Governmental subsidy plan modeling and optimization for liquefied natural gas as fuel for maritime transportation

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Abstract

Environmental concerns are currently a major issue in the maritime transportation industry. A practical approach to implementing green maritime transportation is to adopt liquefied natural gas (LNG) as marine fuel. Government subsidies would efficiently stimulate the adoption of LNG in maritime transportation as marine fuel. However, the question of how to determine the appropriate amount of subsidies has not yet been investigated in depth. In this paper, a trilevel programming model is proposed to address the subsidy optimization problem. Decisions at the government, port, and ship levels are integrated into the model, which aims to maximize the social benefit government's net profit. Based on the behavior rules of ship operators, a tailored method is proposed to convert the bilevel (port level and ship level) problem into an equivalent single-level problem. Embedded in an enumeration algorithm, the method significantly reduces the difficulty of solving the problem. A series of numerical experiments with realistic parameters were conducted to show the significance of this study and validate the proposed model and algorithm.

Keywords: maritime transportation; liquefied natural gas (LNG); governmental subsidy; trilevel programming.

1. Introduction

The shipping industry plays an important role in international trade, as it is responsible for transporting approximately 90% of the global cargo volume (International Maritime Organization, 2019). According to the Fourth International Maritime Organization (IMO) Greenhouse Gas Study (Faber et al., 2020), the shipping industry is responsible for 15% of the nitrogen oxides (NO_X), 13% of the sulfur dioxide (SO_2), and 2.7% of the carbon dioxide (CO_2) emitted through human activities. The numbers are even higher in coastal areas (Viana et al., 2014). In the Review of Maritime Transport 2019 (UNCTAD, 2019) commissioned by the United Nations, environmental concerns were recognized as a major issue in the maritime industry for 2019–2024. To reduce the air pollution caused by shipping emissions, stringent regulations on the quality of bunker fuels have recently come into effect. Quality restrictions on bunker fuels used by vessels in inland river areas are more stringent because such vessels go deep into countries' interiors. For example, according to the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution (The National People's Congress of the People's Republic of China, 2018), ships that sail along China's inland rivers must use regular diesel oil available on the market, which contains no more than 0.005% sulfur; such oil is highly expensive. There are a number of other methods that can reduce shipping emissions, such as sulfur scrubbers that clean ship emissions before release, internal engine modifications that control the production of NO_X in the combustion

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process, and alternative energy sources such as biofuels, wind and solar power, LNG and hydrogen fuels as bunker fuel. Among these methods, using LNG as a marine fuel is one of the most promising options.

LNG has been recognized as one of the cleanest fossil energies for ship on Earth. The products of the full combustion of pure LNG are CO_2 and water (H_2O). Compared with ships powered by traditional bunker fuel oil, LNG-fueled ships generate much lower emissions. Studies have found that LNG reduces SO_X and PM by nearly 100%, NO_X by up to 85–90%, and CO_2 by 15–20% (Wang and Notteboom, 2014; New South Wales Environment Protection Authority of Australia, 2015). Therefore, using LNG as bunker fuel can significantly reduce ship emissions and alleviate air pollution problems.

In addition, LNG can lower the operating costs of ships, which encourages ship operators to retrofit their ships. First, LNG is priced more competitively than marine diesel oil (MDO) and marine gas oil (MGO), which are usually adopted by ships to satisfy regulations concerning the sulfur content of marine fuels (International Maritime Organization, 2020, 2016). Apart from the bunkering cost, the adoption of LNG as marine fuel can also reduce a ship's maintenance cost, because LNG-fueled engines and related equipment require less maintenance and have a longer service life than traditional ship engines (Oxford Institute for Energy Studies, 2018). Given these benefits, several attempts have been made to develop and use LNG-fueled ships. For example, the CMA CGM Group, a world leader in transport and logistics that is committed to energy transition, planned to have 22 LNG fueled container ships in its fleet by 2022 (CMA CGM Group, 2020). However, much remains to be done in terms of developing LNG-fueled ships, and multiple factors still hinder the adoption of LNG as bunker fuel, including the high cost of LNG engines, the extra space required for LNG fuel tank, potential gas leakages and the absence of a complete LNG bunkering infrastructure (Wang and Notteboom, 2014; Acciaro, 2014). Due to the limited capacity of LNG fuel tanks, a complete bunkering system is necessary for LNG fueled ships.

Currently, the construction of LNG bunkering stations is hindered by the "chicken and egg" problem faced by all alternative fuels (Lim and Kuby, 2010; Ko et al., 2017). Today, at an early stage in the introduction of LNG as bunker fuel, many ship operators refuse to retrofit their ships with LNG engines without adequate bunkering stations. At the same time, insufficient LNG refueling demand leaves bunkering stations idle, wasting the investment in building them.

Considering the emission reductions brought by the adoption of LNG-fueled ships, governments become the main force to solve the problem. Subsidies are one of the main approaches to encouraging the extensive use of LNG-fueled ships besides stringent regulations. Europe, one of the first areas starting to promote LNG-fueled ships, opts for governmental financial support as a main approach to encouraging the adoption LNG as marine fuel. In the Rhine-Main-Danube area, a significant portion of the initial investment on the onshore LNG infrastructure will be borne by the European Commission (European Commission, 2012). For example, the European Commission will provide 20% of the LNG bunkering vessel building cost, approximately 11,000,000 EUR (13,400,000 USD), for the Port of Algeciras (Bajic, 2020). According to the Measures for the Administration of Subsidies for the Standardization of Inland River Ship Types (Ministry of Finance of the People's Republic of China and Ministry of Transport of the People's Republic of China, 2014), newly built LNG-fueled ships whose dead weight tonnage is no less than 400 tons will be subsidized. Subsidies of $630,000$–$1,400,000$ CNY (approximately $97,335$–$216,300$ USD) will be granted to ships. As for the LNG bunkering station, the construction projects included in the Layout Scheme of LNG Filling Wharf for Yangtze River Beijing-Hangzhou Grand Canal and Xijiang Shipping Lane (Ministry of Transport of the People's Republic of China, 2017a) have a higher priority in port planning and land use examination and approval (National Development and Reform Commission and Ministry of Transport of the People's Republic of China, 2019). Based on the related policies of the governments of different countries and areas, it is clear that government subsidies are extensively adopted. Therefore, in this paper, we focus on government subsidies for LNG as marine fuel, and aim to identify the optimal subsidy plan.

In practice, there are two types of LNG-fueled vessels. The first is powered purely by LNG; it is also an LNG carrier and can use natural gas produced during transportation for power (Schinas and Butler, 2020). The other is equipped with dual-fuel engines that can switch between traditional bunker fuel oil and LNG during a trip (Fokkema et al., 2017). We consider only dual-fuel ships in this paper because ships powered purely by LNG are self-sufficient.

1.1. Literature Review

Alternative marine fuels are promising methods of alleviating maritime emissions (Deng et al., 2021; Ytreberg et al., 2021; Deng et al., 2021). The literature on the application of LNG as marine fuel can be divided into a stream addressing technical problems (Lim and

Choi, 2020; Aneziris et al., 2020; Milioulis et al., 2021) and a stream addressing management problems (Lim and Kuby, 2010; Ko et al., 2017). Studies of technical problems mainly focus on safety issues (Zheng et al., 2017; Park et al., 2018; Aneziris et al., 2020) and efficiency issues (Guan et al., 2017; Altosole et al., 2018; Lim and Choi, 2020). The literature on management problems can be further subdivided into studies from the ship perspective and from the bunkering station perspective. From the ship perspective, whether and when to invest in ship retrofitting are common topics (Schinas and Butler, 2020). Yoo (2017) focuses on specific ship types and assesses the economic applicability of LNG as a marine fuel for CO_2 carriers. Xu and Yang (2020) study the economic feasibility of LNG-fueled container ships on the Northern Sea Route under the assumption that an LNG refueling station will be constructed in Sabetta Russia, and evaluate the CO_2 reduction compared with deploying ships powered by conventional fuels on this route. Kana and Harrison (2017) adopt Monte Carlo simulations to extend the ship-centric Markov decision process (Kana et al., 2015) and capture the impact of uncertainties in the economic parameters, ECA regulations, and LNG supply chain on the decision whether to retrofit a container ship as an LNG-fueled vessel. From the bunkering station perspective, studies focus on the bunkering network design and the layout of bunkering stations. Network design studies mainly aim to determine the optimal number and positions of bunkering stations in an area (Ursavas et al., 2020). As for the layout of bunkering stations, bunkering method selection (Tam, 2020) and safety zone settling (Park et al., 2018) are frequently discussed. For a detailed review of this literature, please refer to Peng et al. (2021).

The two perspectives focus on either the demand side of LNG (LNG-fueled ships) or the supply side (LNG bunkering stations). However, in practice, the adoption of LNG as marine fuel is still in its infancy, and the two sides are interdependent due to the "chicken and egg" problem (Lim and Kuby, 2010; Ko et al., 2017). Therefore, this problem should be investigated from a systematic perspective. Such a perspective is adopted in several papers that investigate the problem of locating stations for alternative fuel vehicles; please refer to Ko et al. (2017) for a detailed review of this literature. Nevertheless, papers that study this problem focus on road transport, which is different from the problem discussed in this paper for several reasons. First, in road transportation the selection of potential bunkering station positions are more flexible. Second, the vehicles that refuel at bunkering stations are more unpredictable since a large proportion do not travel according to a predetermined schedule. Third, in the problem of locating stations for alternative fuel vehicles, the decision maker try to cover as many paths as possible with estimated alternative fuel demands, rather than taking the interaction between supply side and demand side decisions into consideration. Fourth, in studies that focus on road transport government subsidies are not considered.

In maritime transportation, government subsidies are considered a practical method of promoting the use of green technologies, such as shore power (Wu and Wang, 2020). Wu and Wang (2020) consider the interaction between the decisions of port authorities in constructing a shore power system and ship operators in installing onboard shore power facilities. They integrate government subsidies into the problem as a method of encouraging the application of shore power. However, there are several differences between the work of Wu and Wang (2020) and this paper. First, although both Wu and Wang (2020) and their paper consider the government expenditure and the environmental benefits, the objective functions are different. Wu and Wang (2020) aim to maximize the total environmental benefit with a constraint on the total subsidy amount. In this paper, we do not preset a budget for subsidies, but consider the subsidy amount in the objective function and aim to maximize the net benefit for the government, namely the environmental benefit minus the subsidy expenditure. As a result, the extreme cases with unreasonably high subsidies will not be accepted in this paper. Also, it would be easy to modify the mathematical model to take the subsidy budget as a constraint. Besides, compared with Wu and Wang (2020) considering the budget set subjectively by the government, this paper is able to suggest the proper amount of subsidies that can achieve a significant emission reduction and avoid the waste of financial budget (Aldy et al., 2021). Second, subsidy policies are different. In Wu and Wang (2020), the government plays a dominant role and selects particular ports and ship routes and covers all of their construction or retrofitting costs. In this paper, the government is less dominant and provides one subsidy rate for all ports and another for all ships, and port authorities and ship operators independently decide whether to conduct the construction or retrofitting. Third, the ports in Wu and Wang (2020) make decisions independently, while in this paper we assume all ports are operated by the same port group. In Wu and Wang (2020), for each port, shore power facilities at the other ports encourage ships to be retrofitted and do not impact the shore power demand at this port. Therefore, the influence of shore power facilities at the other ports is positive and easy to handle. In this paper, however, the LNG bunkering stations at the other ports have influences in opposite directions. On one side they will encourage ships to be retrofitted and bring more LNG bunkering demand. But, on the other side, they may lower the LNG bunkering volume of existing dual-fueled ships at the port by providing a more complete bunkering system. Thus, the interrelationships between different ports are more complicated and extremely hard to be integrated into the model. Therefore, it is assumed that all ports are operated by the same port group in this paper. Meanwhile, this assumption is proposed on the basis of certain facts. Considering the highly overlapped visiting ships, the ports along the same inland river tend to cooperate in various operational decisions. For example, the Layout Scheme of LNG Filling Wharf for Yangtze River Beijing-Hangzhou Grand Canal and Xijiang Shipping Lane (Ministry of Transport of the People's Republic of China, 2017a) displays the LNG infrastructure construction plan along three inland rivers in 2017–2025. Given that, in China, ports in the same province tend to be integrated and become a port group company, for example the Jiangsu Port Group Company and the Hubei Port Group Company. Therefore, it is assumed that all ports are operated by the same port group in this paper. These characteristics lead to essential differences between the model proposed in this paper and the model used in Wu and Wang (2020), and the solution method proposed by Wu and Wang (2020) is not applicable to the problem in this paper. In conclusion, although the backgrounds and problem structure of the two papers are similar, this paper is substantially different from Wu and Wang (2020).

The scientific contribution of this paper is threefold. First, this is the first paper to investigate the subsidy policy optimization problem for LNG as marine fuel. As far as we can determine, papers on the topic to date are limited to qualitative analysis or policy evaluation (Wan et al., 2019). Second, we propose a new trilevel model to describe the problem. This model can also be adapted to other alternative marine fuels, such as biofuels.

Third, based on port authorities' and ship operators' behavior, the bilevel problem involving the port-level and ship-level decisions is converted into an equivalent single-level problem, which significantly reduces the difficulty of solving the problem.

The remainder of the paper is organized as follows: Section 2 gives the problem description and presents the model. Section 3 shows how the model is converted and then solved. Our numerical experiments and their results are presented in Section 4. Last, Section 5 presents our conclusions.

2. Model Formulation

A trilevel model that consists of the government, port, and ship levels is proposed in this section. The interrelationships among decisions considered at different levels are clearly described through the trilevel structure.

2.1. Problem description

In this paper, we consider a river under a government's regulatory regime. A set of physical ports, denoted by $\mathcal{P}$, all of which are managed by a port group, are located along the river. Within the set $\mathcal{P} = \{1, 2, ..., |\mathcal{P}|\}$, 1 represents the physical port farthest downstream and $|\mathcal{P}|$ represents the physical port farthest upstream.

There is a set $\mathcal{V}$ of vessels that sail on this river and fulfill transportation demands between the ports in $\mathcal{P}$. Each ship has its own route, and ships stick to their routes during the time span under consideration. We denote the physical port farthest downstream (the physical port farthest upstream) on the route of ship $j \in \mathcal{V}$ as $MD_j\,(MU_j)$. As shown in Figure 1, a route is a closed loop: ship j on its route starts from MD_j, visits ports upstream until MU_j, then reverses direction and finally goes back to MD_j. After returning to MD_j, the ship repeats the route. Because the route along the river is nearly linear, to complete a route, ship j will either visit or pass each physical port between MD_j and MU_j in the order $MD_j, MD_j+1, ..., MU_j-1, MU_j, MU_j-1, ..., MD_j+1$. In practice, the closed route finishes when the ship arrive at MD_j in the backward sailing voyage. However, the final visit is also the beginning of the next round trip, and therefore this visit is omitted in the model formulation to avoid the duplication. We denote these ports as a new set $\mathcal{P}'_j$ and $k \in \mathcal{P}'_j$ represents the k^{th} port along the route, $k = 1, ..., 2(MU_j - MD_j)$. We further define a binary parameter T_{jk} that equals 1 if the k^{th} port along the route of ship j is visited by the ship and 0 otherwise, and we set a binary parameter B_{jki} that equals 1 if the k^{th} port (no matter whether it is visited or passed) corresponds to physical port $i \in \mathcal{P}$, and 0 otherwise. In the example given in Figure 1, the line represents a river along which five physical ports are located; the right-hand side is the downstream end and the left-hand side is the upstream end. The arcs represent the sailing directions of ship j between physical ports; for example, the arc from physical port 2 to physical port 4 means that ship j visits physical port 2 and then sails upstream to visit physical port 4. Physical port 1 is the most downstream port that ship j visits ($MD_j = 1$) and physical port 4 is the most upstream port that ship j visits ($MU_j = 4$). Then, the set of ports along the route of ship j consists of six elements; that is, $\mathcal{P}'_j = \{1, 2, 3, 4, 5, 6\}$ because the second visit to physical port 1 is omitted. Because ship j does not visit physical port 3 when it sails upstream, we have $T_{j1} = 1, T_{j2} = 1, T_{j3} = 0, T_{j4} = 1, T_{j5} = 1$, and $T_{j6} = 1$. As the corresponding physical ports of the first, second, third, fourth, fifth, and sixth ports on the route are port 1, port 2, port 3, port 4, port 3, and port 2, respectively, we further have $B_{j11} = B_{j22} = B_{j33} = B_{j44} = B_{j53} = B_{j62} = 1$.

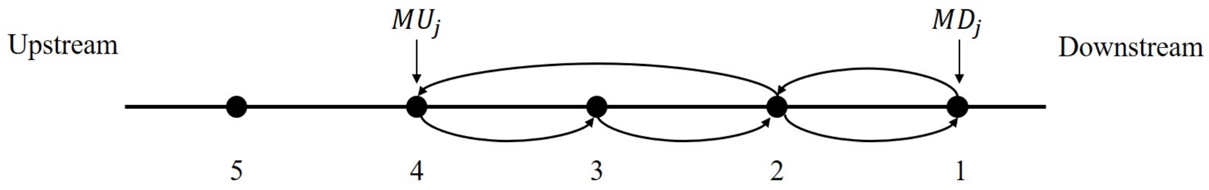

Figure 1: An example of the route of ship j

Ship $j \in \mathcal{V}$ sails at the speed of H_j knots (nautical miles per hour). The distance of the voyage from the k^{th} port along the route to the next is denoted by L_{jk}, $k \in \mathcal{P}'_j$. For $k = 1, 2, ..., |\mathcal{P}'_j| - 1$, L_{jk} is the sailing distance from the k^{th} port to the $(k+1)^{\text{th}}$, while $L_{j|\mathcal{P}'_j|}$ represents the sailing distance from the $|\mathcal{P}'_j|^{\text{th}}$ port to the first (i.e., from physical port $MD_j + 1$ to physical port MD_j). Therefore, the total sailing time for the ship to complete a whole route is $\sum_{k \in \mathcal{P}'_j} L_{jk}/H_j$. Other than the sailing time, ship j has to berth for m_{jk} hours at the k^{th} port for cargo handling (if the k^{th} port is not visited, then $m_{jk} = 0$). As for the LNG bunkering operation, it is assumed that the ship gets refueled after the cargo handling and before the departure. Considering that the LNG bunkering speed of a dual-fueled ship can be up to 330 cubic meters per hour (International Maritime Organization, 2016) and the relatively small capacity of LNG tanks (no larger than 20 cubic meters in this paper), the LNG bunkering time would be no longer than the cargo handling time. Thus, in this paper, it is assumed that the LNG bunkering operation would be finished while handling cargoes. For ports that are not visited by the ship, the time used to refuel the vessel is considered in the model as the extra cost f_j. Then, with a total of S hours of operation time per year, the ship finishes $O_j := S \Big/ \left[\left(\sum_{k \in \mathcal{P}'_j} L_{jk} \Big/ H_j \right) + \sum_{k \in \mathcal{P}'_j} T_{jk} m_{jk} \right]$ trips in a year.

We assume that currently all ships in $\mathcal{V}$ use MDO as the bunker fuel. The price of MDO is U_{MDO} USD/ton, and the combustion of one ton of MDO has a negative environmental impact of E_{MDO} USD. Ship j consumes R^j_{MDO} tons of MDO while sailing one nautical mile and consumes R'^j_{MDO} tons of MDO during berthing for one hour. Apart from the bunker cost, ship j has to pay $\bar{C}^j_{\text{MDO}}$ USD per year for the maintenance of the diesel engine. We denote by G_j the annual revenue of ship j from transporting cargo. Then, the annual profit for ship j is $G_j - \left[\bar{C}^j_{\text{MDO}} + O_j U_{\text{MDO}} \left(R^j_{\text{MDO}} \sum_{k \in \mathcal{P}'_j} L_{jk} + R'^j_{\text{MDO}} \sum_{k \in \mathcal{P}'_j} T_{jk} m_{jk} \right) \right]$ USD, which is assumed to be positive, as otherwise the ship would be likely to exit the market.

Ship j may be retrofitted into dual-fueled, which incurs a fixed retrofitting cost denoted by $\hat{C}^{\mathcal{V}}_j$ (without government subsidy). The annual maintenance cost of the dual-fuel engine is denoted by $\bar{C}^j_{\text{Dual}}$. Ship j, after retrofitting, can switch between MDO and LNG for power. It will require R^j_{LNG} tons of LNG to sail one nautical mile and R'^j_{LNG} tons of LNG to berth for one hour. We assume that the consumption rates of LNG and MDO are proportional; that is, $R'^j_{\text{MDO}} / R'^j_{\text{LNG}} = R^j_{\text{MDO}} / R^j_{\text{LNG}} = R$, $j \in \mathcal{V}$. Therefore, for a ship, consuming 1 ton of LNG means reducing the consumption of MDO by R tons. For instance, according to International Maritime Organization (2016), the net calorific value of MDO is 11.6 MWh/ton and the net calorific value of LNG is 13.7 MWh/ton, and hence $R = 13.7/11.6 \approx 1.18$. Note that ships are not retrofitted yet because of the high retrofitting cost, a lack of LNG bunkering stations at ports, or an insignificant price difference between MDO and LNG.

The negative environmental impact of LNG is much lower than that of MDO. Denote by E_{LNG} the negative environmental impact of one ton of LNG. Since consuming one ton of LNG means reducing the consumption of MDO by R tons, the environmental benefits of consuming one ton of LNG can be calculated as $\Delta_E := R \cdot E_{\mathrm{MDO}} - E_{\mathrm{LNG}}$ USD/ton, in which E_{MDO} and E_{LNG} are the environmental costs when one ton of MDO and LNG are consumed, respectively. The Fourth Greenhouse Gas Study conducted by the IMO (Faber et al., 2020) estimated that a traditional ship totally powered by MDO will emit 0.0001 ton of SO_X, 0.167 ton of NO_X, 3.206 tons of CO_2, and 0.00203 ton of $PM_{2.5}$ while consuming one ton of MDO, and a dual-fueled ship will emit 3.17×10^{-5} ton of SO_X, 0.0466 ton of NO_X, 2.75 tons of CO_2, and 1.26×10^{-4} ton of $PM_{2.5}$ while consuming one ton of LNG. These four pollutants make up more than 99% of ship emissions, and have a significant impact on social welfare. As summarized in Nunes et al. (2019) and Song (2014), the social costs associated with the emissions of SO_X, NO_X, CO_2, and $PM_{2.5}$ are 11,123 USD/ton, 6,282 USD/ton, 33 USD/ton, and 61,179 USD/ton, respectively. As a result, we obtained the values $E_{\mathrm{MDO}} = 1,280.31$ USD/ton, $E_{\mathrm{LNG}} = 391.43$ USD/ton, and $\Delta_E = R \cdot E_{\mathrm{MDO}} - E_{\mathrm{LNG}} = 1,119.33$ USD/ton. Because using LNG as bunker fuel is a promising method of reducing the environmental impact of ship emissions along the river, the government tries to promote the adoption of LNG as bunker fuel by providing subsidies for ports that construct LNG bunkering stations and ships retrofitted as dual-fuel ships. The government's subsidies affect the decisions of the port group on the ports at which to construct LNG bunkering stations, and both the government subsidies and the port group's decisions affect the ship operators' decisions on whether to retrofit their ships as dual-fuel. We model the problem at three levels, namely the government level, the port level, and the ship level, as shown in Figure 2 and elaborated in the next three subsections.

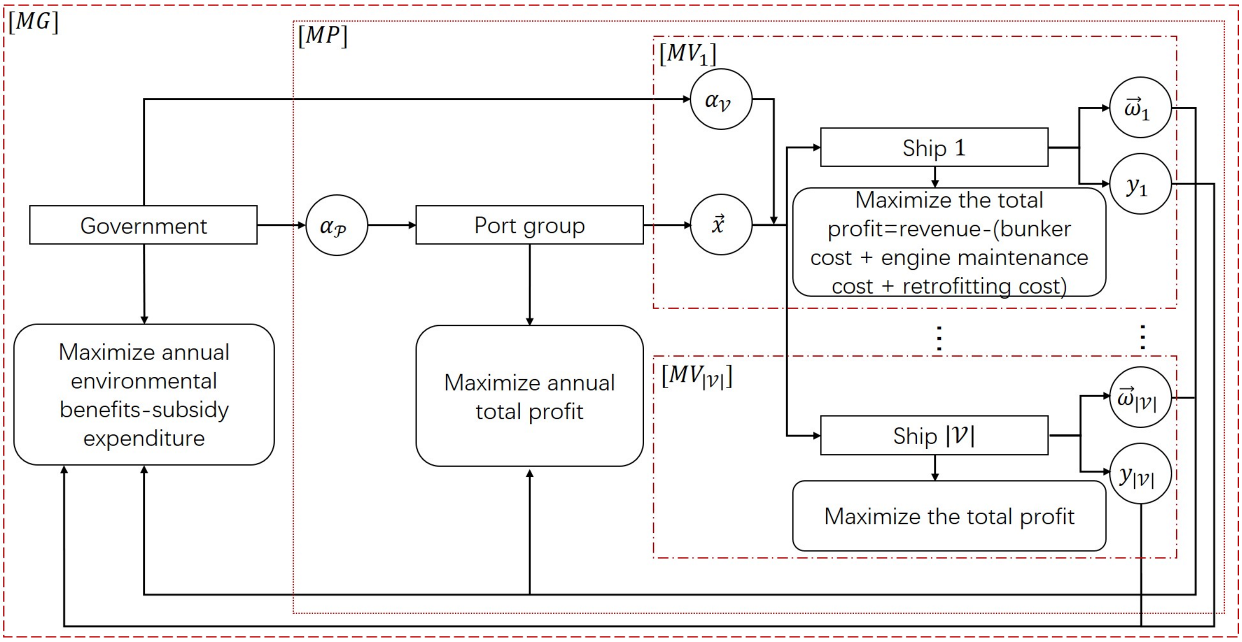

Figure 2: Demonstration of the problem structure

2.1.1. Government level

The government makes decisions at the first level, aiming to maximize its annual total benefits, which equal the annual environmental benefits of emission reduction minus annual average subsidy expenses. Specifically, the government needs to determine the proportion of the bunkering station building cost to subsidize, denoted by $\alpha_{\mathcal{P}}$, and the proportion of the ship retrofitting cost to subsidize, denoted by $\alpha_{\mathcal{V}}$. To insure convenient policy implementation, we assume that the government chooses the values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ from a set of alternatives 0%, 5%, ..., 95%, and 100%. The purpose of the government subsidies is to stimulate the port group to build LNG bunkering stations and to encourage the retrofitting of ships as dual-fuel, so that a significant amount of LNG will be consumed to replace MDO, thus providing environmental benefits.

2.1.2. Port level

At the port level, given the subsidy proportion $\alpha_{\mathcal{P}}$, the port group decides whether or not to construct an LNG bunkering station at each physical port $i \in \mathcal{P}$, denoted by the binary decision variable x_i, with the aim of maximizing its average annual profits. The construction of an LNG bunkering station at physical port $i \in \mathcal{P}$ costs $\hat{C}_i^{\mathcal{P}}$ (without government subsidy), which is a one-off cost. We convert $\hat{C}_i^{\mathcal{P}}$ into an annualized cost $C_i^{\mathcal{P}}$, which applies after depreciation and interest are considered. In this paper, following the study conducted by the International Maritime Organization (2016), we use the equivalent annual cost as $C_i^{\mathcal{P}}$, with 20 years of depreciation time and 8% of interest rate. With the government subsidy, the port group needs to pay an annual cost of $(1 - \alpha_{\mathcal{P}})\, C_i^{\mathcal{P}}$. The port group purchases LNG from a supplier at a fixed price of $\tilde{U}_{\text{LNG}}$. The selling price to ships, namely, the LNG bunkering price, denoted by $\hat{U}_{\text{LNG}}$, is predetermined by the government to ensure that LNG is a more economical option for bunker fuel than MDO. Therefore, the port group could gain $\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}}$ by selling one ton of LNG. The total amount of LNG that the port group can sell depends on the ship operators' decisions, which are affected by the government's subsidy proportion $\alpha_{\mathcal{V}}$ and the availability of LNG bunkering stations at the ports in $\mathcal{P}$.

2.1.3. Ship level

Given the government's subsidy proportion $\alpha_{\mathcal{V}}$ at the first level and the locations of LNG bunkering stations determined at the second level, the operator of each ship $j \in \mathcal{V}$ decides whether to retrofit the ship or not and the refueling volume at each port if the ship is retrofitted (the ship may not refuel at ports that are passed by rather than visited, because the refueling would incur extra cost), to maximize its annual profit. The ship operators' refueling volume decisions affect the government's environmental benefits at the first level and the port group's revenue at the second level.

We denote by y_j a binary decision variable equal to 1 if and only if ship j is retrofitted. We convert the one-off retrofitting cost $\hat{C}_j^{\mathcal{V}}$ into an annualized cost $C_j^{\mathcal{V}}$. We also use equivalent annual cost here with 8% of interest rate here. As for the depreciation time, we consider that retrofitting work will not influence the ship's remaining service life which is taken as the depreciation time of ship retrofitting in this paper. According to the Regulations on the Administration of Old Transport Ships (Ministry of Transport of the People's Republic of China, 2017b), container ships sailing in inland river areas have to go through a special periodic inspection after the age of 29, and be compulsorily scrapped after the age of 35. Thus, we assume a remaining service life of 20 years for ships in this paper. Then, benefiting from the government subsidy, the ship operator needs to pay an annual cost of $(1 - \alpha_{\mathcal{V}})\, C_j^{\mathcal{V}}$ for the retrofitting. If the ship is retrofitted, it will be equipped with an LNG tank with a capacity of q_j tons, and the original diesel engine will be replaced by a dual-fuel engine that has an annual maintenance cost of $\bar{C}_{\text{Dual}}^{j}$ USD. Because consuming one ton of LNG means reducing the consumption of MDO by R tons, the consumption of one ton of LNG implies a fuel cost reduction of $\Delta_U := R \cdot U_{\text{MDO}} - \hat{U}_{\text{LNG}}$ USD for the ship operator.

As the LNG bunkering price is the same at all available ports, if ship j visits a port with an LNG bunkering station, it will fill up its LNG tank. If the ship passes a port rather than visiting it, the ship may stop at the port for LNG refueling, at an extra cost of f_j USD. We define a binary decision variable θ_{jk} that equals 1 if and only if ship j refuels with LNG at port $k \in \mathcal{P}'_j$. We then have $\theta_{jk} = 1$ if $T_{jk} = 1$; a cost f_j will be incurred if $\theta_{jk} = 1$ and $T_{jk} = 0$.

For simplicity, it is assumed that a ship refuels just before leaving a port; that is, LNG purchased at the k^{th} port cannot be used to generate power for the ship when it is berthing at the port. To formulate the amount of LNG consumed by ship j, we define decision variables π_{jk}^{Finish} and π_{jk}^{Leave} as follows. (i) If ship j visits the k^{th} port for cargo handling (i.e., $T_{jk} = 1$), then π_{jk}^{Finish} is the volume of LNG remaining in the LNG tank of ship j when it has just finished cargo handling (before refueling, if any) and π_{jk}^{Leave} is the volume of LNG remaining in the LNG tank of ship j when it leaves the k^{th} port (after refueling, if any). (ii) If ship j stops at the k^{th} port just for refueling (i.e., $T_{jk} = 0$ and $\theta_{jk} = 1$), then π_{jk}^{Finish} represents the volume of LNG remaining in the LNG tank of ship j before refueling and π_{jk}^{Leave} represents the volume after refueling, and we have $\pi_{jk}^{Finish} < \pi_{jk}^{Leave}$. In both cases, $\pi_{jk}^{Finish} \leq \pi_{jk}^{Leave}$. Specifically, if ship j does not refuel at the k^{th} port along its route ($\theta_{jk} = 0$), $\pi_{jk}^{Finish} = \pi_{jk}^{Leave}$. If ship j refuels at the k^{th} port ($\theta_{jk} = 1$), we have $\pi_{jk}^{Finish} < \pi_{jk}^{Leave} = q_j$, because every time the ship refuels the LNG tank will be filled up.

The annual LNG refueling volume of ship j at physical port i, denoted by decision variable ω_{ji}, can now be calculated: $\omega_{ji} = O_j \sum_{k \in \mathcal{P}'_j} B_{jki} \left(\pi_{jk}^{Leave} - \pi_{jk}^{Finish} \right)$, for all $j \in \mathcal{V}$, $i \in \mathcal{P}$. The values of ω_{ji} affect the government's decisions and the port group's decisions: the annual environmental benefit for the government is $\Delta_E \sum_{j \in \mathcal{V}} \sum_{i \in \mathcal{P}} \omega_{ji}$, and the annual gain for the port group from selling LNG is $\left(\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}} \right) \sum_{j \in \mathcal{V}} \sum_{i \in \mathcal{P}} \omega_{ji}$.

2.2. Mathematical model

Before presenting the mathematical model, we list the notations used in this paper.

Sets and parameters

$\mathcal{P}$	the set of physical ports along the river, $\mathcal{P} = \{1, 2, ..., \|\mathcal{P}\|\}$, indexed by i;
$\mathcal{V}$	the set of ships sailing along the river, $\mathcal{V} = \{1, 2, ..., \|\mathcal{V}\|\}$, indexed by j;
$C_i^{\mathcal{P}}$	the annualized construction cost (USD) of LNG bunkering station at physical port $i, \forall i \in \mathcal{P}$;
$C_j^{\mathcal{V}}$	the annualized retrofitting cost (USD) of ship $j, \forall j \in \mathcal{V}$;
G_j	the annual revenue (USD/year) for ship j, $\forall j \in \mathcal{V}$;
Δ_E	the increment in environmental benefits (USD/ton) when one ton of LNG is consumed to replace MDO;
R_{LNG}^j	the LNG consumption rate (ton/nm) of ship j while sailing, if it is retrofitted, $\forall j \in \mathcal{V}$;
U_{MDO}	the MDO bunkering price (USD/ton) paid by ship operators;
$\hat{U}_{\text{LNG}}$	the LNG bunkering price (USD/ton) paid by ship operators;
$\tilde{U}_{\text{LNG}}$	the LNG purchasing price (USD/ton) paid by the port group;
Δ_U	the fuel cost reduction (USD/ton) brought by using one ton of LNG;
$\mathcal{P}'_j$	the set of ports along the route of ship j, $\mathcal{P}'_j = \{1, 2, ..., 2\,(MU_j - MD_j)\}$, indexed by k;
T_{jk}	binary parameter, equal to 1 if the k^{th} port along the route is visited by ship j, 0 otherwise, $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}'_j$;

L_{jk} the sailing distance (nm, nautical mile) from the k^{th} port along the route of ship j to the $(k+1)^{\text{th}}$ port along the route, $k = 1, 2, ..., |\mathcal{P}'_j| - 1, \forall j \in \mathcal{V}$;

$L_{j|\mathcal{P}'_j|}$ the sailing distance (nm) from the $|\mathcal{P}'_j|^{\text{th}}$ port along the route of ship j to the 1^{st} port along the route, $\forall j \in \mathcal{V}$;

m_{jk} the berthing time (hour) of ship j at the k^{th} port along the route, $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}'_j$;

R'^{j}_{LNG} the LNG consumption rate (ton/hour) of ship j while berthing, $\forall j \in \mathcal{V}$;

$\bar{C}^{j}_{\text{MDO}}$ the annual maintenance cost (USD/year) of the diesel engine of ship j if it is not retrofitted;

$\bar{C}^{j}_{\text{Dual}}$ the annual maintenance cost (USD/year) of the dual-fuel engine of ship j if it is retrofitted;

O_j the number of trips that ship j finishes in a year, $\forall j \in \mathcal{V}$;

f_j the extra cost (USD) of ship j refueling at a port that is located along the route but not visited by the ship, $\forall j \in \mathcal{V}$;

q_j the LNG tank capacity (ton) of ship j if it is retrofitted, $\forall j \in \mathcal{V}$;

B_{jki} binary parameter, equal to 1 if the k^{th} port along the route of ship j is physical port i, 0 otherwise, $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}'_j, \forall i \in \mathcal{P}$;

M_i a large constant, $\forall i \in \mathcal{P}$.

Decision variables

x_i binary variable, equal to 1 when an LNG bunkering station is constructed at physical port i, 0 otherwise, $\forall i \in \mathcal{P}$;

y_j — binary variable, equal to 1 when ship j is retrofitted into a dual-fuel ship, 0 otherwise, $j \in \mathcal{V}$;

ω_{ji} — the LNG refueling volume (ton) of ship j at physical port i each year if it is retrofitted, $\forall j \in \mathcal{V}$, $\forall i \in \mathcal{P}$;

θ_{jk} — binary variable, equal to 1 when ship j refuels LNG at the k^{th} port along its route if it is retrofitted, 0 otherwise, $\forall k \in \mathcal{P}_j', \forall j \in \mathcal{V}$;

π_{jk}^{Finish} — the LNG remaining volume (ton) of the ship j when it finished cargo handling at the k^{th} port along the route and before refueling, $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}_j'$;

π_{jk}^{Leave} — the LNG remaining volume (ton) of the ship j when it leaves the k^{th} port along the route after refueling, $\forall j \in \mathcal{V}$, $\forall k \in \mathcal{P}_j'$.

Vectors

$\vec{x}$ — the vector of x_i, $\vec{x} = \left(x_1, ..., x_{|\mathcal{P}|}\right)$;

$\vec{y}$ — the vector of y_j, $\vec{y} = \left(y_1, ..., y_{|\mathcal{V}|}\right)$;

$\vec{\omega}_j$ — the vector of ω_{ji}, $\vec{\omega}_j = \left(\omega_{j1}, ..., \omega_{j|\mathcal{P}|}\right)$, $\forall j \in \mathcal{V}$;

$\vec{\omega}$ — the vector of $\vec{\omega}_j$, $\vec{\omega} = \left(\vec{\omega}_1, ..., \vec{\omega}_{|\mathcal{V}|}\right)$;

$\vec{\pi}_j^{Leave}$ — the vector of π_{jk}^{Leave}, $\vec{\pi}_j^{Leave} = \left(\pi_{j1}^{Leave}, ..., \pi_{j\left|\mathcal{P}_j'\right|}^{Leave}\right)$, $\forall j \in \mathcal{V}$;

$\vec{\pi}_j^{Finish}$ — the vector of π_{jk}^{Finish}, $\vec{\pi}_j^{Finish} = \left(\pi_{j1}^{Finish}, ..., \pi_{j\left|\mathcal{P}_j'\right|}^{Finish}\right)$, $\forall j \in \mathcal{V}$;

$\vec{\theta}_j$ — the vector of θ_{jk}, $\vec{\theta}_j = \left(\theta_{j1}, ..., \theta_{j\left|\mathcal{P}_j'\right|}\right)$, $\forall j \in \mathcal{V}$.

Then the problem faced by the government can be described as the following trilevel optimization model $[MG]$:

$$[\boldsymbol{MG}] \quad \text{maximize } \Delta_E \sum_{j \in \mathcal{V}} \sum_{i \in \mathcal{P}} \omega_{ji} - \alpha_{\mathcal{P}} \sum_{i \in \mathcal{P}} C_i^{\mathcal{P}} x_i - \alpha_{\mathcal{V}} \sum_{j \in \mathcal{V}} C_j^{\mathcal{V}} y_j \tag{1}$$

subject to

$$\alpha_{\mathcal{P}} = 0\%, 5\%, ..., 100\% \tag{2}$$

$$\alpha_{\mathcal{V}} = 0\%, 5\%, ..., 100\% \tag{3}$$

and

$$(\vec{x}, \vec{\omega}, \vec{y}) \in \Psi^{\mathcal{P}} (\alpha_{\mathcal{P}}, \alpha_{\mathcal{V}}) \tag{4}$$

where $\Psi^{\mathcal{P}} (\alpha_{\mathcal{P}}, \alpha_{\mathcal{V}})$ is determined by the following model:

$$[\boldsymbol{MP}] \quad \Psi^{\mathcal{P}} (\alpha_{\mathcal{P}}, \alpha_{\mathcal{V}}) = \underset{\vec{x}, \vec{\omega}, \vec{y}}{\arg\max} \sum_{i \in \mathcal{P}} \left[-(1 - \alpha_{\mathcal{P}}) C_i^{\mathcal{P}} x_i + \sum_{j \in \mathcal{V}} \left(\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}} \right) \omega_{ji} y_j \right] \tag{5}$$

subject to

$$x_i = 0, 1, \forall i \in \mathcal{P} \tag{6}$$

and

$$(y_j, \vec{\omega}_j) \in \Phi_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x}), \forall j \in \mathcal{V} \tag{7}$$

where $\Phi_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x})$ is the projection of $\hat{\Phi}_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x})$ on y_j and $\vec{\omega}_j$ (in other words, $(y_j, \vec{\omega}_j) \in \Phi_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x})$ if and only if there exists $\left(\vec{\theta}_j, \vec{\pi}_j^{Leave}, \vec{\pi}_j^{Finish}\right)$ such that $\left(y_j, \vec{\omega}_j, \vec{\theta}_j, \vec{\pi}_j^{Leave}, \vec{\pi}_j^{Finish}\right) \in \hat{\Phi}_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x})$), where $\hat{\Phi}_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x})$ is determined by the following model:

$$\begin{aligned}[\boldsymbol{MV_j}] \quad \hat{\Phi}_j^{\mathcal{V}}(\alpha_{\mathcal{V}}, \vec{x}) = \underset{y_j, \vec{\omega}_j, \vec{\theta}_j, \vec{\pi}_j^{Leave}, \vec{\pi}_j^{Finish}}{\arg\max}\ & G_j - \left\{ y_j \left[C_j^{\mathcal{V}} (1 - \alpha_{\mathcal{V}}) + O_j \sum_{k \in \mathcal{P}_j'} f_j (1 - T_{jk}) \theta_{jk} + \bar{C}_{\text{Dual}}^j \right.\right. \\ & \left.\left. - O_j \Delta_U \sum_{i \in \mathcal{P}} \omega_{ji} \right] + (1 - y_j) \bar{C}_{\text{MDO}}^j \right\}\end{aligned} \tag{8}$$

subject to

$$\pi_{jk}^{Leave} = \pi_{jk}^{Finish} + \theta_{jk} \left(q_j - \pi_{jk}^{Finish}\right), \forall k \in \mathcal{P}_j' \tag{9}$$

$$\pi_{jk}^{Finish} = \max\left\{0, \pi_{j,k-1}^{Leave} - L_{j,k-1} R_{\text{LNG}}^j - m_{jk} R'^j_{\text{LNG}}\right\}, k = 2, 3, ..., \left|\mathcal{P}_j'\right| \tag{10}$$

$$\pi_{j1}^{Finish} = \max\left\{0, \pi_{j\left|\mathcal{P}_j'\right|}^{Leave} - L_{j\left|\mathcal{P}_j'\right|} R_{\text{LNG}}^j - m_{j1} R'^j_{\text{LNG}}\right\} \tag{11}$$

$$\omega_{ji} = O_j \sum_{k \in \mathcal{P}_j'} B_{jki} \left(\pi_{jk}^{Leave} - \pi_{jk}^{Finish}\right), \forall i \in \mathcal{P} \tag{12}$$

$$\theta_{jk} \leq \sum_{i \in \mathcal{P}} B_{jki} x_i, \forall k \in \mathcal{P}_j' \tag{13}$$

$$\sum_{i \in \mathcal{P}} B_{jki} T_{jk} x_i \leq \theta_{jk}, \forall k \in \mathcal{P}_j' \tag{14}$$

$$0 \leq \pi_{jk}^{Finish} \leq \max\left\{0, q_j - L_{j,k-1} R_{\mathrm{LNG}}^j - m_{jk} R'^j_{\mathrm{LNG}}\right\}, k = 2, ..., \left|\mathcal{P}_j'\right| \tag{15}$$

$$0 \leq \pi_{j1}^{Finish} \leq \max\left\{0, q_j - L_{j,\left|\mathcal{P}_j'\right|} R_{\mathrm{LNG}}^j - m_{j1} R'^j_{\mathrm{LNG}}\right\} \tag{16}$$

$$\theta_{jk} = 0, 1, \forall k \in \mathcal{P}_j' \tag{17}$$

$$y_j = 0, 1 \tag{18}$$

$$0 \leq \pi_{jk}^{Leave} \leq q_j, \forall k \in \mathcal{P}_j'. \tag{19}$$

The objective function (1) at the government level aims to maximize the annual environmental benefits of a reduction in ship emissions minus annual average subsidy expenses. Constraints (2) and (3) specify the domains of the subsidy proportions. In model $[MG]$, some of the parameters, namely ω_{ji}, x_i, and y_j, are not constants; the values of these parameters depend on the decisions of the port group and ship operators, which are described in the port-level and ship-level models. We use the set $\Psi^P(\alpha_P, \alpha_V)$ to denote them.

At the port level, because all physical ports are under the management of the port group, here we present the model $[MP]$ to describe the problem faced by the port group. In this paper we assume that the LNG bunkering stations are large enough, namely the bunkering station capacity is not considered as a constraint. The objective function (5) aims to maximize the annual total profits of the port group, equal to the annual profit of selling LNG, minus the annual average LNG bunkering station construction cost. Constraints (6) define the domain of decision variable x_i. In model $[MP]$, parameters y_j and ω_{ji} are not constants, and their values depend on ship operators' choices, which are described in ship-level models. We use the set $\Psi_j^V(\alpha_V, \vec{x})$ to denote them.

Because different ships at the ship level make their decisions independently, we build $[MV_j]$ for ship j. In this paper, the ship operator aims to maximize its annual profit. Given the annual revenue G_j, it is equivalent to obtaining the minimal operating costs and therefore the decision is only influenced by costs related to retrofitting work. In other words, costs not related to the ship retrofitting, for example the cargo handling cost, are fixed in the problem and therefore their value will not influence the ship operator's decision. For simplicity, these fixed costs are ignored in the model. In objective function (8), the first part is the annual revenue G_j. Next, the objective functions for when ship j is retrofitted or not are listed separately. If ship j is retrofitted, the objective function equals the annual average retrofitting cost, plus the extra cost of refueling at ports that the ship does not visit, plus the annual maintenance cost of the dual-fuel engine minus the annual bunkering cost saving. If ship j is not retrofitted, the objective function equals the annual maintenance cost of the diesel engine. Constraints (9) give the relationship between the remaining LNG volume when the ship finishes cargo handling and other operations at the k^{th} port along the route and the remaining volume when it leaves the port. Constraints (10) and (11) state that the retrofitted ship will consume LNG while sailing from one port to the next and berthing there, and that MDO will be used if LNG is in short supply. These constraints depict an important feature of dual-fueled ships, which is switching between LNG and traditional marine fuel for power. With this feature, the model becomes more realistic and lets the ship operators maximize the benefits of retrofitting their ships. Constraints (12) calculate the annual LNG bunkering volume of ship j at physical port i if the ship is retrofitted. Constraints (13) state that ship j can refuel with LNG at the k^{th} port along the route only if the port group decides to construct an LNG bunkering station at the port. Constraints (14) indicate that ship j will refuel at every port with an LNG bunkering station that it visits. Constraints (15) and (16) states the upper limits of the remaining LNG volume when ship j finishes cargo handling and before LNG refueling, if any, at the k^{th} port. The upper limit will be reached if and only if the ship gets refueled at the $k-1^{\text{th}}$ port. These two constraints narrow the domain of the decision variable $\pi_j^{Finish}k$ and make the model tighter, which will lead to a higher solution speed. The limit will be reached only if the ship refuels at the last port along the route before the k^{th} port. Constraints (17)–(19) define the domains of the decision variables.

2.3. Extensions

On the basis of the model developed in Subsection 2.2, there are several extensions that worth discussion.

The first extension is to take ocean-going ships into consideration. For ocean-going ships, the ship emissions outside the inland river area do not influence the social welfare of the government, namely the decision maker in this paper. Therefore, they would be excluded from the objective function. The LNG bunkering station construction situation of foreign ports visited by the ocean-going ships is assumed to be fixed. Consequently, the LNG and MDO consumption volume of traditional and dual-fueled ship outside the inland river as well as the LNG remaining volume at the first port of call in the inland river area are assumed to be fixed and known. Then, in the ship level model, the ship operators make decisions considering the operating costs of sailing outside the inland river of traditional ship and dual-fueled ships, which are certain and known. The ship will be retrofitted if the total cost of a dual-fueled ship is no less than that of a traditional ship. The port level and government level model are the same as Subsection 2.2 and focus on the inland river area.

The second extension is to consider different capacities of LNG bunkering stations. In this extension, the bunkering station capacity is an decision variable and the ports can choose the capacity from a predetermined set. As for the construction cost we consider it is positively related to the capacity. Meanwhile, in the port level, constraints that assure all LNG bunkering demand of dual-fueled ships have to be satisfied will be added. Therefore, the ports prefer to choose the minimum capacity that can handle the all the demand.

3. Solution method

The main difficulty in solving this problem is its trilevel structure, which leads to interdependence among the decisions of different decision makers. At the government level, subsidy rates $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ are determined. To handle the government-level problem, we enumerate all possible situations for the values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$; then the problem becomes bilevel. In a bilevel problem, there is a leader who first makes a decision and a follower who makes a decision after the leader, and they each make decisions based on their own interests. The leader's decisions will influence the follower's decisions, which in turn, have an impact on the leader's objective function value. In our bilevel problem, the port group that manages all ports is the leader; ship operators who control their own ships are followers who decide independently. In the following subsection, we convert the bilevel problem into an equivalent single-level problem $[SP]$, which can be solved by an off-the-shelf CPLEX solver after model linearization.

3.1. Single-level problem

At the ship level, due to the sufficiently large capacity of LNG bunkering stations, the decisions of ship operators are mutually independent. The only factor that influences the ship operator's decision is the net profit from retrofitting the ship; the ship will be retrofitted if and only if the benefit exceeds the cost. Therefore, the decision-making process at the ship level can be represented by the two sets of binary variables z_j and ξ_j, as follows:

Variables

z_j	binary variable, equal to 1 when ship j can benefit from being retrofitted into a dual-fuel ship, 0 otherwise, $\forall j \in \mathcal{P}$;
ξ_j	parameter used to indicates the difference between z_j and y_j, equal to 0 when $z_j = y_j$, 1 otherwise.

With z_j and ξ_j, the bilevel programming model can be converted to a single-level programming model $[SP]$ as follows:

$$[\boldsymbol{SP}] \quad \max \sum_{i \in \mathcal{P}} \left[-(1-\alpha_{\mathcal{P}})\, C_i^{\mathcal{P}} x_i + \sum_{j \in \mathcal{V}} \left(\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}} \right) \omega_{ji} y_j \right] - \sum_{j \in \mathcal{V}} \hat{M}_j \xi_j \tag{20}$$

subject to constraint (6), constraints (9)–(19) for all $j \in \mathcal{V}$, and the following constraints:

$$z_j - y_j \leq \xi_j, \forall j \in \mathcal{V} \tag{21}$$

$$y_j - z_j \leq \xi_j, \forall j \in \mathcal{V} \tag{22}$$

$$\bar{C}^j_{\text{MDO}} - \left[C^{\mathcal{V}}_j \left(1 - \alpha_{\mathcal{V}}\right) + O_j \sum_{k \in \mathcal{P}'_j} f_j \left(1 - T_{jk}\right) \theta_{jk} + \bar{C}^j_{\text{Dual}} - O_j \Delta_U \sum_{i \in \mathcal{P}} \omega_{ji} \right] \leq M_j z_j,$$

$$\forall j \in \mathcal{V} \tag{23}$$

$$\left[C^{\mathcal{V}}_j \left(1 - \alpha_{\mathcal{V}}\right) + O_j \sum_{k \in \mathcal{P}'_j} f_j \left(1 - T_{jk}\right) \theta_{jk} + \bar{C}^j_{\text{Dual}} - O_j \Delta_U \sum_{i \in \mathcal{P}} \omega_{ji} \right] - \bar{C}^j_{\text{MDO}} \leq M_j \left(1 - z_j\right),$$

$$\forall j \in \mathcal{V} \tag{24}$$

$$\xi_j \geq 0, \forall j \in \mathcal{V}. \tag{25}$$

In $[SP]$, $\hat{M}_j$ and M_j are parameters that are large enough, and the values of $\hat{M}_j$ and M_j are listed below.

Parameters

$\hat{M}_j$ — parameter used in the objective function (20), equal to $\left(\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}}\right) \sum_{k \in \mathcal{P}'_j} L_{jk} R^j_{\text{LNG}} + m_{jk} R'^j_{\text{LNG}}, \forall j \in \mathcal{V}$;

M_j — parameter used in constraints (23) and (24), equal to $\max \left\{ C^{\mathcal{V}}_j \left(1 - \alpha_{\mathcal{V}}\right) + O_j \sum_{k \in \mathcal{P}'_j} f_j \left(1 - T_{jk}\right) + \bar{C}^j_{\text{Dual}}, \bar{C}^j_{\text{MDO}} + \Delta_U \sum_{k \in \mathcal{P}'_j} L_{jk} R^j_{\text{LNG}} + m_{jk} R'^j_{\text{LNG}} \right\}, \forall j \in \mathcal{V}$.

In $[SP]$, constraints (21) and (22) combined with the second part of objective function (20), $\sum_{j\in\mathcal{V}} \hat{M}_j\xi_j$, ensure that $z_j = y_j, j \in \mathcal{V}$. The left-hand side of constraints (23) is the benefit of retrofitting ship j. Constraints (23) and (24) guarantee that $z_j = 1$ if and only if ship j can benefit from being retrofitted. Therefore, the bilevel problem is converted to the equivalent single-level problem $[SP]$, which is a mixed integer nonlinear programming problem, and should be linearized before being solved. The linearization process is given in Appendix A. Solving $[SP]$, we obtain the corresponding government profit $OptG(\alpha_\mathcal{P}, \alpha_\mathcal{V}) = \Delta_E \sum_{j\in\mathcal{V}} \sum_{i\in\mathcal{P}} Opt\omega_{ji} - \alpha_\mathcal{P} \sum_{i\in\mathcal{P}} C_i^\mathcal{P} Optx_i - \alpha_\mathcal{V} \sum_{j\in\mathcal{V}} C_j^\mathcal{V} Opty_j$, in which $Optx_i$, $Opty_j$, and $Opt\omega_{ji}$ are the optimal solution of $[SP]$ with $\alpha_\mathcal{P}$ and $\alpha_\mathcal{V}$. Based on $[SP]$, the trilevel model [MG] can be solved as follows:

$$\text{maximize}_{\alpha_\mathcal{P}=0\%,5\%,\ldots,100\%,\alpha_\mathcal{V}=0\%,5\%,\ldots,100\%} OptG(\alpha_\mathcal{P}, \alpha_\mathcal{V}). \tag{26}$$

4. Numerical Experiments

The algorithm was programmed in C++ with Visual Studio 2019, and we used CPLEX 12.10 to solve $[SP]$ with different values of $\alpha_\mathcal{P}$ and $\alpha_\mathcal{V}$. Multiple numerical experiments were conducted to validate the model and the algorithm. Computational experiments were conducted on a LENOVO XiaoXinPro-13IML 2019 laptop with i7-10710U CPU, 1.10 GHz processing speed and 16 GB of memory.

4.1. Parameter settings

The parameters used in the numerical experiments were collected from previous studies and related reports. First we estimated the environmental benefits of consuming one ton of

LNG, $\Delta_E := R \cdot E_{\text{MDO}} - E_{\text{LNG}}$. Ship emissions contain various pollutants, of which four are considered in this paper: SO_X, NO_X, CO_2, and $PM_{2.5}$. For the value of Δ_E, we adopted $E_{\text{MDO}} = 1,280.31$ USD/ton, $E_{\text{LNG}} = 391.43$ USD/ton, and $\Delta_E = R \cdot E_{\text{MDO}} - E_{\text{LNG}} = 1,119.33$ USD/ton as mentioned in Section 2. Next, we calculated the fuel cost reduction of the ship operator when 1 ton of LNG is consumed, $\Delta_U := R \cdot U_{\text{MDO}} - \hat{U}_{\text{LNG}}$. According to market information, the bunkering price of regular diesel is set at 950 USD/ton and the bunkering price of LNG, $\hat{U}_{\text{LNG}}$, is about 800 USD/ton. Therefore, $\Delta_U = 321$ USD/ton. The LNG purchasing cost of bunkering stations is around 650 USD/ton; thus, $\tilde{U}_{\text{LNG}} = 650$ USD/ton.

To numerically validate the model and algorithm proposed in this paper, we generated a port set of 10 ports and a ship set of 25 ships. According to the International Maritime Organization (2016), the annualized construction cost of an LNG bunkering station is about 4,088,000 USD per year. On this basis, we randomly generated the values of $C_i^{\mathcal{P}}$, $i \in \mathcal{P}$, between 3,270,400 USD ($= 0.8 \times 4,088,000$) and 4,905,600 USD ($= 1.2 \times 4,088,000$).

For ship operators, the total cost of retrofitting a large container ship of 15,000 TEU capacity as a dual-fuel ship is about 25 million to 30 million USD (International Maritime Organization, 2016; Freight Waves, 2019). However, due to waterway conditions, inland river ships have a smaller dead weight tonnage than seagoing vessels do. Therefore, we considered ships with a capacity of around 2000 TEU, whose retrofitting cost ranges from 15 million USD to 20 million USD. We randomly generated the values of $\hat{C}_j^{\mathcal{V}}, j \in \mathcal{V}$. After considering the 8% interest rate and 20 years' depreciation time, the cost was annualized into $C_j^{\mathcal{V}}$. The LNG tank capacity of ship j ranges from 6.39 to 8.52 tons, namely 15 to 20

m^3. The extra cost to ship j of refueling at a port that is not visited by the ship, f_j, ranges from 50 USD to 100 USD. Regarding maintenance costs, a ship that is retrofitted will need less maintenance and repair work, but such work will cost more (International Maritime Organization, 2016). Consequently, we assumed that the annual cost for maintenance and repair is similar for traditional ships and dual-fuel ships; that is, $\bar{C}^j_{\mathrm{Dual}} = \bar{C}^j_{\mathrm{MDO}}, j \in \mathcal{V}$.

We assumed that each ship works for 330 days per year, including sailing and berthing for cargo handling, giving $S = 330 \times 24 = 7920$. The specific amount of annual revenue will not influence the optimal solution as long as the profit of each ship is positive, and we assumed that $G_j = C^{\mathcal{V}}_j + O_j \sum_{k \in \mathcal{P}'_j} f_j(1 - T_{jk}), j \in \mathcal{V}$, which is large enough to keep the profit positive. Ship j visits some of the ports along its route, and which ports the ship visits is randomly generated. The sailing speeds of different ships are randomly generated in the range of 15 to 20 knots, and the LNG consumption rate while sailing, R^j_{LNG}, is closely related to the sailing speed. Meanwhile, the LNG consumption rate while berthing, R'^j_{LNG}, is set to be the same for different ships due to their similar sizes. Considering the small capacity of container ships sailing along the inland river, the berthing time at each port varies from two to five hours.

4.2. Results and Sensitivity Analysis

All of the numerical experiments involved 10 ports along the river and 25 ships sailing among them, and were completed within 2000 seconds. We conducted sensitive analysis with different values of crucial parameters including $C^{\mathcal{P}}_i$, $C^{\mathcal{V}}_j$, Δ_E, U_{MDO}, $\hat{U}_{\mathrm{LNG}}$, and $\tilde{U}_{\mathrm{LNG}}$ to show their influence on the optimization results. Details of the sensitivity analysis are as follows.

First, we conducted the numerical experiment with the parameters given in Subsection 4.1, which is denoted as the basic case ($CBasic$). Next, we solved $[SP]$ with $\alpha_{\mathcal{P}} = \alpha_{\mathcal{V}} = 0$ to represent the scenario without government subsidy, denoted by $CWithout$. The results are presented in Table 1.

Table 1: Results of $CBasic$ and $CWithout$

	$CWithout$	$CBasic$	$C\alpha_{\mathcal{V}}$
$OptG$ (USD)	0	79,681,000	84,604,900
$Opt\alpha_{\mathcal{P}}$	N/A	0.4	0.4
$Opt\alpha_{\mathcal{V}}$	N/A	0.55	$Opt\alpha_{\mathcal{V}1} = 0.45, Opt\alpha_{\mathcal{V}2} = 0.3$
Number of ports with bunkering stations	0	5	6
Number of ships retrofitted	0	25	23
Subsidy expenditure (USD)	0	32,846,100	25,542,300
LNG usage (ton)	0	100,531.65	98,405.44
MDO usage (ton)	$91,712.61$	$6,516.3$	$8,318.17$
Environmental revenue (USD)	0	112,527,000	110,147,000
Solution time (second)	N/A	687.824	N/A

From Table 1 we can see that without the subsidy from the government, no LNG bunkering station will be constructed due to the high cost of investment, and no ship will be retrofitted because of the high cost of investment and the lack of bunkering stations. With the optimal government subsidy plan, an environmental revenue of $112,527,000$ USD can be achieved by providing $32,846,100$ USD of subsidy in total, which yields a net benefit of $79,681,000$ USD. The comparison shows the huge benefit of using LNG as marine fuel and demonstrates the necessity and efficiency of a well-thought-out government subsidy. In practice, the government may provide a higher subsidy rate for particular ports or ships with priority. We conducted case $C\alpha_{\mathcal{V}}$ to indicate the influence of subsidy rates for ports with priority. Considering that the government pays high attention to the environmental revenue that is directly related to the LNG consumption volume, we divide the 25 ships into two groups with different subsidy rates, denoted by $\alpha_{\mathcal{V}1}$ and $\alpha_{\mathcal{V}2}$. Ships in group 2 (ship 2, 11, 12, 13, 15, 18, 22, 24 and 25) have higher LNG consumption rates than those in group 1. From the results in Table 1 we can see that under the differentiated subsidy rates, although the environmental revenue decreases due to the smaller number of retrofitted ships, the lower subsidy expenditure makes $OptG$ even $6.2\%(= (84,604,900-79,681,000)/79,681,000)$ higher than that of $CBasic$. The effectiveness of subsidy plan with priority is indicated by $C\alpha_{\mathcal{V}}$. More in-depth research on subsidy with more complicated priorities should constitute a new research angle. However, differentiated subsidy rates would also lead to extra problems. The potential unfair competition and management difficulty that might brought by the subsidy plan with priorities should be balanced against the higher $OptG$.

Showing how the subsidy rates $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ influence the net government profit $ObjG$ and the consumption volume of LNG as marine fuel, the two sets of results for different values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ are displayed in Figure 3 and Figure 4.

From Figure 3 we can see that a higher $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ do not necessarily lead to higher government net profit; the government must balance environmental revenue and subsidy expenditure to obtain the optimal government subsidy plan. Generally, $ObjG$ is larger when the values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$ are relatively close. In some extreme scenarios, $ObjG$ becomes negative; this phenomenon occurs when there is a wide gap between the values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$. For example, when $\alpha_{\mathcal{P}} = 1$ and $\alpha_{\mathcal{V}} = 0$, most of the ports choose to build bunkering stations, and the government has to pay them a large subsidy. At the ship level, although it is convenient to refuel LNG, the high retrofitting cost prevents ship operators from retrofitting their ships. Therefore, the environmental benefits are trivial, and $ObjG$ becomes negative.

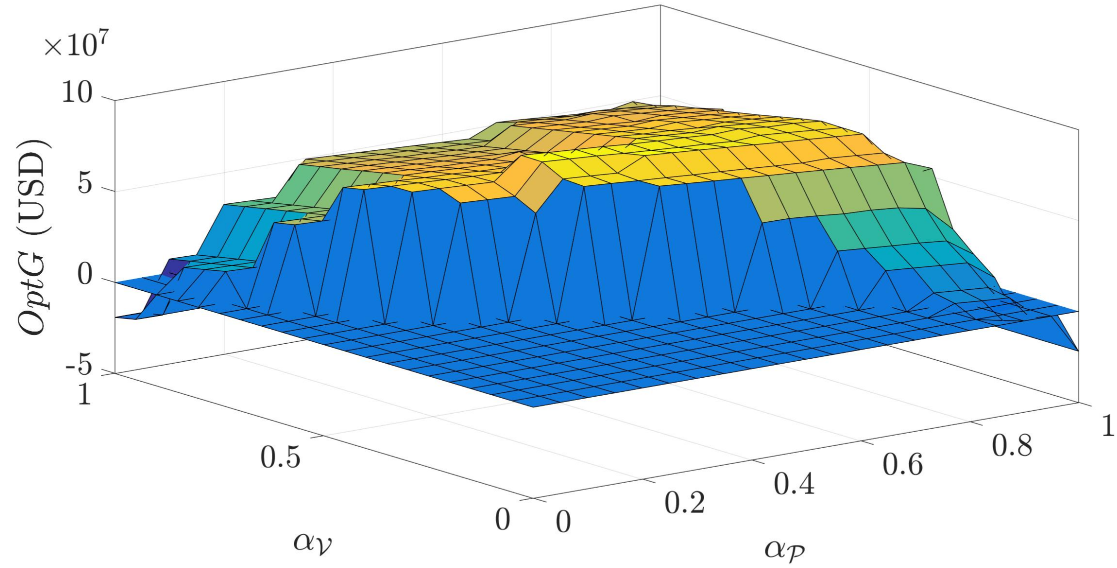

Figure 3: $OptG$ under different values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$

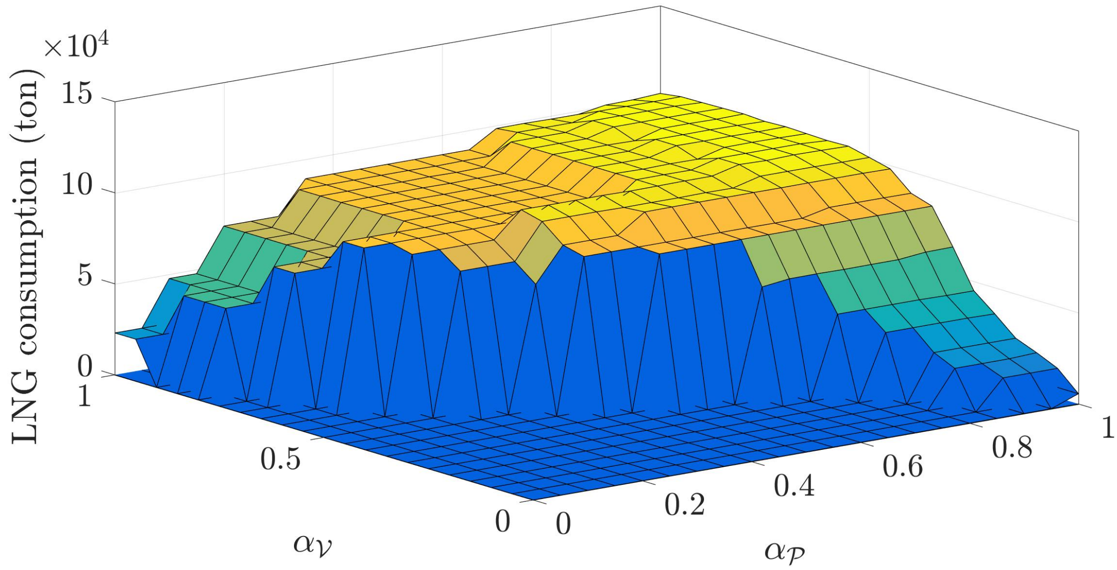

Figure 4: LNG consumption volume under different values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$

Similarly, when $\alpha_{\mathcal{P}} = 0$ and $\alpha_{\mathcal{V}} = 1$, most of the ship operators choose to retrofit their ships and a governmental subsidy is required. Meanwhile, at the port level, with the high demand, very few of the bunkering stations will be built due to the high construction costs. Given this, those retrofitted dual-fueled ships are mainly powered by MDO because of the absence of a complete bunkering system, which yields little environmental benefit. As a result, $ObjG$ becomes negative. This indicates that it is important to determine the subsidy amount wisely, and subsidizing at both the port and ship levels is more efficient than focusing on just one of them. From Figure 4 we can see that with the same value of $\alpha_{\mathcal{P}}$ ($\alpha_{\mathcal{V}}$), a larger $\alpha_{\mathcal{V}}$ ($\alpha_{\mathcal{P}}$) does not always lead to a larger LNG consumption volume. This phenomenon is due to the multi-level structure and different objectives at each level.

Table 2 shows the results of numerical experiments with different values of $C^i_{\mathcal{P}}$, $C^j_{\mathcal{V}}$, Δ_E, U_{MDO}, $\hat{U}_{\text{LNG}}$, and $\tilde{U}_{\text{LNG}}$.

Table 2: Values of crucial parameters

Parameter	Values
Δ_E	500, 700, 900, 1100, 1119.333, 1300, 1500
U_{MDO}	800, 900, 950, 1000, 1100, 1200
$\hat{U}_{\text{LNG}}$	700, 750, 800, 850, 900, 950, 1000
$\tilde{U}_{\text{LNG}}$	550, 600, 650, 700, 750
$C^i_{\mathcal{P}}$ (average value)	3285000, 3650000, 4015000, 4380000, 4745000
$C^j_{\mathcal{V}}$	$[305700, 509500)$, $[509500, 1019000)$, $[1019000, 1528500)$, $[1528500, 2038000)$, $[2038000, 2547500)$

For each crucial parameter, a group of numerical experiments was conducted to analyze the influence of this parameter on $OptG$. For example, in $Group\Delta_E$, there were seven cases with different values of Δ_E, namely $C\Delta_E1$ to $C\Delta_E7$. All of the other parameters of cases in $Group\Delta_E$ were the same as in the basic case $CBasic$. The optimal objective values of the six groups of cases are listed in Figure 5.

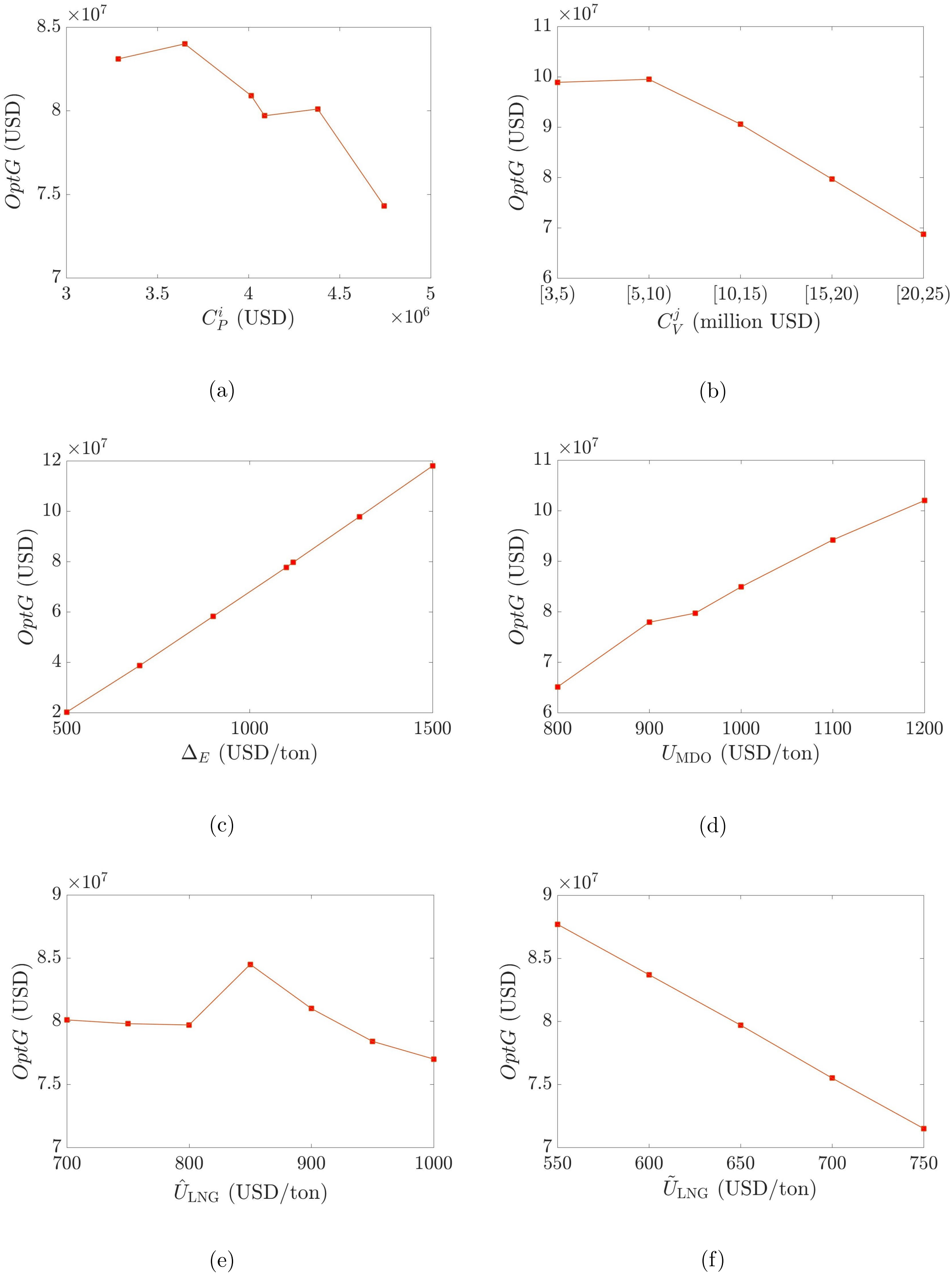

Figure 5: Results of numerical experiments with different values of critical parameters

From Figure 5(a), Figure 5(b), and Figure 5(f) we can see that $OptG$ decreases with $C^i_{\mathcal{P}}$, $C^j_{\mathcal{V}}$, and $\tilde{U}_{LNG}$. This is reasonable because a higher bunkering station construction cost, ship retrofitting cost, and LNG purchasing cost will discourage ports and ships from adopting LNG, so the government needs to provide more generous subsidies in response. Figure 5(c) and Figure 5(d) show that $OptG$ increases with Δ_E, and U_{MDO}. Regarding Δ_E, the result is intuitive, because a larger value of Δ_E leads to higher environmental revenue with the same LNG consumption volume. As for U_{MDO}, the higher the MDO price, the greater the bunker cost that ship operators can save by retrofitting their ships, and the lower the subsidy required to encourage them to do so. The relationship between $OptG$ and $\hat{U}_{\mathrm{LNG}}$ is slightly more complicated, as shown in Figure 5(e), because the value of $\hat{U}_{\mathrm{LNG}}$ influences the bunker cost savings of ship operators and the LNG selling profit of ports in opposite ways. Thus, the subsidies required by ports and ships change in opposite directions.

5. Conclusions

LNG is a promising alternative fuel for the maritime transportation industry, as it can reduce ship emissions and alleviate environmental problems. However, the application of LNG as marine fuel is still in its infancy and is impeded by various factors, such as the "chicken and egg" problem that arises in any transition to alternative fuels. To break the deadlock, the government can provide subsidies for ports and ships to cover part of the costs of constructing LNG bunkering stations and retrofitting ships. Considering the environmental revenue resulting from the use of LNG as marine fuel and the subsidy expenditure, the government needs to select a subsidy rate that will maximize the total profit. Therefore, this study has investigated the government subsidy plan optimization problem for LNG as marine fuel. Three parties are involved in the problem, namely the government, the ports in the area under consideration, and the ships sailing in the area; each party acts in its own interests. Based on this structure, a trilevel programming model was proposed, and then the bilevel problem (port level and ship level) was converted into an equivalent single-level problem. Next, after linearization, the problem becomes a mixed-integer linear problem that can be solved by CPLEX. Finally, an enumeration algorithm was applied to determine the optimal subsidy rates. Two series of numerical experiments were conducted to validate the model and solution method.

Compared with existing literature, this paper reveals the significance of government subsidies in the promotion of LNG as alternative marine fuel and gives a series of operational suggestions on the basis of quantitative analysis. From the results of numerical experiments with different values of $\alpha_{\mathcal{P}}$ and $\alpha_{\mathcal{V}}$, we know that government subsidies significantly promote the application of LNG as marine fuel and therefore achieve a large environmental benefit. Besides, the complex relationships between subsidy rates and net government profit, and between subsidy rates and environmental revenue are also revealed. In extreme cases, the government net profit may become negative. It is therefore necessary to investigate the government subsidy plan optimization problem. Based on the numerical experiments with different values of crucial parameters, their influence on the optimal solution ia revealed. The values of $C^i_{\mathcal{P}}$, $C^j_{\mathcal{V}}$, and $\tilde{U}_{\text{LNG}}$ are negatively related to the government's net profit. Meanwhile, higher values of Δ_E and U_{MDO} lead to higher net government profit. However, the influence of $\hat{U}_{\text{LNG}}$ is more complicated, because $\hat{U}_{\text{LNG}}$ impacts the profit of ports and ships in opposite ways.

Of course, this paper still has its own limitations and interesting potential extensions. First, at the port level, we do not include the competition between ports in the LNG refueling market as well as the traditional marine fuel bunkering market, and future research could take these into account. Meanwhile, the LNG bunkering price can also be decided by the port instead of the government. Second, at the ship level, the ship operators are assumed to work independently, but in reality, they will compete for cargoes in the transportation market. Research considering competition between ships could be developed in the future. Third, based on this paper, the government subsidy plan optimization problem for other alternative marine fuels can be investigated, for example, hydrogen and biofuels. Fourth, we have adopted a subsidy plan with two priority levels in $\alpha_{\mathcal{V}}$; more in-depth research on subsidy plan with more complicated priorities could prove an interesting research direction.

Acknowledgments

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A. Model linearization of $[\boldsymbol{SP}]$

In the objective function (20), there is one nonlinear part, namely the product of y_j ω_{ji}. The product of θ_{jk} and π_{jk}^{Finish} in constraints (9) and the maximum calculations in constraints (10) and (11) also need to be linearized. The following variables are introduced to linearize the model.

Decision variables

$\hat{\omega}_{ji}$	variable introduced to linearize the objective function (20), $\forall j \in \mathcal{V}, \forall i \in \mathcal{P}$;
γ_{jk}^{1}	introduced to linearize constraints (9), $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}'_j$;
γ_{jk}^{2}	binary variable introduced to linearize constraints (10) and (11), $\forall j \in \mathcal{V}, \forall k \in \mathcal{P}'_j$;

To linearize the objective function (20), we replace $y_j\theta_{jk}$ with $\hat{\theta}_{jk}$, and replace $y_j\omega_{ji}$ with $\hat{\omega}_{ji}$. Then the objective function can be rewritten as:

$$[\boldsymbol{SP}] \quad \max \sum_{i\in\mathcal{P}} \left[-(1-\alpha_{\mathcal{P}})\, C_i^{\mathcal{P}} x_i + \sum_{j\in\mathcal{V}} \left(\hat{U}_{\text{LNG}} - \tilde{U}_{\text{LNG}} \right) \hat{\omega}_{ji} \right] - \sum_{j\in\mathcal{V}} \hat{M}_j \xi_j \tag{27}$$

Meanwhile, following constraints should be added:

$$\hat{\omega}_{ji} \le M_{ji} y_j, \forall i \in \mathcal{P}, \forall j \in \mathcal{V} \tag{28}$$

$$\hat{\omega}_{ji} \le \omega_{ji}, \forall i \in \mathcal{P}, \forall j \in \mathcal{V} \tag{29}$$

$$\hat{\omega}_{ji} \ge \omega_{ji} - M_{ji}\left(1 - y_j\right), \forall i \in \mathcal{P}, \forall j \in \mathcal{V} \tag{30}$$

$$\hat{\omega}_{ji} \leq M_{ji}, \forall i \in \mathcal{P}, \forall j \in \mathcal{V} \tag{31}$$

Constraints (9) can be replaced by the following constraints:

$$\pi_{jk}^{Leave} = \pi_{jk}^{Finish} + \theta_{jk} q_j - \gamma_{jk}^1, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{32}$$

$$\gamma_{jk}^1 \leq q_j \theta_{jk}, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{33}$$

$$\pi_{jk}^{Finish} - q_j \left(1 - \theta_{jk}\right) \leq \gamma_{jk}^1, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{34}$$

$$\gamma_{jk}^1 \leq \pi_{jk}^{Finish}, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{35}$$

$$0 \leq \gamma_{jk}^1 \leq q_j, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{36}$$

Constraints (10) and (11) can be replaced by the following constraints:

$$\pi_{jk}^{Finish} \geq 0, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{37}$$

$$\pi_{jk}^{Finish} \leq \pi_{j,k-1}^{Leave} - L_{j,k-1} R_{\text{LNG}}^{j} - m_{jk} R_{\text{LNG}}^{\prime j} + M_{jk} \left(1 - \gamma_{jk}^2\right), k = 2, 3, ..., \left|\mathcal{P}_j'\right|, \forall j \in \mathcal{V} \tag{38}$$

$$\pi_{j1}^{Finish} \leq \pi_{j,\left|\mathcal{P}_j'\right|}^{Leave} - L_{j,\left|\mathcal{P}_j'\right|} R_{\text{LNG}}^{j} - m_{j1} R_{\text{LNG}}^{\prime j} + M_{j1} \left(1 - \gamma_{j1}^2\right), \forall j \in \mathcal{V} \tag{39}$$

$$\pi_{jk}^{Finish} \leq M_{jk} \gamma_{jk}^2, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V} \tag{40}$$

$$\pi_{jk}^{Finish} \geq \pi_{j,k-1}^{Leave} - L_{j,k-1} R_{\text{LNG}}^{j} - m_{jk} R_{\text{LNG}}^{\prime j} - M_{jk} \left(1 - \gamma_{jk}^2\right), k = 2, 3, ..., \left|\mathcal{P}_j'\right|, \forall j \in \mathcal{V} \tag{41}$$

$$\pi_{j1}^{Finish} \geq \pi_{j,\left|\mathcal{P}_j'\right|}^{Leave} - L_{j,\left|\mathcal{P}_j'\right|} R_{\text{LNG}}^{j} - m_{j1} R_{\text{LNG}}^{\prime j} - M_{j1} \left(1 - \gamma_{j1}^2\right), \forall j \in \mathcal{V} \tag{42}$$

$$\pi_{j,k-1}^{Leave} - L_{j,k-1} R_{\text{LNG}}^{j} - m_{jk} R_{\text{LNG}}^{\prime j} \geq -M_{jk} \left(1 - \gamma_{jk}^2\right), k = 2, 3, ..., \left|\mathcal{P}_j'\right|, \forall j \in \mathcal{V} \tag{43}$$

$$\pi_{j,\left|\mathcal{P}_j'\right|}^{Leave} - L_{j,\left|\mathcal{P}_j'\right|} R_{\mathrm{LNG}}^{j} - m_{j1} R_{\mathrm{LNG}}^{\prime j} \geq -M_{j1}\left(1-\gamma_{j1}^{2}\right), \forall j \in \mathcal{V} \tag{44}$$

$$\pi_{j,k-1}^{Leave} - L_{j,k-1} R_{\mathrm{LNG}}^{j} - m_{jk} R_{\mathrm{LNG}}^{\prime j} \leq M_{jk}\gamma_{jk}^{2}, k=2,3,...,\left|\mathcal{P}_j'\right|, \forall j \in \mathcal{V} \tag{45}$$

$$\pi_{j,\left|\mathcal{P}_j'\right|}^{Leave} - L_{j,\left|\mathcal{P}_j'\right|} R_{\mathrm{LNG}}^{j} - m_{j1} R_{\mathrm{LNG}}^{\prime j} \leq M_{j1}\gamma_{j1}^{2}, \forall j \in \mathcal{V} \tag{46}$$

$$\gamma_{jk}^{2} = 0, 1, \forall k \in \mathcal{P}_j', \forall j \in \mathcal{V}. \tag{47}$$

In these constraints, $M_{jk}, j \in \mathcal{V}, k \in \mathcal{P}_j'$ are numbers that are large enough, and the specific values are as follows.

Parameters

M_{jk}	parameter used in constraints (41), equals $q_j + L_{j,k-1}R_{\mathrm{LNG}}^{j} + m_{jk}R_{\mathrm{LNG}}^{\prime j}, \forall j \in \mathcal{V}, k = 2,3,...,\left|\mathcal{P}_j'\right|$;
M_{j1}	parameter used in constraints (42), equals $q_j + L_{j,\left|\mathcal{P}_j'\right|}R_{\mathrm{LNG}}^{j} + m_{j1}R_{\mathrm{LNG}}^{\prime j}, \forall j \in \mathcal{V}$.

B. Extension considering maritime economics

In the mathematical model proposed in the main text, we only consider the operating costs in the ship level model and assume fixed sailing speed and annual revenue in this paper. However, in reality, the sailing speed is a critical decision variable that will influence the annual revenue, which is one of the ship operators' main focuses. Besides, in $[MV_j]$ we ignore the time required for the retrofitting work as well as the revenue loss caused by it. To integrate these factors into the problem, we consider a planning period of Z years. In year $z, z = 1, 2, ..., Z$, the freight rate and sailing demand of ship j are denoted by $freight_j^z$

and $\bar{O}_j^z$, in which $\bar{O}_j^z$ represents the number of round trips that is required to meet the transportation demand and $freight_j^z$ represents the revenue when one round trip is finished by ship j. The operator of ship j decides whether and when to retrofit their ships, denoted by y_j^z, and choose the sailing speed from a predetermined set $\mathcal{S}_j$ at each year, with the aim to maximize the total profit in the planning period. The number of round trips finished in a year depends on the sailing speed and influences the annual revenue. Meanwhile, the fuel LNG consumption rate R_{LNG}^{js} also depends on the sailing speed, and the relationship between the MDO consumption volume R_{MDO}^{js} and R_{LNG}^{js} is the same as in the model proposed in Section 2. In this extension, we develop a new model to describe the problem faced by the operator of ship j in Z years $[MVT_j]$. Before presenting the model, we list the notations needed.

Sets and parameters

Z	the set of years considered, $Z = \{1, 2, ..., \lvert Z \rvert\}$, indexed by z;
$\mathcal{S}_j$	the set of candidate sailing speeds of ship j, indexed by s_j, $\forall j \in \mathcal{V}$;
$freight_j^z$	the freight rate of ship j in year z, $\forall j \in \mathcal{V}, \forall z \in Z$;
O_j^{re}	the time needed to finish the retrofitting work of ship j in the unit of round trip times;
O_{js}^{re}	the time needed to finish the retrofitting work of ship j with sailing speed s_j in the unit of round trip times;
$C_j^{\mathcal{V}z}$	the annual retrofitting cost of ship j if it is retrofitted in year z, $\forall j \in \mathcal{V}, \forall z \in Z$;

842 R_{LNG}^{js} the LNG consumption rate (ton/nm) of ship j while sailing at candidate speed s, $\forall j \in \mathcal{V}, \forall s \in \mathcal{S}_j$;

843 R_{MDO}^{js} the MDO consumption rate (ton/nm) of ship j while sailing at candidate speed s, $\forall j \in \mathcal{V}, \forall s \in \mathcal{S}_j$;

844 $\bar{O}_j^z$ the transportation demand of ship j in year z in the unit of round trips, $\forall j \in \mathcal{V}, \forall z \in Z$;

845 **Decision variables**

846 y_j^z integer variable, equal to 1 when ship j is retrofitted in year z, 0 otherwise, $\forall j \in \mathcal{V}, \forall z \in Z$;

847 $retro_j^z$ integer variable, equal to 1 when ship j is retrofitted in year z or has been retrofitted before, 0 otherwise, $\forall j \in \mathcal{V}, \forall z \in Z$;

848 S_j^{zs} integer variable, equal to 1 when ship j sails at candidate speed s in year z, 0 otherwise, $\forall j \in \mathcal{V}, \forall z \in Z, \forall s \in \mathcal{S}_j$;

849 $Speed_j^z$ the sailing speed of ship j in year z, $\forall j \in \mathcal{V}, \forall z \in Z$;

850 O_j^z the number of trips that ship j finishes in year z, $\forall j \in \mathcal{V}, \forall z \in Z$;

851 $\hat{O}_j^z$ the number of trips that ship j finishes in year z if it keeps working (sailing and berthing at ports for cargo handling or refueling) without a rest, $\forall j \in \mathcal{V}, \forall z \in Z$;

852 θ_{jk}^z binary variable, equal to 1 when ship j refuels LNG at the k^{th} port along its route in year z if it is retrofitted, 0 otherwise, $\forall k \in \mathcal{P}_j', \forall j \in \mathcal{V}, \forall z \in Z$;

853 ω_{ji}^{zs} the LNG refueling volume (ton) of ship j at physical port i in year z with sailing speed s if it is retrofitted, $\forall j \in \mathcal{V}$, $\forall i \in \mathcal{P}, \forall z \in Z, \forall s \in \mathcal{S}_j$;

With these notations, the objective function of $[MVT_j]$ can be written as:

$$[\boldsymbol{MVT_j}] \quad \max \sum_{z\in Z} \left\{ O_j^z freight_j^z - retro_j^z \left[\sum_{z\in Z} C_j^{\mathcal{V}z} y_j^z \left(1-\alpha_{\mathcal{V}}\right) \right.\right.$$
$$\left.\left. + O_j^z \left(\sum_{k\in\mathcal{P}_j'} f_j \left(1-T_{jk}\right) \theta_{jk}^z - \Delta_U \sum_{s\in S_j} S_j^{zs} \omega_{ji}^{zs} \right) + \bar{C}_{Dual}^j \right] - \left(1-retro_j^z\right) \bar{C}_{\text{MDO}}^j \right\} \tag{48}$$

Subject to constraints (9)–(19) for all $s \in \mathcal{S}_j$ and the following constraints:

$$retro_j^1 = y_j^1 \tag{49}$$

$$retro_j^z = retro_j^{z-1} + y_j^z, z = 2, ..., Z \tag{50}$$

$$O_j^{re} = \sum_{s\in\{s|s_j\in S_j\}} O_{js}^{re} S_j^{zs}, \forall z \in Z, \forall j \in \mathcal{V} \tag{51}$$

$$\hat{O}_j^z = S \Big/ \left[\left(\sum_{k\in\mathcal{P}_j'} L_{jk} \Big/ Speed_j^z \right) + \sum_{k\in\mathcal{P}_j'} T_{jk} m_{jk} \right], \forall z \in Z \tag{52}$$

$$O_j^z = \min\left\{ \bar{O}_j^z, \hat{O}_j^z - \max\left\{0, \hat{O}_j^z - \bar{O}_j^z - O_j^{re}\right\} y_j^z \right\}, \forall z \in Z \tag{53}$$

$$Speed_j^z = \sum_{s\in S_j} S_j^{zs} s_j, \forall z \in Z \tag{54}$$

$$\sum_{s_j\in S_j} S_j^{zs} = 1, \forall z \in Z. \tag{55}$$

In the objective function (48), the first part is the freight revenue, which has considered the revenue loss brought by the retrofitting work. The second part represents the minimum operating costs of dual-fueled ships and the third part is the minimum operating costs of traditional ships. The annual retrofitting costs $C_j^{\mathcal{V}z}$ is closely related to the retrofitting timing because it influences the remaining service life of the newly retrofitted ship. Constraints (49) and (50) explain the relationship between y_j^z and $retro_j^z$. Constraints (51) states that the time used to retrofit ship j in the unit of round trip times depends on the sailing speed. Constraints (52) calculate the number of round trips the ship can finish if it keeps working in year z without a rest. Constraints (53) calculate the round trips ship j actually finishes in year z, which depends on the sailing speed, transportation demand and the retrofitting time needed. In this model, we assume that the ship operator will try to use as much as idle time to do the retrofitting work if it is needed. Constraints (54) and (55) state that the ship operator will choose one of the candidate speeds in each year.