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Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective

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A B S T R A C T

Using ammonia as an alternative marine fuel has been gaining interest in reducing greenhouse gas emissions in the maritime sector. This paper describes the development of a discrete event simulation model for bunker supply chain, emphasising how ammonia bunkering affects the operational and economic performance of the system. The results show that the model is a useful tool for ammonia bunker supply chain management, including the selection of the number and capacity of ammonia bunker supply vessels, bunkering flow rate and ammonia demand. Flow rate has a significant impact on bunkering service time, with an effect of up to 51.3% when it is changed by ±50%. The greater the demand for ammonia, the more significant the impact of ammonia bunkering flow rate on bunkering service time. Moreover, the number of ammonia bunker supply vessels is the most sensitive parameter for annual operational cost, with an effect of up to 15.2%.

1. Introduction

Maritime transportation plays a crucial role in international trade and the global economy, where over 80% of international trade by volume is carried by sea (UNCTAD, 2020). Bunker, also called marine fuel, is the fuel supplied to a vessel for its propulsion and operation, and bunkering operation is the bunker delivery from a bunkering supply facility to a vessel (Lam et al., 2011). The annual bunker consumption of fossil-based carbonaceous fuels in global shipping was 339 million tonnes, and it was responsible for greenhouse gas (GHG) emissions of 1,076 million tonnes, accounting for 2.9% of global anthropogenic GHG emissions in 2018 (IMO, 2020). Considering the important role of maritime transportation in dealing with climate change issues, International Maritime Organization (IMO) has adopted a structured plan, known as IMO 2050, to set a target to reduce total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008 (IMO, 2018). As part of the IMO's strategy, the Carbon Intensity Indicator was adopted at the 75th session of the Marine Environment Protection Committee to drive the maritime industry towards carbon intensity reduction (Wu et al., 2022). Moreover, EU lawmakers and negotiators have agreed to add the shipping industry to the EU Emissions Trading System, forcing vessels to pay for their carbon dioxide, methane and nitrogen dioxide emissions. Shipping companies will be required to buy carbon permits to cover at least 40% of their emissions from 2024, rising to 70% in 2025 and 100% in 2026 (European Council and Council of the European Union, 2022). Therefore, there is a strong need to change maritime energy from current fossil-based fuels to low-carbon or carbon-free alternatives, such as liquefied natural gas, biofuel, methanol, ammonia and hydrogen (Al-

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Enazi et al., 2021). Among these alternatives, green ammonia and hydrogen as carbon-free fuels have attracted much attention to achieve the ambitious emission reduction target (Gore et al., 2022).

Compared to hydrogen, there are several advantages of using ammonia as a bunker fuel. Firstly, the energy density of liquid ammonia is 70% more than liquid hydrogen at a refrigerated temperature or three times more than pressured liquid hydrogen at a pressure of 70 MPa (Valera-Medina et al., 2018). For the same energy content, ammonia requires less storage space, resulting in fewer impacts on the current cargo storage capacity (McKinlay et al., 2020). Ammonia tanks onboard also provide cheap bulk storage options (Bicer & Dincer, 2018). As a result, ammonia is better than hydrogen in energy storage. Secondly, unlike typical ambient liquid fuels, such as diesel and biofuel, both ammonia and hydrogen rely on refrigeration or pressurisation to maintain the liquid phase. Ammonia becomes liquefied under −33°C at one atmospheric pressure or standard room temperature at around 10 bar pressure (MacFarlane et al., 2020). Compared to hydrogen, it requires less energy to be liquefied (Al-Aboosi et al., 2021). The ease of ammonia production and its established storage and transportation infrastructure present another advantage (Zincir, 2022). In contrast, the challenges in hydrogen supply infrastructure and the cost of production and distribution are drawbacks of its implementation (Van Hoecke et al., 2021). Thirdly, fuel cells are mostly used in passenger ships with a much higher cost and a lower lifetime, while combustion engines have been used for various types of vessels for decades (Van Hoecke et al., 2021). In terms of fuels utilised in different energy converters, such as fuel cells, combustion engines or gas turbines, ammonia can be applied to these types with fewer modifications, while hydrogen is mainly associated with fuel cells to achieve good efficiency and safety (Valera-Medina et al., 2018; Dimitriou & Javaid, 2020; Chen & Lam, 2022). From an economic point of view, ammonia is a better choice for maritime stakeholders, especially utilised as a bunker fuel for ocean-going vessels. Furthermore, safety and regulatory barriers influence the deployment of ammonia and hydrogen (Christodoulou and Cullinane, 2022). Ammonia can be handled more safely when fire or explosion is critical onboard, as the flammability of ammonia is lower than common hydrocarbon fuels (Bicer & Dincer, 2018).

When ammonia is used as a bunker fuel, the supply chain involves production, storage, transportation, bunkering and bunker consumption. Ammonia can be synthesised by Haber-Bosch, electrochemical or thermochemical processes with hydrogen produced from natural gas, coal, fuel oil or water electrolysis and nitrogen separated from the air (Soloveichik, 2019). 80% of global ammonia production is used in the production of fertilisers, and only 1% is utilised for energy-related purposes (Yara, 2018; Patonia & Poudineh, 2020). In terms of storage and transportation, the relevant network is well established when ammonia is treated as cargo (Valera-Medina et al., 2021). From the ammonia bunker supply perspective, the availability of ammonia for the maritime sector is currently low, especially the green ammonia produced from renewable feedstocks with renewable electricity (MacFarlane et al., 2020).

Ammonia in the maritime sector is typically treated as cargo other than fuel. It can be cracked to liberate hydrogen, which is fed into a fuel cell to generate electricity (Giddey et al., 2017). Ammonia can also be used directly in marine engines and fuel cells with increased efficiency since it does not require decomposition into hydrogen and subsequent purification (Dolan et al., 2021; Morlanés et al., 2021). Moreover, ammonia as a bunker fuel is applicable to many types of vessels, and ammonia carriers can be suited as the first type of vessel to be powered by ammonia (de Vries et al., 2020). The International Association of Classification Societies proposed several provisional guidelines for designing ammonia fuelled ships and ammonia bunkering operations (ABS, 2021; DNV, 2020; KR, 2021; LR, 2020). From the ammonia bunker demand perspective, ammonia fuelled vessel requires more volume (1.6–2.3 times) than conventional marine fuel oil (MFO) fuelled vessels (Kim et al., 2020). Furthermore, the utilisation of ammonia as a dual fuel in marine engines can decrease total GHG emissions (Bicer & Dincer, 2018). For a ship's voyage powered by dual fuels, the proportion of energy provided by ammonia is not determined, and it will influence ammonia bunker demand dynamics. Therefore, it is a timely manner to study the supply and demand dynamics of ammonia bunker, and the dynamics of ammonia bunkering is one of the crucial parts.

However, there are no established bunkering facilities or infrastructure to supply ammonia as a bunker fuel. In terms of bunkering-related studies, most of them focused on bunker consumption and management (Yao et al., 2012; Wang et al., 2013; Wang & Meng, 2015) and bunkering services (Lam et al., 2011; Wang et al., 2014). Ammonia bunkering needs more effort to be investigated, although there are several industrial projects on ammonia bunkering at a strategic planning level (Maersk, 2021; ITOCHU Corporation, 2021; The Maritime Executive, 2022). To our knowledge, no published literature has reported the supply and demand dynamics of ammonia bunkering and the corresponding impacts on supply chain system performance. Therefore, there is a strong need to develop a model to quantitatively evaluate the system performance of bunker supply chain considering the supply and demand dynamics of ammonia bunkering.

To fill these research gaps, this study aims to evaluate how ammonia bunkering affects the system performance of bunker supply chain from bunkering supply and demand perspectives. For supply chain management research, simulation types include spreadsheet simulation, system dynamics, business games and discrete event system simulation (Kleijnen & Smits, 2003). This study views the ammonia bunker supply chain as a discrete event system and develops a simulation model to investigate system performance from operational and economic aspects. The simulation study makes it possible to explain the dynamics and variables that characterise the bunker supply chain.

The rest of this paper is organised as follows. Section 2 describes a discrete event simulation model for ammonia ship-to-ship bunkering operation and presents the difference between MFO bunkering and ammonia bunkering. In addition, the estimation of the system performance measures for a comprehensive analysis of ammonia bunkering is proposed in Section 2. To demonstrate the simulation model, a case study of MFO bunkering, ammonia bunkering and ammonia-MFO dual fuel bunkering for a bunker supplier in Singapore is conducted in Section 3. Subsequently, Section 4 describes the results, discussion and implications obtained from the case study. Finally, Section 5 provides several conclusions with main contributions.

2. Method

This section presents the proposed method for the estimation of bunker supply chain system performance. As shown in Fig. 1, bunkering activities of a bunker supply vessel are identified first. Then, a bunker supply chain flow chart is created, and a simulation model is built. Subsequently, a bunker supply chain simulation model with MFO bunkering is established as the baseline scenario. It is validated by actual bunkering operation records. By considering various ammonia bunkering supply and demand scenarios, different kinds of what-if analyses are developed, including MFO bunkering, ammonia-MFO dual fuel bunkering and ammonia bunkering. Finally, the system performance is calculated by analysing bunkering service time per operation and annual operational cost for a bunker supplier.

2.1. Simulation model

2.1.1. Model development

Bunker supply chain is a complex system with different stakeholders, various processes, dynamics, the uncertainty of information and ammonia bunker flows. As shown in Fig. 2, bunker producers, bunker suppliers and ship owners are involved in the inbound and outbound logistics of the bunker supply chain. Bunker suppliers play a vital role in the bunker supply chain, participating in both bunker loading process and bunkering operation process. Hence, it is crucial to focus on the bunker suppliers for the feasibility study of ammonia bunkering. Moreover, the current bunkering methods for commercial use include ship-to-ship bunkering, truck-to-ship bunkering and terminal pipeline-to-ship bunkering. Among these bunkering modes, ship-to-ship bunkering is the most common method of delivering marine fuels to ships (Draffin, 2010). Therefore, in the development of a bunker supply chain simulation model, this study focuses on the system performance of ammonia ship-to-ship bunkering operation for a bunker supplier. In addition, when comparing the impact of ammonia bunkering on the bunker supply chain, the energy demand for a bunker receiving vessel is assumed to be constant. Hence, bunker fuel consumption management and vessel routes are outside the research scope of this study.

The first step in developing a simulation model is to identify the simulation procedures, assumptions, input and expected output information (Cao & Lam, 2018). As shown in Fig. 3, the simulation starts with bunker supply and receiving vessels' arrival and ends with the departure. Once the bunker supply vessel and receiving vessel are available for bunkering operation, an entity of "bunker receiving vessel" goes through the procedures of mooring alongside, preparing documentation, connecting hose, starting pumping, completing pumping, disconnecting hose and completing documentation in sequence (Draffin, 2010). The simulation of bunkering operation is carried out in the Arena SIMAN Rockwell package, which facilitates modelling bunker cargo tanks, control logic, discrete event bunkering steps and continuous bunker flow between bunker supply vessels and receiving vessels.

The "Tank" module in Arena represents a holding area where the bunker is stored in a bunker supply vessel and defines the regulators that control flow out of the holding area. Receiving vessel arrival is implemented by the "Create" module in Arena. In the real bunkering operation, the schedule of receiving vessel arrival is fixed. After the "bunker receiving vessel" entity is generated, the availability of bunkering operation is checked in the "Decide" module. If the bunker supply vessel inventory is available for bunkering operation, bunker receiving vessel will seize the cargo tank of the bunker supply vessel by the "Seize Regulator" module. If the bunkering operation is not available, the receiving vessel will be waiting for the preparation, and the bunker supply vessel will carry out loading operation at an oil storage terminal.

Then, the bunkering starting time will be assigned in the "Assign" module. Once the bunker supply vessel completes mooring alongside the receiving vessel, the pre-delivery conference will be conducted between the representatives of the bunker supply vessel and receiving vessel. Several documents need to be prepared, such as the bunker requisition form, bunkering pre-delivery safety checklist, mass flow metering system seals checklist and meter reading record form, etc. Then, the process of hose connection will begin, and representatives will inspect the sampling equipment and take custody transfer samples at the manifold of the receiving vessel. In this simulation model, the mooring alongside, preparing documentation and connecting hose processes are set in the "Delay" module.

From starting pumping to completing pumping, the receiving vessel will ensure the agreed pumping rate is adhered to by the bunker supply vessel within the safe operating practice. The pumping rate, also called flow rate, depends on the hose dimension, the tank size and the height of the freeboard of bunker receiving vessel, etc. The pumping process is a continuous process. In this study, the pumping rate is assigned in the "Assign" module. Then, the cargo tank, as the regulator, is monitored output from the bunker supply vessel, and the maximum flow rate can be adjusted by the "Regulate" module. Pumping time is obtained as the difference between the

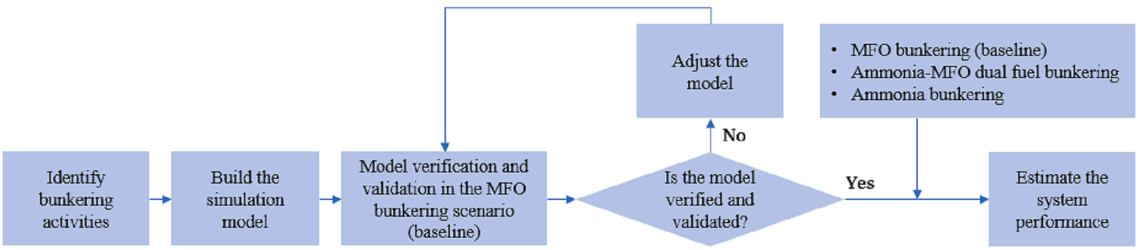

Fig. 1. Research flow to develop and analyse the scenarios. Source: Authors.

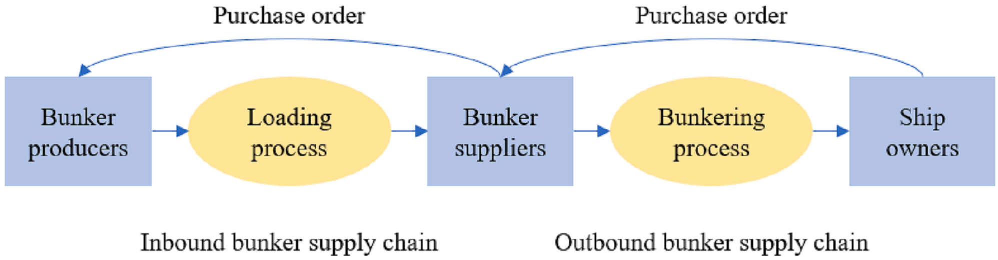

Fig. 2. Inbound and outbound bunker supply chain. Source: Authors.

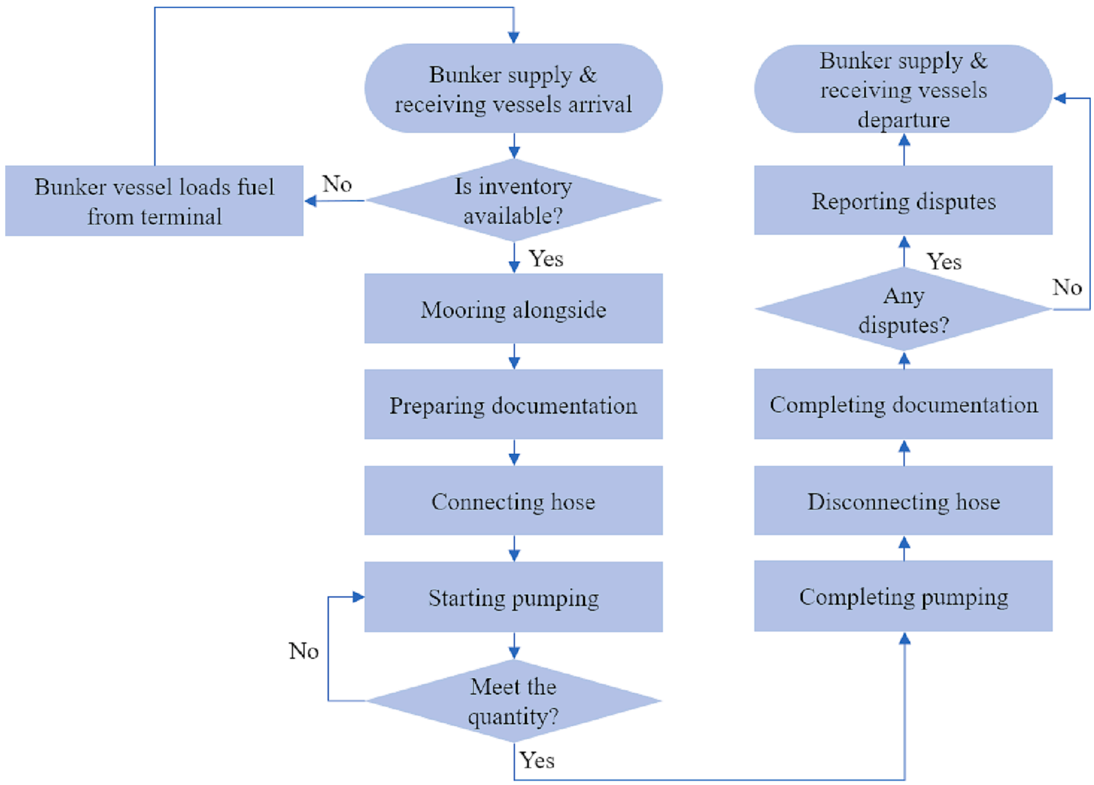

Fig. 3. Bunker supply chain simulation flow chart. Source: Authors.

start to the end of the pumping, and it is presented by the “Flow” module.

After completing pumping, crews or cargo officer will disconnect hose and complete documentation, which are implemented by the “Delay” module. In real situations, there may be some disputes on bunker quality or bunker quantity. The probability of disputes is set in the “Decide” module. A cargo officer and a chief engineer will settle disputes onboard and submit the claims and reports. Then, the bunker receiving vessel will release bunker tank by the “Release Regulator” module. Finally, the bunker supply vessel will cast off and be departure, which is set in the “Dispose” module. The statistical distributions of inputs are obtained through the function of “Input Analyser” in Arena and set in the “Assign” module. Furthermore, “Record” module in Arena is used to record default and customised outputs. In this study, bunkering service time per operation, the number of bunkering operations and the number of disputes are identified as outputs of the simulation model. The input and output parameters are summarised in Table 1.

2.1.2. Model verification and validation

For simulation study, model verification is to determine whether the assumptions are correctly translated into the computer program and ensure the model behaves as intended, while model validation is to ensure the simulation model accurately represents the system (Kelton, 2002). This study uses “step” feature and introduces a single entity into the system for debugging to verify whether the entity proceeds according to the model logic. The single entity goes through each module in sequence without any pauses and error messages, and it disappears in the “Dispose” module finally. The result of the check shows that the model follows the logic. Therefore, the simulation model runs as expected. For model validation, we compare the model outputs with the actual bunkering service time per

Table 1
Inputs and expected outputs of bunker supply chain simulation model.

Category		Parameter
Inputs	Bunker supply vessel	Number of bunker supply vessels Capacity of a bunker supply vessel Flow rate Loading time
	Bunker receiving vessel	Time between arrivals Bunker volume
	Bunkering information	Process time of mooring alongside Process time of preparing documentation Process time of connecting hose Process time of disconnecting hose Process time of completing documentation Percentage of disputes Process time of reporting disputes
Outputs	Bunker supply vessel	Bunkering service time per operation Number of bunkering operations Number of disputes

Source: Authors.

operation. A valid model should exhibit a good match of inputs and outputs with the real system. This study sets an initial replication number and adjusts it by Equation (1), where n_0 is the initial replication number, h_0 is the half-width of the results obtained from n_0 replications, and h is the ideal half-width (Kelton, 2002).

$$n \cong n_0 \frac{h_0^2}{h^2} \tag{1}$$

2.2. Bunkering of marine fuel oil and ammonia

In this study, the bunkering demand includes pure MFO bunkering, ammonia and MFO dual fuel bunkering and pure ammonia bunkering. Considering there are no existing ammonia bunkering operation and regulated standards, we use existing MFO bunkering experience as a reference for conducting the simulations of ammonia bunkering and dual fuel bunkering. It is assumed that the energy demand for a bunker receiving vessel keeps constant. In the dual fuel bunkering condition, the MFO bunkering and ammonia bunkering operations are considered in series.

It is worth noting that ammonia characteristics, such as toxicity and corrosion, will influence ammonia bunkering procedures. The features of saturated liquid should be considered because the ammonia bunkering process is to refill anhydrous ammonia as a saturated liquid. Hence, this paper highlights the key differences between MFO bunkering and ammonia bunkering. Firstly, based on the fuel properties, ammonia is toxic and corrosive (de Vries, 2019). The main risks of using ammonia as a bunker fuel are the corrosion and the toxicity of ammonia exposure to humans, aquatic life and the environment (de Vries, 2019; Valera-Medina et al., 2021). Inerting nitrogen gas into hoses and pipelines is recommended to eliminate the presence of moisture and oxygen to prevent stress corrosion cracking (Gezerman, 2016). After that, the remaining system is purged with ammonia vapour to remove the remaining nitrogen. Inerting and purging processes are additional operations that differ from the MFO bunkering (MESD, 2022).

Secondly, unlike conventional liquid marine fuels such as diesel or residual oil, anhydrous ammonia is a saturated liquid which relies on refrigeration or pressure to maintain the liquid phase (Elishav et al., 2021). Boil-off gas (BOG) or flash gas will be generated when the temperature increases or the pressure decreases. Compared to MFO stored onboard for propulsion, it requires BOG management system, ammonia vapour return line and ventilation system to maintain the pressure in the ammonia fuel tank (Al-Breiki & Bicer, 2020; Kim et al., 2020; Seo & Han, 2021). Moreover, the maximum capacity of ammonia to be used as fuel is 94% of the total tank capacity because the maximum filling limit at the supply port is 98% to prevent overpressure, and a heel remaining in the tank is 4% (Salmon et al., 2021).

Thirdly, to provide the same amount of energy based on a lower heating value (LHV), ammonia fuelled vessel requires more volume because the energy density LHV of MFO is 40.4 MJ/kg, and liquid ammonia is 18.6 MJ/kg (de Vries, 2019). When switching from MFO to ammonia bunkering, the flow rate needs to be adjusted to maintain the bunkering schedule. Furthermore, an after-treatment system is required to reduce NOx emissions when ammonia is used as a compression-ignition fuel (Dimitriou & Javaid, 2020; Morlanés et al., 2021). In summary, these key differences between MFO and ammonia bunkering will influence the system performance of bunker supply chain.

2.3. System performance measures

The previous sections describe a model to simulate bunker supply chain considering MFO and ammonia bunkering for a bunker supplier. This section discusses the measures that are used to characterise the system performance of bunker supply chain, including bunkering service time per operation and annual operational cost.

2.3.1. Bunkering service time

The selection of a bunkering port is a multi-criteria decision problem with relevant key performance factors (Wang et al., 2014). The average bunkering service time, mean waiting time, bunker barge usage and berth utilisation efficiency are important performance factors for evaluating bunkering services (Chang & Chen, 2006). From the bunker supply point of view, supply waiting time is also one of the important factors affecting bunkering competitiveness (Acosta et al., 2011). In terms of the bunker demand, Aronietis et al. (2017) studied the bunkering determinants and found that the level of trustworthiness in terms of correct bunker quality and quantity affects the competition between different bunker suppliers. Tuljak-Suban (2019) summarised the literature factors affecting bunkering performance and listed the efficiency of bunker supply and supply waiting time as important factors. In this study, bunkering service time is chosen as one of the measures to evaluate the bunker supply chain performance. In addition, bunkering service time per operation is one of the outputs of the simulation model, which is the time from bunker supply vessel arrival to the departure.

2.3.2. Annual operational cost

All the systems and equipment are assumed to be ready for ammonia bunkering operation. The capital expenditure of new systems and equipment is excluded from this study. As presented in Section 2.1, inbound and outbound logistics in the bunker supply chain represent the bunker supply vessel loading process and bunkering operation process, respectively. Hence, the components of annual operational cost for a bunker supplier consider bunkering and loading operations as well as MFO and ammonia bunker types, as shown in Fig. 4. The annual operational cost consists of four sub-costs, namely cost of MFO loading operation, cost of ammonia loading operation, cost of MFO bunkering operation and cost of ammonia bunkering operation, as shown in Equation (2). These four sub-costs are presented by Equations (3) to (6), respectively. The cost of MFO or ammonia loading process is represented by the bunker supply vessel charter fee during the loading process. The cost of MFO or ammonia bunkering operation consists of bunkering licence fee, port dues, charter fee and dispute cost. In this study, it is assumed that the charter fee includes bunker consumption cost of bunker supply vessel, maintenance cost, labour cost and insurance. Besides, the dispute cost is settled at 50% of the disputed bunker fuel cost based on the experience of the bunkering industry. In summary, the annual operational cost for a bunker supplier is estimated as the sum of inbound and outbound bunker supply chain costs, as shown in Equations (2) to (6). The explanation of the variables is shown in Table 2.

$$C = C_L^M + C_L^A + C_B^M + C_B^A \tag{2}$$

$$C_L^M = \sum_{a=1}^{A} \sum_{i=1}^{I} (t_L^M)_{ai} \times (C_C^M)_a \tag{3}$$

$$C_L^A = \sum_{b=1}^{B} \sum_{j=1}^{J} (t_L^A)_{bj} \times (C_C^A)_b \tag{4}$$

$$C_B^M = \sum_{a=1}^{A} [(C_{licence}^M)_a + (C_{dues}^M)_a + \sum_{m=1}^{M} (t_B^M)_{am} \times (C_C^M)_a + 50\% \times \sum_{p=1}^{P} (v_{dispute}^M)_p \times (C_{fuel}^M)_a] \tag{5}$$

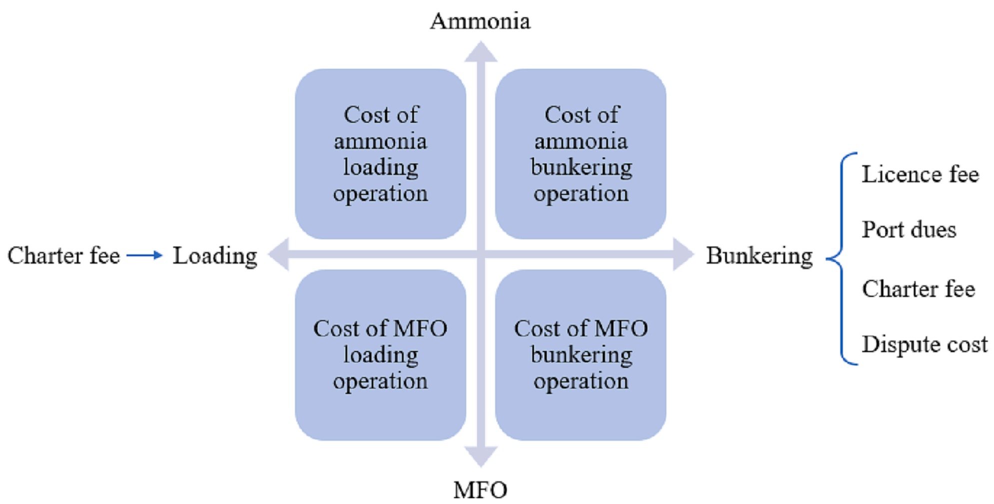

Fig. 4. Components of annual operational cost. Source: Authors.

Table 2
The explanation of variables in the calculation.

Variables	Description
A (a)	Number of MFO bunker supply vessel
B (b)	Number of ammonia bunker supply vessel
I (i)	Number of MFO loading operations per vessel
J (j)	Number of ammonia loading operations per vessel
M (m)	Number of MFO bunkering operations per vessel
N (n)	Number of ammonia bunkering operations per vessel
P (p)	Number of disputes during MFO bunkering per vessel
Q (q)	Number of disputes during ammonia bunkering per vessel
C	Annual operational cost
C_B^A	Cost of ammonia bunkering operation
C_B^M	Cost of MFO bunkering operation
C_C^A	Charter fee of an ammonia bunker supply vessel
C_C^M	Charter fee of an MFO bunker supply vessel
C_{dues}^A	Port dues of an ammonia bunker supply vessel
C_{dues}^M	Port dues of an MFO bunker supply vessel
C_{fuel}^A	Ammonia bunker fuel price
C_{fuel}^M	MFO bunker fuel price
$C_{licence}^A$	Licence fee of an ammonia bunker supply vessel
$C_{licence}^M$	Licence fee of an MFO bunker supply vessel
C_L^A	Cost of ammonia loading operation
C_L^M	Cost of MFO loading operation
t_B^A	Ammonia bunkering service time per operation per vessel
t_B^M	MFO bunkering service time per operation per vessel
t_L^A	Ammonia loading time per operation per vessel
t_L^M	MFO loading time per operation per vessel
$v_{dispute}^A$	Ammonia bunkering disputed volume per case
$v_{dispute}^M$	MFO bunkering disputed volume per case

Source: Authors.

$$C_B^A = \sum_{b=1}^{B}[(C_{licence}^A)_b + (C_{dues}^A)_b + \sum_{n=1}^{N}(t_B^A)_{bn} \times (C_C^A)_b + 50\% \times \sum_{q=1}^{Q}(v_{dispute}^A)_q \times (C_{fuel}^A)_b] \tag{6}$$

3. Case study

3.1. MFO bunkering scenario

Singapore is one of the largest bunkering ports, and it is selected as a potential ammonia bunkering port in this study. A bunker supplier is assumed to charter four bunker supply vessels based on the average number of bunker supply vessels of a bunker supplier in Singapore (MPA, 2021a). The operations of bunker supply vessels are assumed to be a rolling 24 h/365 days operation. The actual bunkering operation time log records are based on the interviews of bunker suppliers. The probability distributions for each input are obtained by the “best fit” function with the lowest square error in the “Input Analyser” of Arena (Kelton, 2002). The distribution expressions of operational parameter inputs are shown in Table 3.

Table 3
Operational parameters for MFO bunkering.

Parameter	Expression/ Value	Unit
Number of bunker supply vessels	4	
Capacity of a bunker supply vessel	6,000	tonnes
Flow rate	TRIA (200, 350, 500)	tonnes/hour
Loading time	18	hours
Time between arrivals of bunker receiving vessels	TRIA (6, 10, 14)	hours
Bunker volume of a receiving vessel	TRIA (500, 1,200, 2,000)	tonnes
Process time of mooring alongside	0.52 + LOGN (1.03, 0.616)	hours
Process time of preparing documentation	LOGN (0.304, 0.195)	hours
Process time of connecting hose	NORM (0.741, 0.244)	hours
Process time of disconnecting hose	0.15 + 2.13 * BETA (1.79, 1.77)	hours
Process time of completing documentation	NORM (0.539, 0.107)	hours
Percentage of disputes	5%	
Process time of reporting disputes	TRIA (0.5, 1, 3)	hours

Source: Compiled by authors based on the data from interviews of ship owners and data from MPA (2021a).

In this study, a validation approach is proposed to test the accuracy of the proposed model by comparing the simulated bunkering service time with the actual bunkering service time of MFO bunkering, as shown in Table 4. The differences between actual and simulated bunkering service time can be acceptable. Therefore, this model is valid and good for further analysis.

3.2. Determination of ammonia bunkering supply and demand scenarios

Ammonia bunkering and ammonia-MFO dual fuel bunkering scenarios are identified in four categories based on the dynamics of ammonia bunkering supply and demand, as shown in Table 5. The number of ammonia bunker supply vessels, the capacities, and flow rates are chosen as the bunkering supply parameters. In addition, the proportion of energy provided by ammonia and MFO in each bunker receiving vessel is selected as the bunkering demand parameter. After identifying these key parameters, the next step is to define the scopes and scales of these parameters and adjust the ranges for sensitivity analysis. In this study, the values of all selected parameters are adjusted with ± 50% ranges, as shown in supply scenarios S1 to S9 and demand scenarios D1 to D4 in Table 5.

For ammonia bunkering supply side, it is assumed that the bunker supplier's profile is not changed, and the supplier charters the same fleet size (4 bunker supply vessels). Two ammonia bunker supply vessels and two MFO bunker supply vessels are set as the general case. Moreover, the energy density LHV of MFO and liquid ammonia are 40.4 MJ/kg and 18.6 MJ/kg, respectively (de Vries, 2019). For MFO bunkering, the capacity of each MFO bunker supply vessel is 6,000 tonnes, and the flow rate is TRIA (200, 350, 500) tonnes per hour. Based on the equivalent energy density, the capacity of ammonia bunker supply vessel shall be 13,032 tonnes handysize tanker. By the same method, ammonia bunkering flow rate shall be TRIA (434, 760, 1,086) tonnes per hour.

For ammonia bunkering demand side, ammonia can be used as a dual fuel for bunker receiving vessels (Zamfirescu & Dincer, 2008; Bicer & Dincer, 2018). In this study, it is assumed that the energy demand for a bunker receiving vessel remains the same under the condition of ammonia bunkering and dual fuel bunkering. Considering the IMO 2050 target, we set the proportion of energy demand provided ammonia at 50%. To find the effect of the ammonia energy demand on the bunkering supply chain, we adjust its value with ±50% ranges. Therefore, the proportion of energy provided by ammonia in each receiving vessel is 25%, 50% and 75% for dual fuel bunkering and 100% for pure ammonia bunkering. At the same time, the proportion of energy provided by MFO in each vessel decreases from 75%, 50%, 25% to 0 to keep the same energy demand for a receiving vessel's voyage. Four different sets of ammonia bunkering demand can reflect different targets for GHG emissions reduction. As shown in Table 5, demand scenarios D1, D2 and D3 represent ammonia-MFO dual fuel bunkering. D4 represents a pure ammonia bunkering scenario, and the proportions of energy provided by ammonia and MFO are 0 and 100%, respectively. In addition, different proportions of energy provided by ammonia or MFO in each receiving vessel are indicated by bunker volume. For example, MFO bunker volume is TRIA (500, 1,200, 2,000) tonnes for pure MFO bunkering in the baseline scenario. Based on the equivalent energy density, ammonia bunker volume shall be TRIA (1,086, 2,606, 4,344) tonnes for pure ammonia bunkering. In summary, nine ammonia bunkering supply scenarios are proposed to meet the requirements of four ammonia bunkering demand scenarios. Therefore, there are 36 combinations of supply and demand scenarios for ammonia bunkering and ammonia-MFO dual fuel bunkering. In this situation, the bunkering service time of each receiving vessel is composed of ammonia bunkering service time and MFO bunkering service time.

Comparing MFO bunkering settings in Table 3, the discussion on ammonia bunkering settings is as follows. The ammonia storage terminal consists of storage tanks, loading arms and pumps to transfer ammonia to ammonia bunker vessel. It is assumed that ammonia terminal tanks are large enough for refilling ammonia bunker supply vessels, and these vessels do not wait at the ammonia storage terminal. In order to find out the impact of ammonia bunkering on bunkering supply chain, it is assumed that the ammonia loading time is the same as the MFO loading time, which is 18 h. As described in Section 2.2, purging and inerting operations are recommended for ammonia bunkering operations based on safety considerations. Based on the interview with experts in ammonia safety, it is assumed that the time of purging and inerting operation is 0.5 h. Hence, an additional 0.5 h would be in the process time of hose connection and disconnection for ammonia bunkering. Similar to MFO bunkering, the other process time will not be changed, such as the process time of bunker supply vessel mooring alongside, preparing documentation, completing documentation and reporting disputes.

3.3. Analysis of economic parameters

Table 6 lists the economic parameters used for MFO bunkering and ammonia bunkering. According to the tariffs and charges published in MPA (2021b), the bunkering licence fee is 150 SGD per year, and port dues for a bunker supply vessel is 100 SGD per year per 10 gross tonnages (GT). For a bunker supply vessel carrying 6,000 tonnes of MFO, the gross tonnage is assumed to be 5,972 based on the profile of a bunker supply vessel which currently operates in Singapore (Marine Traffic, 2021). According to the interviews with bunker suppliers, the charter fee is 350 USD per hour for a 6,000 tonnes bunker supply vessel. The charter fee of a small handysize ammonia carrier is estimated at 450 USD per hour (HELLENIC SHIPPING NEWS, 2021).

Table 4
Model validation.

Bunker volume (tonnes)	Flow Rate (tonnes/hour)	Actual Bunkering Service Time (hour)	Simulated Bunkering Service Time (hour)	Differences
855	239	8.5	8.1	4.7%
1,384	308	9.0	9.1	1.1%
2,000	348	9.8	10.2	4.1%

Table 5
Supply and demand scenarios of ammonia-MFO dual fuel bunkering.

		Ammonia	MFO
General Case	Number of bunker supply vessels	2	2
	Capacity of a bunker supply vessel	13,032 tonnes	6000 tonnes
	Flow rate	TRIA (434, 760, 1,086) tonnes/hour	TRIA (200, 350, 500) tonnes/hour
Category 1: Number of bunker supply vessels	**Scenario**	**Ammonia**	**MFO**
	S1	1	3
	S2	2	2
	S3	3	1
Category 2: Capacity of a bunker supply vessel	**Scenario**	**Ammonia (tonnes)**	**MFO (tonnes)**
	S4	7,000	6,000
	S5	14,000	6,000
	S6	21,000	6,000
Category 3: Flow rate	**Scenario**	**Ammonia (tonnes/hour)**	**MFO (tonnes/hour)**
	S7	TRIA (350, 400, 450)	TRIA (200, 350, 500)
	S8	TRIA (700, 800, 900)	TRIA (200, 350, 500)
	S9	TRIA (1,050, 1,200, 1,350)	TRIA (200, 350, 500)
Category 4: Proportion of energy demand per vessel	**Scenario**	**Ammonia**	**MFO**
	D1	25% (Volume: TRIA (272, 652, 1,086) tonnes)	75% (Volume: TRIA (375, 900, 1,500) tonnes)
	D2	50% (Volume: TRIA (543, 1,303, 2,172) tonnes)	50% (Volume: TRIA (250, 600, 1,000) tonnes)
	D3	75% (Volume: TRIA (815, 1,955, 3,258) tonnes)	25% (Volume: TRIA (125, 300, 500) tonnes)
	D4	100% (Volume: TRIA (1,086, 2,606, 4,344) tonnes)	0

Source: Authors based on industry practice.

Table 6
Economic parameters for MFO bunkering and ammonia bunkering.

Parameters	MFO bunkering	Ammonia Bunkering	Source
Bunkering licence fee	150 SGD/year/vessel	150 SGD/year/vessel	MPA (2021b)
Port dues	100 SGD/year/vessel/10 GT	100 SGD/year/vessel/10 GT	MPA (2021b)
Charter fee	350 USD/vessel/hour (6000 MT bunker supply vessel)	450 USD/vessel/hour (Handysize ammonia carrier)	Interviews of bunker suppliers, HELLENIC SHIPPING NEWS (2021)
Bunker price	451 USD/tonne	300 USD/tonne	Ship & Bunker (2021), MacFarlane et al. (2020)
Disputed bunker volume	15 tonnes	33 tonnes	Interviews of bunker suppliers

Furthermore, MFO bunker price is 451 USD per tonne based on the average Mean of Platts Singapore price in 2021. Ammonia bunker price is assumed to be 300 USD per tonne in this study (MacFarlane et al., 2020). Additionally, bunker shortage tolerance is 1% to 1.5% of bunker volume based on the experience of the bunkering industry, and the disputed bunker volume is assumed to be 15 tonnes per dispute settlement. Based on the equivalent energy density, the disputed ammonia volume is assumed to be 33 tonnes per dispute settlement. US dollars to Singapore dollars exchange rate is set to 1.345 (MAS, 2021).

4. Results and discussion

Before running a model, the warm-up period and replication length should be specified. Start-up bias is one of the common issues in simulation models. If the simulation model starts empty and idle but the bunkering system does not, the statistics for the model run will be biased. The warm-up period is the time necessary for the model to reach a steady state, and it is set to 1 day in this study.

Replication length defines the length of a single replication in a specified time unit, which was set to 30 days in this study to simulate MFO and ammonia bunkering operations. Furthermore, a larger replication number leads to a smaller half-width of the confidence interval on the sample mean (Kelton, 2002). Estimating by Equation (1) in Section 2.1.2, the number of replications is set to

50, and we get the average value for the outputs.

4.1. Bunkering service time

This study conducts the simulation of pure MFO bunkering for a bunker supplier who charters four bunker supply vessels, each with a capacity of 6,000 tonnes. The results show that the average bunkering service time for pure MFO bunkering is 7.3 h per operation, and the number of bunkering operations per year is 3,032 for a bunker supplier. In addition, there is no queue for the pure MFO bunkering scenario because the number and capacity of bunker vessels are sufficient to meet the requirement of current MFO bunker demand in Singapore. The simulation result of pure MFO bunkering is set as the baseline. After that, we analyse the bunkering service time of each ammonia-MFO dual fuel bunkering and pure ammonia bunkering under the conditions of different ammonia bunkering supply and demand scenarios, as shown in Fig. 5.

A sensitivity analysis is performed to investigate the effect of the number of ammonia bunker supply vessels on bunkering service time, considering ammonia bunkering supply scenarios S1, S2, S3, and bunkering demand scenarios D1, D2, D3, and D4. For ammonia-MFO dual fuel bunkering, bunkering service time is more than that of pure MFO bunkering with a maximum difference of up to 6.2 h (84.9% difference), and this case happens in the S3&D1 scenario. For pure ammonia bunkering, the increase of bunkering service time is up to 1.5 h (20.5% difference) in the S1&D4 scenario. While chartering one ammonia bunker supply vessel (S1 scenario) does not meet ammonia demand (D1, D2, D3 & D4 scenarios) with up to 0.7 h of queue time for each ammonia bunker receiving vessel. The sensitivity result shows when the number of ammonia bunker supply vessels is changed by ± 50%, its effect on bunkering service time is up to 3.1% for dual fuel bunkering and 4.8% for pure ammonia bunkering.

The effect of the capacity of ammonia bunker supply vessels on bunkering service time is analysed by considering ammonia supply scenarios S4, S5, S6, and ammonia demand scenarios D1, D2, D3, and D4. For dual fuel bunkering, bunkering service time is more than

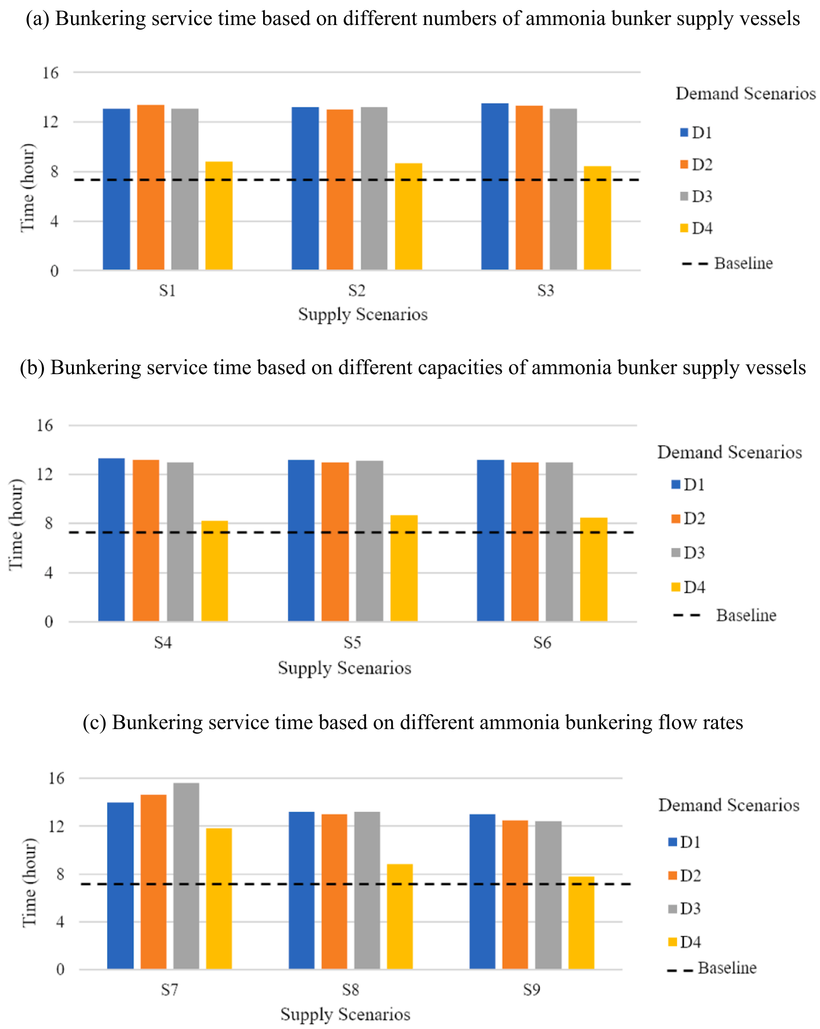

Fig. 5. Bunkering service time in different bunkering supply and demand scenarios.

that of pure MFO bunkering, with a maximum difference of up to 6.0 h (82.2% differences) in the S4&D1 scenario. For pure ammonia bunkering, the increase in bunkering service time is 1.4 h (19.2% difference) in the S5&D4 scenario. In addition, when the capacity of ammonia bunker supply tankers is changed by ± 50%, there is up to 1.5% change in bunkering service time for dual fuel bunkering and 6.1% change in bunkering service time for pure ammonia bunkering.

Subsequently, this study conducts research on the effect of the ammonia bunkering flow rate on bunkering service time considering ammonia supply scenarios S7, S8, S9, and ammonia demand scenarios D1, D2, D3, and D4. The results show that ammonia-MFO dual fuel bunkering service time is more than pure MFO bunkering service time, with a difference of up to 8.3 h (113.7% difference) in the S7&D3 scenario. Compared to pure MFO bunkering service time, pure ammonia bunkering service time can increase by only 0.5 h in the S9&D4 scenario. The higher flow rate provides the potential for pure ammonia bunkering to maintain the same bunkering service time as MFO bunkering. Moreover, for each ammonia bunkering demand, the ammonia bunkering flow rate has a significant impact on bunkering service time. When the ammonia bunkering flow rate is changed by ± 50%, bunkering service time can vary by 25.8% for dual fuel bunkering and 51.3% for pure ammonia bunkering. The greater the demand for ammonia, the more significant the impact of ammonia bunkering flow rate on bunkering service time.

Furthermore, the effect of the proportion of energy provided by ammonia is evaluated. For each ammonia bunkering supply scenario, the changes in bunkering service time are from 32.2% to 66.7% considering demand scenarios D1, D2, D3, and D4. For pure ammonia bunkering, the increase in bunkering service time is 0.5 to 4.5 h (6.8% to 61.6% difference) compared to pure MFO bunkering. The results of the 36 supply and demand scenarios indicate that the bunkering service time of dual fuel bunkering is more than pure MFO bunkering or pure ammonia bunkering. The main reason is that bunker supplier is assumed to conduct dual fuel bunkering operations in series for scenarios D1-D3, rather than simultaneous bunkering operations.

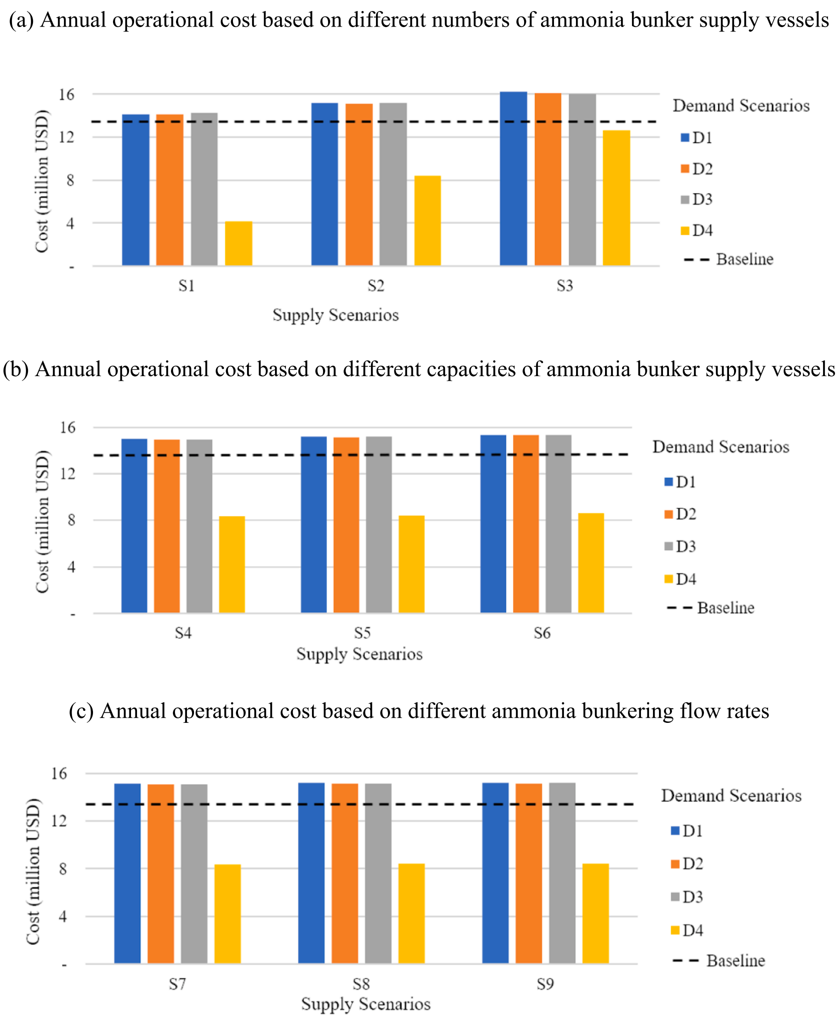

Fig. 6. Annual operational cost in different bunkering supply and demand scenarios.

4.2. Annual operational cost

For the pure MFO bunkering scenario, the simulation result shows that the annual operational cost for a bunker supplier is around 13.7 million USD. It is set as the baseline to evaluate the effects of bunkering supply and demand parameters on annual operational cost, as shown in Fig. 6. As described in Section 4.1, there is a queue when chartering one ammonia bunker supply vessel (supply scenario S1). Except for supply scenario S3, the ammonia-related subtotal cost is higher than MFO-related subtotal cost under each demand scenario (D1, D2, D3 and D4).

For the effect of the number of ammonia bunker supply vessels, annual operational cost of ammonia-MFO dual fuel bunkering increases by up to 19.1% compared with that of pure MFO bunkering. For pure ammonia bunkering, annual operational cost is lower than that of pure MFO bunkering in this case study. The results show that the number of ammonia bunker supply vessels has a significant impact on annual operational cost, especially when the receiving vessel is powered entirely by ammonia. When the number of ammonia bunker supply vessels is changed by ± 50%, there is up to a 15.2% change in annual operational cost in dual fuel bunkering scenarios. The lower demand for ammonia as a dual fuel, the greater the impact of the number of ammonia bunker supply vessels on annual operational cost.

This study also investigates the effect of the capacity of ammonia bunker supply vessels on annual operational cost. For ammonia-MFO dual fuel bunkering, annual operational cost increases by up to 12.3% compared with pure MFO bunkering. Meanwhile, for pure ammonia bunkering, the annual operational cost is much lower than that of pure MFO bunkering. The reason is that only two ammonia bunker supply vessels are chartered by a bunker supplier as the general case, and the annual charter cost of pure ammonia bunkering is much less than that of pure MFO bunkering. For each ammonia bunkering demand rising from 25% to 100%, the capacity of ammonia bunker supply tankers has little impact on annual operational cost. When the capacity of ammonia bunker supply vessel is changed by ± 50%, annual operational cost ranges from 2.1% to 3.1%. The reason is that the charter fee of different ammonia bunker capacities is assumed to be the same in this study. In addition, the higher demand for ammonia, the greater the impact of the capacity of ammonia bunker supply vessels on annual operational cost.

For the effect of ammonia bunkering flow rate, annual operational cost of ammonia-MFO dual fuel bunkering increases by up to 11.3% compared with pure MFO bunkering. While for pure ammonia bunkering, the annual operational cost is much lower than that of pure MFO bunkering since only two ammonia bunker supply vessels are chartered as the general case. For each ammonia bunkering demand, the impact of the ammonia bunkering flow rate on annual operational cost can be ignored because when the flow rate is changed by ± 50%, there is a 0.5% to 0.9% change in annual operational cost. Furthermore, from an ammonia bunkering demand perspective, the effect of the proportion of energy provided by ammonia on annual operational cost ranges from 28.8% to 239.1%.

4.3. Implications

The results above have several implications for the adoption of ammonia as a bunker fuel from operational, economic, technical and environmental perspectives. Firstly, this work conducts the simulation of different supply and demand scenarios of pure MFO bunkering, ammonia-MFO dual fuel bunkering and pure ammonia bunkering. It provides insightful knowledge for bunker suppliers to know the impacts of ammonia bunkering on bunkering supply chain, such as the bunkering service time for an operation, the number of operations per year and the number of dispute settlements. Considering the different needs of ship owners for ammonia bunker demand, bunker suppliers can choose the most suitable bunkering supply configuration in terms of operational feasibility. Secondly, from the economic perspective, the number of ammonia bunker supply vessels is the most sensitive parameter for annual operational cost, and it will be the most important factor when supplying ammonia as an alternative bunker fuel in future. The analysis of annual operational cost in ammonia-MFO dual fuel bunkering and pure ammonia bunkering scenarios will be helpful for bunker suppliers' business planning and investment.

Moreover, the results provide relevant implications to bunker suppliers and mass flow meter manufacturers that the flow rate significantly impacts bunkering service time, especially under the condition of a higher ammonia bunkering demand. In the future, the flow rate can be adjusted to improve ammonia bunkering efficiency by adding more bunker hoses or using larger hoses. This simulation model can also address this, which will help with the technical design of bunker hose and bunker supply system onboard. It is worth noting that the hose design shall also consider the engineering constraints onboard. In addition, bunkering service time is one of the most critical factors in determining the probability of the occurrence of leaks (Jeong et al., 2018). The bunkering service time obtained from this study can be used as a reference for risk assessment of ammonia release and mitigation measures. Therefore, the results and analysis in this study can be applied as a guide for bunker supplier decision-making.

Driven by the policy requirements on the environment, the shipping industry has considered ammonia as a marine fuel. This study is an important initial step to show the impacts of ammonia bunkering dynamics on the current supply chain. The novelty of this research is to identify the impact of ammonia bunkering supply allocation on the bunkering supply chain under different ammonia demand perspectives. The analysis of bunkering service time can help a port authority plan and manage port operations. Based on the impact of ammonia bunkering on bunker supply chain, port operators should explore cooperation models and investment risk sharing to formulate suitable policy solutions.

5. Conclusions

This study assesses the operational and economic impacts of ammonia bunkering on bunker supply chain by designing a discrete event simulation model. The model considers key activities of MFO and ammonia bunkering in bunker inbound and outbound supply chain. For ammonia bunkering and ammonia-MFO dual fuel bunkering scenarios, the key parameters from bunkering supply and demand perspectives are discussed, including the number and capacity of ammonia bunker supply vessels, ammonia bunkering flow rate, and the proportion of energy provided by ammonia in each bunker receiving vessel. By using the average profile of a bunker supplier in Singapore as an example, the bunkering service time and annual operational cost are obtained.

Through this study, we find that (1) The increase in bunkering service time compared with pure MFO bunkering is up to 113.7% for ammonia-MFO dual fuel bunkering, and up to 61.6% for pure ammonia bunkering; (2) Ammonia bunkering flow rate is the most sensitive parameter for bunkering service time, with an effect of up to 25.8% for ammonia-MFO dual fuel bunkering and 51.3% for pure ammonia bunkering when the flow rate is changed by $\pm$ 50%. The greater the demand for ammonia, the greater the impact of ammonia bunkering flow rate on bunkering service time; (3) The increase of annual operational cost for a bunker supplier is up to 19.1% under the condition of ammonia-MFO dual fuel bunkering. However, the annual operational cost of pure ammonia bunkering can be reduced when charting fewer ammonia bunker supply vessels; (4) The number of ammonia bunker supply vessels is the most sensitive parameter for annual operational cost. When it is changed by $\pm$ 50%, annual operational cost variability is as high as 15.2%. The lower demand for ammonia as a dual fuel, the greater the impact of the number of ammonia bunker supply vessels on annual operational cost.

This study contributes to both knowledge and practice. On the one hand, it contributes to the literature by narrowing the gaps in the ammonia bunker supply chain. It is the first time in the literature to compare MFO bunkering and ammonia bunkering system performance. Additionally, it is a pioneer in applying a discrete event simulation method in the study of ammonia bunkering supply chain considering different bunkering supply and demand scenarios, which can be served as the reference for ammonia bunkering disruption study. Furthermore, the bunkering industry will not be dominated by one alternative fuel but a combination of various fuels to achieve maritime decarbonisation (Hansson et al., 2020). This study is a pioneering feasibility study for ammonia-MFO dual fuel bunkering. The model can be applied to other alternative marine fuels, such as ammonia-methanol dual fuel bunkering, which will provide wider insights into maritime decarbonisation. On the other hand, this study contributes practical guidelines to the maritime industry and government. It provides ammonia planning guidelines for policy makers and stakeholders in the bunkering industry. The results and discussions on bunkering service time and annual operational cost can be useful references for bunker suppliers' decisions in terms of operational, economic and technical feasibility. The ammonia bunkering flow rate should be taken into attention to keep the bunkering efficiency and schedule. The discussions would help improve bunkering port competition when bunkering of different types of alternative fuels is required for the maritime industry. Subsequently, it also provides implications for governments to make policy adjustments, such as supply chain planning for alternative fuels.

There are still some limitations in this study. BOG management cost and social carbon cost are not considered in the model. Differences in bunkering time for different types of vessels were not discussed in this study. Future work could focus on refining the model to consider BOG management cost and carbon tax in more detail. The model can also be applied to physical ammonia bunkering scenarios to compare against the actual ammonia bunkering data and annual operational cost. Moreover, ammonia truck-to-ship bunkering and terminal pipeline-to-ship bunkering could be considered in the ammonia bunker supply chain model.

CRediT authorship contribution statement

Mengyao Yang: Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Jasmine Siu Lee Lam:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Project administration.

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.

Data availability

The data that has been used is confidential.

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