Optimal subsidy design for energy generation in ship berthing

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Abstract

Shipping, the backbone of economic development, poses a significant environmental threat. Many government agencies have implemented regulations to mitigate ship air pollution. Three commonly used methods for compliance during berthing are marine diesel oil, scrubber, and shore power. Scrubber and shore power have greater emission reduction potential but can be costlier than marine diesel oil. To encourage their adoption, we optimize the subsidy plan through a bi-level mixed integer programming model where the government at the upper level minimizes the total subsidy amount while ship operators at the lower level choose the most cost-effective energy supply. The problem's complexity arises from the interdependence in the bi-level structure and the nonlinearity in the model. We address this by first converting the model into an equivalent single-level form and then reformulating the model by linearization. Numerical experiments are conducted to assess the model's performance. Results suggest that the promotion of scrubber or shore power starts with large ships in the initial stage. Increasing the number of ships with these technologies reduces subsidies. Additionally, each subsidy corresponds to a specific utilization range, allowing the government to adjust amounts based on target utilization levels.

Keywords

Subsidy design, green shipping, bi-level optimization, scrubber, shore power

1. Introduction

Environment is the foundation for human survival and development, so environmental protection has undoubtedly become the consensus of all walks of life. Shipping, the backbone of economic development, has become one of the biggest threats to the environment. According to the Fourth IMO GHG Study, shipping emissions, including greenhouse gas (GHG), SOx, and particulate matter (PM), represent a non-negligible percentage of total annual anthropogenic emissions and are increasing every year. These exhaust emissions cause more than 70,000 premature deaths annually all over the world (Huang, et al. 2018). Endresen et al. (2003) show that nearly 70% of ship emissions come within 400 km of land, greatly contribute to air quality degradation in coastal areas. This pollution is of particular concern due to its proximity to the population in coastal areas and its potential to grow continually. If no effective control measures are implemented, problems caused by exhaust emissions will

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be exacerbated.

To reduce ship air pollution, IMO (International Maritime Organization) enacted MARPOL Annex VI[1] to limit the main air pollutants, SOx and NOx, contained in ships exhaust gas and revised it by reducing the maximum sulphur content in the exhaust gas to 0.1% by 2015 in emission control area (ECA) and globally to 0.5% by 2020. This sulphur content cap could be achieved by using abatement technologies, such as scrubber, or alternative compliant fuels.

According to the Fourth IMO GHG Study, heavy fuel oil (HFO), cheap but high in sulphur, remains the dominant fuel in international shipping, accounting for 79% of total fuel consumption by energy content in 2018. This type of oil, with a sulphur content of up to 3.5%, cannot meet the requirement of IMO and thus needs to use scrubber to clean exhaust gap before emission. Marine diesel oil (MDO) that is more expensive than HFO but can abide by the 0.5% sulphur content regulation has experienced 6% market share growth in recent years. Another emerging and promising energy supply method, shore power, has been successfully implemented in several ports around the world (Qi, Wang, and Peng 2020). All these methods could greatly reduce sulphur emission and comply with IMO regulations, but their efficiency and costs vary significantly. For example, scrubber can reduce 90–99% SOx and 60–85% PM and using shore power will not generate emissions in port areas. As for the cost, the acquisition costs of scrubbers for 15,000, 110,000, and 310,000 dwt ships are 2.6, 3.3 and 4.2 million USD respectively (Lindstad, Rehn, and Eskeland 2017). Prices of HFO and MDO change every day. Taking Singapore as an example, the prices of HFO and MDO were 390 and 648.5 USD/mt, respectively, on 7 February 2023, but changed to 406.5 and 662.5 USD/mt, respectively, on the next day. The modification cost of a ship to receive onshore power ranges from 500,000 to 2 million USD (Wang, Mao, and Rutherford 2015). The shore power price ranged between 0.17 and 0.2 USD/kWh for ports along the coastline of China in 2019 (Wang, Qi, and Laporte 2022). Since ship operators are most concerned with cost, they usually choose the least costly method, which may not be the most ideal approach to environmental protection. Therefore, the government needs to make subsidy plan to reduce the cost born by ship operators to steer them towards efficient green methods.

Therefore, this research involves two decision-making parties: the government aims to achieve the desired utilization level[2] of each method at the lowest subsidy cost, while the ship operators adopt the least costly energy generating method. A bi-level optimization model is developed to formulate this problem, which is difficult to solve

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[1] The introduction of MARPOL Annex VI can refer to this website: https://www.imo.org/en/OurWork/Environment/Pages/Index-of-MEPC-Resolutions-and-Guidelines-related-to-MARPOL-Annex-VI.aspx

[2] Since green technologies such as scrubber and shore power can significantly reduce harmful emissions, to promote the use of these technologies, some governments may set target utilization level. For example, the California Air Resources Board (CARB) requires that every vessel coming into a regulated California port either use shore power (e.g., plug in to the local electrical grid) or a CARB-approved control technology, such as scrubber, to reduce harmful emissions.

due to the interdependence and nonlinearity. We therefore convert the bi-level model into single-level model and linearize the nonlinear components to make it computationally tractable. Several numerical experiments are conducted to evaluate the performance of the model. Valuable managerial insights are also derived from sensitivity analyses.

The rest of the paper is organized as follows. Section 2 briefly reviews related literature. Section 3 describes the problem and formulates it as a bi-level mixed integer programming model. The solution method is proposed in Section 4 and several numerical experiments are conducted in Section 5. Finally, we provide a conclusion in Section 6.

2. Literature review

The improvement of environmental awareness has made scrubber and shore power hot topics. There are many studies discussing their economic feasibility as well as environmental benefits. Panasiuk and Turkina (2015) use cash flow model to compare the profitability of scrubber and low sulphur fuel under IMO emission requirements. It mentions that investment in scrubber is an effective choice. Lindstad, Rehn, and Eskeland (2017) explore the ways to abide by IMO Sulphur regulations. It recommends scrubber for ships with the highest fuel consumption, diesel for smaller vessels when price of crude oil is lower than $50 per barrel, and desulphurised HFO for less fuel-guzzling ships. Andersson, Jeong, and Jang (2020) compare two different types of wet scrubber via life cycle assessment technique. Closed-loop scrubber is preferred when environment is the priority while open-loop scrubber is better if payback time is more important. Zis, Cullinane, and Ricci (2022) investigate economic and environmental impacts under a series of sulfur reduction regulations. The quantitative analysis confirms that scrubber is more suitable when fuel price is high and ships sail longer time. Similar research can be found on shore power. Yu, Voß, and Tang (2019) study whether it is beneficial to install shore-side electricity equipment and the best time to invest. A case study of Dalian port indicates that ships with higher visiting frequency are more suitable to be equipped with shore power devices; It is more cost-effective for domestic and near-sea shipping to use alternatives to shore power, such as LNG or scrubber; Larger ships are more environmentally beneficial. Lathwal, Vaishnav, and Morgan (2021) investigate cost and emission reduction when ships switch from high-sulfur fuel to shore-based electricity. Results show that using shore power could reduce 88% PM2.5, 39% SO_2, 85% NO (x), $73 million for high-sulfur fuel, and $370 million for low-sulfur fuel, but increases CO_2 emissions by 17%. Stolz et al. (2021) also quantify emission reduction when ships switch from fossil fuels to shore side electricity. It uses Automatic Identification System (AIS) and Monitoring, Reporting and Verification (MRV) scheme data to estimate the auxiliary power demand and emissions at berth for ports in the European Economic Area (EEA) and the United Kingdom (UK). Sun et al. (2022) study the emission reduction effect of ship berthing using shore power. It finds that using shore power requires specific conditions and only a few cities are suitable for using shore power.

The environment protection of scrubber and shore power has been widely recognized, but the investment for these technologies is expensive (Acciaro et al. 2014; Yin et al. 2022). To promote the use of scrubber and shore power and to protect environment, the government usually adopts subsidies. Wang, Qi, and Laporte (2022) design shore power price and subsidy to use shore power. The research finds that pricing and subsidy are effective ways to drive shore power usage, while setting an unreasonably high shore power utilization rate has a negative impact on total profit of ports. Song et al. (2022) use game theory to discuss the influences of government subsidy plan on the usage of shore power between two shipping companies. Compared to other interventions (e.g., environmental taxes and requirements to improve marine oil specifications), subsidies are proved to be better for satisfying multiple participants. Wang, Jiao, and Peng (2023) also use game theory to investigate the impact of government subsidy on shipping company's choice of powering method under different power structures. By comparing the profits with and without government subsidy, it concludes that whether governmental subsidy will have impact on shipping company's choice of shore power or lower sulfur fuel oil depends on carbon price. Lu and Huang (2021) optimize the deployment of shore power considering government subsidy. It finds the optimal conditions for different subsidy strategies.

When considering subsidy, usually multiple parties are involved. Bi-level optimization is a common method for solving multi-party problem (Cai et al. 2020; Liu, Wilson, and Luo 2016). Feng, Pang, and Lodewijks (2015) develop a bi-level model to solve hinterland barge transport planning problem involving both terminal and barge operators. The lower level minimizes turn-around time for barge agent, while the upper level makes sure more requests could be handled at terminal. Chang et al. (2019) redesign maintenance grouping strategies considering interactions between original equipment manufacturer (OEM) and service providers. The upper-level OEM simultaneously minimizes total maintenance service cost, downtime profit loss, and customer dissatisfaction, while all service providers at lower level could select their service components and corresponding service time. Yang, Luo, and Shi (2020) solve problems caused by uncoordinated subsidies for rail transportation of containers in different regions. It develops a bi-level model with network planner in the upper level to decide the optimal subsidy and shippers in the lower level to optimize cost.

After reviewing literature, we can find that most research considers only one innovative technology to solve environmental problem in maritime industry. However, the proliferation of pollution abatement technologies gives ships at berth more options. Therefore, one contribution of this research is to simultaneously consider three techniques: MDO, scrubber, and shore power. Besides, increasing the number of available techniques does not change the model, which means this model is very flexible for practical policy making. There are price differences between these three technologies, so in order to promote a certain technology, we need to consider subsidy. Another contribution is that we consider ship type and target utilization level of three techniques when designing subsidy. Under the same subsidy plan, ships in different types will act differently. Different utilization level will influence subsidy plan. Therefore, results obtained from the model considering ship type and target utilization level are more instructive for practical implementation. The third contribution is that we propose a bi-level mixed integer programming model to solve the problem which is rarely used in subsidy design in ship operation management.

3. Model formulation

3.1 Problem description

This section presents a bi-level optimization model involving government and ship operators. The methodological framework is the Stackelberg game where the government is the leader that determines subsidy for each energy generation method, aiming to achieve the desired utilization levels at the lowest cost, while the ship operators are followers that choose the lowest cost energy generation method considering government subsidies.

In this article we consider a port that abides by 0.5% sulphur content regulation and has already installed shore power facilities to provide shore power service to ships. Ships that visit this port can be divided into four types: without scrubber and shore power equipment, with only scrubber, with only shore power equipment, and with both scrubber and shore power equipment. The first type can only use MDO to supply energy while berthing. The second can choose between MDO and HFO. If HFO is used, exhaust gas needs to be cleaned by scrubber. The third can choose between MDO and shore power. The last one can choose among MDO, HFO, and shore power. The energy generation methods while berthing, i.e., MDO, HFO, and shore power, are represented by a set I. It is indexed by i with $i = 0$ indicating a ship uses MDO to generate energy, $i = 1$ indicating a ship uses HFO to provide energy while using scrubber to clean exhaust gas, and $i = 2$ indicating a ship uses shore power to supply energy. Ships visiting this port are represented by a set V. We assume that information about ship set V is known, including total number of ships, equipment that each ship owns, total energy consumption while berthing, and cost of each method to provide required energy. The total number of ships visiting this port is denoted by n. The number of ships equipped with scrubber but not shore power, with shore power but not scrubber, and with both scrubber and shore power is denoted as n_s, n_p, and n_{sp}, respectively. Since using scrubber and shore power could greatly reduce sulphur emissions, government has set the minimum utilization levels α and β of the two technologies, where $\alpha \leq \frac{n_s+n_{sp}}{n}$, $\beta \leq \frac{n_p+n_{sp}}{n}$, and $\alpha + \beta \leq \frac{n_s+n_p+n_{sp}}{n}$. To achieve these levels, government needs to provide subsidy s_i for a ship that uses energy generation method $i \in I$ to lower the energy cost. The operator of ship $v \in V$ react according to subsidy to make decisions x_i^v on whether to use power generation method i $(x_i^v = 1)$ or not $(x_i^v = 0)$.

3.2 Mathematical model

Before presenting the mathematical model, we list all the notations in Table 1.

Table 1. Notations used in this research

Notations	Definition
Sets and Indices	
I	Set of energy supply methods while berthing, where $I = \{0$=MDO, 1=HFO+scrubber, 2=shore power$\}$
V	Set of ships visiting a port
i	Index of energy supply method while berthing, $i \in I$
v	Index of a ship, $v \in V$
Parameters	
C_i^v	Cost of powering ship v using method i (it does not include government subsidy)
K_i^v	Binary parameter, =1 if ship v can be powered by method i, and =0 otherwise
α	The minimum utilization level of scrubber
β	The minimum utilization level of shore power
Decision variables	
x_i^v	Binary variable, =1 if ship v uses method i to generate energy, and =0 otherwise
s_i	Government subsidy for using method i
$\vec{x}^v$	Vector of decision variable x_i^v for ship v, where $\vec{x}^v = (x_0^v, x_1^v, x_2^v)$
$\vec{s}$	Vector of decision variable s_i, where $s_i = (s_0, s_1, s_2)$

Then, the problem faced by the government can be described by the following model:

$$\text{Min } \sum_{v \in V} \sum_{i \in I} s_i \, x_i^v \tag{1}$$

subject to

$$\frac{\sum_{v \in V} x_1^v}{|V|} \geq \alpha \tag{2}$$

$$\frac{\sum_{v \in V} x_2^v}{|V|} \geq \beta \tag{3}$$

$$s_i \geq 0, \ \forall i \in I \tag{4}$$

$$\vec{x}^v \in \Phi^v(\vec{s}) \ , \ \forall v \in V \tag{5}$$

where $\Phi^v(\vec{s})$ is determined by the following model:

$$\Phi^v(\vec{s}) = \ \text{argmin} \ \sum_{i \in I} (C_i^v - s_i) x_i^v \tag{6}$$

subject to

$$\sum_{i \in I} x_i^v = 1 \tag{7}$$

$$x_i^v \leq K_i^v, \ \forall i \in I \tag{8}$$

$$x_i^v \in \{0,1\}, \ \forall i \in I. \tag{9}$$

The objective function (1) aims to minimize total subsidy. Constraint (2) and (3) set utilization rate for scrubber and shore power separately. Constraints (4) specify the domains of the subsidy decision. Parameters x_i^v depend on decisions of ship operators, which are denoted by $\Phi^v(\vec{s})$.

Since each ship makes decisions independently, we build $\Phi^v(\vec{s})$ for each ship $v \in V$. The objective function (6) aims to minimize its energy cost while berthing. Constraint (7) requires that each ship must choose one method for energy supply. Constraints (8) state that if a ship is to be powered by certain method, it must have corresponding equipment. Constraints (9) are domains of decision of ship operators.

4. Solution method

The problem is difficult to solve because of the interdependence between bi-level structure. The leader's decisions have an impact on the follower's decisions, which in turn, influence the leader's objective function value. What is more, the problem is non-linear. Therefore, we first convert the bilevel model into an equivalent single-level model, and then reformulate the model by linearization. This new model could be easily solved by an off-the-shelf CPLEX solver.

4.1 Single-level model

Since ship operators are most concerned with cost, they will choose the available and least costly method of energy generation. Therefore, the decision-making process at the ship level can be represented by the following constraints:

$$(C_i^v - s_i) - \left(C_j^v - s_j\right) \leq M^v(1 - x_i^v + 1 - K_j^v),\ \forall i \in I,\ j \in I \backslash \{i\},\ v \in V \tag{10}$$

where $M^v = \max_{i=0,1,2} C_i^v$.

Constraints (10) ensure that ship operator will choose the available and lowest cost method.

4.2 Model linearization

The objective (1) contains the product of decision variables, namely $s_i x_i^v$. We linearize it by introducing decision variables z_i^v, which means the subsidy for ship v to be powered by method i. Then, the objective function is converted to:

$$\text{Min } \sum_{v \in V} \sum_{i \in I} z_i^v \tag{11}$$

with four set of constraints:

$$s_i - z_i^v \leq \widehat{M}(1 - x_i^v)\ ,\ \forall i \in I,\ v \in V \tag{12}$$

$$z_i^v \geq 0,\ \forall i \in I,\ v \in V \tag{13}$$

$$z_i^v \leq s_i,\ \forall i \in I,\ v \in V \tag{14}$$

$$z_i^v \leq \widehat{M} x_i^v,\ \forall i \in I,\ v \in V \tag{15}$$

where $\widehat{M} = \max_{v \in V} \max_{i=0,1,2} C_i^v$.

The bilevel model is therefore converted into an equivalent single-level model with objective function (11) and constraints (2)–(4), (7)–(9), (10), (12)–(15).

5. Numerical experiments

In this section, we conducted multiple numerical experiments to validate the model and derive managerial insights. These experiments have different values of crucial parameters, including C_i^v, K_i^v, α, and β. All the experiments were carried out on a Dell XPS 15 9500 laptop with i7-10750H CPU, 2.60 GHz processing speed and 16 GB of memory. The model was implemented in C++ and solved by CPLEX 12.10.

5.1 Parameter setting

The parameters were based on existing studies and reports. The Port of Shanghai (POS) is selected to test subsidy plan under different experiments. Dai et al. (2019) divide container ships visiting POS into 4 categories according to their capacities, i.e., 0–4000 TEU, 4000–8000 TEU, 8000–12000 TEU and 12000 + TEU. For each category, ships fall into this category are the same, which means that these ships have the same capacity, power consumption at berth, and gross tonnage that are set to the average values of this category. The total annual energy consumption for ships that belong to category t while berthing is calculated by following equations:

$$E_t = N_t \times AP_t \times T_t \tag{16}$$

$$AP_t = W_t \times R \times L \tag{17}$$

where E_t is the total annual energy consumption at berth (kWh); N_t is the total number of annual ship calls; AP_t is average power consumption at berth (kW); T_t is the average berthing time for each ship call (h). Since when ships use shore power, it takes an average of 2 hours to connect devices, we added 2 hours to T_t for ships using shore power. W_t is the gross tonnage of the ships in category t (ton). R is the ratio of power consumption by tonnage, set to 0.2 kW/t, and L (set to 0.17) is load factor that measures the utilization rate of power consumption. The values of parameters related to energy consumption are shown in Table 2.

Table 2. Parameter values related to the ship category

	Ship category			
	I	II	III	IV
Average capacity (TEU)	2000	6000	10,000	15,000
Average gross tonnage (ton)	20,000	60,000	100,000	150,000
Total ship calls	6612	2628	1608	1152
Average time at berth (h)	33.2	19.8	24.8	28.9

To calculate cost for each energy supply method per ship call, we first calculate energy consumption of each energy supply method. For MDO and HFO, we need to multiply energy conversion rate. As shown in Wild (2005), it takes an average of 244g MDO or 260.5g HFO to generate 1 kWh energy. We then multiply energy consumption by the corresponding energy price. The price information is obtained from Lindstad, Rehn, and Eskeland (2017) and Yu, Voß, and Tang (2019). The prices for MDO, HFO, and shore power are 644 USD/mt, 491 USD/mt, and 0.12 USD/kWh. Having cost and energy consumption information, the energy cost using different energy supply methods for a ship call can be calculated. The results are shown in Table .

Table 3. Costs (dollar) of energy supply methods per ship call

	Ship category			
	I	II	III	IV
MDO	3548	6347	13250	23160
HFO	6299	7607	14182	23306
Shore power	6489	8024	14606	23673

Table 2 shows ship category according to average gross tonnage. We also mentioned in Section 3.1 that ships visiting a port can be divided into four types: without scrubber and shore power equipment, with only scrubber, with only shore power equipment, and with both scrubber and shore power equipment. Therefore, we have 16 ship types and we use parameter r_c^t to represent the ratio of ships that are equipped with t devices, where $t = \{$neither, scrubber, shore power, both$\}$, in category c, where $c = \{$I, II, III, IV$\}$. For example, if $r_I^{scrubber} = 5\%$, it means that the number of ships that are equipped with scrubber in category I is 331 $(6612 \times 5\%)$. We set 6 scenarios for the ratio which are shown in Table . We assume that the proportion of ships equipped with a certain device is equal in different ship categories.

Table 4. Scenarios for type ratio

	Neither	Scrubber	Shore power	Both
Scenario 1	85%	5%	5%	5%
Scenario 2	70%	10%	10%	10%
Scenario 3	55%	15%	15%	15%
Scenario 4	40%	20%	20%	20%
Scenario 5	25%	25%	25%	25%
Scenario 6	10%	30%	30%	30%

5.2 Computational performance

We set both α and β to 5% under 6 scenarios. The computational results under 6 scenarios are shown in Table 3. The second column is the total subsidy for all ship calls. The third column is the subsidy for each energy supply method for one ship call, where the first number is the subsidy for using MDO, the second one is the subsidy when powering ships with HFO and cleaning exhaust gas with scrubber, and the last number is the subsidy for using shore power. The last column is the running time.

Table 3. Results for 6 scenarios

	Objective (USD)	Subsidy for Methods (USD)	Time (s)
Scenario 1	3415200	{0, 2751, 2941}	2.75
Scenario 2	1762200	{0, 1260, 1677}	14.3
Scenario 3	1372800	{0, 932, 1356}	37.02
Scenario 4	1372800	{0, 932, 1356}	121.27
Scenario 5	1372800	{0, 932, 1356}	109.94
Scenario 6	-	-	>7200

Note: "-" means results cannot be obtained within 7200s.

Table 3 shows that under the same value of α and β, increasing the proportion of ships equipped with scrubber and shore power devices could reduce total subsidy. Because both shore power and scrubber have scale economy, which means it is more beneficial for large-size ships. With the increase of ship size, the cost gap between energy supply methods becomes smaller and thus the subsidies for energy supply methods decrease. From scenario 1 to 6, the ratio of ships equipped with scrubber, shore power devices, and both increase from 5% to 30%, which means more large ships have the mentioned equipment. Since the subsidy for larger ships is cheaper and the requirements for ships using scrubber and shore power remain the same, more large-size ships will be subsidized and thus the total subsidy reduces.

The subsidy for each energy supply method will also reduce. As ships will choose the cheapest available supply method (i.e., MDO), to make ships use scrubber, the subsidy for using scrubber should be at least the cost gap between MDO and scrubber. It is the same for shore power. Since we set requirements for both scrubber and shore power, the cost for these three methods should be equal for at least one category. The cost gaps decrease as ship size increases. With more large ships being able to use scrubber and shore power, the subsidies for these two methods decrease.

Solution time increases with scenario and for scenarios 6, results even cannot be obtained within 7200s. Because as the ratio increases, the constraints become more and more relaxed, the number of iterations increases during the solution process, and the convergence becomes slower, so the solution time becomes longer.

Figure 1 shows the proportion of ships using different energy supply methods in each category under 5 scenarios (Results for scenarios 6 are not shown since we did not obtain them). We can find that the proportion of ships using scrubber and shore power decreases in category I and II while increases in category III and IV when the ratio of ships equipped with these devices increases. This suggests that when promoting scrubber and shore power in maritime industry, it is more cost-effective to implement on large ships.

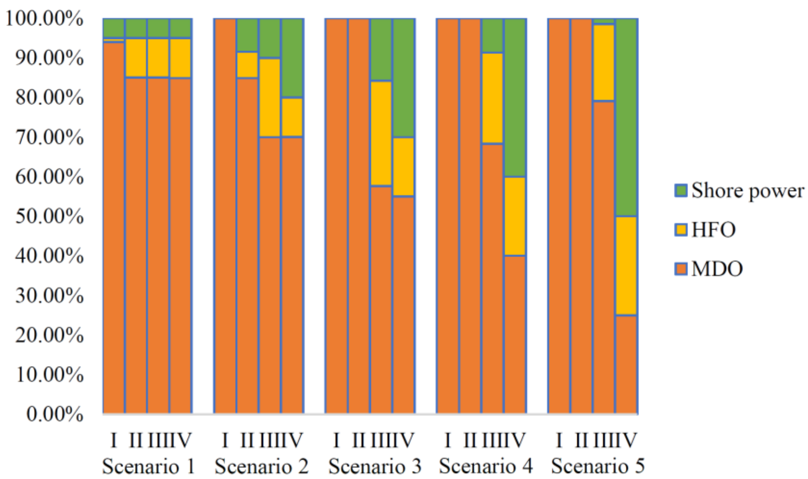


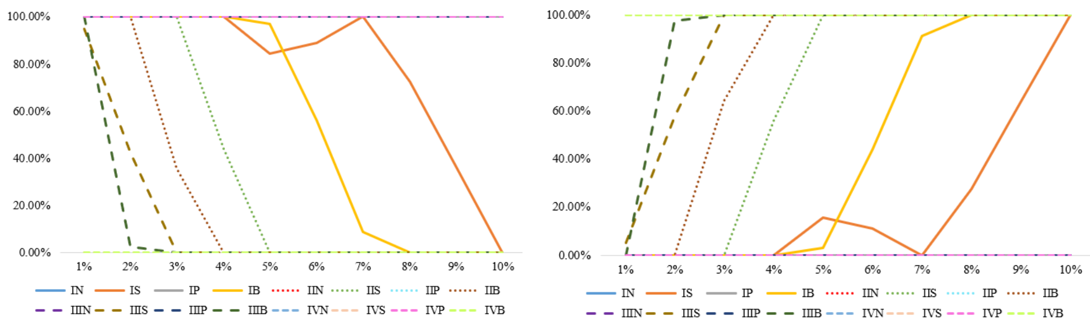
Figure 1. The proportion of ships using different energy supply methods in each category under 5 scenarios

5.3 Sensitivity analysis

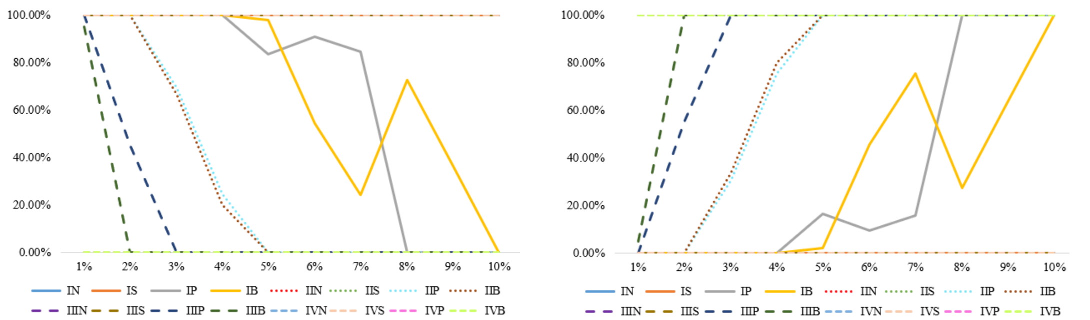
In this section, we investigated the impacts of some crucial parameters, such as α, β, and K_i^v. Since all scenarios should have the same trend, only with different key points, we conducted the sensitivity analysis on scenario 1.

In scenario 1, the ratios of ships equipped without any devices, with only scrubber, with only shore power devices, and with both equipment are 85%, 5%, 5%, and 5%, respectively. To study the impacts of α and β, we set one of them to 0 and the other from 1% to 10%. Figure 2 shows the proportion of ships using a certain energy supply method in different ship types with the change of α and β. I, II, III, and IV represent ship category, which were mentioned in section 5.1. N, S, P, and B represent the equipment owned by ships, where N means ships have neither scrubber nor shore power devices, S means ships only have scrubber, P means ships only have shore power equipment, and B means ships have both devices. Therefore, we can obtain 16 ship types. Figures 2(a,b) show the impacts of α, which means β was set to 0. Therefore, none of the ships chose shore power because of the expensive cost. With the increase of α, the proportion of scrubber-capable ships using MDO is on the decline, such as IS, IB, IIS, IIB, IIIS, IIIB, IVS, and IVB. While the proportion of using scrubbers is on the rise for these ship types. The ratio of category IV changes first, until category I, because the subsidy for ships of category IV to use scrubber is the cheapest while the most expensive for category I. The ratio for IVB remains at 0 for MDO utilization while 100% for HFO. Because all ship calls of this type represent less than 1% of the total number of ship calls. Therefore, to achieve 1% scrubber utilization, all ship calls of this type chose HFO. For ships belong to N and P, since they are not equipped with scrubber, they can only use MDO. The ratio for these ships remains at 100% for MDO utilization while 0 for HFO.

The same trend can be found for the impacts of β in Figures 2(c,d), but for the different ship types. The proportion of ships belong to P and B using MDO declines, while increases for using shore power. For ships belong to N and S, since they do not have shore power equipment, they can only use MDO. The ratio for these ships remains at 100% for MDO utilization while 0 for shore power. The change for category I to IV also has a similar pattern.



(a) The impact of α on the usage of MDO (b) The impact of α on the usage of HFO



(c) The impact of β on the usage of MDO (d) The impact of β on the usage of shore power

Figure 2. The proportion of ships using different energy supply methods

The impacts of α and β on subsidy is shown in Figure 3. When we discuss the impacts of α, the subsidy for both MDO and shore power are 0. Therefore, we only show the trend for the subsidy for scrubber. This is the same for β, where we only show the subsidy for shore power. We can see that with the increase of α and β, the subsidy for scrubber and shore power also increases. Because large ships require less subsidies, they are given priority.

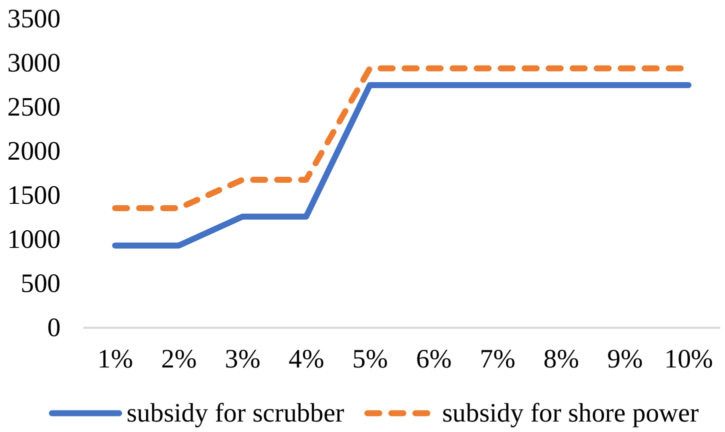


Figure 3. The impacts of α and β on subsidy

To investigate the impacts of K_i^v, we designed a new scenario where all ships are equipped with both scrubber and shore power devices, because we want to figure out what the subsidy plan will be without equipment restriction. When all ships can choose among all the energy supply methods, they will choose the cheapest one. Table 6 shows the subsidy for scrubber and the range of α when only subsidy for scrubber is allowed. When no subsidy is given, all ship calls chose MDO. When the subsidy is 146, the cost of using MDO and HFO is the same for ship category IV. Therefore, all ship calls of category IV can choose between MDO and HFO. When the subsidy is 932, the cost of using MDO and HFO is the same for ship category III, while HFO is the cheapest in category IV. Therefore, all ship calls of category IV chose HFO while those of category III can choose between MDO and HFO. It is the same when subsidy is 1260 and 2750. Table 7 shows the subsidy for shore power and the range of β when only subsidy for shore power is allowed. Table 8 shows the subsidy for scrubber and shore power and the range of α and β. The calculation rule for subsidy and the range is the same as that in Table 6. Figure 4 compares the subsidy for scrubber and shore power under seven scenarios when α and β are set to 5%. We can find that when more ships are equipped with scrubber and shore power devices, the subsidy can be reduced during promotion.

Table 6. The subsidy for scrubber and the range of α when only subsidy for scrubber is allowed

Subsidy for scrubber	The range of α
0	0
146	0–9.6%
932	9.6%–23%
1260	23%–44.9%
2750	44.9%–100%

Table 7. The subsidy for shore power and the range of β when only subsidy for shore power is allowed

Subsidy for shore power	The range of β
0	0
513	0–9.6%
1356	9.6%–23%
1677	23%–44.9%
2941	44.9%–100%

Table 8. The subsidy for scrubber and shore power and the range of α and β

Subsidy for scrubber	Subsidy for shore power	The range of α	The range of β	The range of $a+b$
0	0	0	0	0
146	513	0–a	0–b	0–9.6%
932	1356	0–a	9.6%–9.6%+b	0–13.4%
1260	1677	13.4%–13.4%+a	9.6%–9.6%+b	0–21.9%
2750	2941	44.9%–44.9%+a	0–b	0–55.1%

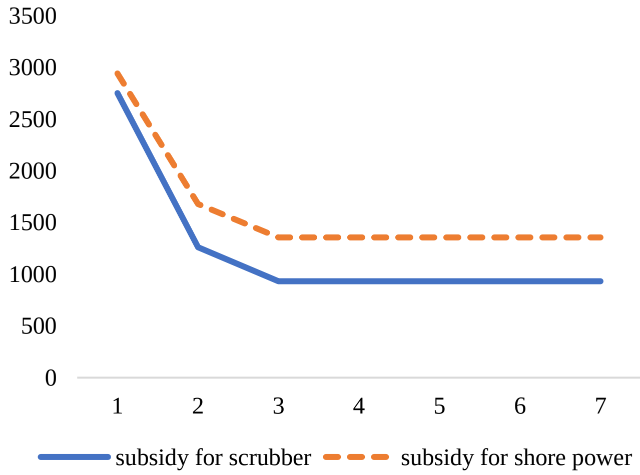


Figure 4. The subsidy for scrubber and shore power under 7 scenarios

We could also study the impacts of C_i^v. But it is obvious that reducing cost could reduce subsidy because the gap will become closer. When technology development makes the cost of using scrubber and shore power lower than MDO, no subsidy will be needed. All ships will actively choose these two supply methods.

From the analysis of section 5.2 and 5.3, we can obtain the following managerial insights. First, in the initial stage of the promotion of scrubber or shore power, we should start with large ships. This is because there is scale economy when installing scrubber or shore power for large ships. Besides, large ships consume more energy. The unit energy consumption cost of HFO and shore power is lower than MDO. Therefore, it is more cost-effective and easier to persuade large ships to use scrubber or shore power than small-size ships. Second, increasing the number of ships equipped with scrubber or shore power will reduce subsidy. Usually, the government chooses a one-time subsidy for ships willing to install the equipment. This research suggests that the government could also consider subsidizing ships for usage of scrubber or shore power. The more ships that are willing to install these devices, the less subsidy that the government will pay. Third, each subsidy corresponds to a utilization range. The government can choose the subsidy amount according to the target utilization level.

6. Conclusion

This research optimizes subsidy plan to promote the use of scrubber and shore power in maritime industry to reduce berth emissions. A bi-level optimization model is developed to formulate this problem where the government in the upper level minimizes total subsidy amount, while ship operators in the lower level choose the cheapest available energy supply method. The problem is difficult to solve due to the interdependence and nonlinearity. We therefore convert the bi-level model into single-level model and linearize the nonlinear components to make it computationally tractable.

We conduct several numerical experiments using the data of Port of Shanghai to evaluate the performance of the model. Results suggest that in the initial stage of the promotion of scrubber or shore power, we should start with large ships. Besides, increasing the number of ships equipped with scrubber or shore power will reduce subsidy. Third, each subsidy corresponds to a utilization range. The government can choose the subsidy amount according to the target utilization level. These results can provide guidance for the practical implementation of subsidies to promote the adoption of green technologies.

One limitation of this research is that we use average value of each ship category due to data limitation. It would be better if we could get more accurate data. For future research, first, we can use machine learning to predict the parameter values for each ship category and use them as model input. Second, we can reformulate a more comprehensive model. For example, we can incorporate the emission reduction efficiency of different green technologies in the objective function. We take the sum of total subsidy and emission amount as a new objective function in the upper level. Also, for the lower-level problem, we can add ship operation cost in the model. For instance, different green technologies may have differences in fuel consumption, and we add the sum of bunkering cost in the objective function. Correspondingly, we need to add constraints regarding fuel consumption. Modifying the objective functions and constraints can make the model more comprehensive.

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