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Optimization of Fleet Scrubber Installation and Utilization Considering Sulfur Emission Control Areas and Marine Fuel Switching

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Abstract: With the rising environmental consciousness, emission pollution has become one of the major concerns of the maritime industry, which is the artery of international trade. To handle the significant cost increase resulting from stringent emission regulations, ship operators have adopted multiple methods, including operational and technical methods. Scrubbers are a mature and effective technology that can reduce sulfur dioxide and particulate matter emissions by cleaning the exhaust gases before emitting them. However, the existing literature regarding the operation of scrubbers does not consider the prohibition of open scrubber usage in the vicinity of certain ports or the variable costs of using scrubbers. Therefore, this study explores the fleet scrubber installation and utilization problem, considering sulfur emission control areas, marine fuel switching, and open-scrubber-prohibited areas. A mixed-integer nonlinear model was developed to formulate and address the problem. Numerical experiments and sensitive analyses based on practical data were conducted to validate the originally proposed model and show the effectiveness of this technology under various scenarios. The results indicated that the operational cost was effectively reduced by using scrubbers, compared to not using them. Additionally, the disparity between total costs with and without scrubbers was significant, regardless of the sailing speed and proportion of the regulation areas. It was also proven that spreading the scrubber installation work over several years will relieve financial pressures due to scrubber investment and thus obtain a better installation plan.

Keywords: maritime transportation; emission reduction technology; onboard scrubber; sulfur emission control area; sustainable shipping

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1. Introduction

Transportation is the backbone of the world's economy and has a close relationship with international trade [1–5]. Given the substantial impacts of the COVID-19 pandemic on the transportation industry [6], shipping still plays a crucial role in the global economy, transporting more than 80% of the world's cargo [7]. Due to the significance of maritime transportation, numerous academic studies have been conducted on management problems in this industry [8–11]. According to the investigation and prediction of United Nations Conference on Trade and Development (UNCTD) [7], the maritime industry's environmental impact cannot be overlooked, and there are plenty of studies focusing on the sustainability aspect of shipping transportation [12–14]. The shipping industry can produce numerous sulfur dioxide emissions that pollute the air and water, leading to health problems for people residing near ports and coastal areas, and have significant negative impacts on the oceans and marine ecosystems [15].

In response, the International Maritime Organization (IMO) has developed and implemented several regulations, particularly the regulation of emission control areas (ECAs). ECAs refer to sea areas in which stricter controls are used to minimize shipping emissions, such as sulfur oxides and nitrogen oxides. The sulfur ECA (SECA), as one ECA, focuses on limiting sulfur oxide emissions. Since 1 January 2015, ships have been subject to a more stringent upper limit of 0.1% for sulfur content within SECAs [16]. Starting from 1 January 2020, another regulation involves limiting the sulfur content used on board outside the SECAs. It regulates that globally marine fuels with a sulfur content of more than 0.5% by mass cannot be adopted on board unless the exhaust gases are properly processed. These regulations regarding marine fuel sulfur content are compulsory unless technical measures with equivalent emission reduction effects are adopted.

As marine fuel prices vary significantly with sulfur content, regulations of the sulfur content limit considerably impact bunker costs, which make up over 60% of the total operating costs and 35% of the total freight rate of a shipping company [7,17–20]. Therefore, shipping companies have been actively seeking countermeasures to control operating costs while obeying stringent regulations.

The first group of methods is operation-based, such as slow steaming [21], fuel efficiency enhancements [22], and shipping route optimization considering emission reduction regulations [23]. While these operation-based methods have proven helpful in certain scenarios, their effectiveness in reducing emissions is limited. As more stringent regulations come into effect, excessive adjustments to operational plans for emission reduction purposes potentially impact service levels or freight revenue. For instance, reducing emissions through slow steaming may result in longer voyage times, leading to increased operating costs and potential delays.

In contrast, technique-based methods offer more comprehensive solutions. One option is to employ exhaust gas treatment methods prior to emission, which includes internal engine modifications and scrubbers. In recent years, emerging technologies have also been explored to reduce shipping emissions. For example, renewable energy sources, represented by wind and solar power, have been investigated as a promising solution to the emission problem [24,25]. Combined with battery systems [26] and fuel cells [27], these renewable energy sources can provide clean and stable power for ships. These technique-based methods hold great promise in significantly reducing shipping emissions while promoting sustainable and environmentally friendly practices in the maritime industry.

However, implementing these advanced technologies has been challenging due to several factors. One major obstacle is the lack of supporting infrastructure, which limits their operational range [28]. Moreover, for existing vessels, significant modifications are required to adapt to these new technologies, resulting in high installation costs and a complex retrofitting process. These factors pose significant challenges to the widespread adoption of new technologies in the shipping industry.

Of all the emission control methods mentioned above, scrubbers are extensively applied due to their mature technology and relatively convenient installation [29]. Scrubbers can help remove sulfur oxides and particulate matter from gases, allowing ships to use high-sulfur fuels while complying with sulfur emission regulations [30]. Although the initial installation costs may be high, the ongoing maintenance costs of scrubber systems are generally lower than those associated with alternative compliance options. As scrubber technology continues to improve, more and more ship owners and operators will likely choose to install these systems to improve their environmental performance and maintain their competitiveness in the industry. These advantages make scrubbers [29,30] an attractive option for ship owners attending to reduce sulfur emissions without switching to more expensive cleaner fuels or investing intensively in new technologies [31–33]. However, the existing literature has not considered the variable costs associated with the use of scrubber systems, nor has it considered the characteristics of different scrubber systems, including differences in variable costs and usage restrictions. Therefore, in this study, we originally proposed a nonlinear model to address these issues. Specifically, an optimization model was developed to formulate the problem. Then, numerical experiments based on data collected from existing studies and official reports were carried out to validate the proposed model and capture managerial insights. The main academic contribution of this study can be summarized as follows.

Firstly, the installation and utilization of fleet scrubbers in liner shipping were investigated, considering SECAs and fuel switching. Secondly, an integer nonlinear programming model was initially developed to formulate the problem. The characteristics of different types of scrubbers and the variable costs of using them were integrated into the proposed model. Considering SECAs and open-scrubber-prohibited areas (OSPA) simultaneously enables companies to make more informed decisions regarding compliance with these emission regulations. Additionally, various numerical experiments and sensitivity analyses were conducted to validate the effectiveness and robustness of the proposed model. Finally, some managerial insights gained from this study are provided to assist shipping companies in reducing costs, improving environmental performance, and maintaining competitiveness in the shipping industry.

The following sections begin by reviewing related works to underscore the academic contributions of this study. Subsequently, in Section 3, a mathematical model is formulated to demonstrate the optimization problem investigated. Then, explanations regarding how to use the proposed model to enhance shipping efficiency while considering emission constraints are provided. Abundant numerical experiments and sensitivity analysis are demonstrated in Section 4 to validate the effectiveness and robustness of the proposed model. Section 5 gives the overall conclusion and directions for further research.

2. Literature Review

2.1. Management Problems with Different Emission Reduction Methods

The shipping industry is responsible for a significant portion of air and water pollution. In response, the IMO has introduced various standards to restrict the emissions of pollutants from ships [34,35]. As a result, reducing pollutant emissions while lowering costs has become an urgent challenge. Numerous studies have been conducted regarding the management problems that emerge in the decision-making process of ship operators/owners, aiming to reduce operational costs and avoid violations of the regulations.

The first stream of literature is about operation-based methods. One approach is the implementation of slow-steaming operations for sailing vessels. Since the shipping fuel consumption rate typically follows a cubic function in relation to shipping speed [36], this can lead to substantial fuel savings and sulfur emission reduction. Marques et al. [37] demonstrated the feasibility of slow steaming by analyzing the cost and emissions from mandatory speed reductions on the global merchant ship fleet. Pelic et al. [38] analyzed the effects of slow steaming using numerical models of two-stroke and four-stroke diesel engines, with a focus on specific fuel consumption and emission reduction. Another effective way is through optimizing route planning to reduce emissions. Moradi et al. [39] developed an artificial intelligence-based model to dynamically adjust a ship's direction and speed, resulting in reduced fuel consumption and shipping expenses. Similarly, Poonthalir et al. [40] employed a hybrid particle swarm optimization approach and incorporated route cost and carbon emissions into the objective function. Moreover, shipping routes and speed can be jointly considered to minimize total fuel consumption and reduce fuel emissions [21,41]. By incorporating these factors into route optimization, shipping companies can achieve significant reductions in both fuel consumption and emissions.

The second group of methods is technique-based, which involves reducing shipping emissions by implementing various technologies. One measure is to use renewable fuels to reduce sulfur emissions. Korberg et al. [25] conducted a thorough analysis of the costs associated with a range of fuel options, including biofuels, electrofuels, bio-electrofuels, liquid hydrogen, and electricity. They identified the most suitable fuel categories for four distinct ship types, aiming to simultaneously reduce emissions and minimize costs. Another measure is to use cleaner fossil fuels. This usually requires ship modifications, such as installing dual-fuel engines designed to operate on two different fuels, typically a conventional fuel like diesel and an alternative fuel like liquefied natural gas (LNG). Tan et al. [31] proposed a mixed-integer model that considers the combinational aspects of different fuel types to minimize the total cost of bunker purchases. To meet the standards of SECA, Shih et al. [42] presented an optimization model based on the dual-fuel engine configuration. Their method considered LNG and low-sulfur fuel oils (LSFOs) with a sulfur content of 0.1% and 0.5% to comply with IMO requirements. The implementation of dual-fuel engines enables ships to seamlessly switch between different fuels during various operating modes, resulting in reduced fuel consumption and emissions. However, carrying different types of fuels will increase the complexity and maintenance difficulty of the ship, as well as its operating costs.

In summary, the literature above explores various methods for reducing shipping emissions in the shipping industry. These studies emphasize the significance of incorporating operational strategies and technique-based solutions to attain reductions in fuel consumption, operational expenses, and adherence to emission regulations. Research about the adoption of onboard scrubbers is reviewed in Section 2.2.

2.2. Studies Regarding Onboard Scrubbers

Onboard scrubbers are an effective system for reducing sulfur and particulate matter emissions from ships' exhaust gases. Multiple studies have validated the effectiveness of scrubbers in emission reduction. Flagiello et al. [30] found that scrubbers can greatly reduce pollutant emissions. The emissions of polycyclic aromatic hydrocarbons in scrubber-washed water were found to be well within the quality standards established by the European Union and the United States of America guidelines. Furthermore, the concentrations of heavy metals resulting from scrubbing were generally better than the water quality standards. Meanwhile, the comparison between onboard scrubbers and other emission reduction methods constitutes a non-negligible part of the existing literature. Tan et al. [43] conducted a study on the impact of stream velocity on two approaches to emission reduction: green fuels and scrubbers. Their research indicated that, in most cases, scrubbers are a more favorable choice for reducing sulfur emissions compared to green fuels.

The cost-effectiveness of scrubbers is another topic that has attracted extensive attention. For instance, Zhu et al. [29] conducted a cost–benefit analysis comparing three methods: LSFOs, scrubber installation, and the use of non-petroleum-based fuels. Their analysis concluded that scrubbers are more economically viable, with a higher net present value and lower annual unit cost. Zis et al. [33] conducted a comprehensive investigation into the economic and environmental impacts of onboard scrubbers employed to comply with sulfur limits for different types of ships in SECAs. Their findings suggested that investing in scrubbers is more profitable when fuel prices are higher, particularly for ships that spend a relatively greater amount of time sailing. In another study, Fan et al. [32] developed a refined net present value model to analyze the decision-making process of container shipping companies considering fuel switching and scrubber installation for mixed compliance options. After investigating various factors, they found that installing scrubbers becomes the most beneficial option with a large price disparity between very low sulfur fuel oil and heavy fuel oil (HFO). Similarly, Han and Wang [18] developed a conditional value-at-risk model to evaluate the economic impact of installing scrubbers on existing vessels to purify exhaust gases. The model examined various combinations of shipping fuel costs over ten years and concluded that scrubber installation is the optimal strategy for emission reduction and cost minimization.

The aforementioned studies highlighted the feasibility and effectiveness of onboard scrubbers as a viable solution for ships to reduce their pollutant emissions, particularly sulfur emissions, and compliance with emission regulations. However, these traditional approaches mainly considered scrubbers as an operational strategy or merely explored the economic benefits of scrubber usage without delving into the impacts of different scrubbers and fuel types on costs. Moreover, they did not consider OSPAs in their model, focusing solely on SECAs, which limits the applicability of their scenarios.

Based on these findings, this study aims to delve deeper into the practical application of scrubbers in maritime operations. Specifically, this study aims to investigate how operational costs can be minimized through a combination of fuel switching and scrubber utilization in line with the requirements of SECAs and OSPAs. The goal of this study is to explore a more cost-effective operational approach in the maritime industry, pioneering new insights in this domain. Thus, this study investigates the management problem regarding onboard scrubbers, optimizing the fleet scrubber installation and utilization while considering SECAs and fuel switching. By addressing this issue, this study seeks to contribute to the understanding and resolution of challenges associated with reducing shipping emissions practically and efficiently.

3. Problem Description and Model Formulation

This section includes background information on the proposed model, the definition of the shipping management problem, and the development of a scrubber-based scheduling method.

3.1. Background Information

The shipping company currently faces the challenge of operating one shipping route while complying with increasingly strict emission regulations, including the sulfur content limits of marine fuels used in and out of SECAs. Given the regulation, the shipping company decides to install scrubbers on the fleet deployed, which consists of a set of container ships, denoted by $P, j \in P$. All deployed ships sail at a predetermined speed, and the fuel consumption rates of ship j while sailing and berthing are denoted by g_j^{S} and g_j^{B}. Currently, there are two types of scrubbers available: closed scrubbers and open scrubbers. For the same ship, closed scrubbers have a higher fixed installation and more variable costs than open scrubbers, namely $FI_j^{\mathrm{C}} > FI_j^{\mathrm{O}}$, $VI_j^{\mathrm{CS}} > VI_j^{\mathrm{OS}}$, and $VI_j^{\mathrm{CB}} > VI_j^{\mathrm{OB}}$. In practice, open scrubbers emit liquid exhaust while operating, which can lead to ocean acidification and pose health problems for people residing near ports or coastal areas. Therefore, some ports set OSPAs to forbid the use of open scrubbers in the vicinity to control pollution. The main characteristics of open and closed scrubbers are summarized as follows.

- Open scrubber, which involves using seawater to wash out sulfur dioxide from the exhaust gases. Disadvantages: it can cause seawater pollution, so some ports prohibit the use of open scrubbers while berthed or sailing near the port. Advantages: lower installation cost and lower variable cost during usage (pollutes seawater but not the atmosphere).
- Closed scrubber, which involves reacting sodium bicarbonate with sulfur dioxide in the ship's exhaust gases. Disadvantages: higher installation cost and higher variable cost during usage. Advantages: the solid by-products generated can be offloaded at the port without causing pollution; therefore, there is no restriction on the application area from competent authorities.

Combining the regulation of SECAs and OSPAs, the set of regulation scenarios along the shipping route R includes four situations: no emission regulation, being within a SECA, being within an OSPA, and being within both an OSPA and a SECA. Figure 1 shows an example of a liner shipping route with three ports of call. The blue double line represents the SECA, and the orange circle represents the OSPA. Specifically, a SECA refers to specific coastal areas with a more stringent upper limit of 0.1% for marine fuel sulfur content. On the other hand, OSPAs are designated zones around ports where the use of open scrubbers is restricted. In the real world, there may be an overlap between these two areas.

Figure 1. Illustration of sulfur emission control areas and open-scrubber-prohibited areas.

To complete a closed loop along the route, a deployed container ship needs to sail D_r nm and berth T_r hours under regulation scenario r, $r \in R$. According to the regulation details, a set of marine fuels, denoted by F, with different sulfur contents and fuel prices p_f, $f \in F$, can be used while a ship is operated along part of the route. Considering the current sulfur content regulations on marine fuel used onboard, three types of fuels are included, which have the sulfur content of 0.1%, 0.5%, and 3.5%, respectively.

With the objective to minimize the total operational costs, the shipping company has to decide whether to install a scrubber on ship j, $j \in P$ and which kind of scrubber to install, denoted by η_j^N, η_j^O, η_j^C. Additionally, given the variable cost of using scrubbers and the price disparity between different fuel types, the shipping company also makes a scrubber usage plan, denoted by $\zeta_{jr}^{OS}, \zeta_{jr}^{OB}, \zeta_{jr}^{CS}, \zeta_{jr}^{CS}$, and marine fuel choices, denoted by π_{jrf}^S, π_{jrf}^B, under different emission regulation scenarios.

According to the regulations set by the IMO, the sulfur content in marine fuel should not exceed 0.5%. In SECAs, the sulfur content of the fuel used should not exceed 0.1%. However, when utilizing a scrubber, fuel with a sulfur content of 3.5% can be used and still not violate the sulfur content regulation. It is important to note that LSFOs with lower sulfur content generally come at a higher price. Based on this information, Table 1 illustrates the permitted fuels for different scrubber installations in various areas. Additionally, considering that the scrubber installation cost is a one-time investment at the beginning of the scrubber usage, an upper bound of the total scrubber installation costs for the whole fleet is set, denoted by FI.

Table 1. The marine fuel sulfur content limits under different scenarios.

Scrubber Usage	None	SECA	OSPA	SECA & OSPA
None	$\leq$0.5%	$\leq$0.1%	$\leq$0.5%	$\leq$0.1%
Open scrubber	No requirement	No requirement	$\leq$0.1%	$\leq$0.1%
Closed scrubber	No requirement	No requirement	No requirement	No requirement

3.2. Model Formulation

3.2.1. Notations Used to Formulate the Problem

Before the mathematical model, Tables 2 and 3 display the notations that are used to construct the proposed model to solve the proposed scrubber management problem.

Table 2. Notations of the parameter.

Parameter	Description
P	the set of ships sailing along the route, indexed by j
R	the set of emission regulation scenarios on the route, where 1 represents no emission regulation, 2 represents being within a SECA, 3 represents being within an OSPA, and 4 represents being within both an OSPA and a SECA, indexed by r
F	the set of available fuels, where 1 represents fuel with a sulfur content of 3.5%, 2 represents fuel with a sulfur content of 0.5%, and 3 represents fuel with a sulfur content of 0.1%, indexed by f
D_r	the sailing distance under regulation scenario r to finish a closed trip, measured in nautical miles (nm), $\forall r \in R$
T_r	the berthing time under regulation scenario r to finish a closed trip, measured in hours, $\forall r \in R$
g_j^{S}	the fuel consumption rate of ship j while sailing, measured in ton/nm, $\forall j \in P$
g_j^{B}	the fuel consumption rate of ship j while berthing, measured in ton/hour, $\forall j \in P$
P_f	the price of fuel type f, measured in USD/ton, $\forall f \in F$
FI_j^{O}	the equivalent hourly fixed installation costs of a closed scrubber of ship j, measured in USD/hour, $\forall j \in P$
FI_j^{C}	the equivalent hourly fixed installation costs of an open scrubber of ship j, measured in USD/hour, $\forall j \in P$
$Speed$	the sailing speed of deployed ships, measured in nm/hour
TFI_j^{O}	the total fixed installation costs of an open scrubber of ship j, measured in USD, $\forall j \in P$
TFI_j^{C}	the total fixed installation costs of a closed scrubber of ship j, measured in USD, $\forall j \in P$
FI	the upper bound of total installation costs, measured in USD
VI_j^{OS}	the variable costs of an open scrubber while sailing of ship j, measured in USD/nm, $\forall j \in P$
VI_j^{OB}	the variable costs of an open scrubber while berthing of ship j, measured in USD/hour, $\forall j \in P$
VI_j^{CS}	the variable costs of a closed scrubber while sailing of ship j, USD/nm, $\forall j \in P$
VI_j^{CB}	the variable costs of a closed scrubber while berthing of ship j, USD/hour, $\forall j \in P$

Table 3. Notations of the decision variable.

Variable	Description
η_j^{N}	binary variable, equal to 1 if no scrubber is installed on ship j, 0 otherwise
η_j^{O}	binary variable, equal to 1 if the open scrubber is installed on ship j, 0 otherwise
η_j^{C}	binary variable, equal to 1 if the closed scrubber is installed on ship j, 0 otherwise
ξ_{jr}^{OS}	binary variable, equal to 1 if the open scrubber of ship j is used under scenario r while sailing, 0 otherwise
ξ_{jr}^{OB}	binary variable, equal to 1 if the open scrubber of ship j is used under scenario r while berthing, 0 otherwise
ξ_{jr}^{CS}	binary variable, equal to 1 if the closed scrubber of ship j is used under scenario r while sailing, 0 otherwise
ξ_{jr}^{CB}	binary variable, equal to 1 if the closed scrubber of ship j is used under scenario r while sailing, 0 otherwise
π_{jrf}^{S}	binary variable, equal to 1 if fuel f is used on ship j under scenario r while berthing, 0 otherwise
π_{jrf}^{B}	binary variable, equal to 1 if fuel f is used on ship j under scenario r while sailing, 0 otherwise

3.2.2. Formula for the Scrubber-Based Shipping Management Problem

The objective function is to minimize the operational cost, which is calculated as the sum of the fixed installation costs of scrubbers (considering the average costs over their lifespan), the variable costs associated with using scrubbers (such as sodium bicarbonate and additional fuel consumption), and bunker costs. For the convenience of expression, the planning period is set at P weeks. Then, the objective function can be expressed as:

$$
\begin{gathered}
[\mathrm{M1}] \ \rightarrow \ \min \textstyle\sum_{j \in P} \sum_{r \in R} \left[\left(\eta_j^{\mathrm{O}} \cdot FI_j^{\mathrm{O}} + \eta_j^{\mathrm{C}} \cdot FI_j^{\mathrm{C}} \right) \cdot \left(D_r / Speed + T_r \right) \right] + \\
\textstyle\sum_{j \in P} \sum_{r \in R} \left(\xi_{jr}^{\mathrm{OS}} \cdot VI_j^{\mathrm{OS}} \cdot D_r + \xi_{jr}^{\mathrm{OB}} \cdot VI_j^{\mathrm{OB}} \cdot T_r + \xi_{jr}^{\mathrm{CS}} \cdot VI_j^{\mathrm{CS}} \cdot D_r + \xi_{jr}^{\mathrm{CB}} \cdot VI_j^{\mathrm{CB}} \cdot T_r \right) + \\
\textstyle\sum_{j \in P} \sum_{r \in R} \sum_{f \in F} [P_f \cdot \left(\pi_{jrf}^{\mathrm{S}} \cdot g_j^{\mathrm{S}} \cdot D_r + \pi_{jrf}^{\mathrm{B}} \cdot g_j^{\mathrm{B}} \cdot T_r \right)], \forall j \in P, \forall r \in R, \forall f \in F
\end{gathered} \tag{1}
$$

The objective function needs to satisfy the following constraints. First, as shown in constraint (2), each ship in the fleet can be equipped with either a closed scrubber, an open scrubber, or no scrubber, and only one of them can be chosen.

$$\eta_j^{\mathrm{N}} + \eta_j^{\mathrm{O}} + \eta_j^{\mathrm{C}} = 1,\ \forall j \in P \tag{2}$$

Next, as shown in constraint (3), due to the one-time investment required for scrubber installation costs, the shipping company sets an upper limit of FI on the total expenditure for scrubber installations to ensure smooth cash flow management.

$$\sum_{j \in P} \left(TFI_j^{\mathrm{O}} \cdot \eta_j^{\mathrm{O}} + TFI_j^{\mathrm{C}} \cdot \eta_j^{\mathrm{C}} \right) \leq FI \tag{3}$$

Additionally, constraints (4) and (5) state that scrubbers can be used only when they are installed.

$$\xi_{jr}^{\mathrm{OS}}, \xi_{jr}^{\mathrm{OB}} \leq \eta_j^{O},\ \forall j \in P, \forall r \in R \tag{4}$$

$$\xi_{jr}^{\mathrm{CS}}, \xi_{jr}^{\mathrm{CB}} \leq \eta_j^{C},\ \forall j \in P, \forall r \in R \tag{5}$$

Finally, constraints (6) and (7) imply that for each ship j in scenario r, it is mandatory to utilize at least one type of fuel during sailing and berthing operations.

$$\pi_{jr1}^{\mathrm{S}} + \pi_{jr2}^{\mathrm{S}} + \pi_{jr3}^{\mathrm{S}} = 1,\ \forall j \in P, \forall r \in R \tag{6}$$

$$\pi_{jr1}^{\mathrm{B}} + \pi_{jr2}^{\mathrm{B}} + \pi_{jr3}^{\mathrm{B}} = 1,\ \forall j \in P, \forall r \in R \tag{7}$$

In the first scenario (r = 1), when the ships are out of the SECA and OSPA, the satisfaction of constraints (8)–(13) is required. Constraints (8) and (9) demonstrate that without installing a scrubber, fuel with a sulfur content exceeding 0.5% cannot be used. Constraints (10)–(13) show that by installing an open/closed scrubber but not using them, the sulfur content of the fuel must also be limited to 0.5% or less. However, when an open/closed scrubber is used, the choice of fuel becomes unrestricted.

$$\eta_j^{\mathrm{N}} \cdot \pi_{j11}^{\mathrm{S}} = 0,\ \forall j \in P \tag{8}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j11}^{\mathrm{B}} = 0,\ \forall j \in P \tag{9}$$

$$1 - \left(\eta_j^{\mathrm{O}} - \xi_{j1}^{\mathrm{OS}} \right) \geq \pi_{j11}^{\mathrm{S}},\ \forall j \in P \tag{10}$$

$$1 - \left(\eta_j^{\mathrm{O}} - \xi_{j1}^{\mathrm{OB}} \right) \geq \pi_{j11}^{\mathrm{B}},\ \forall j \in P \tag{11}$$

$$1 - \left(\eta_j^{\mathrm{C}} - \xi_{j1}^{\mathrm{CS}} \right) \geq \pi_{j11}^{\mathrm{S}},\ \forall j \in P \tag{12}$$

$$1 - \left(\eta_j^{\mathrm{C}} - \xi_{j1}^{\mathrm{CB}} \right) \geq \pi_{j11}^{\mathrm{B}},\ \forall j \in P \tag{13}$$

In the second scenario (r = 2), when the ships are within a SECA and out of an OSPA, the satisfaction of constraints (14)–(25) is required. Constraints (14)–(17) stipulate that fuel containing more than 0.1% sulfur cannot be utilized when no scrubber is installed. Constraints (18)–(25), moreover, indicate that when an open/closed scrubber is installed but not utilized, the sulfur content of the fuel must also be restricted to 0.1% or lower. Nonetheless, the utilization of an open/closed scrubber allows for unrestricted fuel selection in this scenario.

$$\eta_j^{\mathrm{N}} \cdot \pi_{j21}^{\mathrm{S}} = 0,\ \forall j \in P \tag{14}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j21}^{\mathrm{B}} = 0,\ \forall j \in P \tag{15}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j22}^{\mathrm{S}} = 0,\ \forall j \in P \tag{16}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j22}^{\mathrm{B}} = 0,\ \forall j \in P \tag{17}$$

$$1 - (\eta_j^{\mathrm{O}} - \xi_{j2}^{\mathrm{OS}}) \geq \pi_{j21}^{\mathrm{S}},\ \forall j \in P \tag{18}$$

$$1 - (\eta_j^{\mathrm{O}} - \xi_{j2}^{\mathrm{OB}}) \geq \pi_{j21}^{\mathrm{B}},\ \forall j \in P \tag{19}$$

$$1 - (\eta_j^{\mathrm{O}} - \xi_{j2}^{\mathrm{OS}}) \geq \pi_{j22}^{\mathrm{S}},\ \forall j \in P \tag{20}$$

$$1 - (\eta_j^{\mathrm{O}} - \xi_{j2}^{\mathrm{OB}}) \geq \pi_{j22}^{\mathrm{B}},\ \forall j \in P \tag{21}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j2}^{\mathrm{CS}}) \geq \pi_{j21}^{\mathrm{S}},\ \forall j \in P \tag{22}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j2}^{\mathrm{CB}}) \geq \pi_{j21}^{\mathrm{B}},\ \forall j \in P \tag{23}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j2}^{\mathrm{CS}}) \geq \pi_{j22}^{\mathrm{S}},\ \forall j \in P \tag{24}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j2}^{\mathrm{CB}}) \geq \pi_{j22}^{\mathrm{B}},\ \forall j \in P \tag{25}$$

In the third scenario (r = 3), compliance with constraints (26)–(31) is essential within the restricted area of open scrubber operation. Constraints (26)–(29) show that without a closed scrubber, fuel containing over 0.5% sulfur cannot be adopted. Constraints (30) and (31) indicate that when a closed scrubber is installed but not utilized, the sulfur content of the fuel must also be restricted to 0.5% or lower. However, when a closed scrubber is installed and actively utilized, there are no limitations on fuel selection.

$$\eta_j^{\mathrm{N}} \cdot \pi_{j31}^{\mathrm{S}} = 0,\ \forall j \in P \tag{26}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j31}^{\mathrm{B}} = 0,\ \forall j \in P \tag{27}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j31}^{\mathrm{S}} = 0,\ \forall j \in P \tag{28}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j31}^{\mathrm{B}} = 0,\ \forall j \in P \tag{29}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j3}^{\mathrm{CS}}) \geq \pi_{j31}^{\mathrm{S}},\ \forall j \in P \tag{30}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j3}^{\mathrm{CB}}) \geq \pi_{j31}^{\mathrm{B}},\ \forall j \in P \tag{31}$$

In the fourth scenario (r = 4), when operating within the prohibited area for open scrubbers and the SECAs, it is necessary to satisfy constraints (32)–(43). Constraints (32)–(39) state that in the absence of an installed scrubber, only fuel with a sulfur content not exceeding 0.1% can be utilized. Constraints (40)–(43) indicate that when a closed scrubber is installed but not utilized, the sulfur content of the fuel must also be restricted to 0.1% or lower. However, when a closed scrubber is installed and actively utilized, there are no restrictions on fuel usage.

$$\eta_j^{\mathrm{N}} \cdot \pi_{j41}^{\mathrm{S}} = 0,\ \forall j \in P \tag{32}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j41}^{\mathrm{B}} = 0,\ \forall j \in P \tag{33}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j42}^{\mathrm{S}} = 0,\ \forall j \in P \tag{34}$$

$$\eta_j^{\mathrm{N}} \cdot \pi_{j42}^{\mathrm{B}} = 0,\ \forall j \in P \tag{35}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j41}^{\mathrm{S}} = 0,\ \forall j \in P \tag{36}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j41}^{\mathrm{B}} = 0,\ \forall j \in P \tag{37}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j42}^{\mathrm{S}} = 0,\ \forall j \in P \tag{38}$$

$$\eta_j^{\mathrm{O}} \cdot \pi_{j42}^{\mathrm{B}} = 0,\ \forall j \in P \tag{39}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j4}^{\mathrm{CS}}) \geq \pi_{j41}^{\mathrm{S}},\ \forall j \in P \tag{40}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j4}^{\mathrm{CB}}) \geq \pi_{j41}^{\mathrm{B}},\ \forall j \in P \tag{41}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j4}^{\mathrm{CS}}) \geq \pi_{j42}^{\mathrm{S}},\ \forall j \in P \tag{42}$$

$$1 - (\eta_j^{\mathrm{C}} - \xi_{j4}^{\mathrm{CB}}) \geq \pi_{j42}^{\mathrm{B}},\ \forall j \in P \tag{43}$$

Constraint (44) represents a range of values for each variable, with all variables being binary and restricted to values of either 0 or 1.

$$\eta_j^{\mathrm{N}}, \eta_j^{\mathrm{O}}, \eta_j^{\mathrm{C}},\ \xi_{jr}^{\mathrm{OS}}, \xi_{jr}^{\mathrm{OB}},\ \xi_{jr}^{\mathrm{CS}}, \xi_{jr}^{\mathrm{CB}}, \pi_{jrf}^{\mathrm{S}}, \pi_{jrf}^{\mathrm{B}} = 0, 1,\ \forall j \in P,\ \forall r \in R,\ \forall f \in F \tag{44}$$

The originally proposed model [M1] is an integer nonlinear programming model, which contains nonlinear constraints that can be linearized in a standard method. For detailed information about the linearization of [M1], please see Appendix A.

4. Results and Analysis

The linearized model was programmed in Python 3.8.16 and Gurobipy 10.0.1. The following experiments were conducted on a laptop equipped with AMD Ryzen 4800H CPU (2.90 GHz) and 32 GB of memory (3200 MHz) made by JAZER in Shenzhen, China.

4.1. Parameter Settings

The parameters utilized in the subsequent experiments are derived from prior studies and relevant reports. Since this study does not cover speed optimization, the sailing speed and ship number have a relationship that can be expressed as shown in constraint (45). Considering the sailing speed range of container ships, along with the sailing distance and berthing time required to complete a closed loop of the route, the fleet is designed to consist of eight ships sailing at a speed of 18.857 knots, unless explicitly stated otherwise. This experiment incorporates price variations among various types of oils. To be specific, three types of fuels with different sulfur contents are used, including oil with 3.5% sulfur content priced at 334,704 USD/ton, oil with 0.5% sulfur content priced at 522,739 USD/ton, and oil with 0.1% sulfur content priced at 703,494 USD/ton.

The lifespan of each ship is randomly generated between 20 to 25 years using a uniform distribution, according to the guidelines provided by the UNCTD [7]. Additionally, the speed of all ships is uniformly set according to constraint (45), where $|P|$ represents the number of deployed ships.

$$\left(\sum_{r \in R} D_r / Speed \right) + \sum_{r \in R} T_r = |P| \times 168 \tag{45}$$

Once the sailing speed of the ships has been established, the fuel consumption rate during sailing, denoted as g_j^{S} for ship j, is generated using constraint (46). The parameters a and b are randomly generated using a uniform distribution within the range of 0.012 to 0.013 and 2.7 to 3.3, respectively, as reported in the work of Wang and Meng [44].

$$g_j^S = a_j \times (1/SPEED)^{(1-b_j)}/24, \ \forall j \in P \tag{46}$$

To determine the fuel consumption rate when berthing g_j^B for each ship, the data obtained from the IMO is used [34]. Initially, the container size range of the previously generated g_j^S is calculated. Subsequently, within this specific range, the energy consumption information pertaining to the ship's berthing process is used. Finally, the value of g_j^B is generated randomly using a uniform distribution between 0.95 and 1.05 tons per hour.

The cost of scrubbers is determined based on the data from Sheng et al. [45] and Andersson et al. [46]. Open scrubbers, which directly discharge pollutants into the ocean, have relatively lower operating costs than closed scrubbers. In order to replicate this scenario, the variable costs associated with the sailing and berthing processes of closed scrubbers are higher than those of open scrubbers, as shown in Table 4.

Table 4. Variable costs of open and closed scrubbers.

P	VI_j^{OS}	VI_j^{OB}	VI_j^{CS}	VI_j^{CB}
1	0.072	0.149	6.172	73.935
2	0.134	0.182	5.074	73.110
3	0.031	0.159	4.757	75.976
4	0.159	0.145	5.758	71.216
5	0.118	0.219	5.644	88.538
6	0.134	0.163	5.930	66.547
7	0.219	0.126	3.501	69.772
8	0.069	0.118	6.479	85.387

4.2. Installation Plan under Regular Scenario

The optimal value under the regular scenario is demonstrated in Table 5, with a total cost of 67,829,986.38 USD. While ships 1, 2, 4, 5, 6, and 7 are equipped with a closed scrubber, ship 8 is equipped with an open scrubber, and ship 3 is not equipped with a scrubber. It can be seen that the installation rate of scrubbers in the optimal solution is as high as 87.5 percent, which fully demonstrates the effectiveness of scrubbers in reducing the total cost.

Table 5. Optimal values of the objective function.

Costs	Value (USD)
Scrubber fixed costs	889,023.91
Scrubber variable costs	2,930,798.69
Bunker costs	64,010,623.73
Total costs	67,829,986.38

Table 6 presents the utilization of scrubbers during sailing and berthing. It is evident that ships equipped with scrubbers use the equipment selectively. When berthing, ships with closed scrubbers tend to deactivate it at the first and third emission regulation scenarios and use fuel with a sulfur content of 0.5% to save the total cost. Only the sixth ship turns the closed scrubber on regardless of sailing and berthing. On the other hand, the eighth ship, equipped with open scrubbers, deactivates the open scrubber during the third and fourth emission regulation scenarios for both sailing and berthing. This is due to the prohibition of open scrubber usage in these areas and vessels' different fuel consumption rates while sailing and berthing.

Table 6. Scrubber usage under different emission regulation scenarios.

R	Emission Regulation Scenarios															
	None				SECA				OSPA				SECA & OSPA			
P	ζ_{jr}^{OS}	ζ_{jr}^{OB}	ζ_{jr}^{CS}	ζ_{jr}^{CB}	ζ_{jr}^{OS}	ζ_{jr}^{OB}	ζ_{jr}^{CS}	ζ_{jr}^{CB}	ζ_{jr}^{OS}	ζ_{jr}^{OB}	ζ_{jr}^{CS}	ζ_{jr}^{CB}	ζ_{jr}^{OS}	ζ_{jr}^{OB}	ζ_{jr}^{CS}	ζ_{jr}^{CB}
1	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1
2	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1
5	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1
6	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
7	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1
8	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0

Table 7 illustrates the fuel consumption of each ship. It can be seen that due to the high variable costs, ships equipped with closed scrubbers tend to use fuel with a sulfur content of 0.5% when berthing at the first and third emission regulation scenarios. Only the sixth ship uses HFO across every emission regulation scenario. The third ship, not equipped with any scrubber, must rely on cost-effective fuels that meet the emission regulations.

Table 7. Fuel usage under different emission regulation scenarios.

R		Emission Regulation Scenarios							
		None		SECA		OSPA		SECA & OSPA	
P	F	π_{jrf}^{S}	π_{jrf}^{B}	π_{jrf}^{S}	π_{jrf}^{S}	π_{jrf}^{S}	π_{jrf}^{B}	π_{jrf}^{S}	π_{jrf}^{B}
1	1	1	0	1	1	1	0	1	1
	2	0	1	0	0	0	1	0	0
	3	0	0	0	0	0	0	0	0
2	1	1	0	1	1	1	0	1	1
	2	0	1	0	0	0	1	0	0
	3	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
4	1	1	0	1	1	1	0	1	1
	2	0	1	0	0	0	1	0	0
	3	0	0	0	0	0	0	0	0
5	1	1	0	1	1	1	0	1	1
	2	0	1	0	0	0	1	0	0
	3	0	0	0	0	0	0	0	0
6	1	1	1	1	1	1	1	1	1
	2	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0
7	1	1	0	1	1	1	0	1	1
	2	0	1	0	0	0	1	0	0
	3	0	0	0	0	0	0	0	0
8	1	1	1	1	1	0	0	0	0
	2	0	0	0	0	1	1	0	0
	3	0	0	0	0	0	0	1	1

4.3. Ship Deployment Plan without Scrubber Installation

This subsection explores the scenario where scrubber installation is not considered. To simulate this, the upper limit of total installation costs FI is set to zero. After optimization, the bunker cost without using scrubbers amounts to 106,429,349.96 USD. This is 56.9% higher than the cost incurred under the regular scenario. These findings demonstrate the effectiveness of the scrubbers in reducing total costs and the necessity of this study. The detailed fuel usage of the optimal solution without scrubber installation is displayed in Table 8.

Table 8. Fuel usage under different emission regulation scenarios (without scrubber installation).

R		**Emission Regulation Scenarios**							
		None		**SECA**		**OSPA**		**SECA & OSPA**	
P	***F***	$\pi^{\mathbf{S}}_{jrf}$	$\pi^{\mathbf{B}}_{jrf}$	$\pi^{\mathbf{S}}_{jrf}$	$\pi^{\mathbf{S}}_{jrf}$	$\pi^{\mathbf{S}}_{jrf}$	$\pi^{\mathbf{B}}_{jrf}$	$\pi^{\mathbf{S}}_{jrf}$	$\pi^{\mathbf{B}}_{jrf}$
1	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
2	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
3	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
4	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
5	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
6	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
7	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1
8	1	0	0	0	0	0	0	0	0
	2	1	1	0	0	1	1	0	0
	3	0	0	1	1	0	0	1	1

4.4. Sensitivity Analysis of Speed

Considering the delivery time and other requirements, the sailing speed of ships deployed on the route might change. In this subsection, numerical experiments with different ship speeds are conducted. The number of ships is adjusted using constraint (45) based on the new speed. For newly introduced ships, their fuel consumption rate during sailing and berthing is generated based on the settings mentioned in Section 4.1. Furthermore, the upper bound of total installation costs (FI) is adjusted proportionally, taking into account the basic scenario with eight ships. Moreover, when calculating the objective function, a coefficient is multiplied to preserve the planning period.

Figure 2 displays the optimal objective values associated with different speed configurations, and Table 9 showcases the scrubber installation status under different speed configurations. "SN-X" represents the use of X number of ships in the experiment. As indicated in constraint (45), the more ships, the lower the sailing speed.

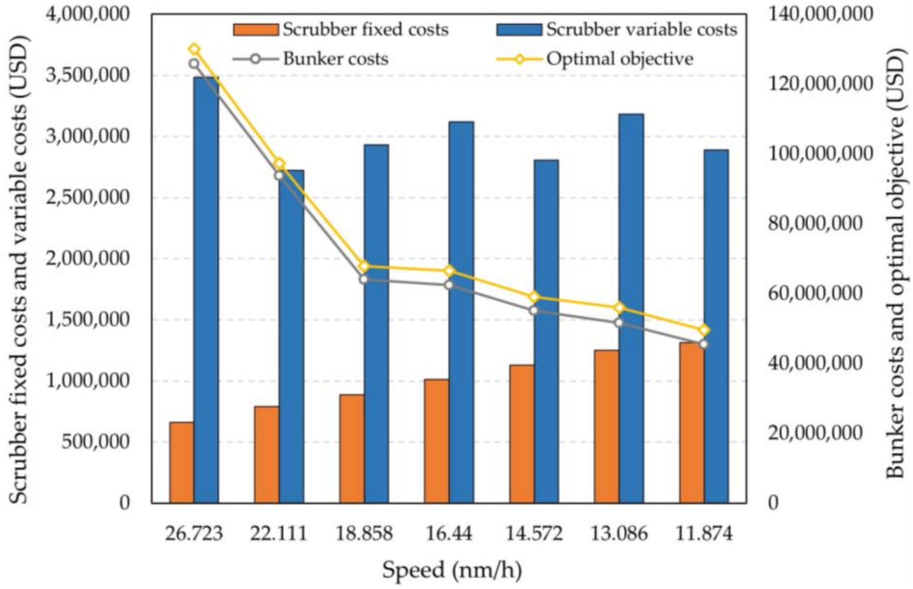

Figure 2. The changes in costs associated with different speed configurations.

Table 9. The scrubber installation status under different speed configurations.

Experiment	Speed	No Scrubber	Open Scrubber	Closed Scrubber
SN-6	26.723	3	-	1, 2, 4, 5, 6
SN-7	22.111	3	1	2, 4, 5, 6, 7
SN-8	18.858	3	8	1, 2, 4, 5, 6, 7
SN-9	16.440	3	9	1, 2, 4, 5, 6, 7, 8
SN-10	14.572	None	3, 10	1, 2, 4, 5, 6, 7, 8, 9
SN-11	13.086	3	10	1, 2, 4, 5, 6, 7, 8, 9, 11
SN-12	11.874	10	11, 12	1, 2, 3, 4, 5, 6, 7, 8, 9

Due to the decrease in speed accompanied by an increase in the number of ships, the increasing installation of scrubbers results in a steady rise in scrubber fixed costs as speed decreases. The utilization of scrubbers varies under different emission regulations, leading to differences in variable costs. As speed decreases, fuel consumption during the navigation process consistently drops, driving an overall cost reduction.

4.5. Sensitivity Analysis of Sulfur Emission Control Areas and Open-Scrubber-Prohibited Areas

Distances under the four emission regulation scenarios change with the locations of ports of call. Therefore, this subsection analyzes the impact of percentages of SECAs and OSPAs on the overall sailing distance. The total sailing distance remains constant before and after the changes to ensure a fair comparison. The results of the modified sailing distances for the second and fourth emission regulation scenarios, which include SECAs, are shown in Tables 10 and 11.

Table 10. Optimal objective values for various increments of sulfur emission control areas.

Magnitude of Change	+10%	+20%	+30%	+40%	+50%	+60%	+70%
Scrubber fixed costs	889,024	889,024	889,024	889,024	889,024	889,024	889,024
Scrubber variable costs	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799
Bunker costs	64,112,340	64,214,515	64,316,691	64,418,867	64,521,042	64,623,218	64,725,394
Optimal objective	67,932,162	68,034,338	68,136,514	68,238,689	68,340,865	68,443,041	68,545,216
Without scrubbers	107,709,905	108,990,461	110,271,016	111,551,571	112,832,127	114,112,682	115,393,237
Gap	36.9%	37.6%	38.2%	38.8%	39.4%	40%	40.6%

Table 11. Optimal objective values for various decrements of sulfur emission control areas.

Magnitude of Change	−10%	−20%	−30%	−40%	−50%	−60%	−70%
Scrubber fixed costs	889,024	889,024	889,024	889,024	889,024	889,024	889,024
Scrubber variable costs	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799	2,930,799
Bunker costs	63,907,988	63,805,812	63,703,637	63,601,461	63,499,285	63,397,109	63,294,934
Optimal objective	67,727,811	67,625,635	67,523,459	67,421,283	67,319,108	67,216,932	67,114,756
Without scrubbers	105,148,795	103,868,239	102,587,684	101,307,129	100,026,573	98,746,018	97,465,462
Gap	35.6%	34.9%	34.2%	33.4%	32.7%	31.9%	31.1%

The results reveal a clear positive correlation between the increase in the percentage of SECAs and overall operating costs. This is because the rise in SECAs leads to higher operating costs for vessels that do not have scrubbers installed. The data from ships without scrubbers indicates that due to the increase in SECAs, the voyage where ships can only use LSFOs becomes longer, resulting in an overall rise in operating costs. Conversely, ships can use marine fuel with 0.5% sulfur content in larger areas and have lower costs when the proportion of SECAs decreases. However, when utilizing scrubbers, the increase in operating costs is very limited, showcasing that the use of scrubbers in SECAs can help decrease overall operating costs. The gap between the optimal total costs with and without considering scrubbers ($Gap = \frac{Without\ scrubbers - Optimal\ objective}{Without\ scrubbers}$) in Tables 10 and 11 show that the cost reduction effect becomes more apparent with the expansion of SECAs.

The results presented in Tables 12 and 13 are determined by adopting modified sailing distances for the third and fourth emission regulation scenarios, namely voyage length in the OSPAs. It is evident the percentage of the OSPA has an opposite impact to that of the SECAs but in a minor way. The expansion of OSPAs does not affect the utilization of the closed scrubber and the operation of ships without scrubber. Only ships equipped with an open scrubber will incur cost increases, as they are restricted to using LSFOs in OSPAs. Meanwhile, since the open scrubber makes up only 14% of all scrubber installations in the basic case and closed scrubbers are expensive to install, the impact is not as significant as that of SECAs, as shown in Figure 3. The figure shows how the gap between the optimal costs with and without considering scrubbers varies with the percentage of SECAs and OSPAs along the whole route. It is indicated that with the increase in OSPAs, the gap will narrow due to the restriction on the usage of open scrubbers. Meanwhile, the gap expands more significantly with SECAs because SECAs will influence the operation of all deployed ships. Therefore, with the growing tendency of SECAs and OSPAs, our model will still be effective in the future and become helpful to shipping companies. When all ports set

OSPAs, this problem will still be worth investigating because open scrubbers can be used on international waters.

Table 12. Optimal objective values for various increments of open-scrubber-prohibited areas.

Magnitude of Change	+10%	+20%	+30%	+40%	+50%	+60%	+70%
Scrubber fixed costs	889,024	889,024	889,024	889,024	889,024	889,024	889,024
Scrubber variable costs	2,930,515	2,930,231	2,929,948	2,929,664	2,929,380	2,929,096	2,928,812
Bunker costs	64,193,600	64,377,070	64,560,574	64,744,113	64,927,685	65,111,292	65,294,932
Optimal objective	68,013,139	68,196,325	68,379,546	68,562,800	68,746,089	68,929,411	69,112,768
Without scrubbers	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350
Gap	36.1%	35.9%	35.8%	35.6%	35.4%	35.2%	35.1%

Table 13. Optimal objective values for various decrements of open-scrubber-prohibited areas.

Magnitude of Change	−10%	−20%	−30%	−40%	−50%	−60%	−70%
Scrubber fixed costs	889,024	889,024	889,024	889,024	889,024	889,024	889,024
Scrubber variable costs	2,930,945	2,931,091	2,931,238	2,931,384	2,931,530	2,931,676	2,931,823
Bunker costs	63,958,902	63,907,639	63,856,377	63,805,115	63,753,853	63,702,590	63,651,328
Optimal objective	67,778,870	67,727,754	67,676,639	67,625,523	67,574,407	67,523,291	67,472,175
Without scrubbers	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350	106,429,350
Gap	36.3%	36.4%	36.4%	36.5%	36.5%	36.6%	36.6%

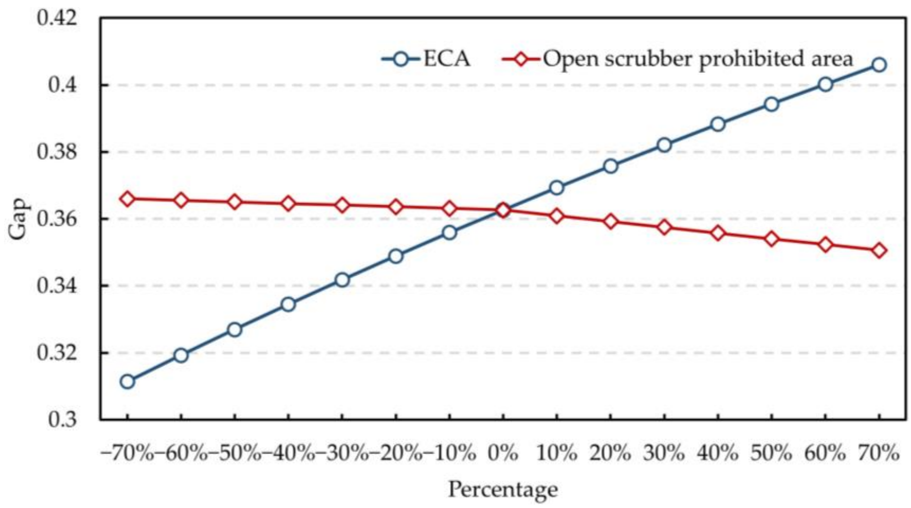

Figure 3. The gap between optimal total costs with and without considering scrubbers.

4.6. Multi-Stage Scrubber Installation Plan

For a shipping company, the scrubber installation can be carried out over several years to obtain the optimal installation plan with milder financial pressures. In this section, a multi-stage scrubber installation plan is considered, which is divided into M years (M = 3). The objective is to determine which scrubbers should be installed at each stage so that the operational costs during the whole planning period can be minimized, including the variable cost of scrubber usage and bunker fuel cost. There are two steps to achieve the target. First, the final optimal installation solution is obtained by removing the upper limit on installation costs. The optimal scrubber installation for every ship is a closed scrubber. Then, the installation work of scrubbers is allocated to different years through an optimization model; for details, please see Appendix B. Table 14 showcases the optimal objective values. It can be calculated that the average operating costs for each year are approximately 69 million USD, which is basically the same as the basic single-stage scrubber installation plan mentioned before. By implementing this installation plan, the company enables the entire fleet to utilize the optimal installation solution without incurring extra annual financial pressures. In the long run, this can lead to lower costs. As shown in Table 15, after optimization, the model finds the optimal scrubber installation plan.

Table 14. Optimal values of the objective function (multi-stage scrubber installation plan).

Costs	Value (USD)
Scrubber variable costs	9,308,510.59
Bunker costs	199,649,025.64
Total costs	208,957,536.23

Table 15. Annual scrubber installation status for each ship.

Experiment	No Scrubber	Open Scrubber	Closed Scrubber
M-1	3, 5, 6, 8	None	1, 2, 4, 7
M-2	3	None	1, 2, 4, 5, 6, 7, 8
M-3	None	None	1, 2, 3, 4, 5, 6, 7, 8

Note: M-X represents the installation plan at X-th year.

The annual scrubber usage pattern presented in Table 16 is similar to that of Table 6. Once installed, ships with a closed scrubber tend to activate it when berthing at the first and third emission regulation scenarios to reduce bunker expenses. The annual fuel usage pattern demonstrated in Table 17 matches the scrubber usage shown in Table 16. When the closed scrubber is deactivated, fuel with a sulfur content of 0.5% is used to meet the emission regulations.

Table 16. Annual scrubber usage under different emission regulation scenarios.

R		Emission Regulation Scenarios							
		None		SECA		OSPA		SECA & OSPA	
M	*P*	ξ_{jr}^{CS}	ξ_{jr}^{CB}	ξ_{jr}^{CS}	ξ_{jr}^{CB}	ξ_{jr}^{CS}	ξ_{jr}^{CB}	ξ_{jr}^{CS}	ξ_{jr}^{CB}
1	1	1	0	1	1	1	0	1	1
	2	1	0	1	1	1	0	1	1
	3	0	0	0	0	0	0	0	0
	4	1	0	1	1	1	0	1	1
	5	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0
	7	1	0	1	1	1	0	1	1
	8	0	0	0	0	0	0	0	0

Table 16. *Cont.*

R		Emission Regulation Scenarios							
		None		SECA		OSPA		SECA & OSPA	
2	1	1	0	1	1	1	0	1	1
	2	1	0	1	1	1	0	1	1
	3	0	0	0	0	0	0	0	0
	4	1	0	1	1	1	0	1	1
	5	1	0	1	1	1	0	1	1
	6	1	1	1	1	1	1	1	1
	7	1	0	1	1	1	0	1	1
	8	1	0	1	1	1	0	1	1
3	1	1	0	1	1	1	0	1	1
	2	1	0	1	1	1	0	1	1
	3	1	0	1	1	1	0	1	1
	4	1	0	1	1	1	0	1	1
	5	1	0	1	1	1	0	1	1
	6	1	1	1	1	1	1	1	1
	7	1	0	1	1	1	0	1	1
	8	1	0	1	1	1	0	1	1

Table 17. Annual fuel usage under different emission regulation scenarios.

	R		Emission Regulation Scenarios							
			None		SECA		OSPA		SECA&OSPA	
M	*P*	*F*	π_{jrf}^{S}	π_{jrf}^{B}	π_{jrf}^{S}	π_{jrf}^{S}	π_{jrf}^{S}	π_{jrf}^{B}	π_{jrf}^{S}	π_{jrf}^{B}
1	1	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	2	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	1	1	0	0
		3	0	0	1	1	0	0	1	1
	4	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	5	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	1	1	0	0
		3	0	0	1	1	0	0	1	1
	6	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	1	1	0	0
		3	0	0	1	1	0	0	1	1
	7	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	8	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	1	1	0	0
		3	0	0	1	1	0	0	1	1

Table 17. *Cont.*

	R		Emission Regulation Scenarios							
			None		SECA		OSPA		SECA&OSPA	
M	*P*	*F*	π^{S}_{jrf}	π^{B}_{jrf}	π^{S}_{jrf}	π^{S}_{jrf}	π^{S}_{jrf}	π^{B}_{jrf}	π^{S}_{jrf}	π^{B}_{jrf}
2	1	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	2	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	1	1	0	0
		3	0	0	1	1	0	0	1	1
	4	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	5	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	6	1	1	1	1	1	1	1	1	1
		2	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0
	7	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	8	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
3	1	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	2	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	3	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	4	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	5	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	6	1	1	1	1	1	1	1	1	1
		2	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0
	7	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0
	8	1	1	0	1	1	1	0	1	1
		2	0	1	0	0	0	1	0	0
		3	0	0	0	0	0	0	0	0

5. Conclusions and Future Work

Sustainable development and emission problems have been listed among the top priorities of the maritime industry. To achieve the emission reduction targets, the IMO has discussed and promoted various regulations on ship operations. One of the most far-reaching policies is the restriction on the sulfur content of marine fuels, leading to a significant rise in bunker costs. Shipping companies have multiple approaches to control the total operating costs, including operational and technical methods. Scrubbers are an effective method that can purify exhaust gases before emitting them, obeying regulations without reducing service quality.

This study initially considers the OSPAs and operating costs of onboard scrubbers, and investigates the scrubber installation and utilization of a container ship fleet with emission regulations and marine fuel-switching operations. A mixed-integer nonlinear programming model was developed to describe the problem and identify the optimal installation and utilization plan of scrubbers that minimized the total operational costs. Numerical experiments were conducted to validate the originally proposed model.

A comparison between the results obtained under the scenarios including and excluding the adoption of scrubbers shows the effectiveness of scrubbers in cost reduction and the necessity of this study. Sensitive analyses regarding the sailing speed, SECAs, and OSPAs demonstrate that the proposed model significantly reduces total operational costs under multiple scenarios. It is also revealed that conducting the scrubber installation work over several years can obtain a better scrubber installation plan without incurring extra financial pressures.

Given the limitations of this study, there are two directions that future research regarding this topic can follow. First, take the time required to consider scrubber installation work. Second, the combination of various emission reduction technologies can be investigated, for example, sailing speed optimization and engine modification.

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Appendix A

In [M1] the nonlinear element exists in constraints (8), (9), (14)–(17), (26)–(29), and (32)–(39) in the form of the product of two binary decision variables. Therefore, constraint (6) is taken as an example to show the linearization of the nonlinear constraints.

Since both the involved decision variables, namely η_j^{N} and π_{j11}^{S}, are binary, constraint (8) can be replaced by an equivalent linear constraint as shown in constraint (A1):

$$\eta_j^{\mathrm{N}} + \pi_{j11}^{\mathrm{S}} \leq 1,\ \forall j \in P. \quad \text{(A1)}$$

The rest of the nonlinear constraints can be linearized using the same method. As a result, an integer linear programming model is obtained that can be solved by off-the-shelf commercial solvers.

Appendix B

In this section, a new model for implementing a scrubber installation plan is developed. The model aims to achieve two objectives: (1) optimal installation outcomes upon completion of the plan; (2) minimization of operational costs during the installation period. The main constraint for this model is the annual budget for scrubber installation.

The definition of the cash flow model is as follows. Firstly, constraint (3) is removed from the previous scheduling model, and the new model yields the optimal scrubber installation scenario without budget constraints. The variables in Table A1 represent the optimal scrubber installation plan under such circumstances.

Table A1. Notations of the optimal scrubber installation plan.

Variable	Description
$\hat{\eta}_j^{\mathrm{N}}$	optimal scrubber installation, equal to 1 if no scrubber is installed on ship j, 0 otherwise
$\hat{\eta}_j^{\mathrm{O}}$	optimal scrubber installation, equal to 1 if open scrubber is installed on ship j, 0 otherwise
$\hat{\eta}_j^{\mathrm{C}}$	optimal scrubber installation, equal to 1 if closed scrubber is installed on ship j, 0 otherwise

Based on the previous definition, the upper limit of the total cost required for scrubber installation is denoted as FI. Given this upper limit, an M-year scrubber installation plan is developed with an installation cost limit of $FI_m^{'}$ in the m-th year. The plan should satisfy the following constraints: $\sum_{m \in M} FI_m^{'} > FI > FI_m^{'}$. This ensures that the overall budget is sufficient to complete the optimal scrubber installation while keeping the annual installation costs relatively low to alleviate cash flow pressure.

The decision variables used in the cash flow model are defined in Table A2.

Table A2. Notations of the decision variables used in cash flow analysis.

Variable	Description
η_{jm}^{N}	binary variable, equal to 1 if no scrubber is available on ship j at year m, 0 otherwise
η_{jm}^{O}	binary variable, equal to 1 if open scrubber is available on ship j at year m, 0 otherwise
η_{jm}^{C}	binary variable, equal to 1 if closed scrubber is available on ship j at year m, 0 otherwise
η'^{O}_{jm}	binary variable, equal to 1 if open scrubber is installed on ship j at year m, 0 otherwise
η'^{C}_{jm}	binary variable, equal to 1 if closed scrubber is installed on ship j at year m, 0 otherwise
ξ_{jrm}^{OS}	binary variable, equal to 1 if the open scrubber of ship j is used under scenario r while sailing at year m, 0 otherwise
ξ_{jrm}^{OB}	binary variable, equal to 1 if the open scrubber of ship j is used under scenario r while berthing at year m, 0 otherwise
ξ_{jrm}^{CS}	binary variable, equal to 1 if the closed scrubber of ship j is used under scenario r while sailing at year m, 0 otherwise
ξ_{jrm}^{CB}	binary variable, equal to 1 if the closed scrubber of ship j is used under scenario r while berthing at year m, 0 otherwise

This model includes the following constraints. Firstly, as shown in constraint (A2), the objective function comprises the variable costs of scrubber installation for all vessels during their sailing and berthing processes, as well as the fuel expenses incurred.

$$[\text{M2}] \rightarrow \sum_{m\in M}\sum_{j\in P}\sum_{r\in R}(\xi^{OS}_{jrm}\cdot VI^{OS}_{j}\cdot D_r+\xi^{OB}_{jrm}\cdot VI^{OB}_{j}\cdot T_r+\xi^{CS}_{jrm}\cdot VI^{CS}_{j}\cdot D_r+\xi^{CB}_{jrm}\cdot VI^{CB}_{j}\cdot T_r)+ \sum_{m\in M}\sum_{j\in P}\sum_{r\in R}\sum_{f\in F}[P_f\cdot(\pi^{S}_{jrfm}\cdot g^{S}_{j}\cdot D_r+\pi^{B}_{jrfm}\cdot g^{B}_{j}\cdot T_r)], \forall m\in M, \forall j\in P, \forall r\in R, \forall f\in F \tag{A1}$$

This objective function needs to satisfy the following constraints. Constraint (A3) ensures that each year, either one type of scrubber is installed or no scrubber is installed at all.

$$\eta^{N}_{jm}+\eta^{O}_{jm}+\eta^{C}_{jm}=1,\ \forall j\in P, \forall m\in M \tag{A3}$$

Constraints (A4) and (A5) ensure that after installing a scrubber, it remains available in the following years.

$$\eta^{O}_{jm} <= \eta^{O}_{jm+1},\ \forall j\in P, \forall m\in M-1 \tag{A4}$$

$$\eta^{C}_{jm} <= \eta^{C}_{jm+1},\ \forall j\in P, \forall m\in M-1 \tag{A5}$$

The variables $\eta\prime^{C}_{jm}$ and $\eta\prime^{O}_{jm}$ track the specific year of scrubber installation, and their update rules are as follows. Firstly, as shown in constraints (A6) and (A7), in the first year, the installation status of the scrubber is determined by the initial decision made for that year.

$$\eta^{C}_{j1}=\eta'^{C}_{j1},\ \forall j\in P \tag{A6}$$

$$\eta^{O}_{j1}=\eta'^{O}_{j1},\ \forall j\in P \tag{A7}$$

The installation status in each subsequent year is determined by the decisions made in previous years, as shown in constraints (A8) and (A9).

$$\eta'^{C}_{jm}=\eta^{C}_{j,m}-\eta^{C}_{j,m-1},\ \forall j\in P, m=2,\ldots,M \tag{A8}$$

$$\eta'^{O}_{jm}=\eta^{O}_{j,m}-\eta^{O}_{j,m-1},\ \forall j\in P, m=2,\ldots,M \tag{A9}$$

Constraints (A10)–(A12) ensure that the final scrubber installation plan aligns with the optimal plan.

$$\eta^{N}_{jM}=\hat{\eta}^{N}_{j},\ \forall j\in P \tag{A10}$$

$$\eta^{C}_{jM}=\hat{\eta}^{C}_{j},\ \forall j\in P \tag{A11}$$

$$\eta^{O}_{jM}=\hat{\eta}^{O}_{j},\ \forall j\in P \tag{A12}$$

Constraint (A13) ensures that the annual scrubber installation cost does not exceed the budget limit for each year.

$$\sum_{j\in P}(TFI^{O}_{j}\cdot\eta'^{O}_{jm}+TFI^{C}_{j}\cdot\eta'^{C}_{jm})\le FI'_{m}, \forall m\in M, \forall j\in P \tag{A13}$$

In the end, incorporate constraints (4)–(44) from the previous context (with additional constraints for $\forall m\in M$.

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