Multimodal Transportation 3 (2024) 100134

Contents lists available at ScienceDirect

Multimodal Transportation

journal homepage: www.elsevier.com/locate/multra

Full Length Article

LNG bunkering infrastructure planning at port

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A R T I C L E I N F O

Keywords:
Maritime transportation
Vessel fuel
Clean energy
Liquid natural gas (LNG) bunkering
Integer linear programming (ILP)

A B S T R A C T

Ships are traditionally powered by fossil fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO), where the emissions, such as particulates, hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_X) and carbon dioxide (CO_2), negatively affect the environment and human health. The International Maritime Organization (IMO) encourages shipping companies to use liquefied natural gas (LNG), which is a green fuel source to power shipping activities and is easy to store, to replace traditional marine fuels. There are three common methods of LNG bunkering: ship-to-ship, truck-to-ship, and port-to-ship. The objective of this study is to determine the optimal bunkering method at a port using an integer linear programming (ILP) model considering three kinds of costs: fixed, variable, and extra. To find the optimal bunkering method, the three methods and their related constraints are modeled into the ILP model. The results indicate that ship-to-ship is the optimal bunkering method for LNG under the scenario of the port considered. Numerical experiments are conducted to validate model performance and generate managerial insights.

1. Introduction

In global trade, more than 80% of cargo is transported by ship (UNCTAD, 2018; Meng et al., 2022; Yan and Wang, 2022), leading to an increased number of ships sailing around the world (Yi et al., 2019, 2020; Zhen et al., 2021; Qiu et al., 2022; Wu et al., 2022a). As ships are typically powered by fossil fuels, fossil fuel consumption by vessels is also increasing, resulting in the emission of particulates, HC, CO, and CO_2. Excessive CO_2 emissions are harmful to the environment (Lagouvardou and Psaraftis, 2022; Lagouvardou et al., 2022; Psaraftis, 2022; Huang and Wang, 2022).

In 2020, 794 million tons of CO_2 were emitted during shipping, and this figure increased by 4.9% to 833 million tons in 2021 (Lloyd's List, 2022). CO_2 emissions negatively affect the environment and human health. Specifically, from an environmental perspective, the greatest harm caused by excessive CO_2 emissions is the greenhouse effect, which is the cause of global warming and results in various problems, e.g., rising surface temperatures, melting glaciers, and rising sea levels. Furthermore, the increasing CO_2 level in the atmosphere also contributes to an increasing number of heat waves and forest fires (Yan and Xu, 2021; Yan et al., 2021a, 2021b, 2021d; Fan and Xie, 2021). From the perspective of human health, the main adverse impact of CO_2 is that it stimulates the human respiratory system, resulting in shortness of breath, which can cause headaches, confusion, and other symptoms. Rapid breathing caused by a high concentration of CO_2 increases oxygen intake, but breathing too rapidly can affect gas exchange in the lungs, further aggravating hypoxia. In this vicious circle, patients with CO_2 poisoning may become comatose for a short period of time. Therefore, a cleaner fuel source to reduce CO_2 emissions is an urgent concern for governments worldwide.

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https://doi.org/10.1016/j.multra.2024.100134
Received 25 September 2023; Received in revised form 10 October 2023; Accepted 13 November 2023

Table 1
Comparison of LNG bunkering methods

Method	Typical Volume (V) and Bunker Rate (Q)	Advantages	Disadvantages
TTS: An LNG truck on the dock is connected to the receiving vessel, typically via a flexible hose	$V \approx 50 - 100\ m^3$ $Q \approx 40 - 60\ m^3/h$	• Low infrastructure requirements • Adaptable to various customer requirements • Can serve various LNG users through point-to-point delivery	• Limited capacity • Limited movement on the terminal side • Roadside restrictions (e.g., traffic restrictions)
STS: Another ship or barge delivers LNG to the receiving ship	$V \approx 100 - 6,500\ m^3$ $Q \approx 500 - 1,000\ m^3/h$	• Does not interfere with cargo operations • The most adaptable LNG bunkering mode • Can deliver high volume with greater efficiency than TTS	• High initial investment • The size of bunkering vessels is limited by the size of the port
PTS: LNG is directly bunkered from small LNG storage units and bunkering stations	$V \approx 500 - 20,000\ m^3$ $Q \approx 400 - 700\ m^3/h$	• Fast delivery and larger quantities • A good choice for ports with long-term bunkering needs	• Limited berthing slots for ships to receive LNG • Availability is hard to be guaranteed in large LNG terminals • Difficult to estimate the amount of LNG available for bunkering in small storage tanks

Source: European maritime safety agency

Natural gas is a more environmentally friendly fuel than many other traditional fuels, e.g., oil, coal, and propane, as it has lower emission levels. For example, each metric million British thermal unit (MMBtu) of natural gas produces about 117 pounds of CO_2, whereas an MMBtu of coal produces more than 200 pounds of CO_2 and an MMBtu of distillate fuel oil produces more than 160 pounds of CO_2 (EIA, 2021). Thus, the shipping industry is being encouraged by International Maritime Organization (IMO) to adopt natural gas as an alternative to traditional fuels. Liquid natural gas (LNG) is a type of natural gas that can be stored under normal pressure after it has been purified and subjected to ultra-low temperature liquefaction. With available technology LNG has to be in a gaseous state or form to be used as a fuel. However, compared with other forms of natural gas, such as compressed natural gas pressurized and stored in a gaseous state, LNG is a better fuel source to power shipping activities, as it requires less storage space and is more suitable for long-distance transportation (Nguyen, 2020; Ma et al., 2020). Thus, LNG is a common alternative fuel choice for shipping companies.

There are many ways to bunker LNG onto ships. We focus on three bunkering modes: truck-to-ship (TTS), ship-to-ship (STS), and port-to-ship (PTS). Detailed information about these three modes is shown in Table 1. Typical volume (V) is the quantity of LNG in cubic meters that can be stored in one truck/ship/port. Bunker rate (Q) is how much LNG can be bunkered from a truck/ship/port to a ship in one hour. As the three modes have different advantages and disadvantages, this study aims to find the most suitable LNG bunkering mode for a given port. An ILP model is built to find the optimal bunkering mode and the optimal bunkering station allocation plan by minimizing the total cost, which equals the fixed cost plus the variable cost and the extra cost for late departure of ships.

The contribution of this paper is three-fold. First, different from previous papers focusing on similar problems, this study considers the bunkering price at a single port in the optimization problem. Second, an ILP model is proposed to model and solve the problem. Third, numerical experiments and sensitive analysis are conducted to validate the model and obtain managerial insights.

The reminder of this paper is organized as follows. Section 2 is the literature review. Then, Section 3 gives the model formulation. Numerical experiments were introduced in Section 4. Finally, Section 5 closes the paper with the conclusions and future research.

2. Literature review

Several studies have provided insights into LNG bunkering management problems, such as bunkering network optimization and bunkering station setting design. The bunkering network setting problem covers site selection issues and bunkering network planning. Kim et al., 2021a used empirical analysis to identify the selection criteria of LNG bunkering ports for shipping companies. Zhao et al. (2022) considered various factors, including natural factors, infrastructure factors, economic factors, safety factors, and policy factors, to construct a comprehensive evaluation system for sites selection of LNG bunkering station. The comprehensive evaluation index constructed in this paper was not perfect because the construction of LNG bunkering stations in coastal ports in China was still in its infancy. Wang (2014) calculated single ship berth bunkering capacity to propose a bunkering network for the Chongqing LNG bunkering port. Ursavas et al. (2020) considered multi-period capacitated demand in a network design model with bunkering via pipeline and TTS. Bunkering network planning also involved fuel demand forecasting. This study suggested that new services to foster terminal utilization and exploring ways to promote price signals were utmost important. Yang (2016) derived a prediction formula for LNG fuel demand according to the number and variety of ships. Dai and Yang (2019) predicted the future LNG bunkering requirements of inland maritime transportation. Park and Park (2019) considered STS and TTS at Busan Port to forecast LNG fuel demand. They constructed a simulation model that considered bunkering strategy, port fuel bunkering price, LNG bunkering facility conditions, and other factors.

In the bunkering station literature, researchers often focus on safety factors because LNG is a cryogenic liquid stored in insulated tanks. Crowl and Louvar (2001) proposed that the release of LNG from stored tanks could potentially lead to asphyxiation, cryogenic burns, fires, or even explosions if the leaked gas met an ignition source. Moreover, such accidents might trigger large chain reactions in an LNG bunkering station (IMO, 2015). Skramstad (2013) presented guidance for meeting safety requirements in LNG bunkering. Jeong et al. (2017) determined the safe zone around an LNG bunkering station. This study did not consider how to guarantee the safety outside the bunkering station when bunkering LNG fuel to ships. Park et al. (2018) conducted computational fluid dynamics simulations and found that wind speed and direction, ship geometry, and loading conditions affect safety zone boundaries. However, environmental conditions such as wind speed, direction and ship geometry affect the safety zone boundaries. Park and Paik (2022) proposed a hybrid method to determine the safety zone during LNG bunkering by the TTS method. This paper introduced a hybrid method, intending to design a more realistic layout for the safety zone in connection with the probability and consequence of leaks occurring during LNG bunkering.

Although many studies have discussed bunkering network design, such as bunkering station and safety zone settings, the optimal LNG bunkering method for a port has been only slightly investigated. Zhao et al. (2015) analyzed the advantages and disadvantages of six types of bunkering methods for LNG-powered ships: shore based, barge based, LNG storage tank, ship based, floating chambers, and storage tank replacement. Lee et al. (2021) used an analytic hierarchy process to find the optimal LNG bunkering method and found that the optimal method was STS, followed by TTS and PTS. Yu et al. (2021) conducted geometric aggregation of four factors, namely LNG supply, fuel supply suitability, spillage risk, and domestic and international standards, and found that STS was the optimal method in Busan port. In this study, we use a different approach to finding the optimal bunkering method by considering the bunkering rate and cost for LNG fuel by developing an ILP model, which has been widely used in transportation studies and infrastructure management (Chan et al., 2016; Yi et al., 2017; Kim et al., 2021b; Ma et al., 2021; Mahmoodjanloo et al., 2021; Wang and Wu, 2021; Yan et al., 2021c; Qu et al., 2022).

3. Model setup

The three LNG bunkering methods have advantages and limitations. Hence, this study aims to explore what kind of LNG bunkering methods should be adopted by a port by formulating an ILP model.

The following assumptions are made as part of the proposed formulations.

1) There is no interruption during bunkering. This assumption ensures that the demand for bunkering can be satisfied and there does not exist other costs during bunkering.
2) Only one method is used to bunker LNG. The number of trucks/ships that bunker LNG to ships remains unchanged throughout the bunkering process. The aim of this assumption is to find the optimal bunkering method.
3) The bunkering start time is no earlier than the ship's arrival time at the port. This assumption follows the study of Aydin et al. (2017).
4) The ship's expected departure time can be later than the bunkering end time. This assumption gives flexibility to the problem.
5) All LNG bunkering requirements should be satisfied at the port, which means that the port has enough LNG to satisfy ships' bunkering demands. This assumption is to simplify the model and the program.
6) Late departure of ships caused by the LNG bunkering service will lead to a penalty for the port. Due to the late departure, the ships need to speed up in later voyages or have a late arrival, both lead to extra costs. Thus, the ship operator may not choose to get refueled at the port in the future. The penalty stands for the potential loss of port resulting from the decline in customer.
7) Time is a moment on a timeline, e.g., 1, 2, and 3, as shown in Fig. 1. Time interval indicates a length of time, e.g., 1st (time 0 to time 1), 2nd (time 1 to time 2), and 3rd (time 2 to time 3). The u_{th} hour is a time interval, which is from time $u-1$ to time u. To make the model comprehensible, we clearly define moment and interval in the timeline.
8) All ship visits are identical, including vessel type and LNG bunkering volume.

The notations used in this study are defined as follows.

Parameters

C_T The purchase cost of a truck (unit: USD)

C_S The purchase cost of a ship (unit: USD)

C_P The cost of building a port that can bunker LNG fuel (unit: USD)

α A factor that converts total cost into hourly cost

αC_T The per hour cost of purchasing a truck (unit: USD/hour)

αC_S The per hour cost of purchasing a ship (unit: USD/hour)

αC_P The per hour cost of building a bunkering port (unit: USD/hour)

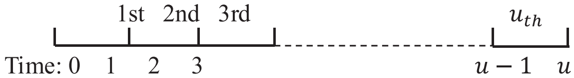

Fig. 1. The definitions of time and time interval

c_T The variable cost per bunkering truck (unit: USD/hour)
c_S The variable cost per bunkering ship (unit: USD/hour)
c_P The variable cost for a bunkering port (unit: USD/hour)
N_T The maximum number of trucks that can simultaneously bunker one ship
N_S The maximum number of ships that can simultaneously bunker one ship
q_T The hourly bunkering volume of a truck (unit: m^3)
q_S The hourly bunkering volume of a ship (unit: m^3)
q_P The hourly bunkering volume of a port (unit: m^3)
W A set of LNG-powered ships that dock at the port
t_{w1} The arrival time of ship w
t_{w2} The expected departure time of ship w (ship w docks at the port from t_{w1} to t_{w2}, so its planned docking time at the port is $t_{w2} - t_{w1}$)
G_w The quantity of LNG fuel for ship w (unit: m^3)
p_w The extra cost incurred if a ship's actual departure time exceeds its planned departure time because of bunkering (unit: USD/hour)
U The set of hours in the planning horizon (unit: hours)
M A larger number, as defined in the following constraints
Decision variables
y_{wT} A decision variable that is set to 1 if a ship is bunkered by a truck/trucks; otherwise, it is set to 0
y_{wS} A decision variable that is set to 1 if a ship is bunkered by a ship/ships; otherwise, it is set to 0
y_{wP} A decision variable that is set to 1 if a ship is bunkered by the port; otherwise, it is set to 0
x_{wT} The number of trucks that bunker ship w
x_{wS} The number of ships that bunker ship w
z_T A nonnegative integer that is the number of trucks purchased for LNG bunkering
z_S A nonnegative integer that is the number of LNG bunkering ships purchased
z_P A binary variable that is set to 1 if the PTS should be constructed; otherwise, it is set to 0
γ_{wuT} The number of trucks to bunker ship w in the u_{th} hour
γ_{wuS} The number of ships to bunker ship w in the u_{th} hour
γ_{wuP} A binary variable that is set to 1 if ship w is PTS bunkered in the u_{th} hour
τ_{w1} The bunkering start time for ship w
τ_{w2} The bunkering end time for ship w; the bunkering period for ship w is $\tau_{w1} - \tau_{w2}$
Δ_{wu1} A decision variable that is set to 1 if the bunkering start time for ship w is u; otherwise, it is set at 0
Δ_{wu2} A decision variable that is set to 1 if the bunkering end time for ship w is u; otherwise, it is set at 0
π_{wu} A decision variable that is set to 1 if the ship is bunkering in u; otherwise, it is set at 0

Furthermore, we denote the total cost by C. Using the above definitions of the parameters and decision variables, the ILP model was formulated as follows:

$$Min\ C = \alpha C_T z_T + \alpha C_S z_s + \alpha C_p z_p + \sum_{w\in W} \left(c_T x_{wT} + c_s x_{ws} + c_P y_{wP}\right)$$
$$+ \sum_{w\in W} p_w \max\left(0,\ \tau_{w2} - t_{w2}\right) \tag{1}$$

subject to

$$y_{wT} + y_{wS} + y_{wP} = 1,\ w \in W \tag{2}$$

$$x_{wT} \le M y_{wT},\ w \in W \tag{3}$$

$$x_{wS} \le M y_{wS},\ w \in W \tag{4}$$

$$x_{wT} \le N_T,\ w \in W \tag{5}$$

$$x_{ws} \le N_S\ w \in W \tag{6}$$

$$M\left(1 - y_{wT}\right) + q_T \sum_{u\in U} \gamma_{wuT} \ge G_w,\ w \in W \tag{7}$$

$$M\left(1 - y_{wS}\right) + q_S \sum_{u\in U} \gamma_{wuS} \ge G_w,\ w \in W \tag{8}$$

$$M\left(1-y_{wP}\right)+q_P\sum_{u\in U}\gamma_{wup}\geq G_w,\ w\in W \tag{9}$$

$$\tau_{w1}\geq t_{w1},\ w\in W \tag{10}$$

$$\sum_{u\in U}\Delta_{wu1}=1,\ w\in W \tag{11}$$

$$\tau_{w1}=\sum_{u\in U}u\Delta_{wu1},\ w\in W \tag{12}$$

$$\sum_{u\in U}\Delta_{wu2}=1,\ w\in W \tag{13}$$

$$\tau_{w2}=\sum_{u\in U}u\Delta_{wu2},\ w\in W \tag{14}$$

$$\pi_{wu}\leq\sum_{u'=1}^{u-1}\Delta_{wu'1},\ u=1,\ 2,\ 3,\ldots,U \tag{15}$$

$$\pi_{wu}\leq\sum_{u'=u}^{U}\Delta_{wu'2},\ u=1,\ 2,\ 3,\ldots,U \tag{16}$$

$$\pi_{wu}\geq\sum_{u'=1}^{u-1}\Delta_{wu'1}+\sum_{u'=u}^{U}\Delta_{wu'2},\ u=1,\ 2,\ 3,\ldots,U \tag{17}$$

$$M\left(\pi_{wu}-1\right)+x_{wT}\leq\gamma_{wuT}\leq M\left(1-\pi_{wu}\right)+x_{wT},\ w\in W,\ u=1,\ 2,\ 3,\ldots,U \tag{18}$$

$$M\left(\pi_{wu}-1\right)+x_{wS}\leq\gamma_{wuS}\leq M\left(1-\pi_{wu}\right)+x_{wS},\ w\in W,\ u=1,\ 2,\ 3,\ldots,U \tag{19}$$

$$M\left(\pi_{wu}-1\right)+y_{wP}\leq\gamma_{wuP}\leq M\left(1-\pi_{wu}\right)+y_{wP},\ w\in W,\ u=1,\ 2,\ 3,\ldots,U \tag{20}$$

$$\sum_{w\in W}\gamma_{wuT}\leq z_T,\ u=1,\ 2,\ 3,\ldots,U \tag{21}$$

$$\sum_{w\in W}\gamma_{wuS}\leq z_S,\ u=1,\ 2,\ 3,\ldots,U \tag{22}$$

$$\gamma_{wuP}\leq z_P,\ u=1,\ 2,\ 3,\ldots,U \tag{23}$$

$$z_P\in(0,\ 1) \tag{24}$$

$$\gamma_{wuP}\in\{0,\ 1\},\ u=1,\ 2,\ 3,\ldots,U \tag{25}$$

$$y_{wT}\in\{0,\ 1\},w=1,\ 2,\ 3,\ldots,W \tag{26}$$

$$y_{wS}\in\{0,\ 1\},w=1,\ 2,\ 3,\ldots,W \tag{27}$$

$$y_{wP}\in\{0,\ 1\},w=1,\ 2,\ 3,\ldots,W \tag{28}$$

$$\Delta_{wu1}\in\{0,\ 1\},\ u=1,\ 2,\ 3,\ldots,U \tag{29}$$

$$\Delta_{wu2}\in\{0,\ 1\},\ u=1,\ 2,\ 3,\ldots,U \tag{30}$$

$$\pi_{wu} \in \{0,\ 1\},\ u = 1,\ 2,\ 3, \dots, U. \tag{31}$$

Objective function (1) minimizes the costs of ship bunkering by LNG. Specifically, the term $\alpha C_T z_T + \alpha C_S z_s + \alpha C_p z_p$ represents the per week fixed cost of the trucks, ships, and port facilities that bunker LNG fuel. The term $\sum_{w\in W}(c_T x_{wT} + c_s x_{ws} + c_P y_{wP})$ represents the total variable cost of the trucks, ships, and port facilities that bunker LNG fuel, including maintenance, management, and labor costs. The term $\sum_{w\in W} p_w \max(0,\ \tau_{w2} - U_{w2})$ represents the extra cost incurred if a ship's actual departure time is after its planned departure time. Constraints (2) ensure that exactly one bunkering method is used for each ship w. Constraints (3) and (4) restrict the number of ships/trucks bunkering LNG fuel to a ship to less than M and less than the maximum number of trucks/ships that can bunker a ship. Constraints (7), (8), and (9) indicate that the quantity of LNG fuel bunkered to ship w is no less than the demand quantity for LNG fuel by trucks/ships/the port. In constraints (7), (8), and (9), M ensures that the LNG fuel available from the trucks/ships/port exceeds the demand quantity. Constraints (7), (8), and (9) should be hold because the largest value of y_{wT}, y_{wS} and y_{wP} is 1. Constraints (10) state that LNG fuel can be bunkered to ship w after its arrival. Constraints (11) and (12) state that the bunkering start time for ship w is u. Constraints (13) and (14) ensure that the bunkering end time for ship w is u. Constraints (15) and (16) state that the bunkering time is later than the bunkering start/end time for ship w. Constraints (17) indicate that bunkering occurs between the bunkering start and end times. Constraints (18) and (19) indicate that the number of trucks/ships used to refuel ship w equals the number of trucks/ships bunkering ship w in the u_{th} interval if bunkering for ship w begins in u. Constraint (20) ensures that the ship is bunkered by the port. Constraints (21) and (22) state that the number of trucks/ships used for bunkering in the u_{th} hour cannot exceed the number of trucks/ships purchased. Constraints (23) state that the PTS LNG bunkering method to ship w occurs in u_{th} hours. Constraints (24)–(31) dictate the domain of the decision variable.

M in Eq. (3) can be set to N_T because no more than N_T trucks can bunker a ship at the same time. Similarly, M in Eq. (4) can be set to N_S. M in Eqs. (7)–(9) can be set to G_w. This is because take Eq. (7) as an example, if $M = G_w$, then when $y_{wT} = 0$, the inequality always holds as long as $\gamma_{wuT} \geq 0$. M in Eqs. (18) and (19) can be set to N_T and N_S, respectively, and M in Eq. (20) can be set to 1.

4. Numerical experiments

To evaluate the proposed model, we perform several computational experiments on a personal computer (Intel Core i7; Memory, 16 GB; Mountain View, CA, USA) using visual studio 2019. The mathematical model used is coded in $C^{\#}$ and implemented in CPLEX 12.6.2.

4.1. Performance of the model

Our parameter settings are as follows. Part of the parameters are set following existing literature and the others are set based on common knowledge. We set the planning horizon to 24 hours. Following Argonne (2013), the cost of purchasing a truck is set at 204 thousand USD. The cost of purchasing a ship, on the other hand, is set at 50 million USD (Marine & Offshore, 2020). Meanwhile, the cost of building a port to bunker ships is 11.7 million USD, according to Ship and Bunker (2021). We assume the service life of the vehicles is one year. Thus, the hourly rates are calculated by dividing the purchase cost by 365 days and 24 hours. We assume that the variable costs for a truck, a ship, and a port to bunker a ship are 50 USD/hour, 100 USD/hour, and 150 USD/hour, respectively (Brouer et al., 2013; Jeong et al., 2018; Liu et al., 2023). From the World Port Sustainability Program (2020), we obtained hourly bunkering volumes for a truck, a ship, and a port, which are 60 m^3, 750 m^3, and 650 m^3, respectively. The arrival and departure times of the ships are randomly generated from 0h to 24h within the planning horizon, following a uniform distribution. The LNG bunkering volume for a ship is randomly generated in a range from 1,000 m^3 to 5,000 m^3 (Jeong et al., 2018). Extra cost is incurred if the actual departure time is later than the planned departure time and is set to 200 USD/hour (Lee et al., 2018).

Several numerical experiments with different numbers of ships are conducted to validate the proposed model. Table 2 lists the results from CPLEX. In Table 2, the "number of ships" column shows the number of ships docking and bunkering at the port for a week. The results in Table 2 show that STS is the optimal bunkering method among the three bunkering methods considered: STS, TTS, and PTS. Table 2 also shows that the CPU time increases as the number of ships considered increases. However, when the number of ships to bunker reaches 30, only 40 CPU seconds are required, which is acceptable.

Table 2
Results provided by CPLEX

Case ID	The number of Ships	The selected method of bunkering ships	CPU Time (second)	Optimal number of purchased ships
1	10	STS	17	3
2	15	STS	21	3
3	20	STS	27	4
4	25	STS	34	4
5	30	STS	40	5

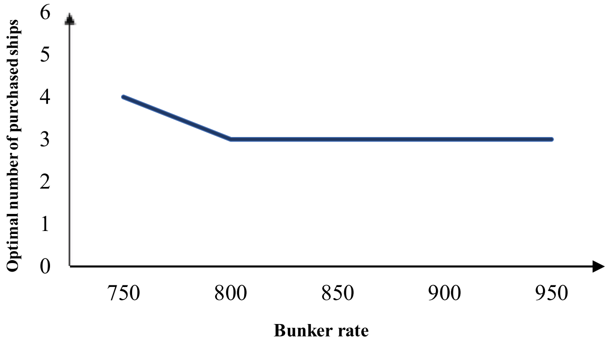

Fig. 2. The number of purchased ships as bunker rate increases.

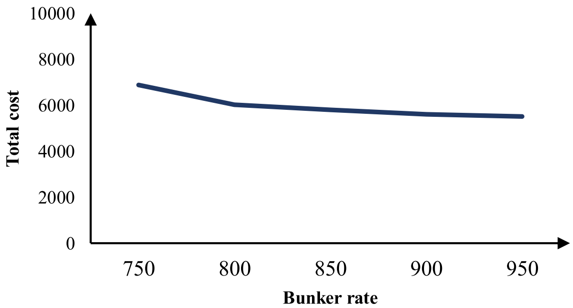

Fig. 3. The total cost as bunker rate increases.

4.2. Sensitivity analysis

Some parameters, e.g., bunker rate, in the ILP model may fluctuate because of variations in fuel tank sizes and LNG fuel demand. Ship bunker rates influence the number of ships required for bunkering, and thus affect fixed and variable costs. Hence, we conduct several groups of sensitivity analysis to consider various bunker rates. First, we consider the case represented in Table 2.

First, we examine the effect of the bunker rate on the optimal number of ships to purchase for LNG fuel bunkering by increasing the bunker rate from $750m^3/h$ to 950 m^3/h. The detailed outputs of the decision variables are given in Appendix A. The results in Fig. 2 indicate that the optimal number of ships to purchase decreases from four to three when the bunker rate increases from $750m^3/h$ to 800 m^3/h. Further, the optimal number of ships to purchase remains three when the bunker rate increases from 800 m^3/h to 950 m^3/h, indicating that the least number of ships that should be purchased for bunkering LNG fuel is three.

Next, we increased the bunker rate from 750 m^3/h to 950 m^3/h to examine the effect of bunker rate on the total cost. As discussed, the bunker rate of ships is 750 m^3/h, and the maximum bunker rate is 1,000 m^3/h. From the results in Fig. 3, two main conclusions can be reached. First, the total cost decreases as the bunker rate increases because bunkering time decreases. Second, the total cost decreases as the bunker rate increases from $750m\ ^3/h$ to 800 m^3/h largely because fewer ships are purchased, decreasing the total cost from 6,880 USD to 6,010 USD.

5. Conclusion and future research

LNG, a form of natural gas, is a promising substitution of traditional fossil fuel in maritime transportation as it can reduce the environmental impacts from shipping activities. There are three common LNG bunkering methods: STS, TTS, and PTS. As each method has its own advantages and limitations, we develop an ILP model to identify the optimal LNG bunkering method for a given port. The results show that STS is the optimal method for the port. This result, together with the insights obtained, can be helpful for the government to build an LNG station for STS bunkering.

Then, we conduct sensitivity analyses on the bunker rate as it is influenced by the size of ships' fuel tanks and the demand for LNG fuel. By observing the number of purchased ships by increasing the bunker rate, we found that the optimal number of ships to purchase decreases from four to three when the bunker rate increases from $750m^3/h$ to 800 m^3/h. Further, the optimal number of ships to purchase remains three when the bunker rate increases from 800 m^3/h to 950 m^3/h, indicating that the least number of ships that should be purchased for bunkering LNG fuel is three. By observing the total cost changes with increasing bunker rates, we have two main conclusions. First, the total cost decreases as the bunker rate increases because bunkering time decreases. Second, the total cost decreases as the bunker rate increases from $750m\ ^3/h$ to 800 m^3/h largely because fewer ships are purchased, decreasing the total cost from 6,880 USD to 6,010 USD.

This study has some shortcomings. First, some of the data used in the numerical experiments are randomly generated, such as ship arrival and departure times and LNG bunkering volumes. Hence, future research could collect real data to derive more practical insights and conclusions. Moreover, we do not consider the case when there are two or more ships arriving at the port simultaneously (Cheaitou et al., 2021; Zisi et al., 2021; Wu et al., 2022b), which would result in some ships waiting for bunkering. Thus, future research could consider a more complex situation by adding ship waiting time to the ILP model. Second, in this study we do not consider probability distribution of ships arrival, which is an important characteristic of ship visits. Future research could take the distribution into consideration (Long and Qi, 2014; Hall et al., 2015; Conejo et al., 2021) and use game theory to solve the new problem. Third, we do not consider competitions between ports for bunkering services. Hence, such competition could be considered in future research (He at al., 2022; Liu et al., 2022; Zhang et al., 2022).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study is supported by the Research Grants Council of the Hong Kong Special Administrative Region, China (Project Number 15202019).

Appendix A. Outputs of the decision variables in sensitivity analysis

Table A1: The results of decision variables (Bunker Rate: $750m^3$).

Ship NO.	y_{wT}	y_{wS}	y_{wP}	x_{wT}	x_{wS}	τ_{w1}	τ_{w2}
1	0	1	0	0	2	15	18
2	0	1	0	0	2	4	7
3	0	1	0	0	2	21	22
4	0	1	0	0	2	1	4
5	0	1	0	0	1	17	23
6	0	1	0	0	2	13	15
7	0	1	0	0	1	9	12
8	0	1	0	0	2	2	5
9	0	1	0	0	1	9	12
10	0	1	0	0	2	6	8

Table A2: The results of decision variables (Bunker Rate: $800m^3$).

Ship NO.	y_{wT}	y_{wS}	y_{wP}	x_{wT}	x_{wS}	τ_{w1}	τ_{w2}
1	0	1	0	0	2	15	18
2	0	1	0	0	2	4	6
3	0	1	0	0	2	13	14
4	0	1	0	0	2	1	4
5	0	1	0	0	1	18	23
6	0	1	0	0	1	12	16
7	0	1	0	0	1	7	10
8	0	1	0	0	1	1	7
9	0	1	0	0	1	9	12
10	0	1	0	0	2	6	8

Table A3: The results of decision variables (Bunker Rate: $850m^3$).

Ship NO.	y_{wT}	y_{wS}	y_{wP}	x_{wT}	x_{wS}	τ_{w1}	τ_{w2}
1	0	1	0	0	2	15	18
2	0	1	0	0	2	4	6
3	0	1	0	0	2	13	14
4	0	1	0	0	2	1	4
5	0	1	0	0	1	18	23
6	0	1	0	0	1	12	16
7	0	1	0	0	1	7	10
8	0	1	0	0	1	1	7
9	0	1	0	0	1	9	12
10	0	1	0	0	2	6	8

Table A4: The results of decision variables (Bunker Rate: $900m^3$).

Ship NO.	y_{wT}	y_{wS}	y_{wP}	x_{wT}	x_{wS}	τ_{w1}	τ_{w2}
1	0	1	0	0	2	15	18
2	0	1	0	0	2	6	8
3	0	1	0	0	2	20	21
4	0	1	0	0	1	1	6
5	0	1	0	0	1	12	17
6	0	1	0	0	1	10	13
7	0	1	0	0	1	11	14
8	0	1	0	0	1	1	6
9	0	1	0	0	1	9	12
10	0	1	0	0	1	3	6

Table A5: The results of decision variables (Bunker Rate: $950m^3$).

Ship NO.	y_{wT}	y_{wS}	y_{wP}	x_{wT}	x_{wS}	τ_{w1}	τ_{w2}
1	0	1	0	0	2	15	18
2	0	1	0	0	2	6	8
3	0	1	0	0	2	13	14
4	0	1	0	0	1	1	6
5	0	1	0	0	2	21	23
6	0	1	0	0	1	13	16
7	0	1	0	0	1	1	4
8	0	1	0	0	1	1	6
9	0	1	0	0	1	8	11
10	0	1	0	0	1	5	8

From Tables A1–A5, the value of decision variable y_{wS} is 1 and the value of decision variables y_{wT} and y_{wP} is 0, which means that STS of ships using LNG is the optimal bunker mode. In this study, the objective function is to minimize the total cost, which indicate that the optimal solution can help us to obtain the minimum cost by using STS mode. The number of trucks to bunker ships (x_{wT}) is 0 because bunker mode TTS is not selected in the study. The number of ships to bunker a ship (x_{wS}) decreases slightly when the bunker rate increases from $750m^3$ to $950m^3$. For example, x_{wS} of ship 10 decrease from 2 to 1 when the bunker rate increases from $850m^3$ to $900m^3$. This indicates that the demand volume of the ships can be quickly satisfied by increasing the bunker rate. τ_{w1} and τ_{w2} are the start bunkering time and the end bunkering time. τ_{w1} and τ_{w2} are decided by the bunker rate and the number of ships for ship bunkering. The time interval is long when the number of ships for ship bunkering decreases from 2 to 1. For example, the time interval of ship 4 is 3 hours when x_{wS} is 2 in Table A1. The time interval of ship 5 is 5 hours when x_{wS} is 1. The time interval between τ_{w1} and τ_{w2} is shorter when bunker rate increases. For example, the time interval is 3 hours in ship 2 as shown in Table A1 when the bunker rate is $750m^3$. The time interval is 2 hours in ship 2 of Table 1 when the bunker rate is $800m^3$

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