there are further four LNG bunker specialist licensed to operate in the Port of Rotterdam, in which in Rotterdam

a) Cardissa
   - LoA x Breadth : 119.94 m x 19.4 m
   - DWT (GT) : 5320 (9816)
   - Capacity : 6,500 m3 (2 tanks IMO type C)
   - Bunkering rate : max 1,100 m3/h
   - Type : LNG (bunkering) Tanker
   - Station : Gate Terminal, Port of Rotterdam
   - Owner : Shell Western LNG

b) FlexFueler 001
   - LoA x Breadth : 76.4 m x 11.45 m
   - Capacity : 4 x 370 m3 – IMO type C vacuum insulated tanks
   - Bunkering rate: 30 – 450 m3 / h
   - Type : non self-propelled barge / pontoon
   - Owner : Titan LNG
   - Station : Port of Amsterdam

c) Coralius
   - LoA x Breadth : 99.6 m x 17.84 m
   - DWT (GT) : 3,077 (5921)
   - Capacity : 5,800 m3 (2 tanks IMO Type C)
   - Bunkering rate : max 1000 m3/h
   - Type : LNG (bunkering) Tanker
   - Station : Skangas Brofjorden Terminal, Skagerrak - Norway
   - Owner : Sirius Veder Gas AB

Appendix E - Scenario Details

Scenario 1

Task loc.	Ship Types	ATA	ETD / ATD	Berth Time (hrs)	Bunkering Time (hrs)	Calculated time window: Earliest start (mins)	Calculated time window: Latest Start (mins)	Calculated time window: ETD (mins)
i, j				*TW*	s_i	a_i	b_i	
C	Large Container (10,000 m³)	30/06/2020 17:39	01/07/2020 07:39	14	10	630	870	1470
G	Small Tanker (2,000 m³)	30/06/2020 10:09	01/07/2020 00:09	14	3	180	840	1020
H	Large Freight Vessel (4,000 m³)	01/07/2020 12:20	02/07/2020 02:20	14	4	1751	2351	2591

		In Date	**In minutes**
Earliest arrival (task G)	:	30/06/2020 10:09	180
Start operation time	:	30/06/2020 07:09	0

*Assumed as 3 hours prior to the earliest ship

Scenario 1 solution

		Location (*i,j*)**	**#**	**C**	**G**	**H**	**Demand (q_i)**
Routing		#	0	1	1	0	-
Routing		C	1	0	0	0	10,000
Routing		G	0	0	0	1	2,000
Routing		H	1	0	0	0	4,000
Scheduling	Arrival Time (p_i^k)	*k=1*	105*	-	-	-	
Scheduling	Arrival Time (p_i^k)	*k=2*	225*	-	-	-	
Scheduling	Arrival Time (p_i^k)	*k=3*	285*	-	-	-	
Scheduling	Arrival Time (p_i^k)	*k=4*	645*	657	1922 (late)	2142	
Scheduling	Arrival Time (p_i^k)	*k=4*	17:54*	18:06	15:27 +1 day	17:56 +1 day	
Scheduling	Arrival Time (p_i^k)	*k=5*	1245*	-	-	-	
Scheduling	Time Window	a_i	0	630	180	1751	
Scheduling	Time Window	b_i	0	870	840	2351	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue

Total Cost (€ per day)	**158,286**
• Fixed Acquisition Cost	5,125
• Variable Cost = Operational Cost + Loading Cost	145,778
• Penalty Cost	7,383

Scenario 2

Scenario 2 resume

Sc.	**Tasks** (location | volume (m^3))	**Remarks**
2a	A | 2,000;	• For each pair: A, C and G, H, same arrival time and time window length are used. • 2a, 2b, and 2c simulate the problem in a 14 hours' time window, while • 2d, and 2e simulate different time window from loose to the tightest window (bunkering time = berth time)
2b	A, C | 2,000; 2,000	
2c	A, C, G, H | 2,000; 2,000; 4,000; 4,000	
2d	A, C, G, H | 2,000; 2,000; 4,000; 4,000	
2e	A, C, G, H | 10,000; 10,000; 20,000; 20,000	

Scenario 2a

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180 and 630	900 and 1350

Scenario 2a solutions

	Location (i,j)	#	A	Demand (q_i)
Routing	#	0	1	-
	A	1	0	2,000
Arrival Time (p_i^k)	$k=1$	105*	-	
	$k=2$	225*	264	
	$k=3$	285*	-	
	$k=4$	645*	684	
	$k=5$	1245*	-	
Time Window	a_i	0	180 / 630	
	b_i	0	900 /1350	

Note:
* Ready Time / Time after finished loading at the depot
**Note: the results for the second time window → yellow

Total Cost	**26,167 / 30,014**
• Fixed Acquisition Cost	3,500 / 5,125
• Variable Cost = Operational Cost + Loading Cost	22,667 / 24,889
• Penalty Cost	-

Scenario 2b

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180	900
C	2000	14	2	0.14	180	900

Scenario 2b solution

	Location (i,j)	**#**	**A**	**C**	**Demand (q_i)**
Routing	#	0	0	1	-
	A	1	0	0	2,000
	C	0	1	0	2,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	
	k=2	225*	-	-	
	k=3	285*	444	297	
	k=4	645*	-	-	
	k=5	1245*	-	-	
Time Window	a_i	0	180	180	
	b_i	0	900	900	

Note:
* Ready Time / Time after finished loading at the depot

Total Cost	**42,944**
• Fixed Acquisition Cost	4,000
• Variable Cost = Operational Cost + Loading Cost	38,944
• Penalty Cost	-

Scenario 2c

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	2000	14	2	0.14	180	900
C	2000	14	2	0.14	180	900
G	4000	14	4	0.28	1451	2051
H	4000	14	4	0.28	1451	2051

Scenario 2c solution

	Location (*i,j*)	**#**	**A**	**C**	**G**	**H**	**Demand (q_i)**
Routing	#	0	0	1	1	0	-
	A	1	0	0	0	0	2,000
	C	0	1	0	0	0	2,000
	G	0	0	0	0	1	4,000
	H	1	0	0	0	0	4,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	
	k=2	225*	-	-	-	-	
	k=3	285*	-	-	-	-	
	k=4	645*	804	657	1676	1956	
	k=5	1245*	-	-	-	-	
Time Window	a_i	0	180	180	1451	1451	
	b_i	0	900	900	2051	2051	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue

Total Cost	**118,903**
• Fixed Acquisition Cost	5,125
• Variable Cost = Operational Cost + Loading Cost	113,778
• Penalty Cost	-

Scenario 2d

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		*TW*	s_i	S_i/TW	a_i	b_i
A	2000	*14 to 2*	2	0.1 to 1	180	vary
C	2000	*14 to 2*	2	0.1 to 1	180	vary
G	4000	*14 to 4*	4	0.1 to 1	1451	vary
H	4000	*14 to 4*	4	0.1 to 1	1451	vary

Scenario 2d solution (s_i/TW = 1)

	Location *(i,j)*	**#**	**A**	**C**	**G**	**H**	**Demand (q_i)**
Routing	#	0	0	1	0	0	-
	A	0	0	0	0	1	2,000
	C	0	1	0	0	0	2,000
	G	1	0	0	0	0	4,000
	H	0	0	0	1	0	4,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	
	k=2	225*	-	-	-	-	
	k=3	285*	-	-	-	-	
	k=4	645*	-	-	-	-	
	k=5	1245*	1404 (late)	1257 (late)	1997 (late)	1717 (late)	
Time Window	a_i	0	180	180	1451	1451	
	b_i	0	180	180	1451	1451	

Note:
* Ready Time / Time after finished loading at the depot

Total Cost	**147,710**
• Fixed Acquisition Cost	7,125
• Variable Cost = Operational Cost + Loading Cost	107,667
• Penalty Cost	32,918

All of the scenarios in scenario 2d are simulated in AIMMS. To be short the following table shows the comparison of all results:

Si / TW	**No. of late task**	**Assigned fleet (k)**	**Fixed Cost**	**Variable Cost**	**Penalty Cost**	**Total Cost**
0.9 – 1	4	5	7,125	107,667	32,918	147,710
0.5 – 0.8	3	5	7,125	107,667	23,842	138,634
0.3 – 0.4	2	5	7,125	107,667	14,766	129,558
0.2	1	4 (2 tours)	5,125	113,778	7,383	126,286
0.1	0	4 (2 tours)	5,125	113,778	0	118,903 (= scenario 2c)

Scenario 2e

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Bunkering time / berth time	Earliest Start (min)	Latest start (min)
i		TW	s_i	S_i/TW	a_i	b_i
A	10,000	*45 to 9*	9	0.21 to 1	180	vary
C	10,000	*45 to 9*	9	0.21 to 1	180	vary
G	20,000	*85 to 18*	18	0.21 to 1	1451	vary
H	20,000	*85 to 18*	18	0.21 to 1	1451	vary

Scenario 2e solution (s_i/TW = 1)

	Location (*i,j*)	**#**	**A**	**C**	**G**	**H**	**Demand (q_i)**
Routing	#	0	1	0	1	1	-
	A	0	0	1	0	0	10,000
	C	1	0	0	0	0	10,000
	G	1	0	0	0	0	20,000
	H	1	0	0	0	0	20,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	
	k=2	225*	-	-	-	-	
	k=3	285*	-	-	-	-	
	k=4	645*	-	-	-	-	
		645*	-	-	-	-	
	k=5	1245*	1284 (late)	1851 (late)	3716 (late)	4956 (late)	
		1245*	-	-	-	-	
Time Window	a_i	0	180	180	1451	1451	
	b_i	0	180	180	1451	1451	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue, third tour → green

Total Cost	**591,434**
• Fixed Acquisition Cost	7,125
• Variable Cost = Operational Cost + Loading Cost	515,001
• Penalty Cost	69,308

All of the scenarios in scenario 2e are simulated in AIMMS. To be short the following table shows the comparison of all results:

Si / TW	**No. of late task**	**Assigned fleet (k)**	**Fixed Cost**	**Variable Cost**	**Penalty Cost**	**Total Cost**
0.4 – 1	4	5 (3 tours)	7,125	515,001	69,308	591,434
0.39	2	4 (1 tour) and 5 (3 tours)	12,250	523,890	34,654	570,794
0.34 – 0.38	1	4 (1 tour) and 5 (3 tours)	12,250	523,890	12,710	548,850
0.32 – 0.33	0	4 (1 tour) and 5 (3 tours)	12,250	523,890	0	536,140
0.25 – 0.3	1	5 (3 tours)	7,125	515,001	12,710	534,836
0.21 – 0.24	0	5 (3 tours)	7,125	515,001	0	522,126
<0.21	*N/A*, since berth time is higher than 85 hours					

Scenario 3

Scenario 3a:

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A	2,000	14	2	630	1350
6	2,000	14	2	630 / 2000	1350 / 2720
C	2,000	14	2	180	900
G	4,000	14	4	1451	2051
H	4,000	14	4	1751	2351

Scenario 3a-i solution

	Location (i,j)	**#**	**A**	**C**	**G**	**H**	**Demand (q_i)**
Routing	#	0	0	1	1	0	-
	A	1	0	0	0	0	2,000
	C	0	1	0	0	0	2,000
	G	0	0	0	0	1	4,000
	H	1	0	0	0	0	4,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	
	k=2	225*	-	-	-	-	
	k=3	285*	-	-	-	-	
	k=4	645*	804	657	1676	1956	
	k=5	1245*	-	-	-	-	
Time Window	a_i	0	630	180	1451	1751	
	b_i	0	1350	900	2051	2351	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue

Total Cost	**118,903**
• Fixed Acquisition Cost	5,125
• Variable Cost = Operational Cost + Loading Cost	113,778
• Penalty Cost	-

Scenario 3a-ii solution

	Location (i,j)	**#**	**A**	**C**	**6**	**G**	**H**	**Demand (q_i)**
Routing	#	0	1	1	0	0	0	-
	A	0	0	0	0	1	0	2,000
	C	0	0	0	1	0	0	2,000
	6	1	0	0	0	0	0	2,000
	G	0	0	0	0	0	1	4,000
	H	1	0	0	0	0	0	4,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	-	
	k=2	225*	-	-	-	-	-	
	k=3	285*	-	297	686	-	-	
	k=4	645*	-	-	-	-	-	
	k=5	1245*	1284	-	-	1557	1837	
Time Window	a_i	0	630	180	630	1451	1751	
	b_i	0	1350	900	1350	2051	2351	

Note:
* Ready Time / Time after finished loading at the depot

Total Cost		141,736
• Fixed Acquisition Cost		11,125
• Variable Cost = Operational Cost + Loading Cost		130,611
• Penalty Cost		-

Scenario 3a-iii solution

	Location (*i,j*)	#	A	C	6	G	H	Demand (q_i)
Routing	#	0	0	1	0	1	0	-
	A	1	0	0	0	0	0	2,000
	C	0	1	0	0	0	0	2,000
	6	1	0	0	0	0	0	2,000
	G	0	0	0	0	0	1	4,000
	H	0	0	0	1	0	0	4,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	-	
	k=2	225*	-	-	-	-	-	
	k=3	285*	-	-	-	-	-	
	k=4	645*	804	657	2380	1676	1956	
	k=5	1245*	-	-	-	-	-	
Time Window	a_i	0	630	180	2000	1451	1751	
	b_i	0	1350	900	2720	2051	2351	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij}) → yellow, Second Tour (Z_{ij}) → blue

Total Cost		134,903
• Fixed Acquisition Cost		5,125
• Variable Cost = Operational Cost + Loading Cost		129,778
• Penalty Cost		-

Scenario 3b

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A + B	2,000 + 2,000	14	2	630	1350
C + D	2,000 + 2,000	14	2	180	900
G + F	4,000 + 4,000	14	4	1451	2051
H + E	4,000 + 4,000	14	4	1751	2351

Scenario 3b solution

	Location *(i,j)*	**#**	**A**	**C**	**B**	**G**	**H**	**F**	**E**	**D**	**Demand (q_i)**
Routing	#			1		1		1			-
	A				1						2,000
	C									1	2,000
	B	1									2,000
	G								1		4,000
	H	1									4,000
	F						1				4,000
	E	1									4,000
	D		1								2,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	-	-	-	-	-	
	k=2	225*	-	-	-	-	-	-	-	-	
	k=3	285*	-	-	-	-	-	-	-	-	
	k=4	645*	947	657	1120	-	2345	1903	-	788	
		645*	-	-	-	1967	-	-	2351	-	
	k=5	1245*	-	-	-	-	-	-	-	-	
Time Window	a_i	0	630	180	630	1451	1751	1451	1751	180	
	b_i	0	1350	900	1350	2051	2351	2051	2351	900	

Note:
* Ready Time / Time after finished loading at the depot
Note: First Tour (X_{ij})→ yellow, Second Tour (Z_{ij}) → blue, third tour* → green

Total Cost	**237,806**
• Fixed Acquisition Cost	5,125 (x 2) ***
• Variable Cost = Operational Cost + Loading Cost	218,667 (+8,889)***
• Penalty Cost	-

***Note: Since the algorithm only can accommodate up to 2 tours, so the third tour in the solution is assumed to be considered as an additional vessel with the suitable capacity (k=4, 10,000m^3). The cost of the additional vessel is manually added to the solution.

Scenario 3c.

Berth Location / Task	Volume (m^3)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
I			s_i	a_i	b_i
A	2,000	14	2	630	1350
C	2,000	14	2	180	900
B	10,000	14	9	630	1350

Scenario 3c solution

	Location (*i,j*)	**#**	**A**	**C**	**B**	**Demand (q_i)**
Routing	#	0	1	1	1	-
	A	1	0	0	0	2,000
	C	1	0	0	0	2,000
	B	1	0	0	0	10,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	
	k=2	225*	-	-	-	
	k=3	285*	708	297	-	
	k=4	645*	-	-	659	
	k=5	1245*	-	-	-	
Time Window	a_i	0	630	180	630	
	b_i	0	1350	900	1350	

Note:
* Ready Time / Time after finished loading at the depot
**Note: First Tour (X_{ij})→ yellow, Second Tour (Z_{ij}) → blue

Total Cost	**143,902**
• Fixed Acquisition Cost	9,125
• Variable Cost = Operational Cost + Loading Cost	134,777
• Penalty Cost	-

Scenario 3d.

Berth Location / Task	Volume (m³)	Berth Time (hrs)	Bunkering Time (hrs)	Earlest Start (min)	Latest start (min)
i			s_i	a_i	b_i
A	10,000	14	9	630	1350
C	4,000	14	2	180	900
B	10,000	14	9	630	1350

Scenario 3d solution

	Location *(i,j)*	**#**	**A**	**C**	**B**	**Demand (q_i)**
Routing	#	0	1	0	1	-
	A	1	0	0	0	10,000
	C	1	0	0	0	2,000
	B	0	0	1	0	10,000
Arrival Time (p_i^k)	*k=1*	105*	-	-	-	
	k=2	225*	-	-	-	
	k=3	285*	-	-	-	
	k=4	645*	684	-	-	
	k=5	1245*	-	1825 (late)	1259	
Time Window	a_i	0	630	180	630	
	b_i	0	1350	900	1350	

Note:
* Ready Time / Time after finished loading at the depot

Total Cost	**143,902**
• Fixed Acquisition Cost	12,250
• Variable Cost = Operational Cost + Loading Cost	196,556
• Penalty Cost	7,383

Appendix F – Manual Solving Step Scenario 1

Step 1

Start Time Calculation & Earliest arrival on 1st location calculation

Step 2

Manual Forward Scheduling for each feasible vessel

Step 3

Feasible Routes and Costs Evaluation

k=5 (20,000)

Step 1

Start time / finished loading at depot

po 1245

Earliest arrival to first location

pi	#	C	G	H
#	0	1257.00	1358.00	1751.00

= Depot

Step 2 — k=5 (20,000)

#-C/G/H

pi	#	C	G	H
#	0	1257	1358	1751

#-C-G/H

pi	#	C	G	H
C	1809	0	1922	1962

#-G-C/H

pi	#	C	G	H
G	1591	1603	0	1751

#-C

pj	#	C	G	H
C	1809	0	1922	1962
G	2155	-	-	2082
H	2355	-	2242	-

#-C-G

pj	#	C	G	H
G	2155	-	-	2082
H	2475	-	-	-

1st feasible route: #-C-G-H-#

#-G-C

pj	#	C	G	H
C	2155	-	-	2308
H	2701	-	-	-

3rd feasible route: #-G-C-H-#

#-G

pj	#	C	G	H
G	1591	1603	0	1751
C	2155	-	-	2308
H	2144	2156	-	-

#-C-H

pj	#	C	G	H
H	2355	-	2242	-
G	2475	-	-	-

2nd feasible route: #-C-H-G-#

#-G-H

pj	#	C	G	H
H	2144	2156	-	-
C	2708	-	-	-

4th feasible route: #-G-H-C-#

#-H

i,j	#	C	G	H
H	2144	2156	2031	0
C	*late*			
G	*late*			

Step 3 — k=5 (20,000)

Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	(-fixed cost)
#-C-G-H-#	7,125	139,667	21,786	168,578	167,786
#-G-C-H-#	7,125	139,667	21,786	168,578	167,786
#-C-H-G-#	7,125	139,667	21,786	168,578	167,786
#-G-H-C-#	7,125	139,667	21,786	168,578	167,786

k=4 (10,000)

Step 1

Start time / finished loading at depot

po 645

Earliest arrival to first location

pi	#	C	G	H
#	0	657	758	1751

= Depot

Step 2 — k=4 (10,000)

1st route

#-C-#

pi	#	C	G	H
#	0	657	758	1751
C	1209	0	1322	1751

2nd route

#-G/H

pi	#	C	G	H
#	-	-	2522	2562

pi	#	C	G	H
G	2755.00	-	-	2682.00
H	2955.00	-	2842.00	-

1st feasible route: #-C-# + #-G-H-#

2nd feasible route: #-C-# + #-H-G-#

Step 3 — k=4 (10,000)

Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	(-fixed cost)	unmet demand
#-C-#	5,125	88,889	-	94,014	93,445	7,000
#-C-# + #-G-H-#	5,125	145,778	7,383	158,286	157,717	-
#-C-# + #-H-G-#	5,125	145,778	7,383	158,286	157,717	-

Step 1

Start Time Calculation & Earliest arrival on 1st location calculation

Step 2

Manual Forward Scheduling for each feasible vessel

Step 3

Feasible Routes and Costs Evaluation

k=3 (4,000)

Start time / finished loading at depot

po 285

Earliest arrival to first location

pi	#	C	G	H
#	0	1059	609	2180

k=3 (4,000)

1st route

#-H-#

pi	#	C	G	H
#	0	1059	609	2180
H	2573	2585	2460	0

or

#-G-#

pi	#	C	G	H
#	0	1059	609	2180
G	842	1059	0	2180

2nd route

#-H-# + #-G-#

pi	#	C	G	H
#	-	-	3493	-
G	3726	-	-	-

#-G-# + #-H-#

pi	#	C	G	H
#	-	-	-	1962
H	2355	-	-	-

k=3 (4,000)

Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	(-fixed cost)	unmet demand
#-H-#	4,000	38,944	-	42,944	42,500	13,000
#-G-#	4,000	22,944	-	26,944	26,500	14,000
#-H-# + #-G-#	4,000	68,832	7,383	80,215	79,771	10,000
#-G-# + #-H-#	4,000	68,832	-	72,832	72,388	10,000

k=2 (3,000)

Start time / finished loading at depot

po 225

Earliest arrival to first location

pi	#	C	G	H
#	0	1059	609	2180

k=2 (3,000)

#-G-#

pi	#	C	G	H
#	0	1059	609	2180
G	842	1059	0	2180

k=2 (3,000)

Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	(-fixed cost)	unmet demand
#-G-#	3,500	22,667	-	26,167	25,778	14,000

Resume on Feasible Routes' Costs Evaluation

Fleet (k)	Type	Feasible Routes	Fixed Cost	Ops Cost	Penalty	Total Cost	unmet demand
5	20,000m3	#-C-G-H-#	7,125	139,667	21,786	168,578	-
		#-G-C-H-#	7,125	139,667	21,786	168,578	-
		#-C-H-G-#	7,125	139,667	21,786	168,578	-
		#-G-H-C-#	7,125	139,667	21,786	168,578	-
4	10,000m3	#-C-#	5,125	88,889	-	94,014	6,000
		#-C-# + #-G-H-#	5,125	145,778	7,383	158,286	-
		#-C-# + #-H-G-#	5,125	145,778	7,383	158,286	-
3	4,000 m3	#-H-#	4,000	38,944	-	42,944	12,000
		#-G-#	4,000	22,944	-	26,944	14,000
		#-H-# + #-G-#	4,000	68,832	7,383	80,215	10,000
		#-G-# + #-H-#	4,000	68,832	-	72,832	10,000
2	3,000 m3	#-G-#	3,500	22,667	-	26,167	14,000
4 & 3		#-C-#	5,125	88,889	-		
		#-G-# + #-H-#	4,000	68,832	-	+	
			9,125	157,721	-	166,846	-

Appendix G – AIMMS Main Model

```
Model Main_Bunkering_FSMVRP_Thesis_BM {
	Parameter LocationNumbers {
		Text: "Number of Tasks";
		Range: integer;
		InitialData: 5;
	}
	Parameter FeasibleVehicleNumbers {
		Text: "Number of bunkering vessels capacble to serve the tasks";
		Range: integer;
		InitialData: 5;
	}
	Set BerthLocations {
		SubsetOf: Integers;
		Index: i, j, h;
		Definition: {
			{0..LocationNumbers}
		}
	}
	Set Vehicle {
		SubsetOf: Integers;
		Index: k;
		Definition: {
			{1..FeasibleVehicleNumbers}
		}
	}
	Parameter OpsCost_c {
		IndexDomain: (k,i,j);
		Text: "Daily Operation Cost (per deployment) + Loading Cost per tasks
volume";
	}
	Parameter FixedAcquisitionCost_f {
		IndexDomain: k;
		Text: "Vessel Fixed Cost";
	}
	Parameter LoadingTime {
		IndexDomain: k;
		Text: "Loading Time per vessel type at depot";
	}
	Parameter TravelTime {
		IndexDomain: (i,j);
	}
	Parameter EarliestStart_a {
		IndexDomain: i;
	}
	Parameter LatestStart_b {
		IndexDomain: i;
	}
	Parameter BunkeringTime_s {
		IndexDomain: i;
	}
	Parameter Demand {
		IndexDomain: (i);
	}
	Parameter PenaltyMultiplier_miu {
		IndexDomain: i;
	}
	Parameter FleetCapacity_q {
		IndexDomain: k;
		Text: "Vessel Capacity";
	}
	Parameter M {
		Text: "large numbers";
		Definition: 1000000;
	}
	Variable X {
```

```
		IndexDomain: (k,i,j)|i<>j;
		Text: "Arc indicator 1st route";
		Range: binary;
	}
	Variable Y {
		IndexDomain: (k,i);
		Text: "Vessel assignment";
		Range: binary;
	}
	Variable Z {
		IndexDomain: (k,i,j)|i<>j;
		Text: "Arc Indicator for additional tour";
		Range: binary;
	}
	Variable p {
		IndexDomain: (k,i);
		Text: "Arrival Time";
		Range: nonnegative;
	}
	Variable LateArrival_u {
		IndexDomain: (k,i)|i>0;
		Text: "late indicator";
		Range: binary;
		Default: 0;
	}
	Variable CumServedDemand_r {
		IndexDomain: (i);
		Text: "Cummulative Demand per Route";
		Range: nonnegative;
	}
	Variable EndTime_g {
		IndexDomain: k;
		Text: "Arrival time at depot before reloading for 2nd tour";
		Range: nonnegative;
	}
	Variable StartTime2ndTour {
		IndexDomain: k;
		Text: "Finished loading time at depot before go to 2nd tour";
		Range: nonnegative;
		Definition: EndTime_g(k)+LoadingTime(k);
	}
	Variable TotalCost {
		Range: free;
		Definition: sum((k,i,j)|i = 0 and
j>0,FixedAcquisitionCost_f(k)*X(k,i,j))+sum((k,i,j),(X(k,i,j)+Z(k,i,j))*(OpsCost_c(
k,i,j)))+sum((k,i),LateArrival_u(k,i)*PenaltyMultiplier_miu(i));
	}
	Constraint CustomerVisit1 {
		IndexDomain: (k,j)| j>0;
		Text: "Each customer can only be visited once with one vessel (1/3)";
		Definition: sum(i,X(k,i,j)+Z(k,i,j))=Y(k,j);
	}
	Constraint CustomerVisit2 {
		IndexDomain: (k,i)|i>0;
		Text: "Each customer can only be visited once with one vessel (2/3)";
		Definition: sum(j,X(k,i,j)+Z(k,i,j))=Y(k,i);
	}
	Constraint oneVehicle {
		IndexDomain: i|i>0;
		Text: "Each customer can only be visited once with one vessel (3/3)";
		Definition: Sum(k,Y(k,i))=1;
	}
	Constraint FlowBalance {
		IndexDomain: (i,k)|i>0;
		Text: "Flow conservation constrain / ROute starts and end at depot
(1/2)";
		Definition: sum( j, X(k,i,j) ) - sum( j, X(k,j,i) ) = 0;
	}
```

```
	Constraint FlowBalance2nd {
		IndexDomain: (i,k)|i>0;
		Text: "Flow conservation constrain / ROute starts and end at depot
(2/2)";
		Definition: sum( j, Z(k,i,j) ) - sum( j, Z(k,j,i) ) = 0;
	}
	Constraint SecondTourCondition {
		IndexDomain: k;
		Text: "second tour only can be activated after 1st tour ends";
		Definition: Sum((i,j),Z(k,i,j))<= LocationNumbers *
sum((i,j),X(k,i,j));
	}
	Constraint ArrivalTimeDepot {
		IndexDomain: (k,i)|i=0;
		Text: "Formula for start time / move from station and loading at
depot";
		Definition: p(k,i)= (LoadingTime(k)+45);
	}
	Constraint TimeWindowConstrain {
		IndexDomain: (k,i,j)|j>0 and i<>j;
		Text: "Formula for arrival time regarding the earliest start time";
		Definition: p(k,j)+ M * (1-X(k,i,j)-Z(k,i,j)) >= EarliestStart_a(j);
	}
	Constraint TimeWindowConstrain2 {
		IndexDomain: (k,i,j)|j>0 and i<>j;
		Text: "Formula for arrival time regarding the latest start time";
		Definition: p(k,j)-M*(1-X(k,i,j)-Z(k,i,j)) <= LatestStart_b(j)+
(M*LateArrival_u(k,j));
	}
	Constraint ScheduleFeasibility {
		IndexDomain: (k,i,j)|i>0 and j>0 and i<>j;
		Text: "FOrmula for the feasible arrival time (1/2)";
		Definition: p(k,j) >= p(k,i) + BunkeringTime_s(i) + TravelTime(i,j) -
M * (1 - X(k,i,j)-Z(k,i,j));
	}
	Constraint ScheduleFeasibility2 {
		IndexDomain: (k,i,j)|i>0 and j>0 and i<>j;
		Text: "FOrmula for the feasible arrival time (2/2)";
		Definition: p(k,j) <= p(k,i) + BunkeringTime_s(i) + TravelTime(i,j) +
M * (1 - X(k,i,j)-Z(k,i,j) );
	}
	Constraint ScheduleFeasibilityDepot1stTour {
		IndexDomain: (k,i,j)|i=0 and j>0;
		Text: "FOrmula for the feasible arrival time at first location (1/2)";
		Definition: p(k,j) >= p(k,i)+ TravelTime(i,j) - M * (1 - X(k,i,j));
	}
	Constraint ScheduleFeasibilityDepot1stTour2 {
		IndexDomain: (k,i,j)|i=0 and j>0;
		Text: "FOrmula for the feasible arrival time at first location (2/2)";
		Definition: p(k,j) <= p(k,i)+ TravelTime(i,j) + M * (1 - X(k,i,j));
	}
	Constraint ScheduleFeasibilityEnd1stTour {
		IndexDomain: (k,i,j)|i>0 and j=0;
		Text: "FOrmula for the feasible end time at depot before reloading for
2nd tour (1/2)";
		Definition: EndTime_g(k) >= p(k,i) + BunkeringTime_s(i) +
TravelTime(i,j) - M * (1 - X(k,i,j));
	}
	Constraint ScheduleFeasibilityEnd1stTour2 {
		IndexDomain: (k,i,j)|i>0 and j=0;
		Text: "FOrmula for the feasible end time at depot before reloading for
2nd tour (2/2)";
		Definition: EndTIme_g(k) <= p(k,i) + BunkeringTime_s(i) +
TravelTime(i,j) + M * (1 - X(k,i,j) );
	}
	Constraint ScheduleFeasibilityDepot2ndTour {
		IndexDomain: (k,i,j)|i=0 and j>0;
```

```
            Text: "FOrmula for the feasible arrival time at first location in the 2nd tour (1/2)";
            Definition: p(k,j) >= StartTime2ndTour(k)+ TravelTime(i,j) - M * (1 - Z(k,i,j));
        }
        Constraint ScheduleFeasibilityDepot2ndTour2 {
            IndexDomain: (k,i,j)|i=0 and j>0;
            Text: "FOrmula for the feasible arrival time at first location in the 2nd tour (2/2)";
            Definition: p(k,j) <= StartTime2ndTour(k)+ TravelTime(i,j) + M * (1 - Z(k,i,j));
        }
        Constraint DemandStart {
            IndexDomain: (i)|i=0;
            Text: "Reset point for route demand";
            Definition: CumServedDemand_r(i)=0;
        }
        Constraint RouteDemand {
            IndexDomain: (i,j)|j>0 and i<>j;
            Text: "cummulative demand served up to location j";
            Definition: CumServedDemand_r(j) - CumServedDemand_r(i) >= Demand(j)-(M*(1-sum(k,X(k,i,j))));
        }
        Constraint RouteDemand2ndTour {
            IndexDomain: (i,j)|j>0 and i<>j;
            Text: "2nd tour cummulative demand constrain";
            Definition: CumServedDemand_r(j) - CumServedDemand_r(i) >= Demand(j)-(M*(1-sum(k,Z(k,i,j))));
        }
        Constraint CapacityConstraint {
            IndexDomain: j|j>0;
            Definition: CumServedDemand_r(j)<=sum(k,FleetCapacity_q(k)*Y(k,j));
        }
        MathematicalProgram LeastCost {
            Objective: TotalCost;
            Direction: minimize;
            Constraints: AllConstraints;
            Variables: AllVariables;
            Type: MIP;
        }
        Procedure MainInitialization {
            Comment: "Add initialization statements here that do NOT require any library being initialized already.";
        }
        Procedure MainExecution {
            Body: {
                ShowProgressWindow;


                solve LeastCost;
            }
        }
        Procedure MainTermination {
            Body: {
                return 1;
            }
            Comment: {
                "Add termination statements here that do not require all libraries to be still alive.
                Return 1 to allow the termination sequence to continue.
                Return 0 if you want to cancel the termination sequence.
                It is recommended to only use the procedure PreMainTermination to cancel the termination sequence and let this procedure always return 1."
            }
        }
}
```