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A Study on the Estimation of Facilities in LNG Bunkering Terminal by Simulation—Busan Port Case

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Abstract: Since 2020, the International Maritime Organization (IMO) has tightened regulations on the emissions of sulfur oxides from ships from less than 3.5% to less than 0.5%. As a countermeasure, shipping companies can adopt one of three potential solutions: using low sulfur fuel (LSFO), installing scrubbers, or using liquefied natural gas (LNG) fuel. However, considering the environmental aspects such as the UN greenhouse gas (GHG) emission reduction program and the reduction of fine dust generation in port areas, LNG fuel is ultimately considered to be the most ideal method in the marine industry. In line with this international trend, major port authorities are considering building LNG bunkering stations, but the proper methods and criteria for estimating the size of LNG bunkering infrastructure are not clear. This study proposes a method of estimating the size of LNG infrastructure required with consideration for the operational status of ports according to the estimated amount of bunkering demand at a future time with the case study of Busan Port in Korea. In order to estimate the detailed demand amount by inbound vessels, a simulation modeling technique is applied as a tool of research.

Keywords: LNG bunkering terminal; LNG bunkering facility; simulation; LNGBV; LNGFV

1. Introduction

The International Maritime Organization (IMO) has decided to limit the emission standards for sulfur oxides in navigational fuel oil to a limit of 0.50% from January 1, 2020 [1]. As a countermeasure against these regulations, international shipping companies can adopt one of three measures such as the use of LSFO (Low Sulfur Fuel Oil), the installation of scrubbers, or the use of liquefied natural gas (LNG) fuel [2]. In addition to IMO regulations, the Intergovernmental Panel on Climate Change (IPCC) emphasizes the need to use LNG fuels to reduce global GHG emissions [3,4]. In the shipping industry, ultimately, the use of LNG fuels is considered the most ideal [3]. In response to this international response trend, major port authorities are considering building LNG bunkering stations, but the proper methods and criteria for estimating the size of LNG bunkering infrastructure are not clear. Recently, the International Association of Ports and Harbors (IAPH) has developed three bunkering schemes: Ship-to-Ship (STS), Truck to Ship (TTS), and Shore-to-Ship [5]. In addition, the International Association of Ports and Harbors (IAPH) provides advantages and disadvantages [5], safety [6], and operational checklists [7] for the three LNG bunkering schemes. In the schemes, there is no mention of how to calculate the quantity of LNG storage tanks, LNG bunkering stations, LNG tank lorries (LNGTLs), jetty berths, or LNG bunkering vessels (LNGBVs).

In Korea, the Ministry of Maritime Affairs and Fisheries selected Busan Port, Incheon Port, Gwangyang Port, Ulsan Port, and Pyeongtaek Port as the ports for constructing LNG bunkering terminals [8]. This study was conducted on the Busan Port as a case study, which has the largest number of inbound and outbound vessels among the five ports selected. Among candidate sites in

Busan Port, Yeondo of Busan New Port was selected as a bunkering station considering the travel distance between the bunkering station and the calling ship's location, natural conditions, fishing rights, vessel traffic, facility safety, operational safety, site expansion, etc. [9].

This study proposes a method to estimate LNG bunkering infrastructure size by applying simulation techniques according to the expected demand on Busan New Port in 2025 and 2030. LNG bunkering facilities size proposals are based on the size of and quantity of the port facilities including berths, LNG storage tanks, LNG bunkering stations, and transportation facilities like LNGTLs and LNGBVs. In this study, we considered only two LNG bunkering systems, STS (Ship-to-Ship) and TTS (Truck-to-Ship) [9]. The reason for choosing the two methods of STS and TTS is that shipping companies consider that these two are proper ways to reduce travel time and waiting time for bunkering. In addition, STS and TTS are the most commonly used bunkering types, which enables bunkering during the unloading operation of the ship, no need to move to another place for bunkering, and no separate construction is required in the harbor for bunkering.

On the other hand, the PTS bunkering method requires piping work to install the LNG pipeline in the port, and the installed LNG pipe is likely to be exposed to the port unloading process and cause an accident. So, PTS is not considered in the study because the terminal operators claim to be excluded due to operational risk and technical safety issues [9].

This study was carried out through the four steps of precedent study and modeling, port analysis, simulation modeling, and finally, LNG facility estimation in order to suggest a procedure for building bunkering stations as shown in Figure 1.

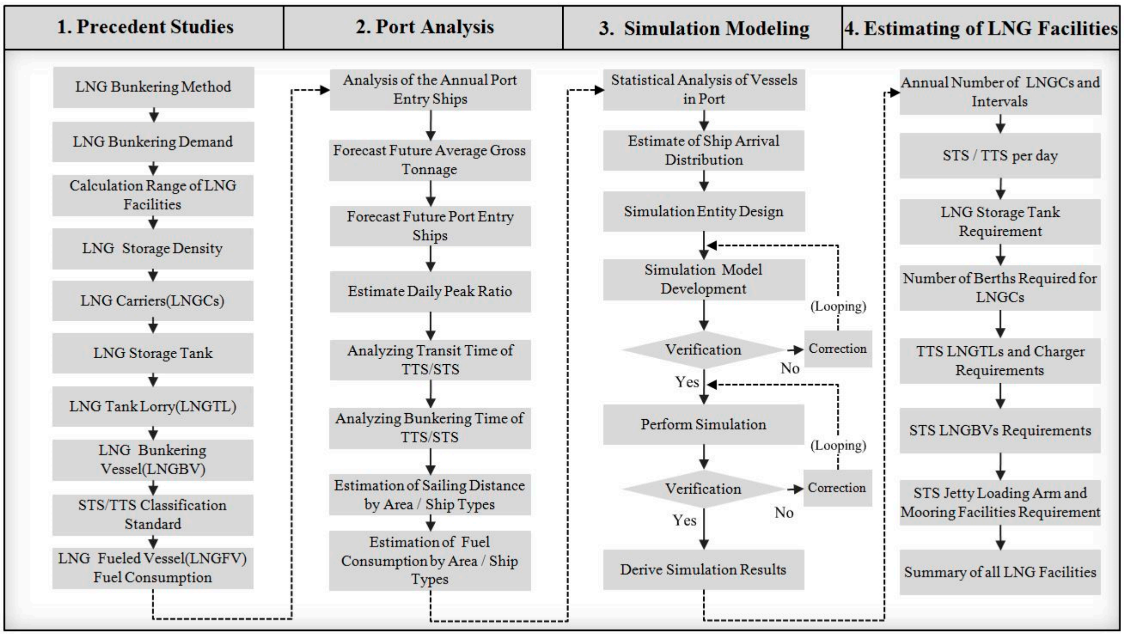

Figure 1. Research Procedure.

In the 1st step, the precedent studies and framework is suggested for calculating the number of facility literature review is dealt with LNG bunkering demand, LNG storage capacity, LNG storage density, LNG carrier (LNGC), LNGTL, LNGBV, STS/TTS bunker type classification standard, and fuel of LNG fueled vessel (LNGFV) consumption are carried out.

In the 2nd step, annual average gross tonnage (GT), the number of calling ships, daily peak ratio, TTS/STS transit time, TTS/STS bunkering time, the sailing distance by region, and fuel consumption by ship type are estimated for 2025 and 2030 respectively.

In the 3rd step, simulation model development, model verification, and suggestion of the simulation results are carried out.

In the 4th step, the annual number of LNGCs and arrival intervals, daily STS/TTS requirements, LNG storage tank requirements, berth requirements of LNGCs, TTS tanker and charger requirements, STS LNGBV requirements, STS jetty loading arm and mooring facilities and the total LNG facility requirements were calculated.

2. Precedent Studies

2.1. LNG Bunkering Type

Lowell, Wang, and Lutsey (2013) proposed three pathways for LNG facilities for bunkering when importing LNG. Pathway 1 is the type of bunkering at the port of entry using a large centralized facility. Pathway 2 is the type of bunkering using a remote storage tank. Pathway 3 is the type of bunkering without the remote storage tank [10].

IMO presents three options for the way in which LNGFVs receive LNG fuel: STS, TTS, bunkering via pipeline (PTS), and it introduces bunkering methods suitable for LNG tank size and vessel type [2].

IAPH has also proposed the three bunkering methods of STS, TTS, and PTS as well as safety guidelines and checklists for LNG bunkering facilities [5].

2.2. LNG Bunkering Demand

As shown in Table 1, the Yokohama Port LNG Bunkering Steering Committee estimated that the conversion rate from Bunker C oil to LNG would be from 5% to 27%, the conversion rate of Lloyd's Register would be 11%, the conversion rate of DNV-GL (Det Norske Veritas-Germanischer Lloyd) would be 6% to 11%, and the conversion rate of IHS (Information Handling Services) would be 8% [11].

Table 1. Demand Forecast of liquefied natural gas bunkering vessels (LNGBVs).

Research Organization	Estimation Time (Year)	Percentage of the Replacement from Heavy Oil to LNG
Boston Consulting Group	2025	5%–27%
Lloyd's Register	2030	11%
DNV-GL	2025	6%–11%
IHS	2030	8%

Lloyd's Register (2012) forecasted global demand for LNG bunkering by ship type, based on emission control scenarios, vessel fuel prices, and newbuilding demand for LNGCs [12]. DNV-GL (2013) predicted the demand for LNG bunkering in Busan Port based on the annual LNG demand through analysis of vessel size and vessel type in Busan Port [13]. Hak-so Kim and Kwang-ho Choi conducted a panel analysis on the oil bunkering and processed cargo volume of each region from 2000 to 2014. The panel analysis was used to estimate the relationship between cargo volume and oil bunkering. The demand for LNG bunkering is predicted to be 3.7 million tons in 2030, and 11.3 million tons in 2040 based on Busan Port estimations [14].

Ministry of Ocean and Fishery (MOF) of Korea anticipates that the demand for LNG bunkering will be 380,000 tons in 2025 and 2,005,000 tons in 2030 based on the Busan Port as shown in Table 2 [9], and the average conversion ratio of Bunker C to LNG fuel will be 27.13% in 2025 and 51.65% in 2030 as shown in Table 3 [9].

Table 2. Demand Forecast of LNG Bunkering Fuel in Busan Port.

Year	2025	2030
Forecasting(tons)	380,000	2,005,000

Table 3. Conversion Ratio to LNG Fueled Vessel by Time.

Year	Bulker	Tanker	Container	General Cargo Ship	Cruiser	Total
2025	19.28%	21.52%	31.25%	47.70%	23.08%	27.13%
2030	39.06%	45.66%	57.41%	72.30%	29.17%	51.65%

2.3. LNG Bunkering Facilities for Estimation

The study of LNG bunkering terminals in Busan Port dealt with statistical analysis of visiting ships, estimation of required LNG consumption, based on the analysis, the number of LNG fuel propulsion ships and LNG bunkering shuttles, LNG demand, capacity and hull structure types of bunkering terminals, etc. were presented [15]. The facilities for LNG bunkering are estimated by the bunkering method using STS and TTS. The required facilities are as follows: the first is the number of LNGCs required to import LNG from outside the port, the second is the number of LNG storage tanks required to store the imported LNG, the third is the berthing facility for LNGBV for STS bunkering, and the fourth is the number of LNGTLs and LNG bunkering stations for the TTS bunkering. In particular, the cost of constructing an onshore LNG storage tank costs between USD 200 million and USD 2000 million (USD) per storage tank, so the construction of floating offshore LNG bunkering terminals (FLBTs) may be considered to reduce construction costs. [16].

2.4. LNG Emission, Technology, Operations, and Fuel Gas Supply Systems

As the number of LNG fuel vessels and the number of LNG bunker vessels have increased, the main issue of LNGBV is how boil-of-gas (BOG) reduce [17]. Considering the inherent harmful characteristics of LNG fuel, the risks of operating LNG fuel vessels are high, so an analysis of the intrinsic relationship between risk factors has been made [18]. Reducing the volume of the FGSS (Fuel Gas Supply Systems), CO2 was considered to serve as the replacement heat medium for conventionally used glycol water during LNG gasification [19].

3. Assumptions for Estimating

3.1. Assumptions for Estimating LNG Bunkering

The LNG bunkering facility depends on the operating conditions and environment of the port where the LNG bunkering facility is to be constructed. Considering the different conditions, the assumptions are applied and displayed in Table 4.

Table 4. Basic Assumptions for Estimating LNG Bunkering Facility.

Classification	Details	Units	Applied Value	Formula Symbols	Basis of Estimation	Reference
Density	LNG Storage Tank	kg/m^3	480	ρ_{st}	410 kg/m^3 ~ 500 kg/m^3	[20]
	LNGTL		480	ρ_{tl}		
	LNGBV		460	ρ_{bv}		
LNGC (LNG carrier)	Storage Tank Size	m^3	170,000	V_{LNGC}	Actual 174,000 cubic meters (m^3) reduced by about 2% on safety standards	Appendix A Table A3. Latest 5 years
		ton	81,600	W_{LNGC}		
	Loading Capacity	ton/hour	5000	C_{LNGC}	Based on KOGAS Tongyeong base	-
LNG Storage Tank	Size	m^3	270,000	V_{st}	KOGAS's largest LNG storage tank scale (Samcheok Station)	[21]
		ton	129,600	W_{st}		
	Minimum Stock Basis	%	10	R_{st}	Maintain a minimum inventory of 6% to 13% for normal self-cooling	-
	Pure Capacity	ton	121,814	P_{st}		
LNGTL (TTS)	Storage Tank Size	m^3	30	V_{tl}		-
		ton	14	W_{tl}		
	Charging Capacity (Tank→LNGTL)	ton/min	0.25	C_{tl}	14 ton/hour	-
	Loading Capacity (LNGTL→LNGFV)			C_{tl_fv}		
LNGBV (STS)	Storage Tank Size	m^3	5000	V_{bv}	LNG bunkering vessel (ENGIE ZEEBRUGGE, IMO: 9750024) Technical standards	[17]
		ton	2300	W_{bv}		
	Minimum Stock Basis	%	6	R_{bv}	Maintain at least 6% pre-stock for self-cooling and fuel	-
	Pure Capacity	ton	2162	P_{bv}		-
	Loading Arm System Loading Capacity (Tank→LNGBV)	m^3/hour (ton/hour)	1000 (460)	C_{bv}	In 2017, Hanjin Heavy Industries LNG bunker shuttle vessel (ENGIE ZEEBRUGGE, IMO: 9750024) Technical standards	[22]
	Charging Capacity (LNGBV→ LNGFV)	m^3/hour (ton/hour)	600 (276)	C_{bv_fv}		
STS/TTS Classification Standard		ton	100	-	100ton↓(TTS), 100ton↑(STS)	[2]
LNGFV's Fuel Consumption	Reference Engine Model	g/kWh	MAN B&W (Germany)	-	LNG Engine Model: S90ME-C9-GI	[23]
	LNG Usage Calculation	m^3	Lloyd's of the UK	-	LNG-as-Fuel Tank Capacity Calculator	[24]

The main estimates applied in Table 4 are shown in Equations (1)–(6).

$$W_{LNGC}\ [ton] = V_{LNGC} \times \rho_{st} \tag{1}$$

$$W_{st}\ [ton] = V_{st} \times \rho_{st} \tag{2}$$

$$P_{st}\ [ton] = W_{st} \times \left(1 - \frac{R_{st}}{100}\right) \tag{3}$$

$$W_{tl}\ [ton] = V_{tl} \times \rho_{tl} \tag{4}$$

$$W_{bv}\ [ton] = V_{bv} \times \rho_{bv} \tag{5}$$

$$P_{bv}\ [ton] = W_{bv} \times \left(1 - \frac{R_{st}}{100}\right) \tag{6}$$

3.2. Formulas for Estimating LNG Bunkering Facility

Peak ratio (R_p) is applied for Equation (7) in order to cope with cases where large vessels or many vessels enter the port on a certain day based on the average gross tonnage of all vessels. The upper 20 days (AGT_{20}) means the highest 20 days among the average gross tonnage of vessels on entry per year, which can be adjusted as needed. AGT_d is the daily average gross tonnage of ships entering the port for a year.

$$R_p = \left(\frac{AGT_{20}}{AGT_d}\right) \times 100\% \tag{7}$$

Equations (8) and (9) are applied to estimate the charging time ($T_{tl\_charging}$) and the bunkering time ($T_{tl\_bunkering}$) in the TTS bunkering system.

$$T_{tl\_charging} = \left(\frac{W_{tl}}{C_{tl}}\right) \tag{8}$$

$$T_{tl\_bunkering} = \left(\frac{W_{tl}}{C_{tl\_fv}}\right) \tag{9}$$

Equations (10) and (11) are applied to estimate the loading time ($T_{bv\_loading}$) and the bunkering time ($T_{bv\_bunkering}$) in the STS bunkering system.

$$T_{bv\_loading} = \left(\frac{W_{bv}}{C_{bv}}\right) \tag{10}$$

$$T_{bv\_bunkering} = \left(\frac{W_{bv}}{C_{bv\_fv}}\right) \tag{11}$$

Equation (12) is applied to calculate LNG consumption (F_{total}) according to the sailing area by ship type and ship size. D_n is the sailing distance of the ship, S_n is the average speed of the ship, and F_n is the daily fuel consumption per ship size by ship type.

$$F_{total}\ [ton] = \sum_{n=1}^{N}\left(\frac{D_n}{S_n \times 24\ hour} \times F_n\right) \tag{12}$$

Equations (13) and (14) are applied to calculate the number of LNG carriers (N_{LNGC}) and ship arrival interval ($T_{LNGC\_interval}$).

$$N_{LNGC} = \left(\frac{F_{total}}{W_{LNGC}}\right) \tag{13}$$

$$T_{LNGC\_interval}\ [days] = \left(\frac{365\ days}{N_{LNGC}}\right) \tag{14}$$

The peak rate of Equation (7) was applied to Equation (15) to calculate the maximum daily LNG requirement (F_{max_day}). F_{ave_day} means average LNG fuel requirements per day.

$$F_{max\_day}\ [\text{ton}] = F_{ave\_day}\ (\text{ton}) \times R_p \tag{15}$$

Equations (16)–(18) are applied in order to estimate the number of LNG storage tanks (N_{st}), reflecting the warranty period of inventory ($T_{warranty}$). N_{st} is the number of pure LNG storage tanks.

$$W_{total\_min}\ [\text{ton}] = F_{ave\_day} \times T_{warranty}\ (\text{day}) \tag{16}$$

$$N_{st}\ [\text{unit}] = \left(\frac{W_{total\_min}}{P_{st}}\right) \tag{17}$$

$$W_{LNGC\_total}\ [\text{ton}] = \text{Interger}(\text{Wmin}) = P_{st} \times N_{st} \tag{18}$$

Equations (19) and (20) are applied to estimate the number of berths for LNGCs.

$$T_{LNGC\_unloading}\ [\text{hour}] = \left(\frac{W_{LNGC}}{C_{LNGC}}\right) \tag{19}$$

$$T_{LNGC\_total}\ [\text{hour}] = T_{LNGC\_unloading} + T_{LNGC\_docking} \tag{20}$$

Equations (21)–(24) were applied to estimate the requirements of LNGTLs ($N_{tl\_required}$) and charger requirements ($N_{charger\_required}$) for TTS bunkering. The total time (T_{tl_total}) required for one-time bunkering of tank lorry add up the charging time ($T_{tl\_charging}$), travel time (T_{tl_moving}), bunkering time ($T_{tl\_bunkering}$), return time (T_{tl_return}) as shown in Equation (21).

The required number of tank lorry per day ($N_{tl\_required}$) is calculated by dividing the number of bunkering per day (N_{tl_day}) by the number of tank lorry per day (n_{tl_day}) as shown in Equation (22).

The required number of chargers ($N_{charger\_day}$) per day is calculated by dividing the daily operation time ($T_{charger\_day}$) of the charger by the daily chargeable time ($T_{charging}$) per charger as shown in Equation (22).

$$T_{tl\_total}\ [\text{hour}] = T_{tl\_charging} + T_{tl\_moving} + T_{tl\_bunkering} + T_{tl\_return} \tag{21}$$

$$N_{tl\_required}\ [\text{unit}] = \left(\frac{N_{tl\_day}}{n_{tl\_day}}\right) \tag{22}$$

$$N_{charger\_day}\ [\text{count}] = \left(\frac{T_{charger\_day}(\text{hour})}{T_{charging}(\text{hour})}\right) \tag{23}$$

$$N_{charger\_required}[\text{unit}] = \left(\frac{N_{tl\_required}}{N_{charger\_day}}\right) \tag{24}$$

Equations (25)–(29) are applied to estimate the amount of LNGBVs ($N_{bv\_required}$) required for STS bunkering. The average number of supplies per LNGBV ($N_{bv\_ave\_supply}$) is calculated by dividing the number of STS supply requirements ($N_{supply\_required}$) by the quantity of LNGBVs (N_{bv_supply}) as shown in Equation (25). The total travel time per LNGBV ($T_{bv\_total\_moving}$) at sea is calculated by multiplying the average number of supply per LNGBV ($N_{bv\_ave\_supply}$) at sea and the sum of average travel time (T_{bv_moving}) and average berthing time ($T_{bv\_berthing}$) per LNGBV as shown in Equation (26).

The total time ($T_{bv\_total\_reqiured}$) spent by one LNGBV for bunkering is calculated by summing up the loading time ($T_{bv\_loading}$), travel time (T_{bv_moving}), The return time (T_{bv_return}) as shown in Equation (27).

The number of operation (n_{bv_day}) of LNGBV per day is calculated by dividing the daily operating time ($T_{bv\_day\_operation}$) of LNGBV by the total required time ($T_{bv\_total\_required}$) of LNGBV as shown in Equation (28).

The required number of LNGBVs ($N_{bv\_required}$) is calculated by dividing the number of bunkering requirements per day($N_{bv\_ave\_supply}$) by the number of revolutions per LNGBV (n_{bv_day}) as shown in Equation (29).

$$N_{bv\_ave\_supply}\ [\text{count}] = \left(\frac{N_{supply\_required}}{N_{bv\_supply}}\right) \tag{25}$$

$$T_{bv\_total\_moving} = N_{bv\_ave\_supply} \times \sum_{n=1}^{N}\left(T_{bv\_movingn} + T_{bv\_berthing_n}\right) \tag{26}$$

$$T_{bv\_total\_reqiured} = T_{bv\_loading} + T_{bv\_moving} + T_{bv\_around\_moving} + T_{bv\_return} \tag{27}$$

$$n_{bv\_day}\ [\text{count}] = \left(\frac{T_{bv\_day\_operation}(\text{hour})}{T_{bv\_total\_reqiured}(\text{hour})}\right) \tag{28}$$

$$N_{bv\_required}\ [\text{unit}] = \left(\frac{N_{bv\_ave\_supply}}{n_{bv\_day}}\right) \tag{29}$$

Equation (30) and (31) is applied to estimate the amount of STS Jetty Loading Arm ($N_{arm\_required}$) required for bunkering. The daily operation number ($n_{arm\_day\_operation}$) of the jetty loading arm is calculated by dividing the daily operation time ($T_{arm\_day\_operation}$) of one loading arm by the loading time ($T_{bv\_loading}$) of one LNGBV as shown in Equation (30).

The requirement of jetty loading arm ($N_{arm\_required}$) is calculated by dividing the requirement of LNGBVs ($N_{bv\_required}$) by the daily operation number of jetty loading arm ($n_{arm\_day\_operation}$).

$$n_{arm\_day\_operation}\ [\text{count}] = \left(\frac{T_{arm\_day\_operation}(\text{hour})}{T_{bv\_loading}\ (\text{hour})}\right) \tag{30}$$

$$N_{arm\_required}[\text{unit}] = \left(\frac{N_{bv\_required}}{n_{arm\_day\_operation}}\right) \tag{31}$$

The important point here is to calculate the number of bunkering required per day (N_{tl_day}) of tank lorry (LNGTLs) in Equation (22) and daily bunkering requirement($N_{supply\_required}$) in Equation (25). However, it is not easy to estimate them exactly. For this reason, in this paper, the simulation technique is applied to predict the number of bunkering supply and bunkering requirements according to the ship type, ship size, and navigation area of the ports.

3.3. Estimation of Fuel Consumption by Region and Ship Type

The daily LNG consumption of the LNGFVs was derived by applying MAN B&W's LNG fuel-use engine (Model: S90ME-C9-GI) [23] and Lloyd's Register LNG tank fuel calculator [24].

The average speed of sailing by ship type was applied as follows: container ships are 22 knots, bulk carrier and general cargo ship are 15 knots, tankers are 16 knots, and cruise ships are 22 knots. Total power, maximum continuous rating (MCR), LNG density, and ship average speed were considered to estimate fuel consumption. The fuel consumption calculation section was applied to 7 sections as follows: 5,178 kWh/9,988 kWh/14,500 kWh/25,000 kWh/47,500 kWh/53,500 kWh/65,000 kWh (see Table 5).

The analysis subjects were classified into four types of vessels which are classified as container ships, bulker and general cargo ships, tankers, and cruise ships. After estimating fuel consumption, the consumption of LNGFV by GT or Twenty-foot Equivalent Units (TEU) basis was derived by regression analysis.

Table 5. Basic Assumptions and Analysis Results for Estimating LNG Fuel Consumption by Ship Types.

	Classification	Container	Bulker, General Cargo	Tanker	Cruiser
Basic Assumptions	Total Power (kWh)	5178/9988/14,500/25,000/47,500/53,500/65,000			
	MCR (%)	75%	50%	75%	75%
	LNG Consumption (g/kWh)	156.3	159.5	156.3	156.3
	LNG Density (kg/m^3)	442			
	Average Speed (knots)	22.0	15.0	16.0	22.0

The regression analysis performed in this study was applied on the assumption that 500TEU-8000TEU is valid for container ships and 6500GT-190,000GT is valid for bulk carriers, general cargo ships, tankers, and cruise ships. Based on these assumptions, Equations (32)–(35) were derived.

The results of the regression analysis for capacity (TEU) and daily fuel consumption of container line ($F_{container}$) are shown in Equation (32) and Figure 2.

$$\begin{gathered} F_{container} = (2E-11)\times\left(TEU^3\right)-(9E-07)\times\left(TEU^2\right)+(0.02\times TEU) \\ \text{The result is valid under the range of 500TEU} \sim 18,000\text{TEU} \end{gathered} \tag{32}$$

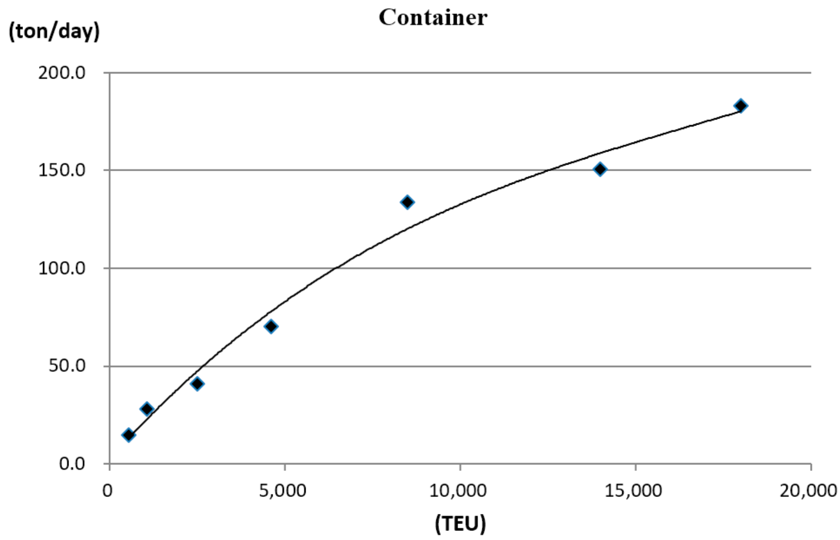

Figure 2. Daily LNG Fuel Consumption of Container.

The regression results for the total tonnage and daily fuel consumption of the bulk carriers and general cargo ships ($F_{gerneral\_cargo}$) are present in Equation (33) and Figure 3.

$$\begin{gathered} F_{gerneral_{cargo}} = (8E-15)\times\left(GT^3\right)-(4E-09)\times\left(GT^2\right)+(0.0012\times GT)-0.5226 \\ \text{The result is valid under the range of 6500GT} \sim 190,000\text{GT} \end{gathered} \tag{33}$$

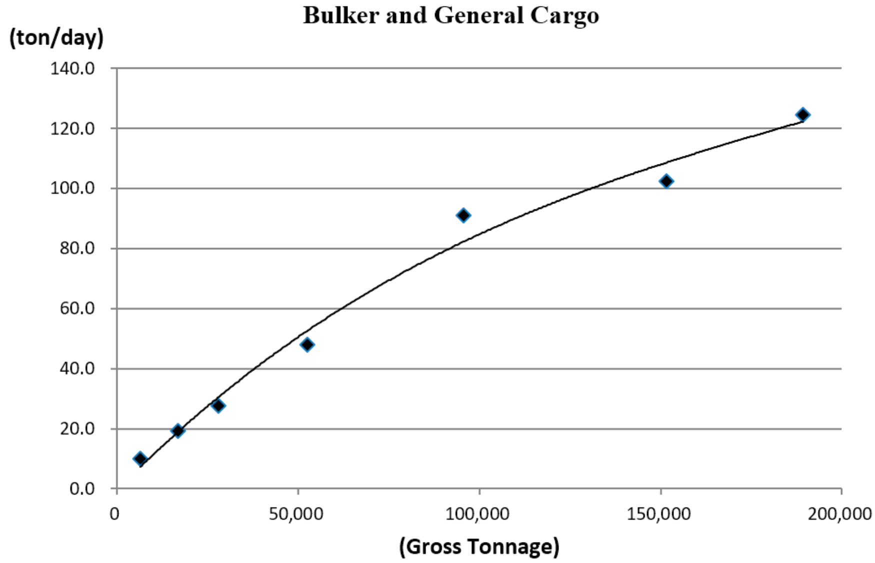

Figure 3. Daily LNG Fuel Consumption of Bulker and General Cargo.

The regression results for the total tonnage of the tanker line and the fuel consumption per day ($F_{\tan\mathrm{ker}}$) are shown in Equation (34) and Figure 4.

$$F_{\tan\mathrm{ker}} = (-3E-09)\times\left(GT^2\right) + (0.0016 \times GT) + 2.4714 \quad (34)$$
The result is valid under the range of 6500GT ~ 190,000GT

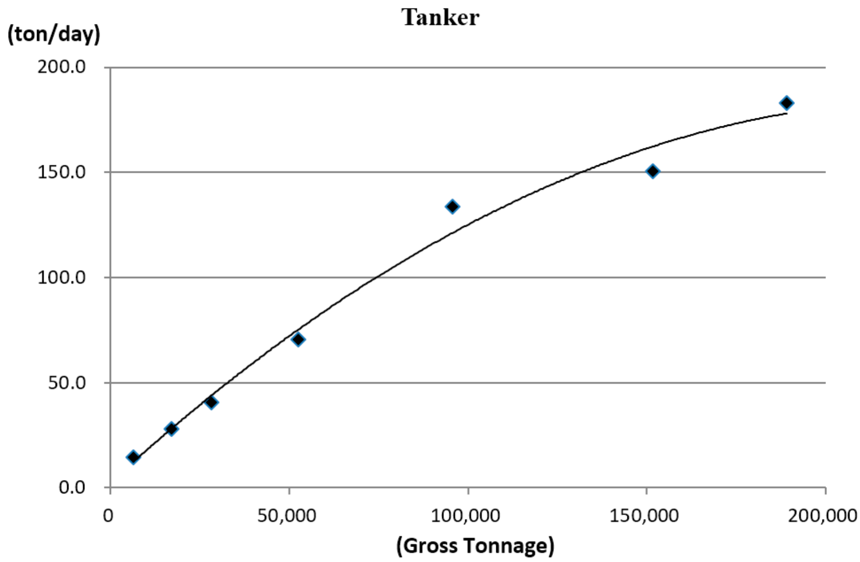

Figure 4. Daily LNG Fuel Consumption of Tanker.

The regression results for the gross tonnage of the cruise ship and the daily fuel consumption (F_{cruise}) are displayed in Equation (35) and Figure 5.

$$F_{\mathrm{cruise}} = (-7E-09)\times\left(GT^2\right) + (0.0031\times GT) + 4.9431 \quad (35)$$
The result is valid under the range of 6500GT ~ 190,000GT

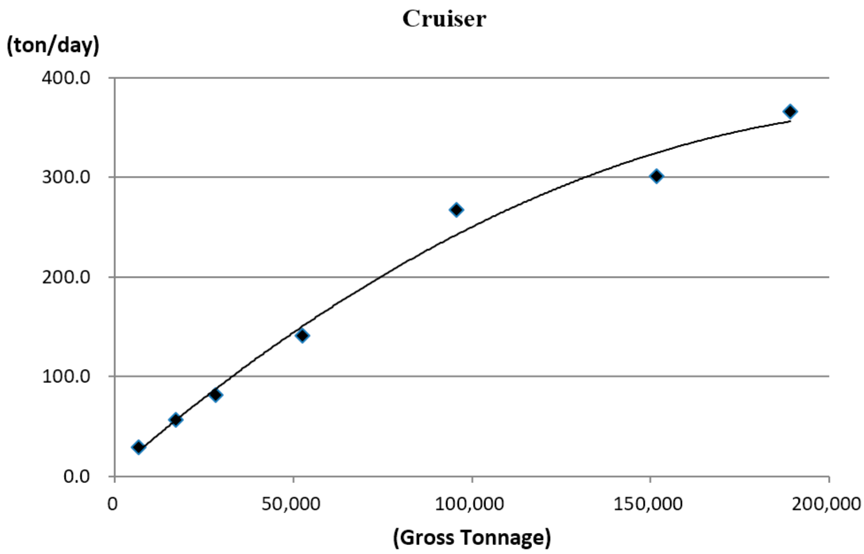

Figure 5. Daily LNG Fuel Consumption of Cruiser.

4. Case Study: LNG Bunkering Environment of Busan Port

4.1. Analysis of Vessels Entering the Port of Busan

The PORT-MIS data of the Port of Busan was used for the analysis of 27,310 vessels for 1 year from January 1, 2018, to December 31, 2018 [25]. In the PORT-MIS, 5 types of vessels (bulkers, tankers, containers, general cargo ships, and cruisers) were analyzed.

As a result of analysis, bulkers made up 947 of the ships (3.47%), 1245 (4.56%) were tankers, 15,277 (55.94%) were containers, 5849 (21.42%) were general cargo ships, 3838 (14.05%) were cruisers, various others not falling into the above classifications consisted of 190 ships (0.56%) as shown in Table 6.

Table 6. Ship Analysis of Busan Port in 2018.

Types of Ships	Count of Ships	Ratio	Gross Tonnage (GT)	Average Gross Tonnage (AGT)
Bulker	947	3.47%	28,184,196	29,777
Tanker	1245	4.56%	11,010,155	8843
Container	15,277	55.94%	556,413,868	36,422
General Cargo Ship	5849	21.42%	36,514,892	6243
Cruiser	3838	14.05%	19,005,955	4952
Other	154	0.56%	1,695,311	11,009
Total	27,310	100.00%	652,824,376	23,905

As of 2018, the number of vessels entering Busan Port has increased steadily from 27,400 to 27,800 over the past 17 years. The gross tonnage (GT) of vessels entering the port has steadily increased from 10,000 GT in 2002 to 24,000 GT in 2018.

Estimation of the average gross tonnage (AGT) using the estimation formula (36) shows a predicted 30,648 GT in 2025 and 35,313 GT in 2030 as shown in Figure 6 and Table 7. It is estimated that the ship numbers will increase to 27,739 vessels in 2025 and 27,812 vessels in 2030 as shown in Figure 7 and Table 7. The regression equation between years and an average gross tonnage of calling ships is shown in Equation (36).

$$\mathrm{AGT} = (933.11 \times \mathrm{Year}) - 1858900 \tag{36}$$

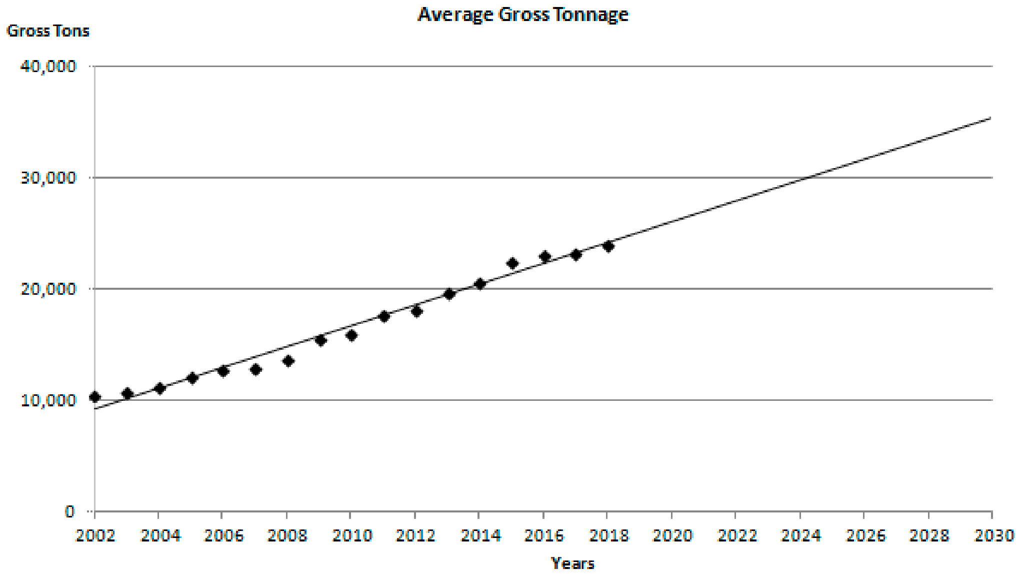

Figure 6. Changes in the Gross Tonnage (17 Years in Busan Port).

Table 7. Ship Size Increase Rate in Busan Port.

Year	2018 (Actual)	2025 (Estimation)	2030 (Estimation)
Increase Rate	-	27.08%	46.43%
Average Gross Tonnage	24,116	30,648	35,313
Number of Vessels	27,636	27,739	27,812

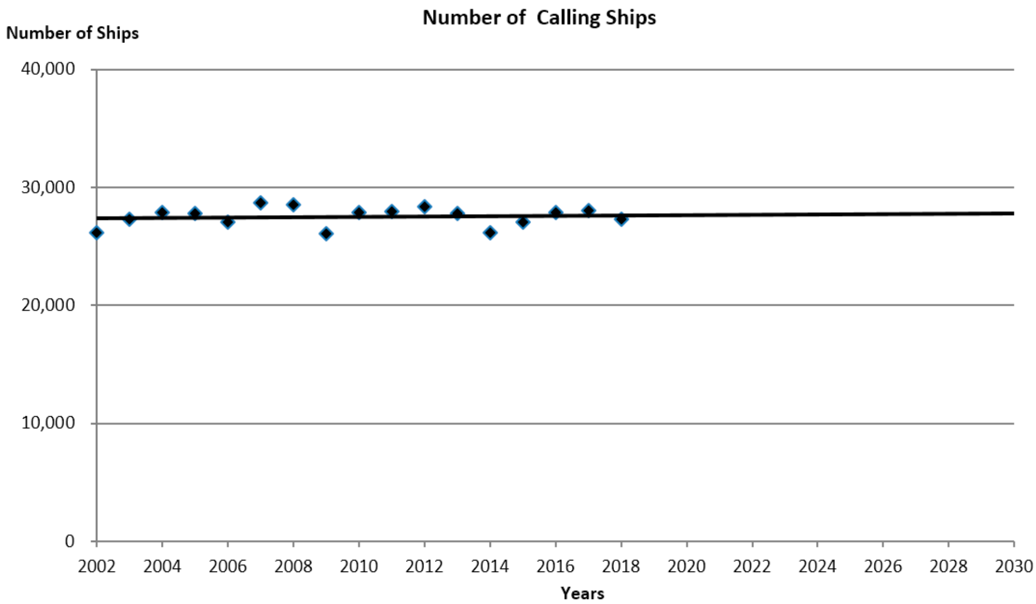

Figure 7. Changes in the Number of Vessels (17 Years in Busan Port).

The regression equation between years and the number of calling ships ($N_{calling\_ships}$) is shown in Equation (37).

$$N_{calling\_ships} = (14.637 \times \text{Year}) - 1901.2 \tag{37}$$

In estimating the LNG bunkering facility, the peak ratio of LNG fuels is to be considered for large vessels at peak times. As of 2018, Busan Port has 27,310 ships per year, with a total of 652,824,376 GT of inbound vessels, with an average of 75 vessels arriving daily, and with a gross tonnage of 1,792,034 tons (a) (see Table 8).

Table 8. The Peak Ratio of Gross Tonnage of Calling Ships in Busan Port.

Classification	Ship Count (2018)	Gross Tonnage (GT)	Peak Ratio
Total	27,310	652,824,376	-
Average Ships per Day	75	1,792,034 (a)	-
Average Ships for Upper 20 Days	86	2,468,302 (b)	137.7% ((b/a) × 100%)

Considering the upper 20 days with the largest gross tonnage of vessels during the year, the average of 86 vessels per day, arrived and the total GT of vessels per day is 2,468,302 tons (b). The peak ratio is calculated by dividing the gross tonnage (b) of the upper 20 days by the daily average gross tonnage (a) as in Equation (7).

4.2. Analysis of Transit Time, Charging Time and Bunkering Time

Busan Port consists of Busan New Port, Busan North Port, and Gamcheon Port as shown in Figure 8. Among them, the Busan New Port accounts for 70% of the volume, so the LNG bunkering station is assumed to be located in the new port of Busan Port. It is necessary to measure the transit time to North Port and Gamcheon Port according to the STS and TTS bunkering type based this assumption [26,27].

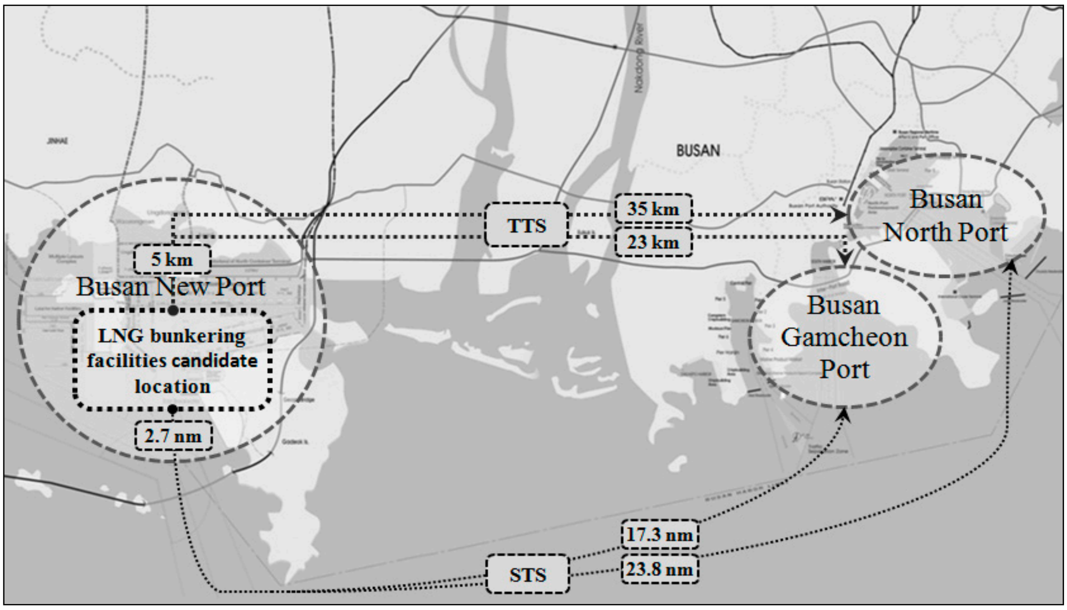

Figure 8. Reprinted the Map of Busan Port under Permission of Busan Port Authority (Modified from Ref. [28]).

Assuming that an average speed of truck (TTS) is 40 km/h, the distance within Busan New Port from the bunkering station in Busan New Port is about 5 km (7.5 min), about 23 km (34.5 min) to the Gamcheon Port central pier, and about 35 km (52.5 min) to Sinsundae Pier as presented in Table 9.

Table 9. Transit Time by TTS in Busan Port.

Classification	Busan New Port (Yeondo)	Gamcheon Port (Joongang Pier)	North Port (Sinsundae Pier)	Average
Distance	5 km	23 km	35 km	21 km
LNGTL (truck) Speed	40 km/h			
Transit Time	7.5 min	34.5 min	52.5 min	31.5 min
	0.12 h	0.58 h	0.88 h	0.53 h

Assuming that an average speed of LNGBV (STS) is 8-14knots according to Navigation Rule of Busan Port [29], the distance to Gamcheon Port anchorage point from the bunkering station in Busan New Port is about 32 km (74.1 min), and the distance to the front of Sinsundae Pier is 44 km (101.8 min) as shown in Table 10.

Table 10. Transit Time by STS in Busan Port.

Classification	Busan New Port (Yeondo)	Gamcheon Port (Anchorage Area)	North Port (Shinsundae Pier)	Average	In Port
Distance	5 km (2.7 nm)	32 km (17.3 nm)	44 km (23.8 nm)	5 km (2.7 nm)	-
LNGBV Speed	10 knots	14 knots		-	8 knots
Transit Time	16.2 min	74.1 min	101.8 min	-	20.2 min
	0.27 h	1.23 h	1.70 h	1.07 h	0.34 h

According to TIMELINE [30], the time required for charging in the LNG bunkering station and the time required for bunkering LNGFVs was analyzed for each bunker type of TTS and STS. In the case of TTS with the tank capacity of 14 tons, it takes 1.1 h for a one-time charging and 1.1 h for bunkering, therefore a total of 2.20 h as shown in Table 11.

Table 11. LNG Charging Time and Bunking Time by TTS Method in Pusan Port.

Classification		Required Time	Comment
TTS Charging	Preparatory Time before Charging (min)	5 min	Bunkering Station → LNGTL
	Charging Time (min)	56 min	
	Cleanup Time after Charge (min)	5 min	
	Sub Total (a)	1.1 h	
TTS Bunkering	Preparatory Time before Bunkering (min)	5 min	LNGTL → LNGFV
	Bunkering Time (min)	56 min	
	Cleanup Time after Bunkering (min)	5 min	
	Sub Total (b)	1.1 h	
Total (= a + b)		2.2 h	

The charging time of 56 min was calculated by dividing the tank capacity (14 tons) by the filling capacity (0.25 tons/min) as shown in Equation (8). The bunkering time of 56 min was calculated by dividing tank storage capacity (14 tons) by the bunkering capacity (0.25 tons/min) as shown in Equation (9).

For an STS type with LNGBV loading capacity of 5000 m^3, it takes a total of 15.78 h of which 6.7 h are required for a one-time loading and 9.08 h for one-time bunkering as displayed in Table 12. Here, the loading time of 282 min is derived by dividing the pure capacity (2,162 tons) of LNGBV by the loading capacity (460 tons/hour) as shown in Equation (10), and the bunkering time of 470 min is calculated as the pure capacity (2162 tons) was divided by the bunkering capacity (276 tons/hour) as shown in Equation (11).

Table 12. LNG Charging Time and Bunking Time by STS Type in Busan Port.

Classification		Required Time	Comment
STS Loading	Berthing Time and Preparatory Time before Loading (min)	60 min	Loading Arm System → LNGBV
	Loading Time (min)	282 min	
	Cleanup Time and Unberthing Time after Loading (min)	60 min	
	Sub Total (a)	6.70 h	
STS Bunkering	Berthing Time and Preparatory Time before Bunkering (min)	40 min	LNGBV → LNGFV
	Bunkering Time (min)	470 min	
	Cleanup Time and Unberthing Time after Bunkering (min)	35 min	
	Sub Total (b)	9.08 h	
Total (= a + b)		15.78 h	

4.3. Estimation of Sailing Distance by Area and by Ship Type

In order to estimate the LNG demand per vessel entering the port in Busan, we calculated the representative sailing distance by region and divided the distance by the average speed by vessel type to derive the sailing days as shown in Tables 13 and 14 [31] and Appendix A Table A1. LNG fuel consumption by ship size from Busan Port to Osaka. Shanghai, Singapore, Mumbai, Doha and Rotterdam, Cape Town, Los Angelos, San Padito, San Antonio, Sydney and Seria are shown in Appendix A Table A2.

Table 13. Sailing Distance and Sailing Days of Main Area of Busan Port Origin (continued).

Classification			Japan	Far East	South East Asia	South West Asia	Middle East Asia	Europe
Representative Countries and Ports		Average Speed (knots)	Japan /Osaka	China /Shanghai	Singapore	India /Mumbai	Catarrh /Doha	Netherlands /Rotterdam
Sailing Distance (knots)		-	372	492	2503	4938	6111	10,791
Sailing Days (days)	Container, Cruiser	22.0	0.70	0.93	4.74	9.35	11.57	20.44
	Tanker	16.0	0.97	1.28	6.52	12.86	15.79	28.1
	Bulker, General Cargo Ship	15.0	1.03	1.37	6.95	13.72	16.98	29.98

Table 14. Sailing Distance and Sailing Days of Main Area of Busan Port Origin.

Classification			Africa	North America	Middle South America	South America	Oceania	Other Countries
Representative Countries and Ports		Average Speed (knots)	South Africa /Cape Town	USA /LA	Mexico /San-Padito Port	Chile /San Antonio	Australia /Sydney	Brunei /Seria
Sailing Distance (knots)		-	7968	5230	6375	9883	4583	2004
Sailing Days (days)	Container, Cruiser	22.0	15.09	9.91	12.07	18.72	8.68	3.80
	Tanker	16.0	20.75	13.62	16.6	25.74	11.93	5.22
	Bulker, General Cargo Ship	15.0	22.13	14.53	17.71	27.45	12.73	5.57

5. Case Study: Simulation Modeling and Results

5.1. Statistical Analysis of Vessel Arrival

Arrival distribution was created by analyzing the arrival time intervals of 27,310 vessels entering Busan Port in 2018 as shown in Table 15. The simulation was performed using Rockwell Automation's Arena simulation software in the USA.

Table 15. Ship Arrival and Arrival Distribution of Busan Port in 2018.

Classification		Values	Remarks
Port Name		Busan Port	PORT-MIS of MOF in Korea
Analysis Period		Jan. 1, 2018–Dec. 31, 2018	1 year
Count of Arrival Ships in 2018		27,310	Ocean-going Vessels
Analysis Tool	Data Analysis	Input Analyzer	Rockwell Automation Co. Ltd. (USA)
	Simulation Modeling	Arena Version 12.4	
Statistical Distribution Summary	Probability Distribution	Exponential	
	Arrival Formula	-0.001 + EXPO (19.1)	Unit: Min.
	Deviation	0.000177	Square Error

5.2. Simulation Model Development

In order to develop the simulation model, six input variables and 21 output variables are defined as shown in Table 16.

Table 16. Design Input and Output Variables of Simulation Model.

Classification		Description	Source
Input Variables	Arrival Formula	Arrival distribution	Table 15
	Ratio of 16 Ship Types	Percentage by 16 Ship Types	Appendix A Table A4.
	Ratio of 12 Voyage Areas	Percentage of 12 Navigation Zones	
	Gross Tonnage per Ship Types & Voyage Areas	12 Types of Navigation Zones by Type of Ship	Distribution
	Increase Rate of Gross Tonnage	Gross Tonnage Increase Rate	Table 7
	Conversion Ratio to LNGFVs	Conversion rate to LNG fueled vessels	Table 3
Output Variables	Count of Ship Arrivals	Number of Calling Ships	
	Time of Entry	Arrival Time	
	Ship Type 1	16 Ship Types	
	Ship Type 2	5 Ship Types	
	Voyage Area	12 Navigation Zones	Tables 13 and 14
	Gross Tonnage	Percentage of 12 Navigation zones	
	Ship Average Speed (knots)	Average Speeds by 5 Ship Types	Table 5
	Representative Port of Voyage Area	-	Tables 13 and 14
	LNG Consumption per Day (ton)	-	Equations (32)–(35)
	One-way Voyage Distance (km)	-	Tables 13 and 14
	One-way Sailing Day (day)	-	Tables 13 and 14
	One-way LNG Consumption (ton)	-	-
	Round-trip sailing distance (km)	-	Tables 13 and 14
	Round-trip sailing day (day)	-	Tables 13 and 14
	Round-trip LNG consumption (ton)	-	-
	Whether to use LNG Fuel	-	Table 3
	Bunkering Type	-	TTS or STS
	Number of Supply of TTS	-	TTS Case
	Number of LNGTLs	Number of TTS Bunkering Tank Lorries	"
	Number of Supply of STS	-	STS Case
	Number of LNGBVs	Number of STS Bunkering Shuttle Vessels	"

Using the simulation model [32,33] and Table 14, simulation modeling as shown in Figure 9 was carried out in 13 steps. Based on the generated Excel file, the analysis process included up to an additional three steps. The steps are summarized as follows:

The 1st step is to apply the "Arrival Formula" value of "-0.001 + EXPO (19.1)" in Table 14 to generate the ship arrival.

The 2nd step is to set the number of arrivals and arrival times of the arriving vessel.

The 3rd step is to classify the vessels entering the ship by applying the ship entry rate according to 16 ship type classifications by MOF.

The 4th step is to set the type of vessel to be statistically classified.

The 5th step is to classify the vessels entering Busan port according to 12 navigation area classifications by MOF.

The 6th step is to set the designated voyage area and the representative port.

The 7th step is to estimate the one-way and round-trip distance from the Busan Port to the representative port of each navigational area.

The 8th step is to set the gross tonnage according to the 16 different vessel types and the 12 regions.

The 9th step is to reclassify the 16 ship types into 5 ship types. The reason for the reclassification is to apply the daily LNG fuel use formula according to these 5 broader categories of ships.

The 10th step is to determine whether the vessel will use LNG fuel according to the ratio of conversion of LNGFVs.

The 11th step is to apply the gross tonnage increase rate as shown in Table 7.

The 12th step is to record the simulation values from Step 2 to Step 11 into an Excel file.

The 13th step is the final stage of the simulation.

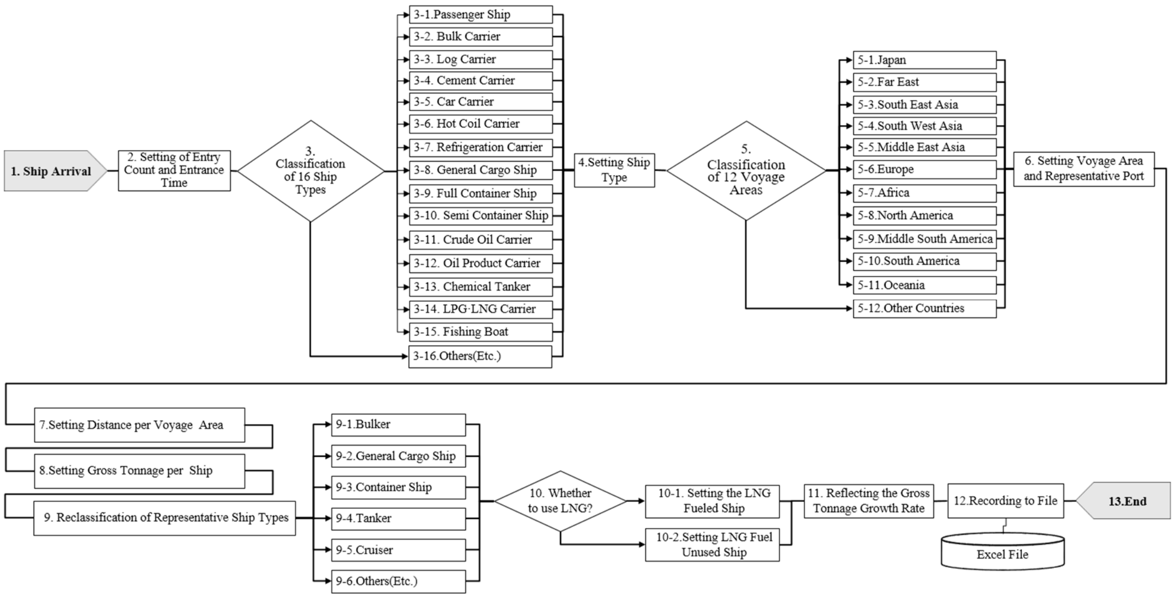

Figure 9. Simulation Modeling Process.

After the simulation, additional analysis of steps 14–16 are performed. The 14th step is to calculate daily LNG fuel consumption (y) for each type of ship by applying the gross tonnage as the input value (x) to the LNG fuel consumption estimation equation (Table 12). In this case, TEU is used as the input value for the container line, not gross tonnage, and the relationship between gross tonnage and TEU is applied to Equation (38) of Marine Traffic [34].

$$TEU = (0.0956 \times GT) - 351.11 \tag{38}$$

In step 15, the sailing days are calculated by applying the average speed of each vessel in Table 13 to the one-way or round-trip distance of each sailing area. Therefore, multiplying LNG fuel consumption per ship type by one-way or round-trip sailing days will allow LNG fuel consumption for each vessel to be calculated according to the sailing area.

In the 16th stage, the TTS bunkering method is applied when the amount of LNG fuel is less than 100 tons, and the STS bunkering method is applied when the amount is 100 tons or more. As a result, the number of supply, the number of LNGBVs and number of LNGTLs were calculated for 2025 and 2030.

5.3. Simulation Execution Results

As a result of simulations based on 2025 and 2030, the number of supply and the number of LNGBVs for STS bunkering were analyzed and are presented in Table 17. For each bunkering type, the TTS bunkering type is adopted when the LNG consumption is less than 100 tons, and the STS bunkering type is adopted when the amount is 100 tons or more. The LNG fuel consumption is calculated as shown in Equation (12).

Table 17. Number of Supply and the Number of LNGBVs by Simulation.

Year	Count of Arrival Ships	LNG Fuel Requirements (ton)	STS		TTS	
			Number of Supply	Number of LNGBVs	Number of Supply	Number of LNGTLs
2025	27,879	380,884	395	155.62	1970	4196.08
2030	28,037	2005,683	1894	826.08	8547	21,120.92

Table 16 shows the simulation results of the statistical analysis of 27,310 vessels entering the Port of Busan in 2018. The main input parameters of the simulation are arrival distribution, 5 types of ships which convert 16 Ship types to 5 as explained previously, 12 voyage areas, and gross tonnage distribution of vessels.

5.4. Verification of Simulation Modeling Results

The accuracy rate between the estimated number of arriving ships (a) and the simulated arrival number (b) is 99.33%, and the variation is within 0.67%. Also, the accuracy of the predicted average gross tonnage (c) and the average gross tonnage (d) in the simulation is 100.25%, and the deviation is within 0.25% as shown in Table 18.

Comparing the predicted value (a) of the LNG fuel consumption with the simulation results (b), the agreement rate is almost the same as 100.02% - 100.32% as shown in Table 19. Estimates of future LNG fuel usage based on the proven simulation model are estimated at 380,884 tons in 2025 and 2,005,683 tons in 2030.

Table 18. Verification of Simulation Results.

Year	Arrival Formula (Unit: min)	Count of Arrival Ships				Average Gross Tonnage			
		Estimation (a)	Simulation (b)	Accuracy (b/a*100%)	Variation	Estimation (c)	Simulation (d)	Accuracy (d/c*100%)	Variation
2018	-0.001 + EXPO (19.1)	27,636	27,452	99.33%	-0.67%	24,116	24,177	100.25%	+0.25%
2025	-0.001 + EXPO (18.8)	27,739	27,879	100.50%	+0.50%	30,648	31,281	102.07%	+2.07%
2030	-0.001 + EXPO (18.7)	27,812	28,037	100.81%	+0.81%	35,313	36,384	103.03%	+3.03%

Table 19. Prediction of LNG Fuel Consumption by Simulation.

Year	Prediction (a)	Simulation (b)	Accuracy (b/a*100%)	Variation
2025	380,000 tons	380,884 tons	100.02%	+0.02%
2030	2,005,000 tons	2,005,683 tons	100.03%	+0.03%

6. Case Study: Estimation of LNG Bunkering Facilities Using Simulation Results

6.1. Results of Detailed Items

The number of LNGCs (N_{LNGC}) and the interval between ship arrivals ($T_{LNGC\_interval}$) are calculated to be 4.67 and 78.20 days in 2025, and 24.58 and 14.85 days in 2030 as presented in Appendix A Table A5 and in Equation (13).

The number of supply, number of LNGBVs, daily supply and average supply tonnage per one-time were analyzed using STS and TTS by applying the peak ratio as shown in Equation (7) and in Appendix A Table A6.

The inventory period of LNG was based on the Korean government's recommendation of 30 days of daily average sales volume [35] (see Appendix A Table A7). The required LNG storage tanks (N_{st}) were calculated by applying the equations (16), (17), and (18) to the LNG storage tank space of 270,000 m^3 (116,640 tons). In the result, 1 storage tank is needed in 2025 and 2 storage tanks are required in 2030.

The number of berths of LNGCs was estimated by applying Equation (19) and Equation (20) based on the LNGC's capacity of 170,000 m^3 and cargo handling capacity 14,130 m^3 per hour. Therefore, one berth is required as shown in Appendix A Table A8.

It takes about 3.25 h to complete bunkering for one TTS at Busan New Port. Thus, it is estimated to operate three times a day under the assumption that it can operate 10 h a day (8:00 a.m.–6:00 p.m.) as shown in Appendix A Table A9.

The requirement of the charger for TTS requires 2 units in 2025 and 6 units in 2030 under the assumption that it can operate 18 h a day (6:00 a.m. – 12:00 p.m.). In addition, the required amount of the LNGTL parking facility is estimated to be 16 in 2025 and 80 in 2030 as shown in Appendix A Table A10.

The turnover rates of the LNGBV and the jetty wall for STS were analyzed by applying Equations (25)–(28) as shown in Appendix A Table A11. The number of revolutions per bunker shuttle (n_{bv_day}) is 1.31 times in 2025 and 1.21 times in 2030.

The number of operations per day (turnover rate) ($n_{arm\_day\_operation}$) of the jetty loading arm was calculated to be 3.58 by applying Equation (30) shown in Appendix A Table A12.

According to the analysis results, it is expected that the requirement of the LNGBV ($N_{bv\_required}$) should be 1 vessel in 2025 and 3 vessels in 2030 under the assumption that the vessel can operate 24 h a day as displayed in Appendix A Table A13 and in Equation (29).

The jetty loading arm ($N_{arm\_required}$) is estimated to be 1 in 2025 and also in 2030. The amount of the mooring facilities of the LNGBV is the same as that of the LNGBV shown in Appendix A Table A14.

6.2. Main Facility Specification

The major onshore facilities for LNG bunkering consist of processes including the LNG Unloading System, LNG Storage System, Boil Off Gas (BOG) Processing System, LNG Weighing System, LNG Reloading System, Vapor Return System, and Flare System as shown in Appendix A Table A15.

The LNG storage tank has a design density of 480 kg/m3, a tank diameter of 94.80 m, a height of 59.65 m, and a reloading pump capacity of 5000 m^3/h as shown in Appendix A Table A16.

The berth infrastructure for LNGCs were designed to allow the maximum size of LNGCs to berth and to be unloaded within 24 h with a loading capacity of 14,000 m^3/h as shown in Appendix A Table A17.

6.3. Summary of Results

In 2030, Busan Port will be equipped with 160,000 GT berth for LNGC, 3 LNG storage tanks (270,000 m^3), 27 LNGTLs for TTS, 3 LNGBVs for STS, and 1 jetty-type quay wall for 7400 GT ships (see Table 20 & Figure 10)

Table 20. Summary of the Results of Estimating the Size of LNG Bunkering Facility in Busan Port.

Classification	Detailed Items		Symbols	Unit	Specifications	Facilities Required		
						Unit	2025	2030
Land Facilities	LNG Storage Tank		(a)	m^3	270,000	EA	1	3
	TTS (Bunkering Station)	Chargers	(b)	ton/min	0.25	EA	2	6
		Tank Lorries (LNGTLs)	(c)	ton(m^3)	14(30)	EA	5	27
		Parking Facilities	(d)	EA	-	EA	5	27
Offshore Facilities	LNG carriers (LNGC)	Mooring Facilities	(e)	G/T	160,000	Berth	1	1
	STS (Bunkering Shuttle Vessel)	Jetty Berth	(f)	m^3	5000	Berth	1	1
		Loading Arm System	(g)	ton/hour	500	EA	1	1
		Bunkering Shuttle Vessels (LNGBVs)	(h)	m^3	5000	EA	1	3
		Mooring Facilities	(i)	G/T	7,400	Berth	1	3
Total						EA	18	72

(**a**) LNG Storage Tank (**b**) TTS - Chargers (**c**) TTS - Tank Lorries (LNGTLs)

(**d**) TTS - Parking Facilities (**e**) LNG Carriers - Mooring Facilities (**f**) STS - Jetty Berth

(**g**) STS - Loading Arm System (**h**) STS - Bunkering Shuttle Vessels (**i**) STS - Mooring Facilities

Figure 10. Reprinted the Photos of LNG Bunkering Port Facilities under Permission of Korea Gas Corporations (modified from ref. [36]).

The results in Table 20 are derived on the assumptions about demand in Table 2, the assumptions about the conversion rate of LNG vessels in Table 3, and the assumptions about the LNG density, the capacity of LNGC, LNGTL, LNGBV, LNG storage tank, STS/ TTS classification criteria, and fuel consumption of LNGFV in Table 4.

7. Conclusions

IMO has decided to limit the sulfur oxides emission standards of navigation vessel fuels to 0.50% starting on the 1st of January 2020. One of the countermeasures to reach full compliance is to use LNG as a fuel for shipping companies. Ports in each country are considering the construction of LNG bunkering terminals to provide smooth service to LNG carriers. Considering the enormous budget to build LNG bunkering ports and facilities, it is important to calculate the criteria and quantity for each facility constituting the LNG bunkering infrastructure. So far, only engineering related to port construction has been emphasized, but there have not been many studies about scientific models to discover proper facility requirements.

The purpose of this study is to determine how to estimate the LNG bunkering demand and to present the estimation procedure and the number and size of LNG bunkering facilities needed. After applying the simulation modeling technique with Arena software, LNG demand and bunkering scales are derived according to TTS or STS bunkering type based on 2025 and 2030. In particular, the research method applying the simulation modeling is useful for calculating the appropriate capacity in terms of port logistics by logically approaching complex harbors that are difficult to calculate mathematically due to various variables and scenarios occurring in such ports.

Here, the demand for LNG bunkering by each vessel can be changed according to various variables and conditions such as bunkering strategy of shipping companies operating the vessel, bunkering price by the port of entry, and conditions of the bunkering infrastructure.

It is impossible to precisely grasp and predict the variables and conditions that can anticipate all changes in the next 10 to 20 years. Despite acknowledging the limitations of this study, the approach and procedure for the analysis of the required amount of LNG bunkering infrastructure proposed in this study are of sufficient utility value for carrying out similar studies.

The required specifications and quantity for each port facility needed for LNG bunkering as a case study are presented in the paper. As a result of the study based on 2030, it is necessary to have three LNG storage tanks, six LNGTL chargers, 27 LNGTLs and 27 parking facilities, one berth for LNGC and 1 berth for STS bunkering jetty, one loading arm system, one LNGBVs, and three berths for LNGBV mooring facilities.

As mentioned in Appendix A Table A18 [9], the cost of constructing the LNG bunkering port is about $9.1 billion (USD), about $0.1 million (USD) for each LNGTL, $1.0 million (USD) for the LNGTL loading arm, $5.0 million (USD) for the LNG jetty loading arm, and $50-70 million (USD) per LNGBV. The combined cost of constructing the LNG bunkering port and the equipment needed for the LNG bunkering service will require an enormous budget of $12-14 billion (USD). In particular, as the construction cost of the LNG storage tank on land is about $200-250 million (USD) per unit.

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Appendix A

Table A1. Sailing Distance from Busan Port Origin (Container Ship Based).

Classification	Japan	Far East	South East Asia	South West Asia	Middle East Asia	Europe	Africa	North America	Middle South America	South America	Oceania	Other Countries
	Japan /Osaka	China /Shanghai	Singapore	India /Mumbai	Catarrh /Doha	Netherlands /Rotterdam	South Africa /Cape Town	USA /LA	Mexico /San Padito Port	Chile /San Antonio	Australia /Sydney	Brunei /Seria
One way - Sailing Distance (days)	0.7	0.93	4.74	9.35	11.57	20.44	15.09	9.91	12.07	18.72	8.68	3.8

Table A2. LNG Fuel Consumption by Ship Size from Busan Port Origin (Container Ship Based).

Classification		Japan	Far East	South East Asia	South West Asia	Middle East Asia	Europe	Africa	North America	Middle South America	South America	Oceania	Other Countries
G/T	TEU	Japan /Osaka	China /Shanghai	Singapore	India /Mumbai	Catarrh /Doha	Netherlands /Rotterdam	South Africa /Cape Town	USA /LA	Mexico /San Padito Port	Chile /San Antonio	Australia /Sydney	Brunei /Seria
50,000	4400	53	70	355	700	867	1530	1130	742	904	1402	650	284
100,000	9200	89	117	597	1178	1458	2575	1901	1248	1521	2358	1094	478
150,000	14,000	113	150	764	1506	1864	3292	2431	1596	1945	3015	1398	611
200,000	18,800	136	180	917	1809	2238	3953	2919	1916	2335	3620	1679	734
220,000	20,700	147	194	988	1949	2411	4258	3144	2064	2516	3900	1808	791

Table A3. Analysis of LNG Carriers and Bunker Shuttles Worldwide (Analysis by November 2017).

Classification	Storage Capacity	No. of Ships	Built Year	Gross Tonnage	Dead Weight	LOA	Width	Maximum Draft	Loading capacity	Loading Time
Unit	**(m^3)**	**-**	**-**	**(G/T)**	**(DWT)**	**(m)**	**(m)**	**(m)**	**(m^3/hour)**	**(hour)**
1	260,000	10	2009	163,922	130,176	345	53.8	12.2	14,000	18.66
2	250,000	3	2009	168,399	155,000	345	55.0	10.7	15,000	17.2
3	210,000	16	2008	136,308	109,239	315	50.0	12.4	14,125	15.07
4	200,000	13	2008	136,952	120,091	314	50.0	13.6	14,769	13.97
5	180,000	2	2017	130,000	96,103	296	50.0	10.9	-	-
6	170,000	52	2015	113,031	92,660	293	46.5	12.1	14,080	12.48
7	160,000	32	2012	106,997	86,512	288	44.8	12.0	13,943	11.7
8	150,000	85	2013	106,363	84,374	288	44.6	11.9	14,368	10.8
9	140,000	96	2007	104,466	81,336	287	44.9	12.0	13,180	11.22
10	130,000	83	2001	101,682	75,195	284	44.6	11.6	12,773	10.87
11	120,000	32	1987	96,593	70,885	277	45.3	11.4	11,268	11.27
12	80,000	2	1993	66,174	48,837	239	40.0	11.0	7600	11.54
13	70,000	5	1993	50,371	43,237	234	34.9	10.4	7214	10.43
14	60,000	2	1997	46,555	35,760	215	33.9	9.5	6400	10.1
15	30,000	2	2016	25,450	16,303	182	32.0	7.4	-	-
16	20,000	7	2011	21,349	18,462	171	26.4	8.6	3300	-
17	10,000	9	2002	15,460	11,889	141	24.2	7.8	2243	-
18	4400	16	2005	5028	4043	98.9	16.3	5.5	824	-
Total	124,444	467	2006	88,617	71,117	256	40.9	10.6	10,318	12.72
Latest 5 years (2013–2017)	170,000	171	2014	114,098	89,912	291	46.5	12.1	14,130	11.66

Table A4. Distribution and Ratio per 12 Navigation Zones per 16 Ship Types.

Classification		Total	1. Passenger	2. Bulk Carrier	3. Log Carrier	4. Cement Carrier	5. Car Carrier
Total	Ratio	1.00000	0.12573	0.03496	0.00004	0.00238	0.01291
Japan	Ratio	0.32255	0.69558	0.18289	0.00000	0.27068	0.30791
	Distribution of GT		NORM (8.92×10^3, 1.84×10^3)	NORM (2.8×10^4, 5.55×10^3)		3,049	NORM (4.54×10^4, 4.6×10^3
Far East	Ratio	0.50731	0.30028	0.38064	0.50000	0.72180	0.51734
	Distribution of GT		(1.09×10^4) + ($1.58e \times 10^5$) $\times$ BETA (1.21, 0.778)	NORM (2.71×10^4, 2.73×10^3)	21,525	4,945	NORM(4.48×10^4, 8.89×10^3)
South East Asia	Ratio	0.04232	0.00128	0.08555	0.00000	0.00000	0.03329
	Distribution of GT		NORM (8.01×10^3, 1.6×10^3)	NORM (3.54×10^4, 3.59×10^3)			45,026
South West Asia	Ratio	0.00048	0.00000	0.00512	0.00000	0.00000	0.00000
	Distribution of GT			33,079			
Middle East Asia	Ratio	0.00589	0.00000	0.00359	0.00000	0.00000	0.00416
	Distribution of GT			40,641			65,545
Europe	Ratio	0.02103	0.00214	0.01486	0.00000	0.00000	0.01803
	Distribution of GT		NORM (7.8×10^4, 1.56×10^4)	36,587			58,226
Africa	Ratio	0.00768	0.00000	0.00564	0.00000	0.00000	0.00555
	Distribution of GT			40,641			61,459
North America	Ratio	0.04125	0.00014	0.17520	0.50000	0.00000	0.07490
	Distribution of GT		35,847	37,583	21,525		52,455

Table A4. *Cont.*

Classification		Total	1. Passenger	2. Bulk Carrier	3. Log Carrier	4. Cement Carrier	5. Car Carrier
Middle South America	Ratio	0.01476	0.00043	0.02510	0.00000	0.00000	0.01664
	Distribution of GT		54,553	34,786			51,716
South America	Ratio	0.00444	0.00000	0.02459	0.00000	0.00000	0.00555
	Distribution of GT			53,530			55,578
Oceania	Ratio	0.01143	0.00000	0.06301	0.00000	0.00000	0.00971
	Distribution of GT			44,444			53,888
Other Countries	Ratio	0.02086	0.00000	0.03381	0.00000	0.00752	0.00693
	Distribution of GT			43,868		3,415	53,730

Classification		6. Hot Coil Carrier	7. Refrigeration Carrier	8. General Cargo Ship	9. Full Container Ship	10. Semi Container Ship	11. Crude Oil Carrier
Total	Ratio	0.00000	0.04254	0.13375	0.53632	0.00070	0.00070
Japan	Ratio		0.17979	0.33182	0.27272	0.00000	0.00000
	Distribution of GT		NORM (1.2×10^3, 240)	NORM (4.2×10^3, 427)	NORM (8.47×10^3, 861)	NORM (8.42×10^3, 836)	
Far East	Ratio		0.62400	0.53642	0.53563	0.13070	0.66667
	Distribution of GT		NORM (3.54×10^3, 352)	NORM (6.22×10^3, 613)	NORM (3.64×10^4, 3.55×10^3)	NORM (6.03×10^3, 297)	NORM (3.82×10^4, 3.82×10^3)
South East Asia	Ratio		0.02316	0.04914	0.05273	0.00370	0.12821
	Distribution of GT		NORM (5.2×10^3, 522)	NORM (1.18×10^4, 1.2×10^3)	NORM (4.51×10^4, 4.54×10^3)	21,517	104,547

Table A4. *Cont.*

Classification		Total	1. Passenger	2. Bulk Carrier	3. Log Carrier	4. Cement Carrier	5. Car Carrier
South West Asia	Ratio		0.00000	0.00040	0.00033	0.00123	0.00000
	Distribution of GT			27,045	NORM (6.42×10^4, 3.24×10^3)	18,391	
Middle East Asia	Ratio		0.00000	0.00187	0.00975	0.00617	0.02564
	Distribution of GT			18,217	NORM (7.29×10^4, 3.64×10^3)	23,132	497
Europe	Ratio		0.04379	0.02102	0.02264	0.00370	0.12821
	Distribution of GT		4,006	6,309	NORM (9.47×10^4, 4.77×10^3)	5,127	50,580
Africa	Ratio		0.00926	0.00254	0.01182	0.00000	0.00000
	Distribution of GT		1,209	16,291	NORM (5.19×10^4, 2.63×10^3)		
North America	Ratio		0.04926	0.02799	0.05082	0.00123	0.02564
	Distribution of GT		NORM (6.6×10^3, 654)	28,252	NORM (7.07×10^4, 7.13×10^3)	25,345	28,777
Middle South America	Ratio		0.00505	0.00830	0.02234	0.00000	0.02564
	Distribution of GT		4,264	17,970	NORM (7.43×10^4, 3.69×10^3)		81,493
South America	Ratio		0.00168	0.00295	0.00518	0.00000	0.00000
	Distribution of GT		13,618	43,719	NORM (8.14×10^4, 4.11×10^3)		
Oceania	Ratio		0.01305	0.00670	0.00838	0.14427	0.00000
	Distribution of GT		NORM (3.39×10^3, 346)	30,099	NORM (5.09×10^4, 2.55×10^3)	20,074	
Other Countries	Ratio		0.05095	0.01085	0.00765	0.00740	0.00000
	Distribution of GT		NORM (3.61×10^3, 364)	12,380	NORM (4.34×10^4, 2.19×10^3)	22,376	

Table A4. *Cont.*

Classification		12. Oil Product Carrier	13. Chemical Tanker	14. LPG·LNG Carrier	15. Fishing Boat	16. Others
Total	Ratio	0.01730	0.02445	0.00355	0.04157	0.00930
Japan	Ratio	0.19979	0.34066	0.26263	0.01637	0.23699
	Distribution of GT	NORM (3.88×10^3, 389)	NORM (2.53×10^3, 252)	NORM (8.3×10^3, 842)	413	NORM (3.77×10^3, 189)
Far East	Ratio	0.56729	0.59927	0.59091	0.69280	0.48940
	Distribution of GT	NORM (5.55×10^3, 547)	NORM (3.68×10^3, 370)	NORM (7.39×10^3, 739)	NORM (1.37×10^3, 136)	NORM (5.88×10^3, 1.01×10^3)
South East Asia	Ratio	0.03209	0.03150	0.04040	0.00474	0.11753
	Distribution of GT	NORM (1.51×10^4, 1.48×10^3)	NORM (1.24×10^4, 1.23×10^3)	NORM (2.97×10^4, 2.97×10^3)	1,052	NORM (4.55×10^3, 462)
South West Asia	Ratio	0.00000	0.00000	0.00000	0.00000	0.00578
	Distribution of GT					9,424
Middle East Asia	Ratio	0.00311	0.00000	0.01010	0.00086	0.00000
	Distribution of GT	14,139		25,088	183	
Europe	Ratio	0.00725	0.00220	0.01010	0.06204	0.02697
	Distribution of GT	23,220	10,917	111,242	1,089	5,148
Africa	Ratio	0.00621	0.00147	0.00505	0.00172	0.01156
	Distribution of GT	4,005	29,093	17,840	565	4,314
North America	Ratio	0.02899	0.00586	0.04040	0.00000	0.02119
	Distribution of GT	24,372	26,176	47,437		44,849
Middle South America	Ratio	0.00725	0.00366	0.01515	0.00000	0.00193
	Distribution of GT	37,082	26,319	37,139		9,025

Table A4. *Cont.*

South America	Ratio	0.00207	0.00073	0.00000	0.00431	0.00385
	Distribution of GT	38,526	28,160		2,217	35,353
Oceania	Ratio	0.01242	0.00293	0.01515	0.00819	0.03854
	Distribution of GT	NORM(1.34×10^4, 1.36×10^3)	17,438	109,588	1,179	42,201
Other Countries	Ratio	0.13354	0.01172	0.01010	0.20896	0.04624
	Distribution of GT	NORM(2.8×10^3, 279)	9,099	48,393	NORM(1.07×10^3, 105)	22,746

Table A5. Number of LNGCs Required per Year.

Year	LNG Fuel Requirements per Year (ton) (a)	LNG Carriers (LNGC)		
		One Time Capacity (ton) (b)	Number of LNGCs Required per Year (c = a/b)	Interval per One Time (days) (d = 365 days /c)
2025	380,885	81,600 (170,000 m^3)	4.67	78.20
2030	2,005,399		24.58	14.85

Table A6. Required STS/TTS per Day.

Year	Average LNG Fuel Requirements per Day (ton) (a)	Peak Ratio (b)	Maximum LNG Fuel Requirements per Day (ton) (c = a*b)	STS (More than 100 tons per Supply)				TTS (Less than 100 tons per Supply)			
				Number of Supply	Number of LNGBVs	Daily Supply(ton)	Average Supply per One Time (ton)	Number of Supply	Number of LNGTLs	Daily Supply (ton)	Average Supply per One Time (ton)
2025	1,043.52	137.7%	1,437	1.5	0.59	1215.31	816.20	7.4	15.83	221.62	29.83
2030	5494.02		7567	7.1	3.12	6,451.12	902.84	32.2	79.68	1115.53	34.60

Table A7. Required LNG Storage Tank.

Year	Average LNG Fuel Requirements per Day (ton) (a)	Inventory Warranty Period(day) (b)	Minimum LNG Inventory(ton) (c = a*b)	Pure LNG Capacity per Tank (ton) (d)	Estimated LNG Storage Tank Quantity (unit) (e = c/d)	Minimum LNG Storage Tank Quantity (unit) (f)	LNG Storage Capacity (ton) (g = d*f)
2025	1043.52	30	31,306	116,640	0.27	1.00	116,640
2030	5494.02		164,851		1.41	2.00	233,280

Table A8. Estimated Total Berth Occupancy Time of LNGC per One.

One Time Capacity of LNGC (m^3) (a)	Unloading Performance (m^3/hour) (b)	Unloading Required Time (hour) (c = a/b)	Docking Required Time(hour) (d)	Total Berth Occupancy Time (hour) (e = c+d)	Comments
170,000	14,130	12.03	2.0 (Docking 1 h + Undocking 1 h)	14.03	Shipboard transit conditions due to tide difference only are not considered.

Table A9. Estimated Time Required for One TTS Bunkering.

Charging Time (hour) (a)	Average Moving Time (hour) (b)	Bunkering Time (hour) (c)	Return Time (hour) (d)	Total Time (hour) (e = a+b+c+d)
1.10	0.53	1.10	0.53	3.25

Table A10. Charger for LNGTL and Bunkering Station, Number of Parking Facilities Required.

Year	Tank Lorries (LNGTLs)			Bunkering Station				Required Parking Facilities (unit) (h)
	Number of LNGTLs Required per Day (a)	Rotation Count per Day (b)	Number of LNGTLs Required (c = a/b)	Charge Time per Charger per Day(hour) (d)	Charging Time per LNGTL (hour) (e)	Chargeable Number of Days per Charger (f = d/e)	Number of Chargers Required (g = a/f)	
2025	16.0	3	5.0	18.0	1.27 (Pure Charging time 1.1 h + margin 10 min added)	14.0	1.14 (2 units)	16.0
2030	80.0		27.0				5.71 (6 units)	80.0

Table A11. Estimated Total Time and Number of Rotation per One STS Bunking.

Year	Loading Time per LNGBV (hour) (a)	Moving Time per LNGBV (hour) (b)	One day						Bunkering Time per One LNGBV (hour) (i)	Return Time per One LNGBV (hour) (j)	Required Total Time per One LNGBV (hour) (k = a+b+h+i+j)	Daily Operation Time per One LNGBV (hour) (l)	Rotation Count per One LNGBV (m = l/k)
			Number of Supply (c)	Count of LNGBV (d)	Average Number of Supply per One LNGBV (e = c/d)	Average Moving Time(hour) (f)	Average Berthing Time(hour) (g)	Total Moving Time per LNGBV (hour) (h = e*(f+g))					
2025	6.70	1.07	1	1	1(1.00)	0.34	1.25	1.59	7.83	1.07	18.25	24.00	1.31
2030			7	3	2(2.33)			3.17			19.84		1.21

Table A12. Jetty Loading Arm's Number of Operations per Day (Rotation Rate).

Operation Time per One Day of Jetty Loading Arm (hour) (a)	Loading Time per LNGBV (hour) (b)	Operation Count per Day (c = a/b)
24.00	6.70	3.58

Table A13. Required LNGBVs.

Year	Number of LNGBV (a)	Rotation Count per One LNGBV (b)	Calculated LNGBVs (c = a/b)	Required LNGBVs (d)
2025	0.59	1.31	0.45	1.0
2030	3.12	1.21	2.58	3.0

Table A14. STS Jetty Loading Arm and Mooring Facilities Required.

Year	Jetty Loading Arm & Berth				Required Mooring Facilities (e)
	Required LNGBVs (a)	Number of Ships Available per Day per Loading Arm (b)	Calculated Loading Arm (c=a/b)	Required Loading Arm & Berth (d)	
2025	1.0	3.58	0.23	1.00	1 berth
2030	3.0		0.84	1.00	3 berths

Table A15. LNG On-shore Facility.

Classification	Description (Name)	Facility Capacity	Etc.
LNG Unloading System	LNG Loading Arm	5000 m^3/h x 3	-
	Vapor Return Arm	14,000 m^3/h	270,000 m^3
	Jetty K.O Drum	26 m^3/h	-
LNG Storage System	LNG Storage Tank	270,000 m^3	-
	LNG Reloading Pump	1000 m^3/h	-
BOG Processing System	BOG Compressor K.O Drum	20 m^3	-
	BOG Compressor	12 ton/h	-
	Liquefaction Unit	2.5 ton/h	-
LNG Weighing System	Weighing and Regulator Unit	1000 m^3/h	-
LNG Reloading System	LNG Reloading Arm	Max 1000 m^3/h	5000 m^3
Vapor Return System	Vapor Return Arm	Max 1000 m^3/h	5000 m^3
Flare System	Flare Stack	70 ton/h	-
	Flare Stack K.O Drum	85 m^3	-

Table A16. LNG Storage Tank.

LNG Storage Capacity	Design Density	Tank Size		Reloading Pump Capacity
		Diameter (Outer)	Height (Total)	
270,000 m^3	480 kg/m^3	94.80 m	59.65 m	1000 m^3/h

Table A17. Berth Facility for LNGCs.

Carrying Capacity	Vessel				Unloading Capacity
	LOA	Width	Height	Draft	
170,000 m^3 ~270,000 m^3	300.0 m ~ 350.0 m	47.0 m ~ 55.0 m	26.0 m ~ 27.0 m	12.0 m ~ 14.0 m	14,000 m^3/h

Table A18. Estimated Cost by Items of LNG Bunkering Facility.

Items	Capacity	Specification	Unit	Estimated Cost (USD)
LNG Tank Lorry (Truck)	30 m^3	30 m^3/hour	EA	100,000
LNG Truck Loading Arm (TTS)	30 m^3	30 m^3/hour	EA	1,000,000
LNG Jetty Loading Arm (STS)	1000 m^3	1000 m^3/hour	EA	5,000,000
LNG Bunkering Shuttle (STS)	5000 m^3	600 m^3/hour	EA	50,000,000
	23,000 m^3	1500 m^3/hour	EA	70,000,000
LNG Bunkering Port Construction (Based on 2035)	LNG Storage Tank: 270,000 m^3 × 3 EA Unloading Berth: 160,000G/T × 1 EA Loading Berth: 7,400G/T × 3 EA		EA	900,000,000-1,100,000,000

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