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Determining the Optimal Locations for the Development of Onshore LNG Bunkering Facilities

by

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Sincere gratefulness to Jesus Christ, my family, and my support system, for the unconditional love and unfailing support.

Be joyful in hope, patient in affliction, faithful in prayer.
Ad maiorem Dei gloriam.

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Abstract

As the new IMO regulation for reducing global sulphur cap is approaching, LNG gains more popularity since it emits zero sulphur oxides and no particulate matter, with 90% less nitrogen oxides compared to the conventional fuel. However, the limited number of LNG bunkering facilities around the world dampen the usage of LNG as maritime fuel by the shipping lines. On the contrary, ports will not provide LNG bunkering services unless they are sure about the prospect of LNG bunkering demand in their port. The presence of bunkering points becomes really crucial in a long-haul voyage, such as from Asia to Europe that is also known as the busiest shipping route.

These contradictory perspectives motivate this thesis to establish a decision support tool for port authorities and any relevant bunker provider, by creating a generic model to identify the optimal location(s) and required capacity for onshore LNG bunkering stations. The model aims to reach a win-win solution in terms of overall cost occurred by ports and shipping lines as well as to satisfy the refuelling demand of shipping lines, thus accommodating the perspectives of both parties.

A sequential approach of literature review, mixed-integer linear programming, data search, robust optimisation, and economic analysis are introduced to achieve the objective while addressing the unforeseen LNG bunkering demand and the uncertain profitability. Empirical model tested on seven major Asian ports along Asia-Europe ocean lane shows that Busan, Tanjung Pelepas, and Jawaharlal Nehru are potential to provide shore-to-ship LNG bunkering services. The robust optimisation also leads to the same results with slightly higher capacity per port to deal with the fluctuating demand. The optimal solutions are confirmed to be profitable after undergoing a breakeven analysis and capacity optimisation.

Notwithstanding the solutions generated by the model, this thesis primarily provides a general framework to identify potential locations for developing onshore LNG bunkering facilities. The demand of LNG bunker is deemed exogenous; thus, the eagerness and strategic planning from the ports play a role to initiate the LNG bunkering project, to ensure sufficient capacity, and to set a competitive price for attracting shipping lines and boosting the usage of LNG as a cleaner maritime fuel.

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List of Abbreviations

Abbreviation	Remarks
AIMMS	Advanced Interactive Multidimensional Modelling System, a mathematical modelling tool to generate optimal solutions for decision-making purpose [1]
BEP	Breakeven Price
BEQ	Breakeven Quantity
CAPEX	Capital Expenditures
EOQ	Economic Order Quantity
GRG	Generalised Reduced Gradient, an algorithm to solve non-linear programming by using some priority principles on the partition of the variables into basic and independent sets for each period [2]
HFO	Heavy Fuel Oil, a type of fuels used to generate motion and/or heat that have a particularly high viscosity and density [3]
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
LSMGO	Low Sulphur Marine Gas Oil, a type of fuels to generate motion and/or heat with lower viscosity and density compared to HFO [4]
OPEX	Operating Expenditures

Source: [1] Roelofs and Bisschop (2019), [2] Lasdon, Fox, and Ratner (1974), [3] Oiltanking (2015), [4] Oiltanking (2015)

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Chapter 1 Introduction

1.1 Background

Starting from 1 January 2020, International Maritime Organization (IMO) will implement a new regulation to lower global sulphur cap of the maritime fuel from the current limit of 3.5% to 0.5%. With this upcoming provision, called IMO 2020, it is eminent that seaborne transportation moves towards a more sustainable way. The shipping companies, who would be highly impacted by this policy, have several options to reduce their emissions. One of the viable alternatives is by running their ships on liquified natural gas (LNG) instead of other high-sulphur fuels. Most experts believe that the conversion to LNG is the most feasible solution in the medium and long term, as it is cleaner and costs less than using marine gas oil or scrubber (Calderon, Illing, and Veiga, 2016).

However, Corkhill (2018) reveals the next big dilemma: who will convert their ship to be LNG-fuelled while there are only limited LNG bunkering hubs, and which port will build LNG bunkering infrastructure without being sure that there will be enough LNG-fuelled vessels to serve? Hence, the underdeveloped LNG bunkering infrastructure in major bunkering ports become a relevant problem within this context. To solve this chicken-and-egg dilemma, port authorities who currently have no LNG bunkering facilities could take the first move by evaluating the feasibility of LNG bunkering at their ports; then they could decide the development of LNG bunkering facilities accordingly.

According to Aronietis et al. (2017), the main driver to trigger port authorities' initiative is the potential demand for LNG bunker from the shipping carriers. This demand could be estimated from the seaborne trade volume in each port since bunkering is always derived from the port call. It is influenced by shipping liner's behaviour as well, for liners have various criteria to choose their bunkering base, i.e. bunker pricing and port call locations. Beside the bunkering demand, the distribution cost of LNG supply to ports is also a criterion to assess the feasibility of LNG bunkering hub, since port authorities need to maximise the profit gain from selling the bunker while minimising the supply cost of LNG.

Competition among ports along the route becomes another motive to install LNG bunkering utilities immediately. As mentioned earlier, bunkering is correlated with the port call – so a port with LNG bunkering infrastructure is preferable for LNG-fuelled fleets to make calls, thus pulling more income for the port in terms of port dues. Diversification of bunker types to include LNG is also a strategy to attain the status of major bunkering port. With the enactment of IMO 2020, more LNG-fuelled vessels are built, so ports shall be ready to provide LNG bunker to maintain its competitiveness among the others.

In the busiest shipping route from Asia to Europe, lack of LNG bunkering points will be an obstacle for shipping companies to move toward cleaner fuel. Berti (2018) mentioned that the existing LNG bunkering facilities in this route are only concentrated in China, Japan, Spain, and the Netherlands. Since LNG takes more volume than heavy fuel oil, LNG-fuelled vessels require more frequent bunkering and expect more bunkering points along the way, not only at the beginning and the end of a long voyage as their typical strategy for conventional bunker (Kirstein et al., 2018). While the shipping lines intend to shift to LNG without detouring from this major trade route, the relevant port authorities should accommodate LNG-fuelled ships by cooperating with LNG bunker operator and providing sufficient LNG fuels.

This thesis comes up with an idea to identify the optimal locations for developing LNG bunkering facilities along a specific route and the required capacity at each location, based on the estimated bunkering plan of the shipping lines. The optimisation would be a valuable recommendation for port authorities to assess their chance for being an LNG bunkering hub, as well as reinforcing the sustainability of their ports after the commencement of new IMO regulation. Since there has not been any model developed for determining the LNG bunkering locations, this research would also be a worthy contribution to academic learning.

1.2 Research Question

The objective of this thesis is to produce a model for identifying the optimal location(s) to build shore-to-ship bunkering facilities for LNG and the required capacity based on the bunkering behaviour of shipping lines, such that the total cost of the system is minimum.

This objective leads to the following research question:

“How can the optimal location(s) for developing new onshore LNG bunkering hubs be determined to facilitate long-distance cargo voyages, based on the projected LNG bunkering demand after the implementation of IMO 2020?”

The sub-questions below provide details for the main research question:

1. What are the main factors that affect the location of LNG bunkering hubs from the perspective of port authorities?
2. What are the costs elements of developing onshore LNG bunkering hubs?
3. How can the optimal location(s) of the LNG bunkering hubs be derived from those factors?
4. Which mathematical model can be used to determine the optimal locations for developing new LNG bunkering stations?
5. How can the model deal with the predictive nature of the LNG bunkering after the implementation of IMO 2020?
6. How can we ensure that the proposed location(s) is economically feasible?

1.3 Approach

A series of literature review, mixed-integer linear programming, data search, robust optimisation, and economic analysis will be performed to answer the above research question and sub-research questions. A rigorous literature review will provide the answer for sub-question 1, sub-question 2, and sub-question 3 as well as giving sufficient basis to develop the mixed-integer linear programming. This optimisation program will be tested on an empirical container shipping route in Asia taken by major container shipping liners for long haul trip. The programming itself, supported by the data search, should be able to respond to the fourth sub-question. Next, the author deploys robust optimisation to address the uncertain circumstances, before the economic analysis is done at the last stage through breakeven analysis and capacity optimisation.

1.4 Structure

This thesis comprises nine chapters, i.e. Chapter 1 - Introduction, Chapter 2 - Literature Review, Chapter 3 - Methodology, Chapter 4 - Deterministic Model Building, Chapter 5 - Robust Optimisation, Chapter 6 - Profitability Analysis, Chapter 7 - Upscaling Effect of the Model, Chapter 8 - Discussion, and Chapter 9 - Conclusion.

Chapter 1 explains the background and relevance of this thesis, lists out the research question and sub-research questions, touches on the organisation of this thesis, and highlights the significance of it.

Chapter 2 contains relevant literature related to the trend of LNG as a maritime fuel, its supply chain, the existing configurations of LNG bunkering facilities, current market conditions in a specific region that will be empirically tested, and factors related to the determination of bunkering facilities. Sub-research question 1 and sub-research question 2 are addressed in Chapter 2.

Chapter 3 provides an answer for sub-research question 3 by assessing the main problem and laying an appropriate framework to achieve the objective, as well as formulating the problem based on the facility-location and inventory-replenishment problem. A hint of future uncertainty is also discussed in this chapter.

Chapter 4 specifies the deterministic model to respond the sub-research question 4, lists the required data for this research along with the approximating method for any missing data, and runs the model to obtain the optimal solutions. By the end of this chapter, verification and validation are performed to ensure that the model works as per its intended purpose and fit to be implemented in a real-world situation.

Chapter 5 is organised to react to sub-research question 5, as it purely focuses on applying the robust optimisation approach and adjusting the deterministic model to incorporate the predictive nature of this case. The robust solutions are discussed and compared to those of the deterministic one.

Chapter 6 checks the profitability of the proposed solutions in terms of the breakeven point and the optimal size of the LNG storage tanks at each bunkering port.

Chapter 7 upscales the implementation of this model by incorporating demand from other strings apart from those tested in Chapter 4, Chapter 5, and Chapter 6.

Chapter 8 looks at the chicken-and-egg dilemma from two perspectives: the shipping lines and the bunkering ports. It also discusses the main findings and applicability of this model from the theoretical and practical point of view.

Eventually, Chapter 9 summarises the result of this study and provide directions for future research.

1.5 Significance

By developing a model for identifying new facility locations with multiple attributes from two different perspectives, this research expectantly gives back to the academic learning in the area of operations research. From the practical aspect, this thesis establishes an applicable model to support port authority and relevant decision-makers for constructing LNG bunkering stations, thus breaking the chicken-egg dilemma as well as supporting the provision of environmentally-friendly marine fuel.

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Chapter 2 Literature Review

In this chapter, previous studies and other pieces of literature are reviewed to understand the growth of LNG as a maritime fuel, context of LNG bunkering, current situations, and any prior approach on deciding the optimal locations to develop LNG bunkering hubs.

2.1 Trend of LNG as Maritime Fuel

LNG bunker is becoming more prevalent across the shipping industry, due to its advent as a low-emission and cost-efficient fuel. With no content of sulphur, also having 12% and 7% lower CO_2 from Heavy Fuel Oil (HFO) and Low Sulphur Marine Gas Oil (LSMGO) respectively, LNG takes the lead in terms of environmental impact. LNG also emits less NO_x emission that is regulated by IMO under MARPOL Annex VI (IMO, 2017). From cost perspectives, LNG has 13% higher heating value than HFO and is cheaper to produce, making it the most affordable fuel compared to the other marine fuels (Elgohary et al., 2015).

By the end of 2018, there are 121 LNG-fuelled ships of various types with another 51 vessels on order, plus 68 ships ready to be converted to use LNG. Out of this number, there are 3 existing LNG-powered containerships and 21 ships currently on order. The growth of LNG-fuelled fleets is believed to increase dramatically until 2030, by around 1.75% per year at the least (Le Fevre, 2018). Beyond 2030, the LNG-powered fleet is predicted to keep growing albeit a slower rate than the first decade of IMO 2020 implementation.

Figure 2.1 below illustrates the number of LNG-fuelled ships from time to time, including its projections for 2020 onwards.

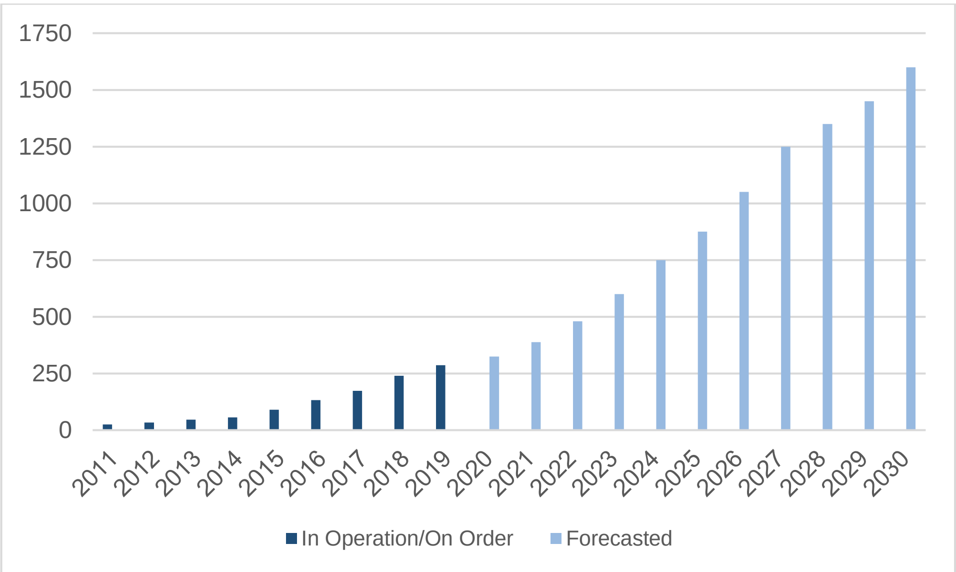

Figure 2.1. Growth of LNG-fuelled Vessels (in unit)
(Le Fevre, 2018)

In the particular area of container ships, a recent study by DNV GL (2018) revealed that the biggest LNG-fuelled containership at the moment has the cargo capacity of 16,300 TEU, equipped with membrane tanks that could accommodate 11,000 cubic metres of LNG bunker. With this volume, the ship could travel for 15,000 nautical miles without refuelling. The advance of technology introduces a membrane tank that makes efficient use of space on board the vessel and tackles the classic problem of the spacious fuel tank. Also, the issue of boil-off gas treatment is well-altered to boost auxiliary engines and electricity.

Nonetheless, another study done by Delta Marin (2018) stipulated that only 60% of the tank capacity could accommodate the voyage, thus leaving it with 9,000 nautical miles to go for every refuelling. Meanwhile, an 8,000-TEU containership vessel having 3,500 cubic meters tank will only be able to sail up to 3,400 nautical miles at the maximum. This fact indicates that LNG bunkering points would be crucial for a long-haul voyage.

2.2. Supply Chain of LNG Bunker

Even though LNG is a potential solution to cope with IMO 2020, ship owners shall be convinced about LNG availability in commercial volumes before they adopt LNG as their bunker of choice. Availability of LNG bunker is essential to encourage the usage of LNG-powered vessels, as LNG is far behind HFO and MGO that are readily available in most ports around the world. Marine Insight (2019) stated that the LNG bunkers availability is steadily growing as a result of the massively developed natural gas liquefaction plants and the growth of LNG carriers. Figure 2.2 illustrates the recent update on the liquefaction plant locations across the globe.

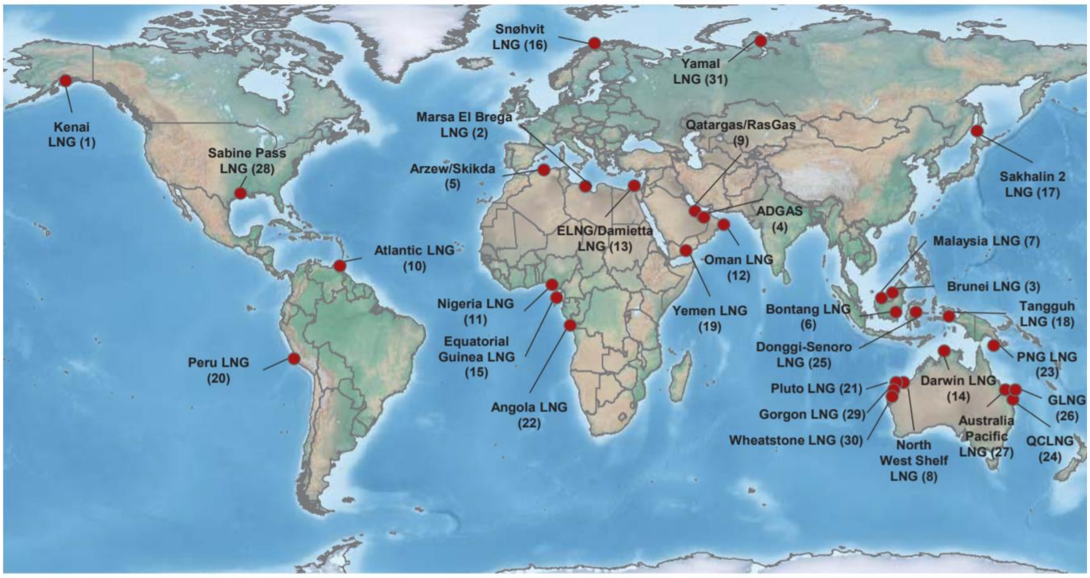

Figure 2.2. Global Natural Gas Liquefaction Plants
(Marine Insight, 2019)

Each of these plants sets its selling price per million British thermal units (mmBtu) of LNG, which mainly depends on the lifting cost, liquefaction cost, and the quality of the natural gas itself (Oxford Institute for Energy Studies, 2018). In spite of the numerous liquefaction plants, not many LNG bunkering facilities exist presently. Berti (2018) assessed that bunkering points could only be found along the major trade route such as Rotterdam, Montreal, Jacksonville, Port Fourchon, Panama, and Tanjung Pelepas with a total capacity of around 15,000 tonnes per annum.

To ensure a continuous supply, there are three common ways for transporting the LNG bunker from LNG liquefaction plants to these bunkering facilities, depicted in Figure 2.3.

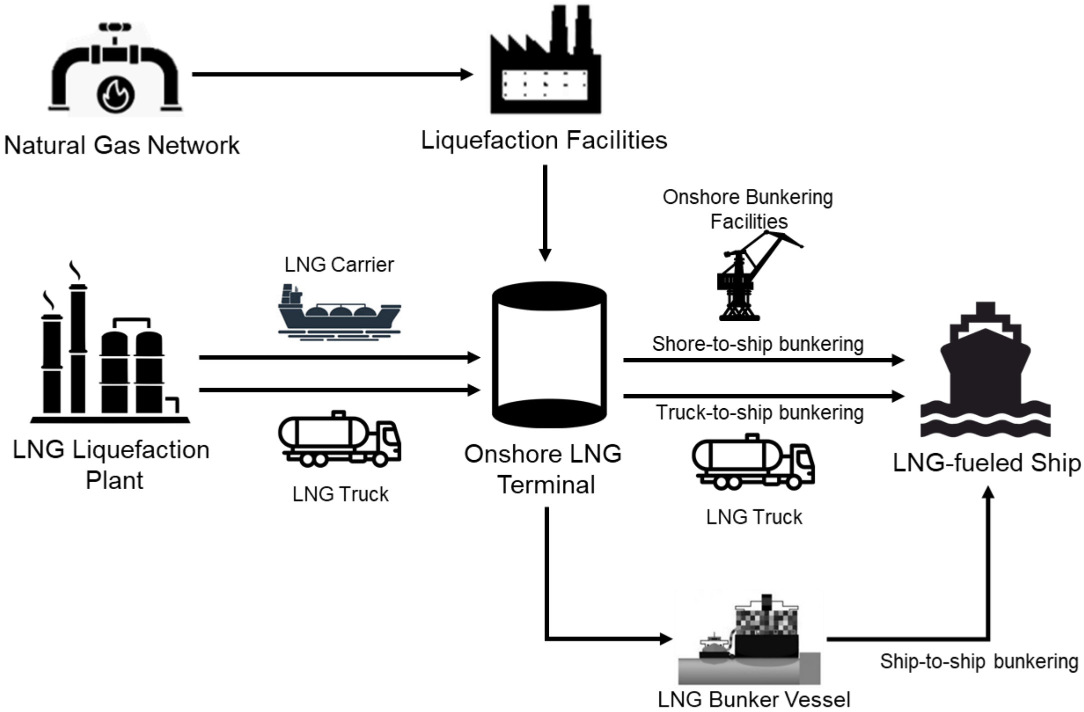

Figure 2.3. Supply Chain of LNG Bunker
(Author's understanding based on Sharples, 2019)

The LNG carrier is the most preferred mode, transporting around 70% of the LNG bunkers in the world, considering its broader coverage of the distribution. The remaining 30% is fairly split between LNG trailer and pipeline. In his study, Sharples (2019) further implied that transporting natural gas through a pipeline is not commercially viable for LNG bunkering purpose, as liquefaction facilities would still be necessary at the final port of bunkering. Meanwhile, LNG trailer is mainly used for small scale deliveries since its maximum capacity is only 50 cubic meters. Hence, this thesis will consider the most massive mean of transportation, which is by LNG carrier.

In certain regions, like in the North Sea and Baltic Sea, LNG terminals have been sophisticatedly developed that they could receive a massive volume of LNG feed and subsequently provide sufficient LNG for bunkering purpose; either at the terminal itself or to the surrounding small-scale LNG terminals via smaller LNG feeder vessels (Sharples, 2019). Also, despite the presence of LNG terminal, a dedicated bunkering facility with separate LNG tank and smaller manifolds is necessary to preserve the pressure and temperature of LNG in the tanks. Nonetheless, the price charged through this mechanism is slightly higher than direct sourcing from the liquefaction plants, as the terminal charges a certain amount of profit margin.

The last mile of the supply chain, which is the loading of LNG bunker to the LNG-fuelled vessels, can be carried out through three methods as elaborated by Bull, Meulendijk-de Mol, and Nijboer (2016): truck-to-ship (using LNG trailer), ship-to-ship (using LNG barge or LNG carrier), and shore-to-ship (by constructing onshore LNG storage tanks). Truck-to-ship is deemed the most flexible method of bunkering, as the LNG trailer will be connected to the ship with a flexible hose without the need of any specific infrastructure, so it incurs very minimum capital investment. Despite being flexible, this method is only viable for a small amount of delivery up to 80 cubic meters with substantially slow flow rate of around 40-60 cubic meters of LNG per hour. The ship-to-ship method might overcome these issues because the average capacity of existing LNG bunker vessels is 3,000 cubic meters with a flow rate of 500-700 cubic meters per hour. Anyhow, busy ports with a potentially high level of bunkering activities might consider building shore-to-ship bunkering, which can handle up to 180,000 cubic meters of LNG per tank with the capability to transfer 2,000 cubic meters of LNG per hour. The drawback of this last option is the requirement of fixed infrastructure onshore, comprising LNG storage tank and loading arms. Anyhow, since only nine LNG bunkering vessels operate in 2019 that mainly cover North European regions, onshore LNG bunkering might be more viable to cope with the global growth of LNG-fuelled ships. Constructing onshore tanks over two years is slightly faster than building an LNG bunkering vessel that might take up to three years.

2.3. Components of an LNG Bunkering Infrastructure

Shore-to-ship LNG bunkering is perceived as a capital-intensive business because of its perceptible safety risk and the complexity of its infrastructure. As per Motsoahole's study (2014), there are some crucial elements to be incorporated into an onshore LNG bunkering station:

a. General Port Facilities
   Due to the high-risk nature of bunkering operations and the LNG characteristics that are highly evaporable, simultaneous operations (SIMOPS) of loading/unloading while bunkering should not be allowed. Therefore, a dedicated jetty for the LNG-powered fleet to have bunkering is necessary, along with the associated loading arms and manifolds.

b. Land-based Tanks
   Highly pressurised storage tanks are required to preserve the liquid forms of LNG, along with the pipelines and manifolds connected to the loading arms.

c. Supporting Elements
   License to operate a bunkering hub is mandatory to obtain from any relevant authority, which might cost around USD 300,000 – 400,000 depending on the regulations of each country. Overhead cost such as personnel wages, maintenance, and any other operational cost shall be counted as well.

In public service ports, the ownership, development, and operations of the bunkering facilities fall under port authorities' domain. In contrast, landlord port authorities will only provide the land for the bunkering terminal and initiate the construction of the basic infrastructure like jetty and quay wall, then leave the bunkering operations to independent bunker operators (World Bank, 2016). However, most port authorities are being more proactive by striving beyond conventional landlord function to expedite the provision of LNG bunkering services. Either way, the output of this research should be useful for the related parties to determine where to build onshore LNG bunkering stations.

2.4. *Current LNG Bunker Market in Asia*

Liang (2019) assessed that the LNG bunkers were only provided by bunkering vessels at Ningbo-Zhoushan (People's Republic of China), Tanjung Pelepas (Malaysia), and Kochi (India) by the end of 2018. In mid-2019, with only a few months before the implementation of IMO 2020, maritime stakeholders in Asia feel the urgency of moving towards LNG. At the moment, Singapore and South Korea are running feasibility study for promoting small-scale LNG bunkering in Port of Singapore and Port of Busan, which decisions are to be taken by 2020. Another noticeable news is that South Korea has placed orders for 140 LNG-fuelled ships to be delivered by 2025, aiming to empower its shipbuilding industry as well as boost the utilisation of LNG bunkering. On top of that, three 20,000-cubic-meter LNG storage tanks are being constructed in Port of Incheon (South Korea) for bunkering purpose, planned to be commissioned by July 2020 (Riviera, 2018). Meanwhile, Brunei has expressed their intention to shift to LNG, although none of these ports presently offers LNG bunker.

The widening interest to promote LNG bunker is supported by numerous natural gas liquefaction plants in the Asia Pacific. International Gas Union (2019) surveyed that large-scale liquefaction plants exist in Australia (Ichthys, Darwin, Browse, Wheatstone), Indonesia (Tangguh, Donggi-Senoro), Malaysia (Bintulu), Brunei, Russia (Sakhalin), Papua New Guinea, and Middle East (Qatar, Oman, Yemen) as previously displayed in Figure 2.2. In total, these plants offer 2.11 billion cubic meters of LNG per year, of which 25% are still uncommitted.

2.5 *Factors affecting the Development of LNG Bunkering Facilities*

Development of LNG bunkering hub depends on the decision of whether to build it or not - and if the answer is yes, then the required capacity should be decided too. As sufficient numbers of LNG bunkering base are essential to support the trend of LNG-fuelled vessels, numerous researches have analysed various factors affecting the feasibility of developing LNG bunkering facilities. The Steering Committee of Yokohama Port Authority (2016) highlighted that LNG bunkering demand in a port is the primary driver to install an LNG bunkering facility, to ensure they will gain payback from the investment. From shipping companies' point of view, Wang et al. (2014) stipulated that bunker price, bunker quality, and safety are the main criteria to select bunkering port. Besides, service route, vessel's speed, access to a port, and geographical location play an important as well (Yao et al., 2012; Notteboom and Vernimmen, 2009). These liner's decision criteria should be considered in developing a new LNG bunkering hub.

Specific feasibility analysis that integrated the above factors was done by Aronietis et al. (2017). They identified shipping lines' determinants on choosing bunkering points, predicted the future LNG demands, and analysed the possibility of building LNG bunkering infrastructure in Antwerp. Their analysis was based on the potential market, bunker purchasing cost, bunker distribution cost, and capital cost in Antwerp and its surrounding area. They also highlighted that "*bunkering is always a derived activity of a port call, and no other port will be called just for bunkering*". Looking into details, the forecasting was carried out through multiple regression using several assumptions on the fuel consumption of LNG-powered fleets, proportion of ship size, and adoption rate of LNG. In spite of the accelerated adoption of LNG as a marine fuel, the result indicated that LNG bunkering volumes in Antwerp would be stagnant until 2050, which should be seen as the primary concern of building an LNG bunkering hub. Shipping lines' strategy of having Rotterdam, a nearby port, as a back-up to obtain lower price needs to be considered as a challenge as well. Although this paper has combined qualitative method by getting experts' judgment on the critical factors and by applying a quantitative approach through discrete choice experiments, it only focused on Port of Antwerp.

Another feasibility study conducted by the Steering Committee of Yokohama Port Authority in 2016 concentrated primarily on the Port of Yokohama, by incorporating the forecast of LNG bunkering demand and the cost competitiveness. They measured the profitability of implementing truck-to-ship, ship-to-ship, and shore-to-ship alternatives. In conclusion, the Japanese government needs to encourage the usage of LNG as marine fuel before initiating the construction of onshore LNG bunkering facilities. To promote competitive bunker price, the study suggested port authorities to select the correct distribution network of LNG and minimise the supply distribution cost.

Kirstein et al. (2018) emphasised that the location of ship bunkering ports depends on their central position along ocean routes and the proximity of refineries. Therefore, it is inevitable to put LNG bunkering facilities on the correct point along the shipping route and LNG supply network, to maximise the revenue from selling the bunker as well as minimising the distribution cost of LNG supply. It could be said that the commercial factor of LNG bunkering demand, the geographical factor of the bunkering location, and the financial factor of capital and distribution cost are essential to decide the location of LNG bunkering hubs.

Moreover, there are various studies about the cost involved in building and operating bunkering facilities of any fuel types. Guler (2003) identified the major cost elements for placing a new bunkering station in Turkey, covering the construction cost of onshore bunkering tanks and yearly maintenance cost. However, this study was not explicitly discussing LNG bunkering facilities; also, there was no highlight on variable cost required to provide each unit of fuel. The previously-mentioned study by Bull, Meulendijk-de Mol, and Nijboer (2016) outlined different elements for the capital expenditure (CAPEX) due to different infrastructure involved, yet the operating expenditure (OPEX) is quite similar comprising delivery cost from the liquefaction plants to ports, storage cost, and maintenance cost. A most recent analysis by ERIA in 2018 revealed that the CAPEX mainly covers the construction of the LNG terminal, pipeline, and associated utilities such as waste treatment plant and control room, while the construction cost of the storage tank might be prorated and depreciated as annual OPEX. The acquisition cost of LNG supplies is also believed to be one substantial cost on top of the previously mentioned elements.

2.6. Previous Similar Studies

Considering the complex factors involved in initiating new LNG bunkering hub, holistic optimisation needs to be performed to satisfy the interests of port authorities without compromising the shipping lines'. Although no research has been done previously for LNG bunkering scope, several studies have conducted holistic approaches in determining the optimal location for distribution centres, retails stores, and electric charging stations.

Thai and Grewal (2005) built a spatial resource allocation model for locating distribution centres. They utilised Centre of Gravity (CoG) principle to find the optimum distances between distribution centres, retailers, and producers, aiming to minimise the distribution costs in this network. Still, they only focused on the geographical aspect and did not touch on revenue maximisation in this paper.

On the other side, Kateryna (2005) implemented Maximum Capture Problem to find the optimal location of a retail store. The objective function is to maximise the market capture area by considering consumer behaviour, despite no interest went to optimise the retail's supply side. It predicted the future consumer behaviour based on past record, which might be applicable for forecasting the shipping liners' behaviour on choosing LNG bunkering base in the future.

One more study carried out by Csonka and Csiszar (2017) about choosing the optimal locations for charging electric vehicle can be used as a reference. With the same nature of vehicle refuelling as this proposed thesis, they assessed several candidate sites located within 250 meters from the national highway. These candidate sites differ on the quality set, i.e. charging speed and availability of restroom, restaurant, minimarket, or motel, which would influence customer choice. The authors applied facility location problem to maximise the service coverage area while considering the traffic volume, the presence of nearby charging station as a competitor, and the existing electricity network. Because this paper has reviewed the demand and supply effect of a refuelling station, its methodology is a suitable benchmark for this thesis.

A specific approach to solve the optimal locations problem was presented by Vygen (2005). In this paper, Vygen discussed various discrete facility location problem, ranging from uncapacitated facility location, greedy and primal-dual algorithms, and capacitated facility location. He emphasised the application of Uncapacitated Facility Location Problem to minimise the cost of a limited set of facilities while fulfilling the demand from a finite set of customers. The latter method might be appropriate for deciding the optimal locations of LNG bunkering facilities as per projected demand, LNG material cost, and LNG distribution cost, though further assessment needs to be commenced.

The required capacity of each bunkering hub would mainly depend on the demand on each port, resulted from shipping lines' bunkering choice. Projected demand for LNG bunkering after the implementation of IMO 2020 can be taken from a forecast presented by Oxford Energy Institute (Le Fevre, 2018), which primarily relied on the present growth of LNG-powered fleet and the proportion of vessel types. Another aspect contributing to the LNG fuel demand is the refuelling range of the shipping lines. Most of the previous works in this area (Tegelberg, 2015; Sheng, Chew, and Lee, 2015) took shipping liners' perspective and focused on the vessels' speed (which will affect fuel consumption and refuelling range), bunker prices, and capacity of the fuel tanks as key elements in deciding whether to bunker or not in a specific port.

Farahani et al. (2015) established a linear program to address both facility location problem and inventory problem, namely location-inventory problem, to identify the strategic locations of supply chain node along with the associated inventory per node. Applying location-inventory problem enabled them to find the optimal distribution network from a set of suppliers to a set of customers along with the inventory level held by each customer.

The abovementioned approaches will be simplified in this research to reflect the primary perspective of the port authority, by considering only the refuelling range of the container ships and the bunker price offered by each port.

2.7 Conclusion

Taking into account the results of previous studies, this research will focus on determining the location of shore-to-ship LNG bunkering facilities to anticipate the growth of LNG bunkering demand after the implementation of IMO 2020. Any relevant calculation would be performed for the period up to 2030, as the growth of LNG-fuelled fleets is deemed to be slower afterwards. The supply chain is assumed to involve the supply of LNG from liquefaction plants, transported to the bunkering hubs, and finally to the LNG-fuelled ships.

Independent factors to be incorporated in the model are refuelling range of shipping lines, bunker price, capital investment, and operational cost, which are considered essential from the perspectives of shipping lines and port authorities. The main costs spent by LNG bunkering ports are the capital cost that occurred during the construction phase, and the operational cost that is routinely paid for operating and maintaining the facilities as well as purchasing the supplies. These statements conclude sub-research question 1 and 2.

The model will then be tested on selected major Asian ports which are mostly visited by container shipping lines. Detailed optimisation approach and relevant aspects will be elaborated further in the subsequent chapters.

Chapter 3 Methodology

This chapter elaborates the core problem identified in Chapter 1 and lays a foundation for developing the model. The first part will discuss the theoretical framework of facility location problem to identify the decision variables and the required parameters. The second part will describe the specific issue concerning the scope of this study, corresponding to the third sub-research question. The third part will touch on the uncertainty element of the LNG bunkering business, while the last section presents a way to analyse the optimisation problem from the economic perspective.

3.1. Problem Description

There are three elements to be considered by port authorities before deciding to install LNG bunkering facilities at their ports. These elements would also be taken as key criteria in developing the optimisation model and the succeeding analysis.

The first element to be thoroughly reviewed is bunkering behaviour of container ships. Subchapter 2.4 already highlighted that bunker price, bunker quality, and safety are the standard norms affecting the shipping lines' choice of bunkering port, on top of the sailing route of a vessel and geographical location of a port. Although the liners could choose to either fully bunker their fleet or only bunker sufficiently to reach the subsequent port(s), this research assumes that the latter applies. The relevant quantitative and measurable aspects to be reflected in the model are the bunker price per port, sailing route of the ship, and the geographical location of the port.

Secondly, the capacity of the LNG bunkering stations should be optimised. Just like the basic of economics (Taylor and Mankiw, 2017), sufficient supply is essential to attract the customer, fulfil the bunkering demand, and stay competitive among the other ports. However, excessive capacity will be a backfire to the total cost incurred by the ports, as the abundant supply with unnecessary storage tanks might increase maintenance cost, storage cost, and operational cost. Uncertainty on the demand side should be paid some attention too to estimate the appropriate capacity at the bunkering ports.

The third element, as also outlined in Subchapter 2.2, relates to the presumption that shore-to-ship LNG bunkering is a capital-intensive business with about 40 years lifetime. Optimal selling price and breakeven volume should be sought to ensure the profitability and sustainability of the business, which could be determined based on the breakeven analysis. The framework of breakeven analysis provides a viable way to assess the minimum required demand of LNG bunker as well as its minimum selling price to cover its capital investment and become profitable in the longer term.

The abovementioned problems are to be addressed by implementing the correct methodology and the appropriate model, as well as by carrying out the breakeven analysis.

3.2. *Problem Formulation*

This research combines the facility location problem and inventory problem to identify the optimal location for the LNG bunkering hubs and the required volume respectively, with a hint of flow-based demand to understand the potential bunkering points of shipping lines. However, these problems are slightly modified to address the objective of the research, which is to find the optimal locations of the LNG bunkering stations and the required capacity. In this subchapter, the author highlights those two individual problems before formulating the model any further.

3.2.1. Facility Location Problem

The first segment of this sub-subchapter will highlight two types of facility location problems: the classic facility location problem and the facility location problem with flow-based demand. Comparison with the central issue of this thesis will be highlighted henceforth.

a. Classic Facility Location Problem

The ultimate purpose of facility location problem is to determine the location of new facilities, such that the total costs of delivering the goods from facilities to the customers are minimised (Liu, 2009). This methodology is mostly applied in the area of supply chain network or public facilities. Some factors like customer demands, locations of the customers, and locations of the facilities are crucial to finding the optimal solutions, besides the capacity of each facility. Subject to two main constraints - the fulfilment of the customers' demand and size of the facilities, the facility location problem will allocate the quantity supplied from each facility to each customer.

Kim (2010) mentioned that two underlying assumptions for this problem are the presence of specific customers with independent demands and the given capacity of each proposed facility. The problem can later be formulated either as a standard linear program merely to conclude the optimal allocation from each facility to the customers or as a mixed-integer linear program when it involves the decision of whether a facility should be opened or not. In the latter method, which is also known as fixed-charge facility location problem, the objective function includes the cost of opening facilities and the cost of distribution from the facilities to their customers. The general model for a fixed-charge facility location problem is depicted as a mixed-integer linear program shown below:

$$\text{Min } \sum_i \sum_j c_{ij} x_{ij} + \sum_j f_j y_j \qquad (3.1)$$

subject to:

$$\sum_j x_{ij} = D_i \qquad \forall\, i \qquad (3.2)$$

$$\sum_i x_{ij} \leq M.y_j \qquad \forall\, i, \forall\, j \qquad (3.3)$$

$$x_{ij} \in \mathbb{N} \qquad \forall\, i, \forall\, j \qquad (3.4)$$

$$y_j \in \mathbb{B} \qquad \forall\, j \qquad (3.5)$$

in which X_{ij} is the allocated supply from Facility j to Customer i and Y_j is the decision whether Facility j is to be built or not.

There are only two terms in the objective function (3.1), corresponding to the transportation cost per unit of goods (c_{ij}) and fixed cost of opening the facility (f_j). Constraint (3.2) ensures that demand per customer i is fulfilled by the total supply from any facility, while Constraint (3.3) indicates that customer can only be supplied from facility j if a facility is opened in j. The facility itself does not have any maximum capacity, so there is no constraint limiting the amount shipped from any facility j.

Slightly different from the classic facility location problem stated above, this thesis principally starts from scratch. With the insignificant role of LNG as a marine fuel at the moment, the demands of LNG bunker cannot be well-defined for every location. Another underlying assumption is not fulfilled too since the demands of LNG bunker are highly dependent on the location of the port, as a result of the limited refuelling range. Besides, instead of being given, the capacity of each facility needs to be figured out from this thesis. Therefore, the model is expected to generate the LNG bunkering demand per port, which then leads to the development of LNG bunkering ports and the necessary capacity of each port.

b. Facility Location Problem with Flow-based Demand

The modified facility location problem for accommodating flow-based demand might close the abovementioned gap between this thesis and the underlying assumptions of the classical theory. This approach assumes that the demand flows on a path between the origin and destination points in a network. It has been implemented broadly for determining convenience stores, refuelling stations, vehicle inspection stations, and advertisement billboards (Kim, 2010).

Kim established a model to find an optimal location for capturing the maximum flow of customers. Its outcome will merely determine which facilities to be opened without revealing each allocation or capacity, which is quite different from the conventional facility location problem. He formulated a pure flow-based demand coverage model with homogenous customers, of which objective function is to capture maximum demand flow. There are only two constraints involved: i) a facility will be built only and if only it can capture the demand flow and ii) the number of facilities to be opened might not exceed the maximum number of facilities allowed.

Anyhow, similar with the goal of any facility location problem, this thesis investigates the optimal locations of new bunkering facilities to minimise the total costs, subjects to the fulfilment of the demand and limitation of the supply capacity. Demand is sought by looking at the flow of major shipping lines and their potential bunkering points throughout the route, depending on their fuel consumption.

3.2.2. Inventory Problem

Anderson et al. (2012, p.17) defined inventory problem as an approach used to maintain sufficient inventory, to satisfy a given level of demand, and to minimise the inventory holding cost at the same time. It aims to have the lowest periodic inventory holding cost, subject to the inventory level at the beginning of a period, the replenishment incurred in the period, and the demand at the respective period. In most cases, it includes the cost of holding inventories and ordering replenishment. Essential parts of the holding cost are insurance and storage cost that depends on the size of inventory, while the ordering cost covers the preparation of the order, processing the order, and also transportation cost per lot.

The general formula used to measure total costs of inventory, as found in Anderson et al. (2012, p.458) is:

$$\text{Total Annual Cost} = \text{Annual Holding Cost} + \text{Annual Ordering Cost}$$

$$\text{TC} = \frac{1}{2}QC_h + \frac{D}{Q}\,C_o \tag{3.6}$$

in which Q is the ordering quantity, C_h is the annual holding cost per unit, D is the annual demand, and C_o is the ordering cost per transaction.

To define the optimum ordering quantity, called Economic Order Quantity (EOQ), formula (3.6) is converted into:

$$\text{EOQ} = \sqrt{\frac{2DC_o}{C_h}} \tag{3.7}$$

As a result, ordering frequency per year can be calculated:

$$\text{Number of orders per year} = \frac{\text{Annual Demand}}{\text{Economic Order Quantity}} \tag{3.8}$$

The analogous approach also applies to this thesis, as the one-time capacity of an onshore LNG bunkering hub reflects the ordering quantity. The ideal scale of bunkering facilities should be figured out to ensure the demand fulfilment without compromising the inventory cost. Nonetheless, materials cost would be incorporated in the thesis to capture all cost elements to be considered by port authorities or relevant bunkering providers.

3.3. Optimisation under Uncertainty

Notwithstanding the claimed accuracy of mathematical programming, real-world problems still contain uncertainty and unknown data by the time a decision must be taken. The optimisation cannot simply ignore the presence of this uncertainty, as uncertain situations could influence the practicality of the model and subsequently, the reliability of the optimal solution as well.

EOS (2019) identified two primary sources of this uncertainty: data measurement error and unforeseen future. The latter is very relevant with the nature of this thesis, as IMO 2020 is yet to be implemented and the impact of its implementation on LNG bunker demand and price cannot be accurately predicted.

3.3.1. Frameworks to Address Uncertainty in Optimisation

There are three well-recognised frameworks to integrate uncertainty into a model; i.e. Stochastic Programming, Dynamic Programming, and Robust Optimisation (Moarefdoost, 2018). In substance, Stochastic Programming has uncertain parameters that are approximated based on the probability distribution, with the possibility of corrective action and carrying out stage-by-stage optimisation. The second method, Dynamic Programming, urges decision making in every state to bring the decision-makers to the next state based on the earlier decision. It involves randomness with some probability in every state, leading to an optimal choice in discrete stages. The latter approach is Robust Optimisation that searches the optimal decisions based on a defined range of the uncertain parameters, so that the uncertainty itself is rather deterministic. The significant difference is that robust optimisation does not accommodate recourse and can be conducted for one-off optimisation. Hence, robust optimisation is more suitable for the one-time decision making of this research, because any recourse is highly unfavourable in a capital-intensive environment. Also, the predictive scope of this research might not provide reliable probability density function for stochastic programming purpose.

3.3.2. Robust Optimisation

Robust optimisation is originated from the use of worst-case analysis and Wald's maximin principle, that are initially acknowledged as non-probabilistic decision-making models (Ben-Tal, El Ghaoui, and Nemirovski, 2009). However, robust optimisation improvises a bit as it incorporates probabilistic element(s) with a deterministic set of uncertainty and generates a feasible solution to satisfy all uncertainty in the set. The objective is to minimise the largest regret over all scenarios, by reducing the gap between the minimum cost possible and the cost of the proposed solution. Unlike worst-case scenario that only counts the worst-case point of view, the robust optimisation considers all scenarios within a given uncertainty range and choose the one with the lowest "opportunity loss".

To run the robust optimisation, a deterministic model needs to be established in the first place, before defining the uncertain parameters and the affected variables. Randomness range of the uncertain parameters should be well represented too, enabling the model to seek the optimal solutions within feasible regions. A robust program with finite uncertainty will develop a deterministic equivalent named robust counterpart to solve the problem, which solution generation is still tractable by the program. The optimal solutions generated by the robust counterpart are known as robust optimal solutions.

In particular, Bertsimass and Sim (2004) applied the robust optimisation to discrete optimisation problems. They formulated the deterministic integer programming as below, before expanding it to its robust counterpart.

$$\mathrm{Min}\ \mathrm{c^T x} \tag{3.9}$$

Subject to:

$$\mathrm{Ax} \leq \mathrm{b} \tag{3.10}$$

$$\mathrm{X_i} \in \mathbb{Z}^{+} \qquad \mathrm{i} = 1,2, \dots . \mathrm{k} \tag{3.11}$$

$$\mathrm{c} \in \mathbb{Z}^{m} \tag{3.12}$$

$$\mathrm{b} \in \mathbb{Z}^{n} \tag{3.13}$$

$$\mathrm{A} \in \mathbb{Z}^{\mathrm{mxn}} \tag{3.14}$$

Basically, the robust optimisation aims to reach the same objective as the deterministic version, considering all uncertain parameters in a given uncertainty set U. With x representing current deterministic decisions and with the assumptions that A and c are random, the robust optimisation will find the feasible solution x based on the worst value of the deterministic objective function, which becomes $\{c^T x: Ax \leq b, \forall\ A \in U_A, \forall\ c \in U_C\}$. Consequently, the robust counterpart can be entirely written as:

$$\min_{x}\{c^T x: Ax \leq b, \forall\ A \in U_A, \forall\ c \in U_C\} \tag{3.15}$$

While detailed of their uncertain regions can be described as follows, with a certain lower bound and upper bound of each uncertain parameter to create a deterministic set of the uncertainty.

$$U_A \rightarrow \tilde{a_i} \in [a_i - \hat{a_i}, a_i + \hat{a_i}] \qquad i = 1,2, \dots . k \tag{3.16}$$

$$U_C \rightarrow \tilde{c_i} \in [c_i, c_i + d_i] \qquad i = 1,2, \dots . k \tag{3.17}$$

When the uncertainty is finite as above, then the robust counterpart will be a linear problem. However, if the uncertainty set is ellipsoid, then the robust counterpart will be a second-order cone program (SOCP). The discussion of the ellipsoid or any other types of uncertainty sets is beyond the scope of this thesis.

3.3.2. Optimisation Tools

Since there is only limited software to run robust optimisation, the deterministic formulation and its robust counterpart are going to be solved by Advanced Interactive Multidimensional Modelling System. Commonly abbreviated as AIMMS, it is state-of-the-art software to support decision making based on the optimisation of mathematical model and capable of solving linear or non-linear program in both deterministic and uncertain environment with the support of various solvers, namely CPLEX, BARON, Gurobi, PATH, SNOPT, and AOA.

CPLEX version 12.8 will be deployed due to its ability to solve Mixed Integer Linear Programming. Citing from AIMMS's website (2019), CPLEX uses the branch-and-bound algorithm and cutting planes to obtain the integer solutions. For any non-linear programming resulted from the model extension of this thesis, AOA is the preferred solver as it can do the non-linear branch-and-bound method. The detailed mechanism will be elaborated later in Chapter 4 and Chapter 5.

3.4. Breakeven Analysis with Semi-fixed Costs

Corresponding to sub-subchapter 3.2.3, a breakeven analysis will be carried out to figure out the minimum level of LNG demand and minimum selling price for the LNG bunkering hub to be profitable. However, considering the nature of LNG bunkering facility, the traditional breakeven analysis is not feasible to be applied. In the traditional analysis, all costs are defined as being fixed or variable (Powers, 1987), while the LNG bunkering business involves what so-called semifixed costs that are mixed between the two. Therefore, the conventional method needs to be slightly adjusted to accommodate this new cost element.

For instance, the operational cost of onshore storage tanks will vary according to the demand of LNG bunker, yet they will not fluctuate at the same rate as the material cost. The operational cost depends on the number of the onshore tanks, which is fixed for a specific range of volume within the tank capacity, but then increases once the required amount goes out of range. The nature of semifixed cost and the associated breakeven analysis is illustrated in Figure 3.1 and 3.2, respectively.

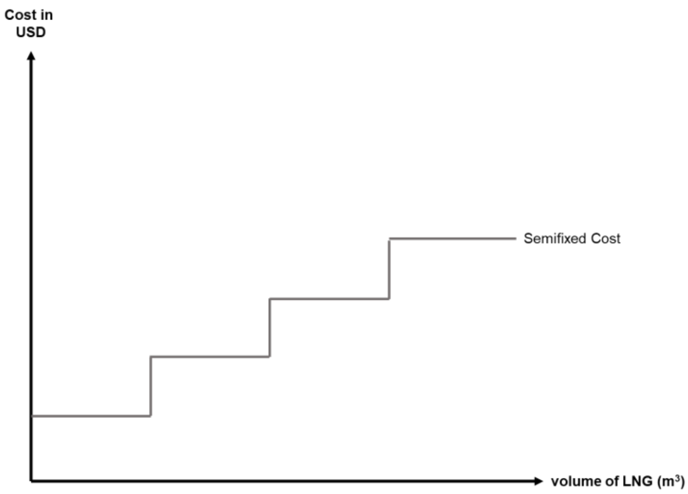

Figure 3.1 The pattern of Semi-fixed Cost
(Author's illustration based on Powers, 1987)

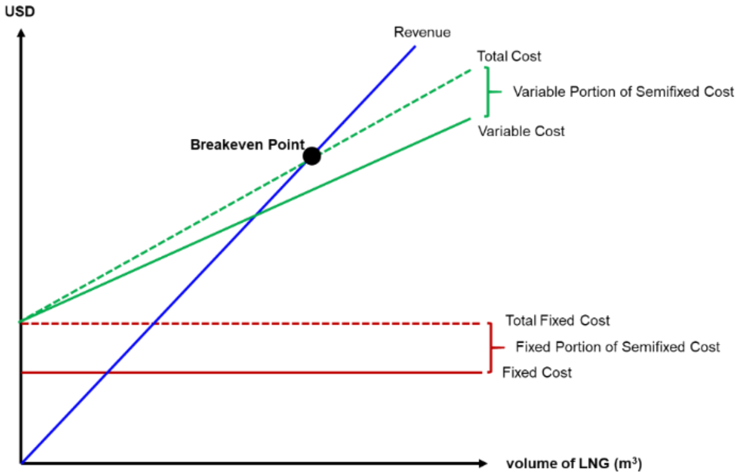

Figure 3.2 Breakeven Analysis with Semi-fixed Cost
(Author's illustration based on Powers, 1987)

In Figure 3.2, the semifixed cost was divided into its fixed and variable elements. The total cost, which is calculated as the sum of the fixed cost, fixed portion of the semi-fixed cost, variable cost, and variable portion of the semi-fixed cost, would then vary for each additional unit of volume. Still, according to Powers (1987), two steps shall be performed to figure out the breakeven volume:

1. Finding net cash flow for each range, by deducting the fixed cost, fixed portion of the semi-fixed cost, and variable portion of the semi-fixed cost from the incoming cash flow.
2. Finding a range that contains the breakeven point, in which the net cash flow becomes positive at the endpoint of the range. The precise breakeven quantity (BEQ) can be interpolated using this formula:

$$\text{BEQ} = \frac{\text{Fixed Cost} + \text{Semifixed Cost}}{\text{Selling Price} - \text{Variable Cost}} \tag{3.18}$$

As the number of tanks will increase by one every 20,000 cubic meters of LNG demand, the range to be used for the breakeven analysis is every 20,000 cubic meters.

On the other hand, setting the optimal selling price is also necessary to ensure the breakeven point is achievable without pushing the customer away because of the unreasonable price. To find the breakeven selling price (BEP), the equation (3.18) is slightly modified by putting Q as the expected volume to be sold.

$$\mathrm{BEP} = \frac{\text{Fixed Cost} + \text{Fixed Portion of Semi} - \text{fixed Cost}}{\text{Expected Volume to be Sold}} + \text{Variable Cost} \tag{3.19}$$

3.5. Conclusion

Regarding the third sub-research question, facility location problem and inventory problem will be used to build a model based on the factors concerned by port authorities. As the decisions taken in the individual problems can influence the global optimum, the combination of both facility location problem and inventory location problem should be established. For instance, ports that are adjacent to each other might not need large capacity compared to a stand-alone port that is far from any nearby port.

The basic concept of facility location problem is necessary to understand the potential bunkering locations of the shipping lines and the estimated volume of LNG bunker at each bunkering station, which subsequently determine which ports should develop the LNG bunkering infrastructure. Meanwhile, the inventory problem will help to identify the optimum capacity of the facilities. The goal of this combination is to minimise the total costs, both from port authorities' and shipping lines’ point of view.

Integer linear programming is mainly chosen for model specification. The expected outcomes of this research; namely decision of the shipping lines to bunker in a specific port, decision of the port authority to build or not the bunkering hub in a particular location, and the capacity of bunkering hubs reflected by the number of onshore LNG tanks; can be displayed as either binary or integer values.

Robust optimisation method will then be applied to address any uncertain data in the model and to obtain a set of robust optimal solutions for satisfying various scenarios under uncertainty. Afterwards, the breakeven analysis would be commenced to confirm the profitability of the proposed solutions.

Chapter 4 Deterministic Optimisation

In general, this thesis focuses on developing a model to suggest the location and capacity of shore-to-ship LNG bunkering. As a stepping stone to achieve that objective, this chapter will firstly develop a cost minimisation model to minimise the total cost from both port's and liner's standpoint. Associated data to run the model are presented subsequently to test the empirical case study in a deterministic environment. Those data will then be plugged into the model to generate optimal solutions. The answer to the main research question will be found in this chapter, together with the model verification and validation proving the applicability of this model to address the actual issue in developing LNG bunkering hub. Sensitivity analysis is also carried out as a part of verification.

4.1. Specification of the Deterministic Model

In specifying the linear program, the author first focuses on identifying the potential bunkering ports, given the set of westbound route, eastbound route, and the assessed ports along each route. The likely bunkering ports will then be used as a basis to develop the shore-to-ship bunkering hub and assess the required capacity in that respective port.

During the model development, the following sets are introduced.

Sets

$\mathbf{i} \in \mathbf{I}$ Set of ports in Route k
$\mathbf{j} \in \mathbf{J}$ Set of subsequent port after Port i in Route k
$\mathbf{k} \in \mathbf{K}$ Set of ship routes

The following parameters are used to establish the model.

Parameters

$\mathbf{C}$ Fuel tank capacity of the smallest LNG vessel (in cubic meter)
$\mathbf{F_i}$ Capital cost of locating LNG bunkering facilities at Port i (in USD)
$\mathbf{FU_{ij}}$ Volume of fuel required to sail from Port i to Port j (in cubic meter)
$\mathbf{H}$ Annual inventory holding cost per unit (in USD)
$\mathbf{M_i}$ Materials and logistics cost per cubic meter of LNG supply to Port i (in USD)
$\mathbf{N_i}$ Estimated number of vessels coming to Port i in a period of time
$\mathbf{O_i}$ Operational cost per onshore LNG tank at Port i (in USD)
$\mathbf{P_i}$ Selling price per cubic meter of LNG bunker at Port i (in USD)
$\mathbf{V}$ Volume per onshore LNG tank (in cubic meter)

Consequently, the decision variables are:

Decision Variables

$\mathbf{Z_{ijk}}$ A binary variable representing the decision to refuel the ship at Port i for sailing from Port i to Port j in Route k, where $Z_{ijk} = 1$ if the vessel bunkers in Port i during the voyage in Route k and $Z_{ijk} = 0$ if otherwise

$\mathbf{Y_i}$ A binary variable representing the decision to build or not to build LNG bunker facilities at Port i, where $Y_i = 1$ if the LNG bunkering infrastructure is built at Port i and $Y_i = 0$ if otherwise

$\mathbf{X_i}$ An integer variable representing the number of 20,000-cubic-meter storage tanks to be constructed at Port i

The problem can be expressed as a Mixed-Integer Linear Program, aiming to minimise the costs incurred by ports and the bunkering cost of shipping lines as well.

Model Specification

$$\text{Min } \sum_i F_i.Y_i + \sum_i \frac{1}{2}.H_i.V.X_i + \sum_i \sum_j \sum_k N_i.M_i.FU_{ij}.Z_{ijk} + \sum_i O_i.X_i + \sum_i \sum_j \sum_k N_i.P_i.FU_{ij}.Z_{ijk} \tag{4.1}$$

subject to:

$$X_i \leq M.Y_i \qquad \forall\, i \in I \tag{4.2}$$

$$\sum_j \sum_k Z_{ijk} \leq M.Y_i \qquad \forall\, i \in I \tag{4.3}$$

$$\sum_i Z_{ijk} = 1 \qquad \forall\, j \in J, k \in K \tag{4.4}$$

$$\sum_j Z_{ijk}.FU_{ij} \leq C \qquad \forall\, i \in I, k \in K \tag{4.5}$$

$$Z_{ijk+1} \leq Z_{ijk} \qquad \forall\, i \in I, j \in J, k \in K \tag{4.6}$$

$$\sum_j \sum_k N_i.Z_{ijk}.FU_{ij} \leq V.X_i \qquad \forall\, i \in I \tag{4.7}$$

$$X_i \in \mathbb{Z} \qquad \forall\, i \in I \tag{4.8}$$

$$Y_i \in \mathbb{B} \qquad \forall\, i \in I \tag{4.9}$$

$$Z_{ijk} \in \mathbb{B} \qquad \forall\, i \in I, j \in J, k \in K \tag{4.10}$$

The objective function (4.1) presents the goal of the model to minimise the total cost incurred by the system, which involves five terms. The first four terms relate to the costs borne by the ports, while the fifth term is the expenditure of the shipping lines. Term 1 is the annual capital cost spent by the port to build the bunkering facilities, excluding the construction cost of the onshore storage tank. Term 2 designates the yearly storage cost with to the capacity installed in a port. Term 3 specifies the material costs spent by the port to acquire the LNG supply from a liquefaction plant. Term 4 expresses the operational cost per onshore storage tank, consisting of maintenance, labour, overhead, as well as the capital portion per tank. Term 5 shows the cost incurred from shipping lines' point of view, which is computed as the multiplication between the annual volume of LNG bunker bought by the shipping lines per port and the selling price of LNG bunker at the particular port.

Constraint (4.2) is applied to ensure that the onshore tank will only be built if the LNG bunkering facility is developed at Port i.

Also, if there is no container ship coming to a port for bunkering in either Route k of the voyage, then there would be no LNG bunkering facility built at Port i, as reflected by Constraint (4.3).

Constraint (4.4) mandates that there should be one port for bunkering to sail to Port j from any Port i in Route k.

Constraint (4.5) dictates that the total volume of LNG bunkered in the refuelling port i shall not exceed the maximum capacity of the vessel's fuel tank. The bunkered volume is the sum of fuel consumption from Port i to any Port j. This constraint should also apply to every Route k.

To make sure that the vessel refuels in sequential order along Route k, Constraint (4.6) is imposed. It requires that if a ship does not refuel at Port i to go to Port j, it cannot bunker at Port i to go to any subsequent port after Port j.

To satisfy all demands of refuelling vessels in Port i while determining the required number of onshore LNG tanks, Constraint (4.7) is implemented. The one-time capacity of the storage tanks at bunkering port shall be enough to cover the bunkering volume of all incoming vessels in a period.

At last, Constraint (4.8), (4.9), and (4.10) are bounding the binary and integer conditions of the decision variables.

Assumptions

The assumptions below are held when developing the model:

1) All container ships sail the same route and have the size of 8,000 TEUs.
2) Speed of the container ship is constant at 14 knots throughout the voyage, leading to stable fuel consumption.
3) The number of inbound vessels to a port is uniformly distributed throughout the year.
4) A specific leg of the Asia - Europe ocean route is taken, comprising the crucial ports in Asia that are routinely visited by major container shipping lines.
5) Every bunkering port purchases its LNG supplies from a liquefaction plant that offers the cheapest materials cost and logistics cost. The supplies will be delivered using a medium-sized LNG carrier on a CIF basis.

4.2 Data

All required data for building the empirical model are listed and extrapolated in this subchapter. The entire data are collected from secondary resources, either from recent publications or academic researches. However, missing information, which does not exist in the current situation, are going to be estimated in the most appropriate way.

4.2.1 Port Selection

Major ocean route from Asia to Europe is taken because it counts for 40.9% of the global seaborne containerised trade and keeps growing by at least 3.5% from year to year (UNCTAD, 2018), implying the importance of LNG bunkering facilities along the way.

A set of Asian ports, comprising Busan in South Korea, Shanghai in the People's Republic of China, Hong Kong, Tanjung Pelepas in Malaysia, Singapore, Jawaharlal Nehru in India, and Fujairah in the United Arab Emirates, are inputted into the model to test it empirically. The first six ports are deemed critical in Asia, since they are regularly called by major container shipping players, namely Maersk, CMA CGM, MSC, Hapag-Lloyd, and Evergreen. The last port, Fujairah, is chosen as the starting point for the eastbound voyage and endpoint for the westbound one, as it is one of the biggest bunkering ports in the world and considered as the gate between two continents.

Pendulum route is assumed to be taken by these shipping lines, reflecting continuous journey to facilitate the trade in Asia. Container ship enters the set through Fujairah in the eastbound voyage then continues to sail up to Busan before heading back to the west and leaving the system through Fujairah once more.

Figure 4.1 illustrates the ports that are going to be observed in the model.

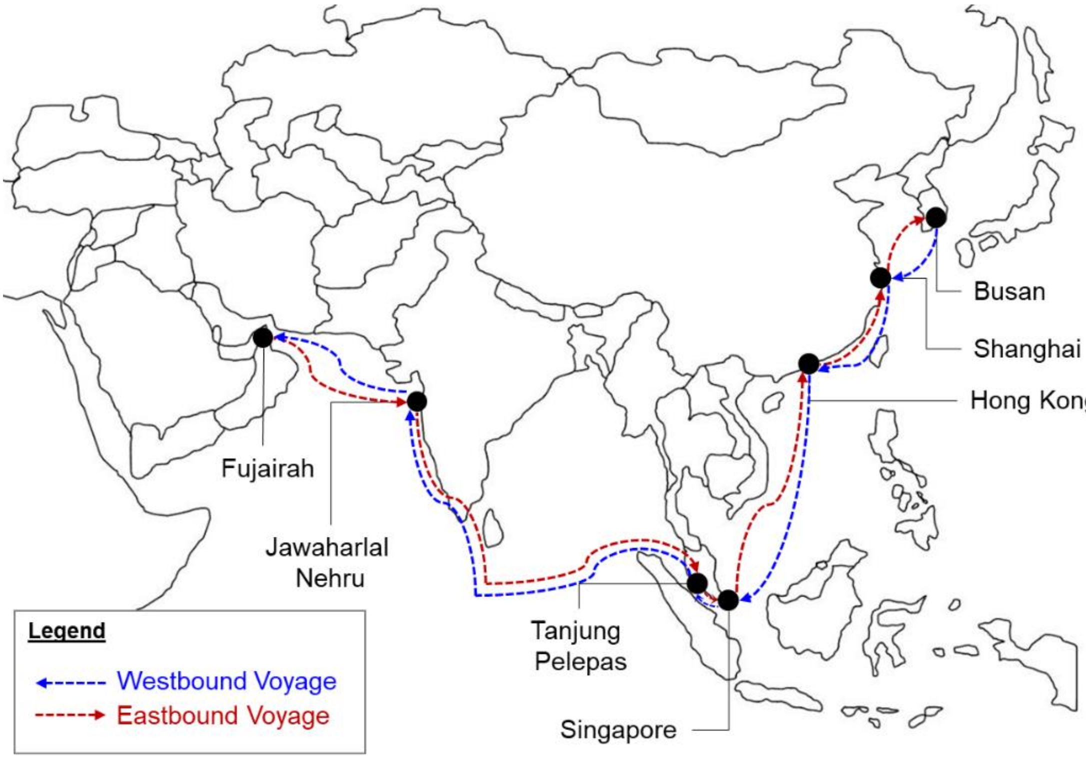

Figure 4.1. Major container ports in Asia
Source: Author's creation with a template from George the Geographer (2014)

The absence of onshore LNG bunkering hubs in Asia underlies the green-field assumptions used in this thesis, so no LNG terminal or LNG bunkering facility is assumed to exist.

4.2.2 Distances between Ports

Distances between ports are taken from Sea Distances (2019). Table 4.1 contains the exact distance from each port to another, all shown in nautical miles.

Table 4.1 Distances between Ports (in nautical miles)

Origin \ Destination	Busan	Shanghai	Hong Kong	Singapore	Tanjung Pelepas	Jawaharlal Nehru	Fujairah
Busan	0	492	1,337	2,819	2,854	5,491	6,826
Shanghai	492	0	845	2,327	2,362	4,999	6,334
Hong Kong	1,337	845	0	1,482	1,517	4,154	5,489
Singapore	2,819	2,327	1,482	0	35	2,672	4,007
Tanjung Pelepas	2,854	2,362	1,517	35	0	2,637	3,972
Jawaharlal Nehru	5,491	4,999	4,154	2,672	2,637	0	1,156
Fujairah	6,826	6,334	5,489	4,007	3,972	1,156	0

Source: Sea Distances (2019)

Fuel consumption of LNG-fuelled ships between ports will be derived from the above distances and be elaborated further in the following sub-subchapter.

4.2.3. Refuelling Range of LNG-fuelled Container Ships

Fuel tanks of the present LNG-powered container ships vary from 3,500 cubic meters to 11,000 cubic meters, which would be able to sail from 3,400 nautical miles to 9,000 nautical miles, respectively (Delta Marin, 2018). The shortest range of 3,400 nautical miles will be used to predict the refuelling plan of the containerships. This shortest-range leads to the average fuel consumption of 1.02 cubic meters of LNG per nautical mile, assuming the ships are slow-steaming at 14 knots. The shortest refuelling range of the smallest seagoing ship should be prioritised as ships with larger fuel tank could sail further without frequent bunkering.

The average fuel consumption for every leg of the route can be concluded accordingly, as shown in Table 4.2.

Table 4.2. Fuel Consumption between Ports (in cubic meter)

Origin \ Destination	Busan	Shanghai	Hong Kong	Singapore	Tanjung Pelepas	Jawaharlal Nehru	Fujairah
Busan	-	502	1,364	2,876	2,911	5,601	6,963
Shanghai	502	-	862	2,374	2,409	5,099	6,461
Hong Kong	1,364	862	-	1,512	1,547	4,237	5,599
Singapore	2,876	2,374	1,512	-	36	2,725	4,087
Tanjung Pelepas	2,911	2,409	1,547	36	-	2,690	4,051
Jawaharlal Nehru	5,601	5,099	4,237	2,725	2,690	-	1,362
Fujairah	6,963	6,461	5,599	4,087	4,051	1,362	-

Source: Author’s calculation based on Sea Distances (2019) and Delta Marin (2018)

The author illustrates the bunkering behaviour of the shipping lines in Figure 4.2. Their bunkering behaviour is presumed to rely heavily on the aforementioned fuel consumption.

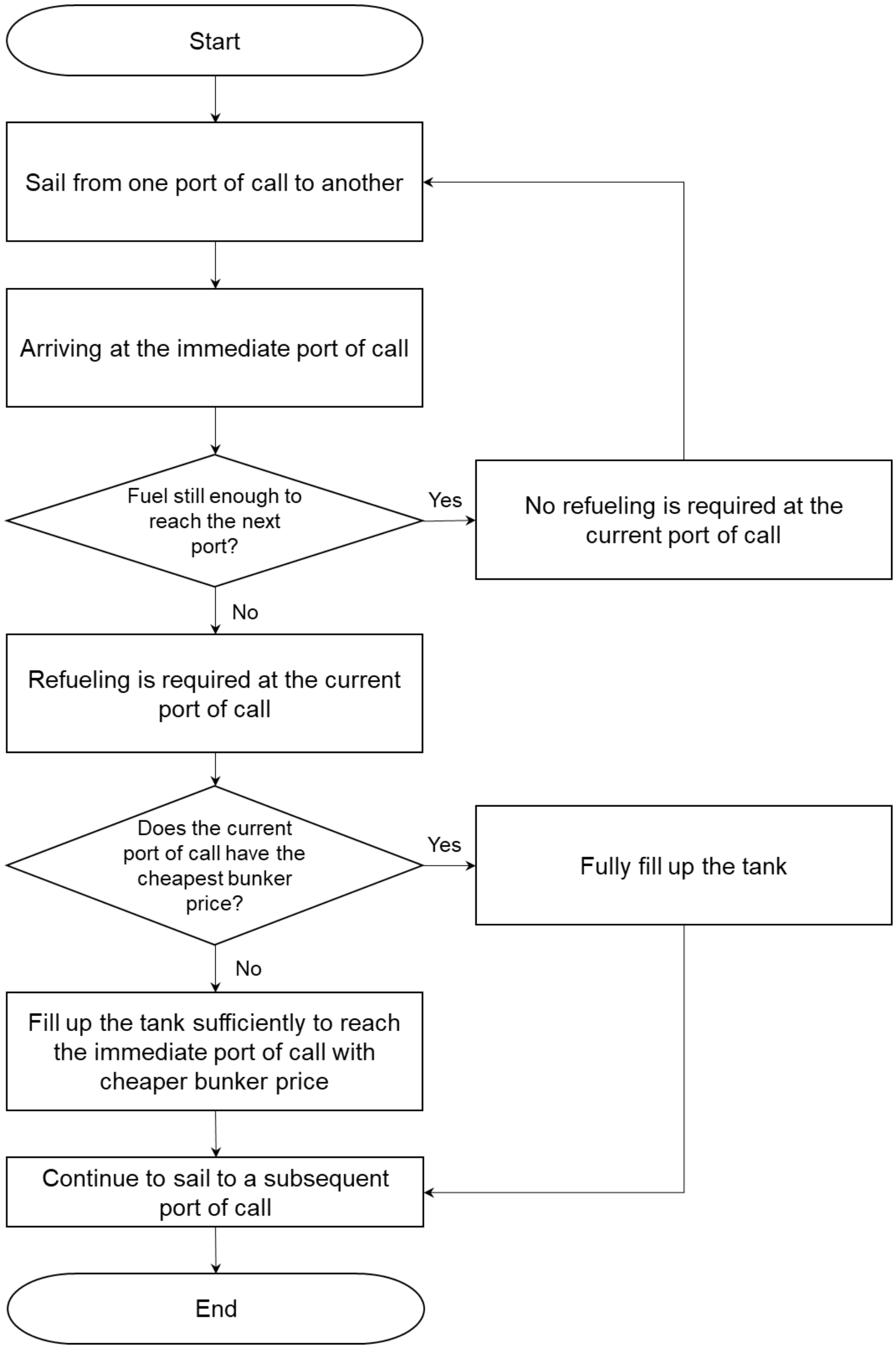

Figure 4.2. Bunkering Behaviour of the Shipping Lines

4.2.4. The Demand of LNG Bunker at Each Port

The absence of shore-to-ship bunkering ports in Asia makes it difficult to estimate the demand for LNG bunker at each port. There are two feasible approaches to approximate the demand: the first one is by forecasting the required LNG bunker based on the existing conventional bunker sales in each port, while the second one is by deriving the LNG demand based on fuel consumption per vessel. The latter is chosen, taking into account the refuelling range of LNG-powered ships and the price preference of shipping lines.

The refuelling range determines the critical location for bunkering, while the fuel consumption defines the amount of bunker required at each of the refuelling locations. Both of them will then estimate the demand of LNG per vessel in each port.

The total demand for LNG bunkering per year can be calculated by multiplying the demand of LNG per vessel and the projected number of incoming vessels per year in a specific port. Data regarding the number of container ships calling in a port are taken from the respective port's statistics.

$$\begin{gathered}\text{Annual demand for LNG bunker} = \\ \text{No. of incoming container ship per year } \times \text{Fuel volume to reach the next bunkering port}\end{gathered} \tag{4.11}$$

The required volume of fuel to sail to the next bunkering port is generated by the model, while the number of incoming container ship to a port can be projected from:

$$\begin{gathered}\text{No. of incoming container ship per year by 2030} = \\ \text{Current no. of total incoming ship } \times \text{Current proportion of LNG fuelled container ship} \\ \times \text{ Growth of LNG fuelled ship by 2030}\end{gathered} \tag{4.12}$$

The proportion of LNG-fuelled container ships compared to the current total fleet is 0.48%, as declared earlier in Chapter 2. Growth in the LNG-powered fleet is predicted to be 8% per year as previously studied by Oxford Energy Institute (2018). By 2030, this growth would increase the total number of LNG-fuelled ships by around 250% compared to those in 2018. Growth in 2030 is intentionally taken to consider the highest possible demand in the next decade, so that the facility would be able to anticipate a significant spike in demand before the growth of LNG-powered ships gets slower from 2030 onwards.

The specific flow from Asia to Europe should also be estimated. According to UNCTAD (2018), the containerised trade from Asia to Europe/the Mediterranean vice versa counted for 24.7 million TEUs in 2018 while the intra-Asian trade and the north-South (European/Asia to Australia vice versa) contributed 6.8 million TEUs and 6.4 million TEUs at the same year. In other words, the number of ships dedicated to Asia to Europe, the Middle East, or the Mediterranean is 65.2% of the total inbound vessels per port in Asia.

Approximated number of LNG-powered container ships serving Asia to Europe/the Mediterranean route that call at each Asian port is presented below, with only sea-going container ships taken into consideration.

Table 4.3. Estimate of LNG-fuelled Containership Calling at Each Port (in unit)

Port	Total Incoming Ships as per 2018	Incoming LNG-fuelled Container Ships by 2030 that sail in Asia - Mediterranean/ Europe Route
(a)	**(b)**	**(c) = (b) x 0.48% * $(100\%+8\%)^{12}$ x 65.2%**
Busan	39,771	313
Shanghai	78,290	617
Hong Kong	40,311	318
Singapore	65,465	516
Tanjung Pelepas	16,212	128
Jawaharlal Nehru	46,227	364
Fujairah	68,784	564

Source: Statistics report of each port

For estimating purpose, all of these inbound vessels are assumed to have the smallest LNG fuel tank, which is 3,500 cubic meters.

4.2.5 Associated Costs of LNG Bunkering Facilities

Considering that the problem outlined in this research aims to minimise total costs incurred by the system, the following cost elements need to be merged into the calculation:

a) Capital Cost

Motsoahole (2014) drew an estimate about the capital cost of a shore-to-ship LNG bunkering station in South Africa. The capital cost comprises a set of dedicated loading arms and jetty, along with the infrastructure installed in the jetty and the license to operate. Meanwhile, the construction cost of the storage tank and associated pipeline and manifold per tank are calculated separately. For such a huge investment, the economic life of the facilities is projected to be 40 years, as a basis for calculating the annual expense.

In order to compute the capital cost of LNG bunkering facilities in Asia, the capital costs of South African ports assessed by Motsoahole in 2014 are escalated based on the inflation rate and then adjusted according to the price index per respective Asian country. Since the lifetime would be around 40 years, the annual capital cost equals one-fortieth of the total capital cost. The final calculation of yearly capital costs is displayed in Column (h) of the same table, with the South African presented in the first row as a reference.

Table 4.4. Capital Cost of LNG Bunkering Hub (in USD)

Port	Price Index	Jetty, Loading Arm, and Filling Station	LNG Infrastructure on Jetty	License to Operate	Total Capital Cost	Economic Lifetime	Annual Capital Cost
(a)	(b)	(c)	(d)	(e)	(f) = (c)+(d)+€	(g)	(h) = (f) / (g)
South Africa	53.3	31,204,622	22,503,333	555,082	54,263,037	40 years	**1,356,576**
Busan	94.0	55,032,541	55,032,541	978,944	111,044,027	40 years	**2,776,101**
Shanghai	55.1	32,258,436	32,258,436	573,828	65,090,701	40 years	**1,627,268**
Hong Kong	95.1	55,676,539	55,676,539	990,400	112,343,478	40 years	**2,808,587**
Singapore	95.8	56,086,356	56,086,356	997,690	113,170,402	40 years	**2,829,260**
Tanjung Pelepas	50.6	29,623,900	29,623,900	526,964	59,774,763	40 years	**1,494,369**
Jawaharlal Nehru	31.3	18,324,665	18,324,665	325,968	36,975,298	40 years	**924,382**
Fujairah	77.9	45,606,755	45,606,755	811,274	92,024,784	40 years	**2,300,620**

Source: Author's estimate based on Motsoahole (2014)

b) Operational Cost

Operational cost (also known as OPEX) covers the costs that occur periodically, such as operations of the tank, operation of the pipeline, personnel wages, and maintenance cost that is required to operate one storage tank. For optimisation purpose, construction cost per storage tank is also included because the operational cost would depend on the number of tanks.

Technically speaking, the storage tank itself is considered to be a full-containment tank, made of inner nickel-steel cylinder surrounded by outer carbon-steel material with a seal between them. The outmost wall of the tank is added to prevent leakage, made of post-stressed concrete. Majority of LNG tanks built in the last decade are full-containment, as it has proven track record of safety and reliability without requiring excessive land space (GIIGNL, 2018).

Motsoahole (2014) has also calculated the operational cost, including the capital cost per 20,000-cubic-meter full-containment LNG tank in South Africa. With the similar approximation made for the capital costs, the operational cost per port are detailed in the following table. The South African costs are kept in the first row as a reference.

Table 4.5. Operational Cost of LNG Bunkering Hub (in USD)

Port	Price Index	Construction Cost per Storage Tank	Annual Construction Cost per Storage Tank	Pipeline and Manifold per Tank	Tank Operations and Maintenance	Personnel Wages	Total Annual Operational Cost
(a)	(b)	(c)	(d) = (c) / 12	(e)	(f)	(g)	(h) = (d)+(e)+(f)+(g)
South Africa	53.3	60,008,888	1,500,222	750,111	3,060,453	1,350,200	6,660,987
Busan	94	105,831,810	2,645,795	1,322,898	5,397,422	2,381,216	11,747,331
Shanghai	55.1	62,035,455	1,550,886	775,443	3,163,808	1,395,798	6,885,935
Hong Kong	95.1	107,070,268	2,676,757	1,338,378	5,460,584	2,409,081	11,884,800
Singapore	95.8	107,858,377	2,696,459	1,348,230	5,500,777	2,426,813	11,972,280
Tanjung Pelepas	50.6	56,969,038	1,424,226	712,113	2,905,421	1,281,803	6,323,563
Jawaharlal Nehru	31.3	35,239,741	880,994	440,497	1,797,227	792,894	3,911,611
Fujairah	77.9	87,705,298	2,192,632	1,096,316	4,472,970	1,973,369	9,735,288

Source: Author's estimate based on Motsoahole (2014)

c) Storage Cost

Storage cost consists of the operational and maintenance cost of the storage facilities, mainly relates to the electricity to keep them running. A research conducted by Enagas (2019) found that the average storage cost of LNG in the 20,000-cubic-meter onshore tank is EUR 32.40 per GWh per day, which can be converted into USD 73.00 per cubic meter per year. This number will be applied equally for all ports.

d) Material Cost

Material cost includes the cost of LNG supply per cubic meter (which equals the selling price of the liquefaction plant) and the logistics cost to transport them from the liquefaction plants. Each of these components will be detailed below.

The first component, LNG prices of liquefaction plants in the Asia Pacific, are taken from research by Oxford Energy Institute (2018) and shown in Table 4.6.

Table 4.6. Material cost of LNG supply
(in USD per cubic meter of LNG)

Liquefaction Plant	LNG Price
(a)	(b)
Brunei	0.294
Tangguh	0.291
Sakhalin 2	0.306
Donggi Senoro	0.290
Papua New Guinea	0.293
Australia	0.292
Qatar	0.295
Oman	0.289
Yemen	0.298

Source: Oxford Institute for Energy Studies (2018)

The supply of LNG takes place under a long-term forward contract at all times to lock the price from a specific LNG plant, so the price listed above is expected to stay fixed for the next three years at the least.

Meanwhile, the associated logistics costs from the above liquefaction plants to the proposed bunkering ports are also taken from research by Oxford Energy Institute (2018), shown in Table 4.7.

Table 4.7. Logistics cost from each liquefaction plant to each port
(in USD per cubic meter of LNG)

Destination / LNG Plants	Busan	Shanghai	Hong Kong	Singapore	Tanjung Pelepas	Jawaharlal Nehru	Fujairah
Brunei	0.214	0.211	0.206	0.205	0.205	0.220	0.227
Tangguh	0.214	0.214	0.213	0.214	0.214	0.229	0.236
Sakhalin 2	0.208	0.211	0.216	0.227	0.227	0.242	0.249
Donggi Senoro	0.215	0.213	0.210	0.208	0.208	0.224	0.229
Papua New Guinea	0.222	0.222	0.221	0.220	0.220	0.233	0.240
Australia	0.218	0.218	0.218	0.214	0.214	0.227	0.234
Qatar	0.231	0.229	0.225	0.218	0.218	0.207	0.202
Oman	0.228	0.226	0.222	0.215	0.215	0.205	0.200
Yemen	0.229	0.226	0.223	0.216	0.215	0.206	0.205

Source: Oxford Institute for Energy Studies (2018)

Specifically, the above logistics costs consist of fuel consumption, boil-off opportunity cost, and charter rate of the LNG carrier to transport the LNG from the liquefaction plant to the port of bunkering. LNG is assumed to be carried by 125,000 cubic meter LNG tanker, the most common size that accounts for 73% of the current fleet (Oxford Institute for Energy Studies, 2018). Oxford Institute of Energy Studies further elaborated that the component of the charter rate is more significant than fuel cost or boil-off rate; so that the distance between liquefaction plants and ports only contributes to around 15-20% of the transportation cost.

As a simplification, LNG supplies are assumed to be carried by an LNG tanker from the liquefaction plant to the port of bunkering in DAP (Delivered-at-Place) basis, INCOTERM 2010. Therefore, the logistics cost includes the rate of LNG tanker chartered by the liquefaction plants and the fuel consumption (and subsequently the boil-off gas) between ports.

Comparison of materials and logistics cost per pair of the liquefaction plant and the port of destination is sum up and shown in the following table.

Table 4.8. Materials and logistics cost from each liquefaction plant to each port (in USD per cubic meter of LNG)

Destination / LNG Plants	Busan	Shanghai	Hong Kong	Singapore	Tanjung Pelepas	Jawaharlal Nehru	Fujairah
Brunei	0.509	***0.506***	***0.501***	0.499	***0.499***	0.514	0.521
Tangguh	0.504	0.504	0.504	0.504	0.504	0.520	0.527
Sakhalin 2	***0.514***	0.517	0.522	0.532	0.533	0.548	0.555
Donggi Senoro	0.505	0.503	0.500	***0.498***	0.498	0.514	0.519
Papua New Guinea	0.515	0.515	0.514	0.513	0.513	0.526	0.533
Australia	0.510	0.510	0.509	0.506	0.506	0.519	0.526
Qatar	0.526	0.524	0.521	0.513	0.513	0.503	0.497
Oman	0.517	0.515	0.512	0.504	0.504	***0.494***	***0.490***
Yemen	0.526	0.524	0.521	0.513	0.513	0.504	0.503

Source: Author's calculation based on Oxford Institute for Energy Studies (2018)

The LNG supply is assumed to be procured from one liquefaction plant having the cheapest cost of materials and logistics, which is printed in ***bold italic*** in Table 4.7 above.

e) Summary of Total Cost per Port

The annual capital cost from Table 4.4, annual operational cost from Table 4.5, annual storage costs from point 4.2.5.c, and materials cost from Table 4.8 are summarised in Table 4.9.

Table 4.9. Associated costs per port (in USD)

Port	Annual Capital Cost	Annual Operational Cost per Tank	Annual Storage Cost per cubic meter of LNG	Materials Cost per cubic meter of LNG
(a)	(b)	(c)	(d)	(e)
Busan	2,776,101	11,747,331	73.0	0.514
Shanghai	1,627,268	6,885,935	73.0	0.506
Hong Kong	2,808,587	11,884,800	73.0	0.501
Singapore	2,829,260	11,972,280	73.0	0.498
Tanjung Pelepas	1,494,369	6,323,563	73.0	0.499
Jawaharlal Nehru	924,382	3,911,611	73.0	0.494
Fujairah	2,300,620	9,735,288	73.0	0.490

Source: Author's compilation from the aforementioned sources

4.2.6. Selling Price of LNG Bunker

To perform the breakeven analysis outlined in Subchapter 3.4, the selling price of LNG bunker needs to be sought from every assessed port. However, since the LNG bunkering does not exist yet in those ports, the selling prices should be estimated.

One feasible approach is by benchmarking against Rotterdam's bunker price, as Rotterdam currently sells both LNG and conventional bunker. Specifically, the LNG bunker price is extrapolated using this formula:

$$\text{LNG Bunker Price at Port i} = \frac{\text{Average Conventional Bunker Price Port i}}{\text{Average Conventional Bunker Price Rotterdam}} \times \text{LNG Bunker Price Rotterdam} \tag{4.13}$$

Based on Ship & Bunker (2019) and Sharples (2019), selling prices of conventional fuels at the evaluated ports are presented in Column (b), (c), and (d) of Table 4.10, while the estimated LNG bunker prices resulted from extrapolation are listed in Column (e) of the same table. All prices are actual as per 31 July 2019.

Table 4.10. Estimated bunker selling price (in USD)

Port	Fuel Price			
	HFO 380 per ton	HFO 180 per ton	MGO per ton	LNG Bunker price per cubic meter
(a)	(b)	(c)	(d)	(e)
Rotterdam	347.5	382	532	135.2
Busan	482	496.5	630	172.4
Shanghai	464	471	698	175.1
Hong Kong	488.5	501.5	606.5	171.2
Singapore	453	486.5	594	164.4
Tanjung Pelepas	465	477	670	172.8
Jawaharlal Nehru	501	553	898	209.3
Fujairah	340	415	670	149.9

Source: Ship & Bunker (2019) and Sharples (2019)

4.3. Deterministic Solutions

In the empirical model of Asian major sailing route, Set K would comprise 2 routes: westbound and eastbound, while each of Set I and Set J would have 7 ports: Busan, Shanghai, Hongkong, Singapore, Tanjung Pelepas, Jawaharlal Nehru, and Fujairah. There would be 112 integer variables in total to be solved, in which 105 of them are binary.

After the model has been established and equipped with sufficient data, it is executed and solved under a deterministic environment in AIMMS. AIMMS employs CPLEX 12.8 as its solver, taking 0.05 sec and 90.3 megabytes of memory to solve the mixed-integer linear programming with 11 iterations.

Table 4.11 details the outcome, which has 0.00% optimality gap.

Table 4.11. Deterministic Solutions

Port	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Estimated Annual Demand	Number of Tanks to be Built
(a)	(b)	(c)	(d)	(e)	(f)
Busan	Yes	No	Build	911,456 m^3	1
Shanghai	No	No	Not Build	-	-
Hong Kong	No	No	Not Build	-	-
Singapore	No	No	Not Build	-	-
Tanjung Pelepas	Yes	Yes	Build	717,056 m^3	1
Jawaharlal Nehru	Yes	Yes	Build	1,970,696 m^3	2
Fujairah	No	No	Not Build	-	-

Table 4.11 states that container ships are predicted to get bunkered at Busan, Tanjung Pelepas, and Jawaharlal Nehru during the westbound voyage, as also illustrated by Figure 4.3. The annual capital and operational cost of Jawaharlal Nehru and Tanjung Pelepas are significantly cheaper than the other proposed ports, regardless of the varying materials cost and bunker selling price. Therefore, the model enforces the development of bunkering hubs at these two ports to reduce the overall cost of the system. Meanwhile, Busan is preferred by the shipping lines because of its lower bunker price compared to the nearby port Shanghai. Although the difference in their prices is not significant, the several-hundred-thousand bunkering volumes exaggerate the gap between them.

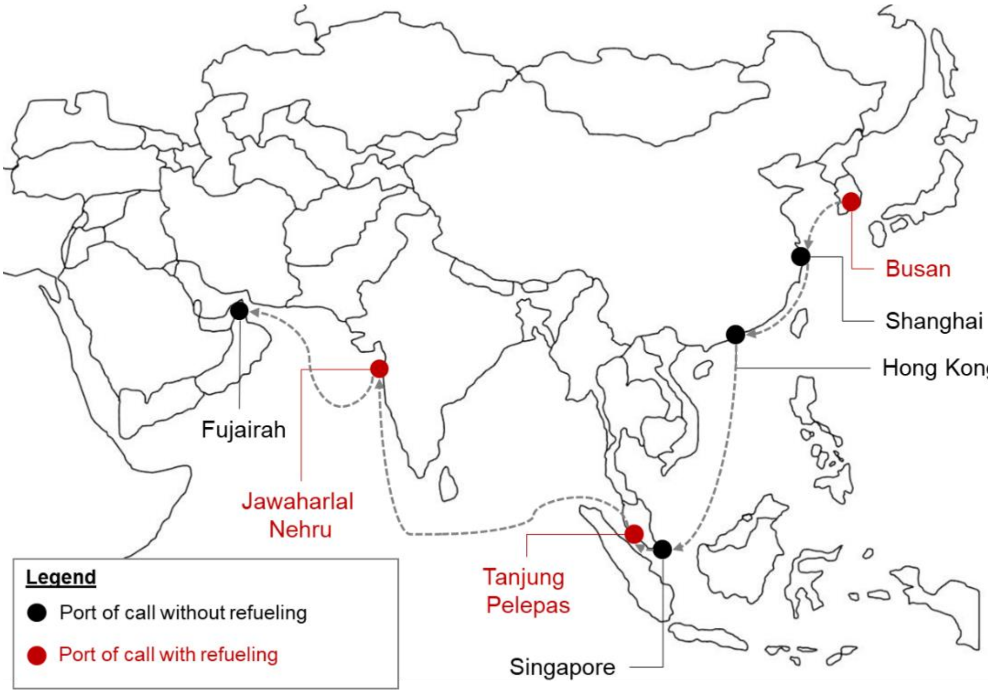

Figure 4.3. Bunkering Ports in the Westbound Voyage
Source: Author's creation with a template from George the Geographer (2014)

As designed, Constraint (4.5) of the refuelling range becomes the most considerable constraints in the model. Reachable distances amongst the first five ports make it feasible for ships to bunker as much as it can in Busan, with relatively lower bunker price than its surrounding ports before heading to the next ports. On the other hand, extensive distance between Tanjung Pelepas and Jawaharlal Nehru forces the shipping lines to bunker at Jawaharlal Nehru despite its high bunker selling price, before continuing the journey westbound. Luckily, low capital cost and operational cost at Jawaharlal Nehru can be seen as compensation to pull down the total costs incurred by the system, particularly from the port authority's or bunkering provider's perspective. This result is aligned with the flow chart designated in Figure 4.2.

One interesting outcome is that the model suggests building bunkering point at Tanjung Pelepas even though Singapore – the neighbouring port - has the lowest bunker price. Although Singapore is cheaper than Tanjung Pelepas, which is logically preferable by the shipping lines, its capital and operational cost are so high that the model suggested putting LNG bunkering hub at Tanjung Pelepas instead. This is also the case with Fujairah, who possesses low bunker price but then high capital and operational costs.

The other constraints bound the result as well. Constraint (4.2), (4.3), and (4.7) are enacted as there is no plan to build LNG bunkering facilities and storage tanks in ports that are not chosen by shipping lines for bunkering.

Constraint (4.4) results on the capability of container ships to travel from one port to another with sufficient bunker for each leg. The fuel demand at each port is then derived from this constraint, resulting in the sum of fuel required to reach Port j.

In the eastbound trip, the ships will refuel at Jawaharlal Nehru and Tanjung Pelepas, before they return westbound at Busan to make a pendulum route. With similar judgment as of the westbound journey, Tanjung Pelepas is chosen based on its economic capital and operational cost despite its bunker price is higher than Singapore. Nothwithstanding its highest bunker price, Jawaharlal Nehru is also selected because of its lowest capital and operational cost in the set.

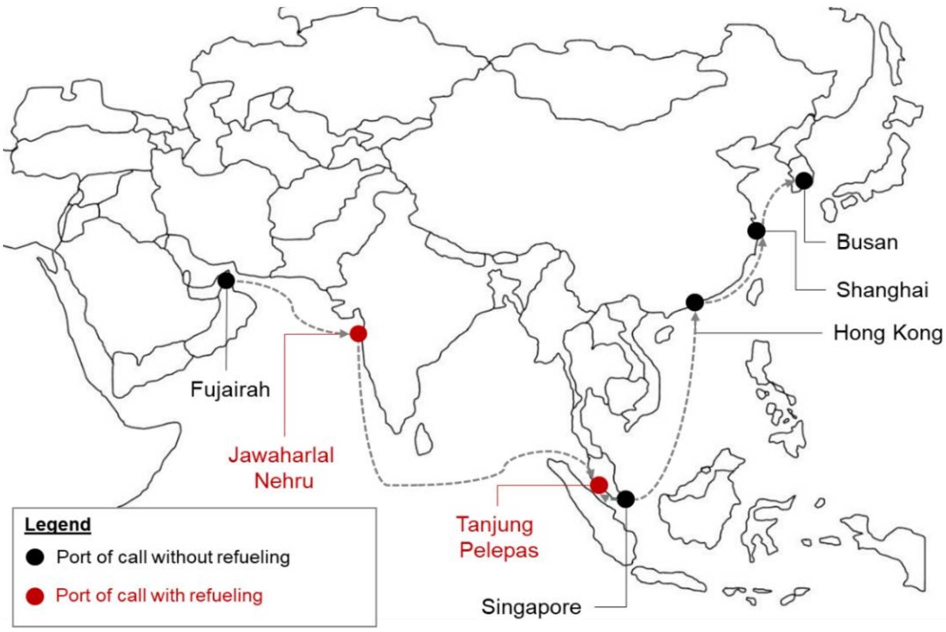

Figure 4.4. Bunkering Ports in the Eastbound Voyage
Source: Author's creation with a template from George the Geographer (2014)

Based on the result of westbound and eastbound optimisation, onshore bunkering hubs are suggested to be placed in Busan, Tanjung Pelepas, and Jawaharlal Nehru. Busan and Tanjung Pelepas only needs one 20,000-cubic-meter onshore tank each to accommodate the projected demand of LNG bunker up to 2030, while there would be two 20,000-cubic-meter onshore tanks in Jawaharlal Nehru to satisfy its numerous calls. In total, USD 35,808,791 is compulsory per year to execute and operate this plan across ports, on top of USD 693,508,964 spent by the shipping lines to purchase the bunkers. Table 4.12 explains the individual cost elements per proposed port, while Figure 4.5 illustrates the proposed optimal locations for LNG bunkering.

Table 4.12. Estimated Total Costs of the Deterministic Optimal Solution

Port	Annual Port Expense					Shipping Lines Expense
	Capital Cost	Inventory Cost	Materials Cost	Operational Cost	Subtotal Port Cost	Bunker Purchase
(a)	(b)	(c)	(d)	(e)	(f)	(g)
Busan	2,776,101	730,000	468,488	11,747,331	15,721,920	157,135,014
Tanjung Pelepas	1,494,369	730,000	357,811	6,323,563	8,905,743	123,907,277
Jawaharlal Nehru	924,382	1,460,000	973,524	7,823,223	11,181,129	412,466,673
TOTAL COST					**729,317,755**	

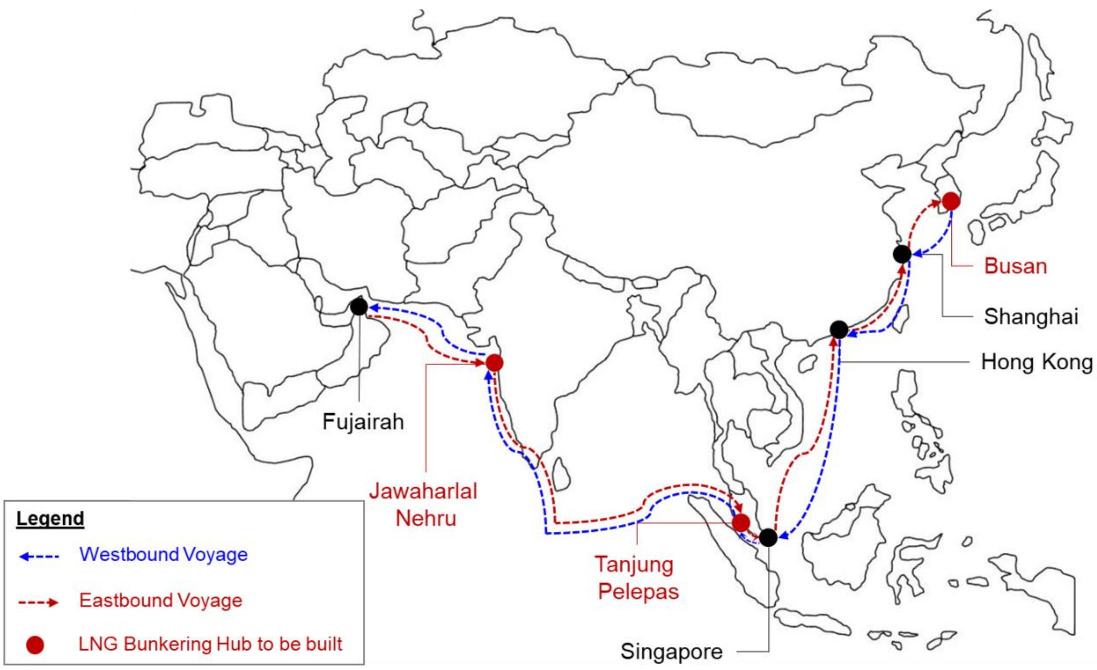

Figure 4.5. Proposed Ports for LNG Bunkering Hub
Source: Author's creation with a template from George the Geographer (2014)

The outcome of the model indicates that LNG bunkering ports should not be adjacent to each other, as the approach to place the LNG bunkering hub is rather different from conventional marine fuel.

Due to its technical complexity to maintain the ultra-low temperature of LNG, cost for constructing LNG bunkering facilities is much more expensive than those of conventional fuel. MAN (2018) highlighted that the cost difference is potentially around 200%, mainly owing to the pressure and temperature insulation requirements. High capital and operational costs also explain the absence of LNG bunkering station at Singapore despite its potentially lowest bunker price. Cheap bunker would be preferable by the shipping lines, but unfavourable by the port authority - especially looking at the high capital cost to install the infrastructure.

The second reason relates to the present demand of LNG bunker which is not as high as HFO or MGO, making it unattractive for port authority or any bunker operator to initiate the LNG bunkering business unless they can secure enough demand to recover the cost. Ironically, the shipping lines will not deploy LNG-powered ship unless they are sure there would be enough bunkering point along the route. In some cases, the shipping lines tend to alter their routes to find bunkering station for their LNG-fuelled fleets. Again, the chicken-and-egg dilemma is inevitable in implementing the solutions.

Anyhow, up to ten years after the IMO 2020 implementation, three proposed ports at Jawaharlal Nehru, Tanjung Pelepas, and Busan are deemed sufficient to satisfy the demand of LNG bunker.

4.4. Verification of the Deterministic Model

To prove that the model works appropriately as designed and to see how sensitive this model responds to any change in its input, verification is done by changing the right-hand side of a constraint. In this case, Constraint (4.4) is modified by testing three parameters separately: the capacity of fuel tank per vessel, the capacity of onshore LNG tank, and the bunker selling price per port.

4.4.1. Changing the capacity of the fuel tank

The first parameter to be adjusted is the fuel tank capacity of each vessel (Parameter “C”), to be increased from 3,500 cubic meters to 11,000 cubic meters assuming that all ships sailing in Asia-Europe route are Ultra Large Container Vessel (ULCV). While doing the verification, all other parameters are held constant.

Table 4.13 Outcome of the Verification after Changing the Fuel Tank Capacity

Port	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Estimated Annual Demand for LNG Bunker	Number of Tanks to be Built
(a)	(b)	(c)	(d)	(e)	(f)
Busan	No	No	Not Build	-	-
Shanghai	No	No	Not Build	-	-
Hong Kong	No	No	Not Build	-	-
Singapore	No	No	Not Build	-	-
Tanjung Pelepas	Yes	Yes	Build	1,435,483 m^3	2
Jawaharlal Nehru	No	Yes	Build	979,910 m^3	1
Fujairah	No	No	Not Build	-	-

Table 4.13 shows the result of the verification, implying that only two bunkering points are required: one at Tanjung Pelepas for refuelling in the eastbound and westbound voyage; and another one at Jawaharlal Nehru for the eastbound only. This outcome is aligned with the expected reality, as 11,000 cubic meters of LNG fuel can indeed accommodate the eastbound sailing from Tanjung Pelepas to Busan, going back westbound to Tanjung Pelepas, and are still sufficient to go to Fujairah and to come back eastbound to Jawaharlal Nehru without the need of refuelling.

Another interesting point is that the demand for bunkering in Tanjung Pelepas is almost doubled while the demand for Jawaharlal Nehru drops significantly. This outcome infers that larger fuel tank provides flexibility for the shipping lines to refuel as much as possible in any cheap bunkering port while trying to avoid the more expensive ones - to the extent allowed by the refuelling range. As a result, the shipping lines would prioritise bunkering at Tanjung Pelepas that offers the cheapest combination of bunker price, capital costs, and operational cost. Jawaharlal Nehru comes as the next priority once the refuelling range constraint kicks in during the pendulum sailing. Although one more tank is required at Tanjung Pelepas, the total cost drops dramatically as shown in Table 4.14, owing to the substantial bunkering volume with low prices at Tanjung Pelepas and to the absence of Busan development.

Table 4.14. Estimated Total Costs after Enlarging the Capacity of Fuel Tank

Port	Annual Port Expense					Shipping Lines Expense
	Capital Cost	Inventory Cost	Materials Cost	Operational Cost	Subtotal Port Cost	Bunker Purchase
(a)	(b)	(c)	(d)	(e)	(f)	(g)
Tanjung Pelepas	1,494,369	1,460,000	716,513	12,647,126	16,318,008	248,051,455
Jawaharlal Nehru	924,382	730,000	484,230	3,911,611	6,050,224	205,095,231
TOTAL COST					**475,514,919**	

4.4.2. Changing the capacity of onshore LNG tank

This second verification will test the sensitivity of the model in case the largest technically-feasible storage tank is to be built, having the size of 180,000 cubic meters. As this verification only focuses on the impact of adjusting one parameter, all other parameters are held constant. The operational cost per tank is also held the same assuming that the operational cost will not differ from 20,000-cubic-meter tank.

After changing Parameter “V” in the original deterministic model from 20,000 cubic meters to 180,000 cubic meters in all ports, AIMMS generates the new optimal solution as follows.

Table 4.15 Outcome of the Verification after Changing the Onshore Tank Capacity

Port	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Estimated Annual Demand for LNG Bunker	Number of Tanks to be Built
(a)	(b)	(c)	(d)	(e)	(f)
Busan	Yes	No	Build	911,456 m^3	1
Shanghai	No	No	Not Build	-	-
Hong Kong	No	No	Not Build	-	-
Singapore	No	No	Not Build	-	-
Tanjung Pelepas	Yes	Yes	Build	717,056 m^3	1
Jawaharlal Nehru	Yes	Yes	Build	1,970,696 m^3	1
Fujairah	No	No	Not Build	-	-

With no change in demand, Jawaharlal Nehru needs a fewer number of tanks as the onshore storage tank gets larger, while Busan and Tanjung Pelepas keep having one tank each. Despite the reduction in operational cost of Jawaharlal Nehru from two tanks to only one, inventory costs of all ports increase dramatically since the storage tank is eight times larger than the initial one.

Table 4.16. Estimated Total Costs after Changing the Onshore Tank Capacity

Port	Annual Port Expense					Shipping Lines Expense
	Capital Cost	Inventory Cost	Materials Cost	Operational Cost	Subtotal Port Cost	Bunker Purchase
(a)	(b)	(c)	(d)	(e)	(f)	(g)
Busan	2,776,101	6,570,000	468,488	11,747,331	21,561,920	157,135,014
Tanjung Pelepas	1,494,369	6,570,000	357,811	6,323,563	14,745,743	123,907,277
Jawaharlal Nehru	924,382	6,570,000	973,524	7,823,223	16,291,129	412,466,673
TOTAL COST					**746,107,756**	

4.4.3. Changing the bunker selling price

Initially, each port charges different bunker price from each other (see Table 4.10). However, this verification scenario assumes the same bunker prices across ports, having the same price as Rotterdam (USD 135.2 per cubic meter).

After running the program, it turns out that there is no difference in the optimal solutions. The same bunker price across ports makes shipping lines indifferent about the bunkering ports, so the only substantial concern for them is refuelling range. However, the ports' perspective becomes essential as the only consideration left is the cost they spend. As the bunker price will be the same for shipping lines regardless of their bunkering point, the model tries to minimise the capital, operational, inventory, and material costs borne by the port, thus suggesting Busan, Tanjung Pelepas, and Jawaharlal Nehru that possess cheaper capital and operational costs compared to the other ports. Anyhow, the total cost will change in accordance with the change of bunker price.

After checking the three scenarios above, we could say that the model responds properly to any adjustment in the parameter and behaves appropriately as per the general logic and common practice.

4.5. Validation of the Deterministic Model

As emphasised by McCarl and Apland (1984), model validation is essential in an empirical study to check if the model works as per its intended purpose and if it reflects the reality, hence enhancing confidence in implementing the computed results. There are two approaches to validate a model, namely validation by construct and validation by results. Validation by construct concludes the validity of a model after ensuring that the model is developed in the best possible way, while validation by results compares the outcome of a model against real-world observations before confirming if a model is valid.

Picking up the predictive nature of this thesis that relies on future circumstances, the validation by results is not feasible due to the absence of real-world outcome for benchmarking purpose. Presently, there are only ship-to-ship LNG bunkering taking place at Ningbo-Zhoushan (People's Republic of China), Tanjung Pelepas (Malaysia), and Kochi (India) (Keller, 2019) with one shore-to-ship infrastructure currently built in Incheon (South Korea), hence motivating this study to presume a green-field situation as the base case.

The only option left is to conduct validation by construct. The following underlying assertions are checked out, to fulfil the criteria set by McCarl and Apland (1984):

a) The right procedures were used to build the model
Development of this thesis involved a rigorous literature review to ensure that the model is consistent with the supply chain of LNG bunker, then enriched with secondary data from credible sources. A reasonable estimating approach was deployed for any missing data to reflect reality as precise as possible.

b) Trial results indicate the model is behaving satisfactorily
The verification process carried out in Subchapter 4.4 satisfies the designated model behaviour set up by Figure 4.2, so this requirement can be checked out as well.

c) Constraints were imposed which restrict the model to realistic solutions
Constraints implemented in this model aim to create a realistic model by enforcing these conditions:

1) Container ships shall have enough fuel to run on each leg of the westbound and eastbound route.
2) If the container ships are running out of fuel, they will bunker in the next immediate port.
3) If no ship comes to bunker in a specified port, the model will decide not to build the bunkering facilities.
4) If bunkering facility is not built, there will be no onshore LNG tank constructed.

Thus, the inconsistent outcome - such as having onshore LNG tanks without building the overall facilities or constructing the facilities without having any container ship coming to bunker – can be eliminated.

4.6. Conclusion

This chapter provided an answer for the fourth sub-research question by creating a mathematical model in line with facility-location problem and inventory problem. Supported by extensive data search, the model generated a feasible optimal solution that satisfies all constraints and suggested the development of onshore LNG bunkering hubs at Busan, Tanjung Pelepas, and Jawaharlal Nehru. The verification and validation performed in Subchapter 4.4 and 4.5 deduced that the model is valid and already behaved as per its designated requirement.

Concerning the unforeseen impact of the IMO 2020 implementation, the estimated data shall not distress the validity of the model since this research aims to produce a general framework for seeking the optimal locations to place new onshore LNG bunkering hubs in Asia. However, as the unpredictable elements have not yet considered in the deterministic model, the model should be improved to accommodate this uncertainty.

Chapter 5 Robust Optimisation

Although the result produced by the deterministic model seems to be the answer to the research question, the real-world situations contain randomness and uncertainty that would complicate the decision-making process. This chapter will perform post-optimal analysis by building the robust counterpart of the deterministic program, as well as verifying the robust counterpart to ensure it behaves as expected. By the end of this chapter, optimal solutions that are still "good" in spite of the worst conditions can be concluded.

5.1. Introducing Uncertainties

Scope of this thesis involves unforeseen circumstances since the idea behind it, IMO 2020, is yet to be implemented. As previously noted in Subchapter 4.2, some data do not exist pending the enactment of the IMO 2020 and cannot be measured at the moment, hence approximation is necessary to obtain those data.

One of the essentials parameters to be approximated is the demand for LNG bunkering at each port. The absence of existing bunkering hubs, as well as the rapid growth of LNG-fuelled ship, make it difficult to estimate the figure accurately. Therefore, this chapter will robustly optimise the deterministic model to cope with the uncertain demand of LNG bunkering and to avoid any misleading decision proposed by the model.

5.2. Defining Uncertainties

Subchapter 3.3 already mentioned the basic concept of robust optimisation, which requires a given set of uncertainty with well-defined lower bound and upper bound. In this case, the demand of LNG bunker at each port, which is derived from the number of inbound vessels per port, becomes the uncertain parameter which range is to be defined.

Roelofs and Bisschop (2019) emphasised that the main focus of setting uncertainty range is "*how to specify a reasonable uncertainty set that is meaningful for a particular application and also yielding a tractable robust counterpart*". Still, determining the uncertainty range for the number of incoming vessels is not that simple because there is no track record of LNG-fuelled container ship's call to each port. A study completed by Ibarra, Hoyos, and Molina (2010) proposed a decision tool based on 5 scenarios: pessimistic, moderately pessimistic, neutral, moderately optimistic, and optimistic, in which the gap between each other is one-third of the parameter set in the neutral scenario. This weight will be adopted in this thesis by having one-third gap between scenarios, although there would only be three scenarios tested to decide the values of the lower bound and upper bound:

a) Most-Likely Scenario
The number of incoming vessels per port is the same as the estimated value in Sub-subchapter 4.2.4 or shortened as "average number of vessels coming to a port" for easier identification.

b) Pessimistic Scenario

The number of incoming vessels per port is one-third less than those in the moderate scenario. This value will be considered as the lower bound of the uncertainty range.

c) Optimistic Scenario

The number of incoming vessels per port is one-third more than those in the moderate scenario. This value will be considered as the upper bound of the uncertainty range.

This uncertainty inevitably affects the decision to build the bunkering facility and the required capacity in case the bunkering facility is to be made. As a consequence, these decision variables are adjustable depending on the number of vessels calling in a particular port.

Uncertain elements for the robust counterpart are summarised below.

Table 5.1. Uncertain Elements of the Robust Counterpart

Uncertain Element	Remarks
Uncertain Parameter	$\mathbf{N_i}$ **Estimated number of vessels coming to Port i in a period of time** Range of uncertainty: - Lower Bound = 0.67× Average Number of Incoming Container Ship at Port i - Upper Bound: 1.33 × Average Number of Incoming Container Ship at Port I
Adjustable Variables depending on the Uncertain Parameter	$\mathbf{Y_i}$ Decision to build or not to build LNG bunker facility at Port i $\mathbf{X_i}$ The number of onshore tanks required to be constructed at Port i

5.3. Specification of the Robust Counterpart

Taking into account the uncertain parameter of LNG bunker demand, specifications of the deterministic model can be re-written as:

Model Specification

$$\mathrm{Min}\left\{\underset{\forall \mathbf{N} \in \mathbf{U}}{\mathbf{Max}} \sum_i F_i . Y_i + \sum_i \frac{1}{2} . H_i . V . X_i + \sum_i \sum_j \sum_k N_i . M_i . FU_{ij} . Z_{ijk} + \sum_i O_i . X_i + \sum_i \sum_j \sum_k N_i . P_i . FU_{ij} . Z_{ijk}\right\} \quad (5.1)$$

subject to:

$$X_i \leq M . Y_I \qquad \forall\, i \in I \quad (5.2)$$

$$\sum_j \sum_k Z_{ijk} \leq M . Y_I \qquad \forall\, i \in I \quad (5.3)$$

$$\sum_i Z_{ijk} = 1 \qquad \forall\, j \in J, k \in K \quad (5.4)$$

$$\sum_j Z_{ijk} . FU_{ij} \leq C \qquad \forall\, i \in I, k \in K \quad (5.5)$$

$$Z_{ijk+1} \leq Z_{ijk} \qquad \forall\, i \in I, j \in J, k \in K \quad (5.6)$$

$\sum_j \sum_k N_i . Z_{ijk} . FU_{ij} \leq V . X_I \qquad \forall\, i \in I,\ \mathbf{N} \in \mathbf{U}$ (5.7)

$X_i \in \mathbb{Z} \qquad \forall\, i \in I$ (5.8)

$Y_I \in \mathbb{B} \qquad \forall\, i \in I$ (5.9)

$Z_{ijk} \in \mathbb{B} \qquad \forall\, i \in I, j \in J, k \in K$ (5.10)

In principal, the terms involved in the objective function and the constraints remain the same. There are only two changes incorporated by the robust counterpart, stressed in **bold,** to reflect the uncertainty; one in the objective function and another one in the sixth constraint. The objective function (5.1) still consists of the same five terms as the deterministic formulation, though it is slightly adjusted to represent the goal of the robust optimisation by minimising the total cost of the system given the maximum cost generated by each scenario. Constraint (5.7) is also modified to test all possible demands of LNG bunker for determining the number of required onshore LNG tanks. In other words, the one-time capacity of the bunkering port shall be sufficient to anticipate the fluctuating demand.

Assumptions

In addition to the assumptions listed in Subchapter 4.2, the robust assumes that the lowest demand is 33% less than the average while the highest one is 33% more than the average.

5.4. Robust Optimal Solution

The Robust Optimisation feature in AIMMS generates a set of robust optimal solutions after the author initiates two steps. Firstly, the deterministic program is modified by declaring $\mathbf{N_i}$ (the number of incoming LNG-fuelled vessel) as “Uncertain Parameter” and defining its lower bound and upper bound. Secondly, the affected variables like $\mathbf{Y_i}$ (decision to build or not to build LNG bunker facility at Port i) and $\mathbf{X_i}$ (the number of onshore tanks required to be constructed at Port i) are declared as “Adjusted Variables”, depending on the number of incoming LNG-fuelled vessel.

After the author does these steps, AIMMS starts generating the robust counterpart based on the uncertain parameters and the adjustable variables. AIMMS will create a mathematical program for every possible scenario within the uncertainty range of LNG demand. It will make a solver session for each mathematical program and let the solver unravel the problem afterwards. At last, the robust optimisation feature will pick the worst result over all scenarios as the maximum costs to be anticipated by the decision-makers.

AIMMS employs CPLEX 12.8 as its solver, running 17 iterations and taking 0.20 sec and 94.7 megabytes of memory to generate a set of robust solutions. It takes slightly more resources than deterministic solver as there are more scenarios to be tested. The following robust optimal solutions are then generated by AIMMS, having 0.00% optimality gap.

Table 5.2. Robust Optimal Solutions

Port	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Estimated Range of Annual Demand for LNG Bunker	Number of Tanks to be Built
(a)	(b)	(c)	(d)	(e)	(f)
Busan	Yes	No	Build	610,675 – 1,212,236 m^3	2
Shanghai	No	No	Not Build	-	-
Hong Kong	No	No	Not Build	-	-
Singapore	No	No	Not Build	-	-
Tanjung Pelepas	Yes	Yes	Build	480,427 – 953,684 m^3	1
Jawaharlal Nehru	Yes	Yes	Build	1,320,366 – 2,621,026 m^3	3
Fujairah	No	No	Not Build	-	-

Consistent with the robust optimisation concept, this set of solution is considered feasible and optimal for the realisation of *any* scenario in the given uncertainty set. In principle, robust counterpart took the upper bound of the demand as the worst scenario, leading to the highest cost incurred by the shipping lines and consequently the highest total costs among the possible scenarios.

The differences between the robust optimal solutions and the deterministic solution can be spotted in terms of the estimated annual demand and the number of tanks to be built. Apart from those points, the proposed ports for LNG bunkering are the same: Busan, Tanjung Pelepas, and Jawaharlal Nehru.

Recalling the deterministic solution, the model previously suggested one tank at Busan, one tank at Tanjung Pelepas, and another two tanks at Jawaharlal Nehru. With the upscaled demand from the robust counterpart, the number of required tanks per port increases accordingly, suggesting one additional tank at Busan and an extra tank at Jawaharlal Nehru. Tanjung Pelepas, which initially has an abundant capacity in the deterministic result, does not need any supplementary tank and is still believed to be adequate with only one storage tank.

The constraint of refuelling range (5.5) remains to be the major limitation, as it drives the shipping lines to bunker at Jawaharlal Nehru despite its expensive bunker price. Meanwhile, Busan and Tanjung Pelepas were chosen due to their lower capital costs and operational costs despite the comparable materials costs and bunker price amongst surrounding ports. As for Singapore, notwithstanding its lowest bunker price that might attract shipping lines, it was still not favourable by the port to install the LNG bunkering facilities because of its high capital and operational cost.

Table 5.3 details the anticipated total cost of this solution.

Table 5.3. Estimated Total Costs of the Robust Optimal Solution (in USD)

Port	Port Expense				Shipping Lines Expense
	Capital Cost	Inventory Cost	Materials Cost	Operational Cost	Bunker Purchase
(a)	(b)	(c)	(d)	(e)	(f)
Busan	2,776,101	1,460,000	622,533	23,494,662	209,279,870
Tanjung Pelepas	1,494,369	730,000	476,026	6,323,563	164,529,688
Jawaharlal Nehru	924,382	2,190,000	1,295,200	11,734,833	549,490,548
TOTAL COST	**975,373,278**				

The robust optimisation leads to a much higher total cost than its deterministic counterpart because it considered the unpredictable worst-case scenario. Consequently, for all realisations of uncertain demand, the total cost would be at most USD 975,373,278. Any decision other than the proposed optimal solution, such as building the LNG bunkering hub in Shanghai or building one more tank in Jawaharlal Nehru, might lead to the total cost that is higher than USD 975,373,278 and no longer believed as optimal. Meanwhile, the deterministic solution only relies its calculation on one definitive point over various possible scenarios.

5.5. Conclusion

The author applied robust optimisation to the deterministic model for dealing with the predictive nature of LNG bunkering. A robust counterpart was formed to test all probable demand across scenarios before producing a set of optimal solutions based on the worst possible result.

The robust optimal solutions are quite similar to the deterministic solutions, apart from the maximum total cost that was based on the highest possible demand. Since a significant part of the total costs is bunker purchases borne by the shipping lines, the highest total cost is derived from the maximum likely demand. Anyhow, from ports' perspectives, higher demand from the shipping lines should be deemed profitable.

From the cost perspective, there is no noteworthy risk caused by the fluctuating demand since the port expenditures do not change significantly across scenarios. However, another assessment from the revenue perspective needs to be done to ensure the profitability of the proposed solutions.

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Chapter 6 Profitability Analysis

Aside from the outcome generated by the deterministic model and its robust counterpart, the revenue side of the port has not been appropriately assessed, bearing in mind the capital-intensive nature of LNG bunkering business. Therefore, this chapter evaluates the profitability of the proposed optimal solutions, which primarily focus on minimising total cost occurred by port and shipping lines. A breakeven analysis will be conducted to check the profitability of the proposed bunkering hubs. Afterwards, the ideal capacity of storage tank capacity is reviewed and discussed.

The current robust outcome is slightly reformatted as Table 6.1 for a more convenient referencing throughout this chapter.

Table 6.1 Summary of the Model Outcome

Port	Estimated LNG bunker price (in USD per cubic meter)	Decision to Build or Not	Estimated Annual Demand of LNG Bunker (in cubic meters)	Number of Tanks to be Built
(a)	(b)	(c)	(d)	(e)
Busan	172.4	Build	610,675 – 1,212,236	2
Shanghai	175.1	Not Build	-	-
Hong Kong	171.2	Not Build	-	-
Singapore	164.6	Not Build	-	-
Tanjung Pelepas	172.8	Build	480,427 – 953,684	1
Jawaharlal Nehru	209.3	Build	1,320,366 – 2,621,026	3
Fujairah	149.9	Not Build	-	-

6.1 Breakeven Analysis of the Optimal Solutions

To ensure that the proposed LNG bunkering facilities would be profitable, the revenue of each port is measured based on the outcome of the model. Revenue per port is the multiplication of LNG bunker selling price and the volume of LNG bunker sold, in which the volume of LNG bunker sold is presumed to be the same as the annual demand per port. Afterwards, the net cash flow is figured out to check whether the breakeven point is achieved.

Two cases will be discussed to understand the profitability of the current result; the first one is to find the breakeven selling price based on the lowest demand and the second one is to investigate the breakeven selling volume based on the current estimated price.

6.1.1 Finding the Breakeven Selling Price, Given the Lowest Demand

To discover the breakeven selling price, equation (3.24) is applied:

$$\text{BEP} = \frac{\text{Fixed Cost} + \text{Semifixed Cost}}{\text{Expected Volume to be Sold}} + \text{Variable Cost}$$

in which the fixed cost is simply the capital cost, while semi-fixed cost contains the operational cost and inventory cost depending on the number of the storage tank. Variable cost is merely the materials cost paid by the port to acquire LNG supply from liquefaction plants.

By applying the pessimistic scenario, we can assess the worst profit (or loss) of LNG bunkering business in an unfavourable demand of LNG bunkering. The lower bound of annual demand listed in Table 6.1 Column (d) is taken as the expected volume to be sold and held constant in the calculation, while Table 6.2 provides the relevant cost that the equation should incorporate.

Applying that formula leads to the required selling price at each proposed port to achieve the breakeven point, as summarised in Table 6.2.

Table 6.2
Breakeven Selling Price for Busan, Tanjung Pelepas, Jawaharlal Nehru

Cost Category	Cost Element	Busan	Tanjung Pelepas	Jawaharlal Nehru
Fixed Cost	Capital Cost (USD)	2,776,101	1,494,369	924,382
Semifixed Cost	Inventory Cost (USD)	1,460,000	730,000	2,190,000
	Operational Cost (USD)	23,494,662	6,323,563	11,734,834
Expected Volume to be Sold	Worst Case of Volume of Sales (m^3)	611,324	479,446	1,321,296
Variable Cost	Materials Cost (USD/m^3)	0.514	0.499	0.494
BEP (USD/m^3)		**46.4**	**18.8**	**12.2**

The breakeven selling prices of Busan, Tanjung Pelepas, and Jawaharlal Nehru are much lower than their estimated selling price. It indicates that these ports are capable to achieve breakeven point with their estimated price. Low breakeven selling price also implies a bigger chance for the ports to be profitable once they initiate the LNG bunkering facilities, which can be achieved via two possible mechanisms as explained hereafter.

First, under the law of demand (Taylor and Mankiw, 2017, p.63), the quantity of goods demanded will increase as the price falls and vice versa. Therefore, setting a lower selling price might boost the volume of LNG sold because more LNG-fuelled fleet will be built to take advantage of cheap LNG bunker. In other words, the ports might focus on the volume over value by setting a lower price as long as it is above the breakeven price. However, a thorough sensitivity analysis needs to be carried out to understand the effect in demand caused by the changes in price, which is beyond the scope of this thesis.

Second, low breakeven price indicates a profit margin that could be grasped by the port. As simulated in this empirical case, Busan, Tanjung Pelepas, and Jawaharlal Nehru are having at least USD 88.6, USD 126.1, and USD 40.7 opportunity margin.

6.1.2. Finding the Breakeven Volume of Sales given the Estimated Selling Price

The second case to be evaluated is finding the required volume to achieve the breakeven point, based on the estimated selling price stipulated in column (b) of Table 6.1. Formula (3.18) is applied:

$$\mathrm{BEQ} = \frac{\text{Fixed Cost} + \text{Semifixed Cost}}{\text{Selling Price} - \text{Variable Cost}}$$

in which the fixed cost only contains the capital cost, while semifixed cost includes the operational cost and inventory cost depending on the number of storage tanks and variable cost represents the material cost borne by the port to purchase LNG feeds from liquefaction plants.

After implementing the formula and following the steps elaborated in Subchapter 3.5, the following breakeven units of sales are found:

Table 6.3.
Breakeven Selling Volume for Busan, Tanjung Pelepas, Jawaharlal Nehru

Cost Category	Cost Element	Busan	Tanjung Pelepas	Jawaharlal Nehru
Fixed Cost	Capital Cost (USD)	2,776,101	1,494,369	924,382
Semifixed Cost	Inventory Cost (USD/tank)	730,000	730,000	730,000
	Operational Cost (USD)	23,494,662	6,323,563	11,734,834
Selling Price	Estimated Bunker Price (USD)	172.4	172.8	209.3
Variable Cost	Materials Cost (USD/m^3)	0.514	0.499	0.494
BEQ (m^3)		**88,741**	**49,611**	**26,656**

Table 6.3 discloses that the breakeven volumes of all ports are even lower than the pessimistic annual demand generated by the model. These low breakeven selling units deduce that even in the unfortunate environment, there would be enough demand to exceed the breakeven point and overcome the cost incurred by the ports.

6.1.3. Breakeven Point of Shanghai, Hong Kong, Singapore, and Fujairah

Other aspects that are interesting to be evaluated is the current outcome of Port of Shanghai, Port of Hong Kong, and Port of Singapore. Albeit the model suggested not to build bunkering facilities at those ports, it is worth to investigate their minimum required demand to be profitable, based on their estimated selling price of LNG bunkers.

With the same approach as Sub-subchapter 6.1.2, breakeven volume for Shanghai, Hong Kong, and Singapore are computed and shown in Table 6.4.

Table 6.4.
Breakeven Selling Volume for Shanghai, Hong Kong, and Singapore

Cost Category	Cost Element	Shanghai	Hong Kong	Singapore	Fujairah
Fixed Cost	Capital Cost (USD)	1,627,268	2,808,587	2,829,260	2,300,620
Semifixed Cost	Inventory Cost (USD)	730,000	730,000	730,000	730,000
	Operational Cost (USD)	6,885,935	11,884,800	11,972,280	9,735,288
Selling Price	Estimated Bunker Price (USD)	175.1	171.2	164.4	149.9
Variable Cost	Materials Cost (USD/m^3)	0.506	0.501	0.498	0.490
BEQ (m^3)		**52,941**	**90,354**	**94,761**	**85,442**

To be considered profitable, Shanghai, Hong Kong, Singapore, and Fujairah shall sell at least 52,941; 90,354; 94,761; and 85,442 cubic meters of LNG bunker, respectively. Significantly higher capital and operational costs of these ports compared to those of Busan, Tanjung Pelepas, and Jawaharlal Nehru make them unattractive for port authorities to invest, as a substantial breakeven volume is required to pay back their investment and cover any annual costs.

Interestingly, even though the breakeven quantity of Shanghai is less than Busan, Shanghai is not proposed to be LNG bunkering hub. The higher selling price of Shanghai requires less volume to be breakeven, but it also makes Shanghai unattractive for shipping lines. Port authority and any bunker provider in Shanghai should bear this in mind when setting up the price, in case they insist on placing an LNG bunkering infrastructure apart from the optimal solution.

Having relatively the same bunker price as Busan and Tanjung Pelepas, Hong Kong has the chance to introduce the bunkering port and stay competitive among the others, though its capital cost and operational cost are slightly higher than Busan and Tanjung Pelepas.

Lastly, Singapore and Fujairah would become the shipping lines' favourites owing to its lowest LNG bunker prices in the system, but unfortunately port authority would not invest there because of their high capital and operational costs that lead to higher breakeven volumes.

6.2. Optimal Capacity of Storage Tanks at Busan, Tanjung Pelepas, and Jawaharlal Nehru

When building the model, onshore storage tank with a capacity of 20,000 cubic meters was chosen as a basis. Anyhow, looking at the estimated annual demand at Busan and Jawaharlal Nehru, more than one tank is required and potentially lead to high operating cost. This subchapter will seek the optimal size of the storage tank at each port to minimise the inventory cost, operational cost, and logistics cost.

In the case of bunkering station, the size of storage tanks is analogous to the ordering size. According to Bull, Meulendijk-de Mol, and Nijboer (2016), the industrial practice reveals that the storage tanks of LNG are commonly made in the unit of tens of thousands, with 20,000 cubic meters as the smallest feasible capacity. Therefore, the ordering size will also be in tens of thousands.

After inserting formula (3.7) as one of the constraints and solving it using AOA non-linear solver, the optimal size of the onshore storage tank at each bunkering location could be defined. While the sets are held the same, the parameters, decision variables, objective function, and associated constraints are extended to some degree:

Parameters

$\mathbf{C}$	Fuel tank capacity of the smallest LNG vessel (in cubic meter)
$\mathbf{F_i}$	Fixed cost of locating LNG bunkering facilities at Port i (in USD)
$\mathbf{FU_{ij}}$	Volume of fuel required to sail from Port i to Port j (in m^3)
$\mathbf{H}$	Annual inventory holding cost per unit (in USD)
$\mathbf{M_i}$	Materials and logistics-related cost per cubic meter of LNG supply to Port i (in USD)
$\mathbf{L}$	Logistics portion of the materials and logistics-related cost per m^3 of LNG supply (in %)
$\mathbf{N_i}$	Estimated number of vessels coming to Port i per year
$\mathbf{O_i}$	Operational cost per onshore LNG tank at Port i (in USD)
$\mathbf{P_i}$	Selling price per cubic meter of LNG bunker at Port i (in USD)

Decision Variables

$\mathbf{Z_{ijk}}$	A binary variable representing the decision to refuel the ship in Port i for sailing from Port i to Port j in Route k, where Z_{ijk} = 1 if the vessel bunkers at Port i during the voyage in Route k and Z_{ijk} = 0 if otherwise
$\mathbf{Y_i}$	A binary variable representing the decision to build or not to build LNG bunker facilities at Port i, where Y_i = 1 if an LNG bunkering facility is built at Port i and Y_i = 0 if otherwise
$\mathbf{V_i}$	**Volume per onshore LNG tank at Port i (in cubic meter)**
$\mathbf{R_i}$	**Frequency of replenishment per year**
$\mathbf{X_i}$	Integer variable representing the number of tanks with capacity V_i to be built at Port i

Model Specification

$$\mathrm{Min}\left\{\underset{\forall N\in U}{\mathrm{Max}} \sum_i F_i.Y_i + \sum_i \frac{1}{2}.H_i.V_i.X_i + \sum_i\sum_j\sum_k N_i.M_i.FU_{ij}.Z_{ijk} + \sum_i O_i.X_i + \sum_i\sum_j\sum_k N_i.P_i.FU_{ij}.Z_{ijk}\right\} \quad (6.1)$$

subject to:

$$X_i \leq M.Y_i \qquad \forall\, i \in I \quad (6.2)$$

$$\sum_j\sum_k Z_{ijk} \leq M.Y_i \qquad \forall\, i \in I \quad (6.3)$$

$$\sum_i Z_{ijk} = 1 \qquad \forall\, j \in J, k \in K \qquad (6.4)$$

$$\sum_j Z_{ijk}.FU_{ijk} \leq C \qquad \forall\, i \in I, k \in K \qquad (6.5)$$

$$Z_{ijk+1} \leq Z_{ijk} \qquad \forall\, i \in I, j \in J, k \in K \qquad (6.6)$$

$$\sum_j \sum_k N_i.Z_{ijk}.FU_{ij} \leq \mathbf{V_i}.\mathbf{R_i}.X_i \qquad \forall\, i \in I, N \in U \qquad (6.7)$$

$$\frac{\mathbf{2.N_i.\sum_j \sum_k Z_{ijk}.FU_{ij}.L.M_i}}{\mathbf{H_i}} \leq \mathbf{V_i} \qquad \forall\, \mathbf{i \in I} \qquad \mathbf{(6.8)}$$

$$V_i \in \mathbb{R} \qquad \forall\, i \in I \qquad (6.9)$$

$$X_i \in \mathbb{Z} \qquad \forall\, i \in I \qquad (6.10)$$

$$Y_i \in \mathbb{B} \qquad \forall\, i \in I \qquad (6.11)$$

$$Z_{ijk} \in \mathbb{B} \qquad \forall\, i \in I, j \in J, k \in K \qquad (6.12)$$

Compared to the robust model stated in Subchapter 5.3, this updated model contains several adjustments that also emphasised above in **bold**:

i. Parameter N_i, the estimated number of vessels coming to Port i, refers to the highest demand as simulated by the robust counterpart. The port should be able to build sufficient capacity to anticipate the maximum possible demand.
ii. The second term of the objective function relates to the capacity of each tank at Port i – notated by decision variable V_i. In other words, this model becomes a non-linear program.
iii. Constraint (6.7) is adopted from Constraint (5.7) with a small modification. The capacity per storage tank multiplied by the number of storage tanks and replenishment frequency reflect the total bunkering capacity managed by a port in year, which shall fulfil the annual demand from the inbound LNG-powered fleets.
iv. Constraint (6.8) is introduced in line with the formula of Economic Order Quantity (3.7), with V_i represents the economic order quantity, $N_i.\sum_j \sum_k Z_{ijk}.FU_{ij}$ indicates the annual demand per port, $L.M_i$ embodies the logistics cost per cubic meter of LNG bunker, and H_i designates the inventory holding cost per cubic meter of LNG.

Assumptions

In addition to the assumptions listed in Subchapter 4.2 and Subchapter 5.3, this model assumes that:

a) The LNG liquefaction plants are capable of delivering the LNG supply to bunkering ports as frequent as possible without any change in cost. The DAP-basis materials cost already included logistics cost; thus, any tanker chartering cost will be borne by the liquefaction plants.
b) The increase in the operational cost of storage tanks for a bigger capacity is assumed to be insignificant and can be neglected.
c) The maximum possible demand is used to ensure that the capacity could accommodate the highest demand in the next 12 years.

Table 6.5 demonstrates the optimal solutions of the extended model. Utilising AOA Solver with CPLEX 12.8 to solve the linear elements and CONOPT 4.0 to solve the non-linear ones, AIMMS spends 0.19 sec and 96.7 megabytes of memory on finding the solutions with 0.00% optimality gap.

Table 6.5. The Outcome of the Extended Model

Port	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Maximum Demand per Year	Capacity per Storage Tank
(a)	(b)	(c)	(d)	(e)	(g)
Busan	Yes	No	Build	1,212,236 m^3	20,000 m^3
Shanghai	No	No	Not Build	-	-
Hong Kong	No	No	Not Build	-	-
Singapore	No	No	Not Build	-	-
Tanjung Pelepas	Yes	Yes	Build	953,684 m^3	20,000 m^3
Jawaharlal Nehru	Yes	Yes	Build	2,621,026 m^3	20,000 m^3
Fujairah	No	No	Not Build	-	-

The optimal ordering quantity for Busan, Tanjung Pelepas, and Busan is 20,000 cubic meters, which subsequently become the size of their LNG storage tanks. Relatively lower cost of logistics compared to the cost of inventory supports the suggestion to build a smaller tank with more frequent replenishment.

Apart from the proposed optimal solution, high operating cost per tank might become a consideration to construct only one tank at each of the three ports. To keep up with the annual demand, ordering frequency should be adjusted accordingly as per Formula 3.8.

$$\text{Number of orders per year} = \frac{\text{Annual Demand}}{\text{Economic Order Quantity}}$$

Table 6.6 shows the optimal ordering frequencies for each proposed bunkering hub:

Table 6.6. Optimal Number of Order per Year

Port	Annual Demand	Economic Order Quantity	Number of Orders per Year
(a)	(b)	(c)	(d) = (b) / (c)
Busan	1,212,236 m^3	20,000 m^3	60
Tanjung Pelepas	953,684 m^3	20,000 m^3	48
Jawaharlal Nehru	2,621,026 m^3	20,000 m^3	131

Busan should replenish its inventory every 6 days, whereas Tanjung Pelepas could do that every 7 days and Jawaharlal Nehru should request supplies per 2 days. At a glance, this frequency seems to be overburdened, so a separate feasibility study is required to check the liquefaction plants' capability on fulfilling this fast pace of replenishment.

Total cost resulted from this extended model is USD 953,612,724, which is around USD 21 million lower than the robust solutions. The operating and inventory costs of each proposed port decrease dramatically owing to the fewer number of storage tanks, while the other cost elements remain the same as the original robust result.

Table 6.7. Change in Inventory Cost generated by the Extended Model

Annual Cost	Busan	Tanjung Pelepas	Jawaharlal Nehru
Initial Inventory Cost	1,460,000	730,000	2,190,000
Initial Operational Cost	23,494,662	6,323,563	11,734,834
Optimised Inventory Cost	**730,000**	**730,000**	**730,000**
Optimised Operational Cost	**11,747,331**	**6,323,563**	**3,911,611**
Savings	**12,447,331**	**-**	**9,283,223**

Costs of Tanjung Pelepas is the same as the previous robust solutions, as the demand is not that high to expand its one-time capacity. Meanwhile, the costs of Busan drop by half and those of Jawaharlal Nehru is cut by one-third as a consequence of fewer tanks. Also, we can conclude that the smallest tank capacity of 20,000 cubic meters is still optimal up to 2030.

6.3. Conclusion

To confirm that the proposed solution can generate sufficient revenue and cover the cost, breakeven point and optimal capacity of the suggested ports were analysed.

From the calculations carried out in Subchapter 6.1, some insights can be gained:

a. The proposed ports of Busan, Tanjung Pelepas, and Jawaharlal Nehru are deemed potential to profit from the development of LNG bunkering hubs.
b. The higher the expected volume of sales, the lower is the selling price to achieve the breakeven point.
c. The higher the selling price, the less volume is required to achieve the breakeven point.

A lower breakeven point is indeed more attractive for investors to install the LNG bunkering facilities. In this case, two considerable ways to lower the breakeven point in the LNG bunkering business are: setting a higher (but competitive) selling price to achieve lower breakeven unit and reducing fixed/semifixed cost.

The size of the onshore storage tank is a crucial aspect that affects the profitability of those ports, as it determines the inventory cost. In the near- and medium-term (up to 2030), the smallest onshore tank with the capacity of around 20,000 cubic meters is more efficient although more frequent replenishment is required.

Chapter 7 Upscaling Effect of the Model

Recalling back the main objective written in Subchapter 1.2, this thesis should produce a model to determine the optimal location(s) for developing onshore LNG bunkering stations, along with the required capacity to be installed at each location. Therefore, the model generated and empirically tested in the previous chapters needs to be upscaled and generalised to provide a universal optimisation model. This chapter will generalise the model by expanding its scope and see its impact on the robust optimal solutions.

The model presented in Chapter 4 and 5 took only the major sailing route for container ship in Asia. In reality, there should be other strings to be considered as well – for example, the container ship sailing from Australia to the Middle East or Russia passing through Asia. Citing from UNCTAD (2018), the containerised trade from Asia to Europe or Mediterranean vice versa counted for 24.7 million TEUs in 2018 while the intra-Asian trade and the North-South (European/Asia/Russia to Australia vice versa) contributed 6.8 million TEUs and 6.4 million TEUs at the same year. In other words, the proportion of current flow represented by the model is 65.2% of the total traffic passing the assessed seven ports.

Concerning this point, the existing robust solutions should be upscaled by increasing the demand based on this proportion – formulated as follows.

$$\text{Upscaled Demand} = \frac{\text{Specific demand of a string}}{\text{Proportion of the string's traffic compared to total traffic in the region}} \tag{7.1}$$

After upscaling the number of incoming vessels in the robust counterpart, the robust optimal solutions are adjusted as below:

Table 7.1 Optimal Solutions of the Expanded Scope

Port	Estimated Range of Annual Demand for LNG Bunker	Refuelling Point in Westbound Voyage	Refuelling Point in Eastbound Voyage	Decision to Build or Not	Number of Tanks to be Built
(a)	(e)	(b)	(c)	(d)	(f)
Busan	937,614 – 1,861,841 m^3	Yes	No	Build	2
Shanghai	-	No	No	Not Build	-
Hong Kong	-	No	No	Not Build	-
Singapore	-	No	No	Not Build	-
Tanjung Pelepas	735,347 – 1,460,337 m^3	Yes	Yes	Build	2
Jawaharlal Nehru	2,026,527 – 4,026,646 m^3	Yes	Yes	Build	4
Fujairah	-	No	No	Not Build	-

Although the potential refuelling points remain the same as the robust solution, the numbers of the required tanks increase to deal with the upscaled demand. Busan does not need additional capacity, yet Tanjung Pelepas and Jawaharlal Nehru require one additional tank each with the tank capacity of 20,000 cubic meters. Anyhow, as separately suggested by the extended model in Chapter 6, no extra tank is necessary as long as more frequent replenishment is taken.

The result in Table 7.1 is believed to be optimal for all container ships going through the assessed ports of Busan, Shanghai, Hong Kong, Singapore, Tanjung Pelepas, Jawaharlal Nehru, and Fujairah up to 2030. In conclusion, the overall traffic of LNG-fuelled vessels in Asian assessed ports could be generalised based on the flow in the Asia – Europe/Mediterranean/Middle-East string. This approach could also be applied to any other region with multiple commodities in addition to the containerised cargo.

Chapter 8 Discussion

The case brought up by this research seems to be a complex scientific problem, as it encompasses contradictory perspectives between the related parties and uncertainty about the future, without any proven methodology to solve it. After all, this thesis has created a model to give direction for the port authority to initiate the onshore LNG bunkering project. This chapter will critically evaluate the model to confirm its usefulness against the interest of both parties, as well as to review the model from theoretical and practical points of view including its applicability, limitation, and comparison with the reality.

8.1. Conflict of Interest between Port Authorities and Shipping Lines

Chapter 4 already indicated the contradictory position of the port authority (or any bunker provider) and the liner shipping company, which leads to the unavoidable chicken-and-egg dilemma. Each party has its own concern that needs to be accommodated for enhancing the usage of LNG as an alternative marine fuel.

Port authorities have two concerns: the stability of demand and the profitability of their investment on LNG bunkering facilities. Safety4Sea (2019) implied that inexperienced staffs to handle LNG, high capital cost, safety hazard in case of leakage, and the extremely low temperature to preserve LNG become main concerns to build LNG bunkering facilities worldwide. Therefore, unless port authorities can foresee a certain amount of LNG bunkering demand and confirm the payback of their investment, they would be in doubt to invest in such a capital-intensive business. Even if they finally construct the LNG bunkering infrastructure, the port authority or any bunker provider tend to charge quite a high price for their bunker to gain profit.

On the other hand, shipping lines aim to choose the cheapest bunkering ports possible along their route by adjusting their speed and optimising the bunkering volume, as evidenced by numerous researches (Yao, Ng, and Lee, 2012; Plum, Pisinger, and Jensen, 2014; Aronietis, 2017). Anyhow, for the LNG-fuelled ship, another consideration kicks in: the availability of the LNG bunkering stations. IMO (2016) and World Maritime News (2018a) highlighted that liner shipping companies would alter their LNG-fuelled fleet's routes to find bunkering points or would only deploy their LNG-powered vessels in an area that has prominent LNG bunkering infrastructures. As explained in the previous chapter, shipping lines will not shift to LNG fuel unless they are sure there would be sufficient bunkering points in their route. Even if the LNG bunker is widely available, they will prefer to refuel in the cheapest port and skip the others. Therefore, the bunker price and availability become the main factors in attracting shipping lines. These two points underlie ports' concern in building an LNG bunkering hub since they are not sure about the demand coming into their port and subsequently, they are also not sure about their profitability.

As this thesis tries to view the problem from the port's standpoint without compromising shipping lines' interest, several actions might be taken by the ports to accommodate shipping lines' concern and break this dilemma. First, port authorities should be aware that the implementation of IMO 2020 would trigger the growth of LNG-fuelled vessels. Unless they provide LNG bunkering services in their port, they might not be able to compete with other ports which offer LNG bunker, since the vessels tend to alter their journey for the sake of bunker availability. Second, sufficient capacity with regular replenishment is essential to attract ultra-large vessels to come and bunker there, particularly in a vital string like Asia-Europe. Third, a fair but competitive price should be set to allow the cost recovery of the port without losing its attractiveness compared to the surrounding ports.

Hence, the empirical results do not bound mandatorily, as this model only gives suggestions to relevant port authorities and leave them to decide their most appropriate strategy. For example, LNG bunkering facilities could also be installed at Shanghai, Hong Kong, Singapore, and Fujairah, as long as they set a competitive price to attract shipping lines while ensuring the recovery of their costs.

8.2. Theoretical Perspective

An interesting study by Melo, Nickel, and da Gama (2007) is brought up to evaluate this thesis theoretically. In line with their research, this thesis has the same agenda: identification of potential sites for new facilities and the required capacities, with the presence of capital investment for opening a new facility. However, this study emphasised the role of facility location problem in supply chain and improvement areas for future research. In this part, we will discuss the contribution of this thesis on closing that gap.

The first improvement area is that only a few models addressed both strategic and operational issues of the supply chain, and even if they do, they perform the facility location problem and other supply chain aspects iteratively. As a result, the model would not accomplish a global optimal. To counter this issue, this thesis came up with the combination of facility location problem and inventory problem. The first problem contributes to the strategic decision making, as installing LNG bunker facilities will have a long-lasting impact on the port portfolio. In the operational level, this thesis employed the inventory control model to support decisions regarding capacity of the bunkering ports and their replenishment frequency. More importantly, instead of solving each problem iteratively to find the local optimum, the model integrated both strategic and operational aspects to achieve global optimal solutions.

Another recent development of the facility location problem is the integration of risk into the strategic planning of a supply chain. The most recognised example of risk is uncertain demand and cost, commonly presented as stochastic parameters. Despite its ability to generate optimal solutions in any scenario, robust optimisation has not been paid much attention. Anyhow, this thesis included the risk management into the model by defining the range of uncertain demand then solved it with robust optimisation framework.

Thirdly, they brought up the importance of profit maximisation objective instead of cost minimisation, since the minimum cost might not be even feasible to reach the breakeven point. Although this thesis first introduced a cost minimisation model, the profitability was tested separately to ensure the economic feasibility of the optimal solutions.

Apart from Melo, Nickel, and da Gama’s review, the last distinction of this thesis relates to the nature of the LNG bunkering demand. The demand for LNG bunker is exogenous, depending heavily on the price and availability of the bunker. Ports can create demand by offering LNG bunkering services, yet the expected volume to be sold will rely on their pricing strategy compared to the surrounding ports. This exogenous demand affects the capacity required by the port as well, which in turn determines the replenishment policy.

8.3. Practical Perspective

Besides checking the contribution of this thesis to academic learning, the practicability of this thesis is also checked against the common industry practice.

The first point relates to the alternative methods of LNG bunkering. Despite the presence of ship-to-ship and truck-to-ship bunkering, this thesis focuses on the shore-to-ship one that is a niche part of the business. The flexibility of ship-to-ship and truck-to-ship methods eases any port to bring in a bunker vessel or bunker truck whenever a ship is coming to refuel, without the necessity of high capital cost. On the other hand, onshore bunkering station is less flexible than bunker vessel and bunker truck, though it has substantially higher volume and faster flow rate that are suitable for major ports with stable long-term bunkering demand. Since this inflexibility would claim careful consideration from the port authority, this thesis provided a model for supporting their decision making on onshore LNG bunkering development. Another reason relates to the number of existing bunker vessels, that is not sufficient to cover all regions and unlikely to be deployed in the next three years due to the shipbuilding lead time. Bunker vessels and bunker trucks also take some amount of time to travel from LNG liquefaction plants or LNG terminals to the bunkering points, thus requiring accurate planning to match the port call window of LNG-powered ships. Even, a sea-going LNG-powered ship might need more than one bunker vessel and more than one bunker truck for a one-time refuelling (Bull, Meulendijk-de Mol, and Nijboer, 2016), leading to uneconomical logistics cost of bunker vessels and bunker trucks.

The second aspect links to the capacity of onshore LNG tank. Subchapter 6.2 theoretically estimated the optimal size of onshore LNG storage tank per port, but the reality might differ due to the requirement of loading limit and uncertain lead time from suppliers. Loading limit is the maximum allowable liquid volume that a tank may load, expressed as a percentage of the total tank capacity (ABS, 2019). This space allowance is mandatory for LNG tanks because the loading/unloading process will expose the contained tank into LNG tanker or LNG fuelled-ship thas has a different environment. The difference in temperature or pressure of the ships would vaporise the LNG inside the onshore storage tank, thus urging the requirement of loading limit. The average loading limit varies between 85% to 95%, depending on the atmospheric conditions around the port. Meanwhile, uncertain lead time should be taken into account as well, in case delay occurs in the delivery of LNG from liquefaction plants. One way to overcome this risk is by setting safety inventories, by taking into account the standard deviation of demand during the lead time and the targeted customer service level (Chopra and Meindl, 2016, p.341). Although loading limit and safety inventories should be addressed in determining the applicable capacity of onshore tanks, the absence of historical lead time and demand still leave some room of uncertainty.

Still corresponds with the onshore storage capacity, the third argument talks about the tanker size for delivering LNG from liquefaction plants to bunkering ports. The model assumes that the port purchases the LNG on DAP basis; thus, the material cost is inclusive of logistics cost regardless of the size of the tanker or the frequency of replenishment. However, bunkering ports sometimes buy the supplies on FOB

(Free on Board) basis as well, so the logistics cost becomes essential. A giant LNG carrier like Q-Max provides attractive economies of scale with its 266,000-cubic-meter capacity, but it imposes higher inventory cost in return. In reality, the bunkering port should deal with this issue to optimise the logistics expense without compromising inventory level.

At last, let us compare the optimal solutions against reality. Ship-to-ship LNG bunkering is already performed at Ningbo-Zhoushan (People's Republic of China), Tanjung Pelepas (Malaysia), and Kochi (India), recently followed by Singapore who commenced its first ship-to-ship bunkering in May 2019 (Safety4Sea, 2019). However, the low capacity per bunker vessel and its slow flow rate might be ineffective to cope with the future growth of LNG bunkering and the nature of these ports as seagoing ports. Meanwhile, shore-to-ship bunkering is currently under assessment by port authorities of Busan and Singapore, yet the result is still inconclusive (Liang, 2019). The only realisation can be seen at Port of Keihin, Japan with an existing onshore LNG bunkering terminal and another one at Port of Incheon, South Korea that is constructing a 60,000-cubic-meter onshore bunkering station.

Although Keihin, Incheon, Kochi, and Ningbo-Zhoushan were not tested in the empirical model of this thesis due to their absence in major container lines' routes, the fact that they are having LNG bunkering proves the exogenous nature of the demand. There are some strategic reasons underlie the building of this capital-intensive project in those ports. The first one relates to the diversification strategy of the port authorities, in the case of Ningbo-Zhoushan and Kochi that initially have LNG terminal. For instance, Kochi started as an LNG terminal for storage and regasification back in 2013, yet the port authority saw a promising opportunity to provide LNG bunker as well. At the moment, Kochi has two bunkering barges to serve small LNG-fuelled vessels (Sea LNG, 2019). Ship-to-ship bunkering is preferred for these "new entrants" to test the market, as it does not require high capital cost. Another motive is to self-supply the port's own LNG-powered fleet, that happens in Incheon. The bunkering vessel exists to supply Econuri, its LNG-fuelled passengers' ferry, while an onshore bunkering infrastructure is being constructed to handle upcoming new LNG-fuelled ships that are currently in order (Riviera, 2018). The last reason applies to strategically located ports, such as Keihin. Although Keihin is not considered as a vital port in Asia-Europe route, its location at one end of the North Pacific trade route makes it the first point for loading and unloading for any cargo heading in Asia – America string (World Maritime News, 2018b). It gives a legit motivation for Keihin to have its own LNG bunkering infrastructure.

In other words, any ports can create its own by installing LNG bunkering infrastructure to attract LNG-fuelled ships for altering their main routes. Ship-to-ship bunkering is also a viable option to provide a small-scale bunkering service without incurring significant amount of investment. Thus, it would be better for future models to keep up with the latest bunkering situations on detecting any potential location for LNG bunkering hub.

Chapter 9 Conclusion

9.1. Concluding Remarks

The upcoming IMO 2020 inevitably triggers the rising popularity of LNG as a cleaner marine fuel with zero particulate matters. However, the fact that the existing LNG bunkering infrastructures are located mainly in Europe becomes a concern for the shipping lines before converting their long-haul fleets to be LNG-fuelled. In contrast, port authority and the bunker provider will think twice before initiating the construction of LNG bunkering facilities unless they are sure about the upcoming number of LNG-powered vessels coming into their port. Concerning that problem, this thesis stands on an objective: to provide a suggestion on breaking this chicken-and-egg issue, by producing a model for identifying the optimal location(s) of new LNG bunkering facilities and its required capacity. The main research question is set accordingly: "*How can the optimal location(s) for developing new onshore LNG bunkering hubs be determined to facilitate long-distance cargo voyages, based on the projected LNG bunkering demand after the implementation of IMO 2020?*". A sequential approach of literature review, mixed-integer linear programming, data search, robust optimisation, and economic analysis is done to answer the above research question.

The literature review has laid the foundation about the factors affecting port authorities' decision on developing an LNG bunkering hub and any cost elements involved in their decision, corresponding to sub-research question 1 and 2. In a nutshell, port authorities and relevant parties are concerned about the competitiveness of their bunker price, about potential incoming LNG-fuelled vessel in line with the distances between ports, and also about any associated costs that consist of capital cost, operational cost, inventory cost, and material purchasing cost.

Chapter 3 drew the line between the literature reviewed and the objective of this thesis. It identified the appropriate methodology on addressing the objective and bringing closure to sub-research question 3 by deciding to apply the combined facility location problem and inventory problem, mixed-integer linear programming, and robust optimisation to a case study involving container shipping route from Asia to Europe.

Chapter 4 specified the model and generated the optimal solution for a case study involving seven ports in Asia, outlining that the bunkering hubs need to be built at Busan, Tanjung Pelepas, and Jawaharlal Nehru with the capacity of 20,000 cubic meters, 20,000 cubic meters, and 40,000 cubic meters respectively. However, this result leaves one question to be solved: how we can convince port authorities and associated parties to break the chicken-and-egg dilemma caused by the uncertain demand of LNG bunkering.

The remaining issue from the initial model was followed-up in Chapter 5, in which post-optimal analysis was performed to create a robust counterpart subjected to various scenarios of LNG bunkering demand. In spite of the uncertainty, the robust optimal solution keeps suggesting Busan, Tanjung Pelepas, and Jawaharlal Nehru for offering onshore LNG bunkering services. The proposed capacities are higher than the deterministic solutions, as a means to cope with the fluctuating demand of LNG bunker. Busan would require 40,000 cubic meters of capacity in total, Jawaharlal Nehru should expand to 60,000 cubic meters, while Tanjung Pelepas could keep its initial suggestion of 20,000 cubic meters volume.

Still, port authorities would not put LNG bunkering facilities at their ports unless they can recover the costs and gain profit from the business later on. Confirming the sub-research question 5, breakeven analysis and EOQ analysis give a hint to the profitability prospect of LNG bunkering services per port, concluding that the recommended bunkering stations at Busan, Tanjung Pelepas, and Jawaharlal Nehru would be able to reach their breakeven point and earn profit without any doubt. To check the applicability of the model and adequately address the main research question, the model was generalised in Chapter 7 and re-checked after theoretical and practical perspectives in Chapter 8.

In conclusion, we can determine optimal locations for developing onshore LNG bunkering facilities by deploying mixed-integer linear programming, which combines facility location problem and inventory problem. To enhance the reliability of the framework, robust optimisation approach can be taken as it incorporates any unforeseen circumstances, particularly in the demand side of LNG bunkering. The economic aspect of the solutions could be checked by applying breakeven analysis and extending the model to seek the optimal storage capacity per bunkering port. At last, upscaling might be required to understand the overall demand from several strings that would come into a port.

9.2. Recommendations for Future Research

The main obstacle for developing the model arose during data collection, as there are not many data about LNG bunkering existence and its related cost in any region. Thus, from practicality aspect, follow-up research might be required to validate all costs based on critical cost analysis for any data beyond 2030, as well as to include any potential locations for LNG bunkering outside the major container route. From the theoretical point, the model requires further research to incorporate multi strings and multi commodities as an input for multiple decision-makers.

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Annex 1. Optimisation Model in AIMMS

```
## ams_version=1.0

Model Main_Stochastic_Model_Thesis {
    DeclarationSection Deterministic_Model_Declarations {
        Set Port {
            Index: i, j;
            OrderBy: User;
        }
        Set SubsequentPort {
            Index: p;
            OrderBy: User;
        }
        Set Route {
            Index: k;
        }
        Variable BuildOrNot {
            IndexDomain: i;
            Text: "Decision to build or not to build bunkering
station at Port i (Yi)";
            Range: binary;
            Dependency: NoOfIncomingVessel(i);
        }
        Variable NoOfTanks {
            IndexDomain: i;
            Text: "Number of tanks to be built at Port i (Xi)";
            Range: integer;
            Dependency: NoOfIncomingVessel(i);
        }
        Variable BunkerOrNot {
            IndexDomain: (k,i,j);
            Text: "Decision of the shipping lines to bunker or
not to bunker at Port i to sail to Port j along the Route k";
            Range: binary;
        }
        Variable BunkeringVolume {
            IndexDomain: (k,i,j);
            Range: free;
            Definition:
RefuelingVolume(k,i,j)*BunkerOrNot(k,i,j);
        }
        Variable SubtotalCapitalCost {
            IndexDomain: i;
            Range: free;
            Definition: CapitalCost(i)*BuildOrNot(i);
        }
        Variable SubtotalInventoryCost {
            IndexDomain: i;
            Range: free;
```

```
            Definition:
0.5*InventoryCost(i)*OnshoreTankCapacity*NoOfTanks(i);
        }
        Variable SubtotalMaterialsCost {
            IndexDomain: i;
            Range: free;
            Property: Adjustable;
            Definition:                              sum[(j,k),
BunkerOrNot(k,i,j)*RefuelingVolume(k,i,j)*NoOfIncomingVessel(i
)*MaterialsCost(i)];
            Dependency: NoOfIncomingVessel(i);
        }
        Variable SubtotalOperationalCost {
            IndexDomain: i;
            Range: free;
            Definition: OperationalCost(i)*NoOfTanks(i);
        }
        Variable SubtotalShippingLinesCost {
            IndexDomain: i;
            Range: free;
            Property: Adjustable;
            Definition:                              sum[(j,k),
BunkerOrNot(k,i,j)*RefuelingVolume(k,i,j)*NoOfIncomingVessel(i
)*BunkerPrice(i)];
            Dependency: NoOfIncomingVessel(i);
        }
        Variable TotalCosts {
            Text: "Objective Function";
            Range: free;
            Definition:
sum[i,SubtotalCapitalCost(i)+SubtotalInventoryCost(i)+Subtotal
MaterialsCost(i)+SubtotalOperationalCost(i)+SubtotalShippingLi
nesCost(i)];
            Dependency: NoOfIncomingVessel(i);
        }
        Variable OneOffBunkeringVolume {
            IndexDomain: (i,k);
            Range: free;
            Definition:
sum(j,RefuelingVolume(k,i,j)*BunkerOrNot(k,i,j));
        }
        Variable AnnualDemandPerPort {
            IndexDomain: i;
            Range: free;
            Property: Adjustable;
            Definition:
sum(k,OneOffBunkeringVolume(i,k))*NoOfIncomingVessel(i);
            Dependency: NoOfIncomingVessel(i);
        }
        Parameter FuelTankCapacity {
            Text: {
```

```
            "C; Fuel tank capacity of the smallest LNG vessel
(in m3)"
            }
        }
        Parameter OnshoreTankCapacity {
            Text: {
                "V; Volume per onshore LNG tank (in m3)"
            }
        }
        Parameter CapitalCost {
            IndexDomain: i;
            Text: {
                "Fi; Capital cost of locating LNG bunkering
facilities at Port i (in USD)"
            }
        }
        Parameter RefuelingVolume {
            IndexDomain: (k,i,j);
            Text: {
                "FUij; Volume of fuel required to sail from Port
i to Port j (in m3)"
            }
        }
        Parameter InventoryCost {
            IndexDomain: i;
            Text: {
            "H; Annual inventory holding cost per unit (in USD)"
            }
        }
        Parameter MaterialsCost {
            IndexDomain: i;
            Text: {
                "Mi; Materials and logistics-related cost per
m3 of LNG supply to Port i (in USD)"
            }
        }
        Parameter NoOfIncomingVessel {
            IndexDomain: i;
            Text: {
            "Ni; Estimated number of vessels coming to Port i"
            }
            Property: Uncertain;
            Definition: data {1 : 313,  2 : 617,  3 : 318,  4
: 516,  5 : 128,  6 : 364, 7:564};
            Region:
Box(LowerBoundOfIncomingVessel(i),UpperBoundOfIncomingVessel(i
));
            Comment: "Standard Deviation of Demand = 0.33";
        }
        Parameter OperationalCost {
            IndexDomain: i;
            Text: {
```

```
            "Oi; Operational cost per onshore LNG tank at Port
i (in USD)"
            }
        }
        Parameter BunkerPrice {
            IndexDomain: i;
            Text: {
                "Pi;Selling price per cubic meter of LNG bunker
at Port i (in USD)"
            }
            InitialData: data {1 : 172.4,  2 : 175.1,  3 :
171.2,  4 : 164.4,  5 : 172.8,  6 : 209.3, 7:149.9};
            Comment: "Standar Deviation of conventional bunker
selling price: 0.16";
        }
        Parameter BigM {
            Definition: 100000;
        }
        Parameter LowerBoundOfIncomingVessel {
            IndexDomain: i;
            Definition: round (0.67 * NoOfIncomingVessel(i));
            Comment: "Lower Bound for Region of Uncertainty of
Incoming Vessel";
        }
        Parameter UpperBoundOfIncomingVessel {
            IndexDomain: i;
            Definition: round (1.33 * NoOfIncomingVessel(i));
            Comment: "Upper Bound for Region of Uncertainty of
Incoming Vessel";
        }
        Parameter RadiusOfIncomingVessel {
            IndexDomain: i;
            Definition: 0.33*NoOfIncomingVessel(i);
            Comment: "Standar Deviation of the Incoming Vessel
(0.33)";
        }
        Parameter LowerBoundOfBunkerPrice {
            IndexDomain: i;
            Definition: round (0.84*BunkerPrice(i));
        }
        Parameter UpperBoundOfBunkerPrice {
            IndexDomain: i;
            Definition: round (1.16*BunkerPrice(i));
        }
        Constraint XY_Relationship {
            IndexDomain: i;
            Text: "No tank will be built if the LNG bunkering
facility is not developed in Port i";
            Definition: NoOfTanks(i)<= (BigM*BuildOrNot(i));
        }
        Constraint YZ_Relationship {
            IndexDomain: i;
```

```
            Text: "If there is no LNG bunkering facility in Port
i, there should be no container ships coming to bunker in any
route.";
            Definition:   sum[(j,k),   BunkerOrNot(k,i,j)]   <=
[BigM*BuildOrNot(i)];
        }
        Constraint MandatoryRefuel {
            IndexDomain: (j,k);
            Text: "There should be one port for bunkering to
sail heading to Port j, for each Route k";
            Definition: {
                sum[i,BunkerOrNot(k,i,j)] = 1

        }

        Constraint RefuelingRange {
            IndexDomain: (i,k);
            Text: "Volume of LNG bunkered in the refuelling port
shall not exceed the maximum capacity of the vessel’s fuel
tank";
            Definition:
sum[(j),RefuelingVolume(k,i,j)*BunkerOrNot(k,i,j)]<=
FuelTankCapacity;
        }
        Constraint RefuelingSequenceWestbound {
            IndexDomain: (k,i,j);
            Definition: {
                if j<i and k="Westbound" then
                BunkerOrNot(k,i,j)=0
                endif;
            }
        }
        Constraint RefuelingSequenceEastbound {
            IndexDomain: (k,i,j);
            Definition: {
                if j>i and k="Eastbound" then
                BunkerOrNot(k,i,j)=0
                endif
            }
        }
        Constraint OnshoreCapacity {
            IndexDomain: i;
            Text: "To satisfy all demands of refuelling vessels
in Port i while determining the required number of onshore LNG
tanks";
            Definition:                            sum[(j,k),
BunkerOrNot(k,i,j)*RefuelingVolume(k,i,j)*NoOfIncomingVessel(i
)/52] <= [OnshoreTankCapacity*NoOfTanks(i)];
            Probability: 1;
            Approximation: 'Automatic';
        }
        Constraint ShippingLinesCostOF {
```

```
            IndexDomain: i;
            Definition:     SubtotalShippingLinesCost(i)     =
sum[(j,k),
BunkerOrNot(k,i,j)*RefuelingVolume(k,i,j)*NoOfIncomingVessel(i
)*BunkerPrice(i)];
        }
        Constraint MaterialsCostOF {
            IndexDomain: i;
            Definition:    SubtotalMaterialsCost(i)=sum[(j,k),
MaterialsCost(i)*NoOfIncomingVessel(i)*RefuelingVolume(k,i,j)*
BunkerOrNot(k,i,j)];
        }
        Constraint AnnualDemand {
            IndexDomain: i;
            Definition:      AnnualDemandPerPort(i)=sum[(j,k),
RefuelingVolume(k,i,j)*NoOfIncomingVessel(i)*BunkerOrNot(k,i,j
)];
        }
        MathematicalProgram DetLeastCost {
            Objective: TotalCosts;
            Direction: minimize;
            Constraints: AllConstraints;
            Variables: AllVariables;
            Type: Automatic;
        }
    }
    DeclarationSection Declaration_GMP {
        File ResultsLog {
            Name: "Results.log";
            Device: window;
            Mode: merge;
        }
        ElementParameter gmp_rc {
            Range: AllGeneratedMathematicalPrograms;
        }
    }
    Section Model_Procedures {
        Procedure MainInitialisation;
        Procedure SolveDeterministicModel {
            Body: {
                solve DetLeastCost;

              if (DetLeastCost.ProgramStatus <> 'Optimal') then
              empty    BuildOrNot,    NoOfTanks,    BunkerOrNot,
TotalCosts;
              endif;
            }
        }
        Procedure SolveRobustModel {
            Body: {
```

```
                gmp_rc:=
GMP::Instance::GenerateRobustCounterpart(DetLeastCost,
AllUncertainParameters,AllUncertaintyConstraints);

                GMP::Instance::Solve( gmp_rc );

                put ResultsLog;
                put "Robust:"/;
                put "Total Costs:", TotalCosts.robust;
                putclose;
            }
        }
        Procedure MainExecution {
            Body: {
                SolveDeterministicModel;
                SolveRobustModel;
            }
        }
        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."
            }
        }
    }
}
```