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# Decarbonizing Maritime Transport through Green Fuel-Powered Vessel Retrofitting: A Game-Theoretic Approach

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**Abstract:** Addressing the urgent global challenge of man-made greenhouse gas emissions and climate change necessitates collaborative action between shipping lines and government regulatory agencies. Aligning with the International Maritime Organization's emissions reduction strategy, this paper presents a novel bi-level programming model that unifies these stakeholders. On the upper level of the proposed bi-level model, a number of shipping lines optimize retrofitting plans for their vessels to maximize economic benefits. On the lower level, the regulatory agency responds to the carbon reduction efforts by setting retrofitting subsidies and emission penalty rates. This framework represents a multi-leader–single-follower game involving shipping lines and the regulatory agency, and its equilibrium is determined through an equilibrium problem with equilibrium constraints (EPEC). The EPEC comprises multiple single-leader–follower problems, each of which can be formulated as a mathematical program with equilibrium constraints (MPEC). The diagonalization algorithm (DM) is employed for its solution. Simulation studies performed based on a ten-year planning period show that the proposed approach can effectively promote vessel retrofitting and the use of green fuels, which leads to an annual emission reduction of over 50%.

**Keywords:** maritime decarbonization; alternative fuels; vessel retrofitting; bi-level programming; MPEC; EPEC

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## 1. Introduction

### *1.1. Background and Motivation*

The marine transportation sector is a critical component of the trillion-dollar global maritime industry, which handles a vast majority of cross-border trade measured by volume ([1]). Despite its critical role in local, regional, and national economic growth and prosperity, the heavy reliance on fossil fuels, particularly heavy fuel oil (a residual fuel high in carbon and sulfur content), has made the maritime transportation sector a significant source of greenhouse gases (GHG) [2,3]. According to the International Maritime Organization (IMO), the maritime transportation industry was responsible for 1,076 million tons of global GHG emissions in 2018, a 9.6% increase from 977 million tons in 2012 [4–8]. Without taking corrective measures, GHG emissions from this sector are predicted to increase up to 130% by 2050 due to increasing demand for maritime trade [9,10]. To prevent such a scenario, the IMO launched an original GHG strategy in 2018 to reduce maritime industry GHG emissions to 40% below 2008 levels by 2030, with a long-term goal of reducing GHG emissions by at least 50% by 2050 [11]. This initiative has received widespread support globally, with the U.S. committing to support the IMO's GHG goals by establishing new maritime emissions reduction and efficiency requirements [12]. The

European Union, on the other hand, is planning to include the shipping industry in its cap-and-trade emission trading system as soon as 2022, as part of its EU climate law, to encourage the industry to move forward more quickly [11].

To reduce GHG emissions from ships and make the shipping industry more environmentally sustainable, the maritime transportation sector has been exploring various alternative clean fuels to replace traditional fossil fuels. Some of the promising clean fuels for ships include liquified natural gas (LNG), hydrogen, ammonia, battery/fuel cell, as well as biofuels [13–15]. These fuels produce no or very little GHG emissions when burned and can be derived using a more environmentally friendly approach compared to fossil fuels. By retrofitting the existing fleet and adopting these clean fuels, the shipping industry can effectively address the fundamental sources of maritime GHG emissions and meet the global emissions reduction targets. Vessel retrofitting involves the modification and enhancement of existing ships to incorporate clean fuel systems. Retrofitting is essential as it allows older vessels, which constitute a significant portion of the global fleet, to align with stringent environmental regulations and emission reduction targets. In the "IMO Original Strategy on Reduction of GHG Emissions from Ships" made by the IMO in 2018, the development and use of low-carbon or zero-carbon fuels has been considered the key to reducing emissions in the IMO's decarbonization strategy [16]. This consideration is also supported by a comprehensive literature survey conducted by [17], which reviewed 150 studies on $CO_2$ emissions in shipping and found that transitioning to alternative fuels is one of the best and most viable ways to reduce shipping's greenhouse gas emissions.

In the quest for greener and more sustainable practices in the shipping industry, major players have also unveiled ambitious plans and initiatives aimed at embracing alternative fuels for emission reduction. For instance, the container shipping line A.P. [18] set a 2030 interim target for a 50% reduction in emissions per transported container and is currently planning to achieve net zero emissions by 2040. The line has purchased 12 vessels using green methanol produced by renewable sources. The line also plans to upgrade a quarter of its vessel fleet to be ready for green fuels in 2030. In 2020, ("K" Line)[19] also revised their long-term environmental guideline to cut $CO_2$ emission efficiency by 50% compared with 2008 levels by 2030, outlined in their "Securing Blue Seas for Tomorrow" report. As the world's third largest container shipping line, CMA CGM has invested in LNG as fuel as the corporation's first steps to achieving carbon neutrality by 2050. By the end of 2021, CMA CGM had deployed six 15,000 TEU LNG-powered vessels on the China–US trade route.

Despite their advantages, the adoption of clean fuels for ships is not straightforward and requires careful consideration of technical, financial, and policy-level factors. Retrofitting a vessel to run on alternative fuels such as LNG or biofuels requires significant modifications to the ship's existing propulsion and fuel storage systems or, sometimes, new propulsion systems and storage tanks. These modifications can be technically complex, particularly for older ships, and thus can result in higher costs and longer lead times when all the modifications add up. Retrofitting a vessel requires the ship to be taken out of service for an extended period of time, which can result in logistical challenges, added delay costs, and even significant disruptions to the supply chain, especially for ships that operate on tight schedules [9]. These factors have so far made it a challenge for ship owners to justify the investment toward decarbonization and reducing their GHG footprints. At the same time, the lack of strong and executable government regulations and the conflicting interests between shipping lines and governments are all hindering the development of green shipping. Therefore, designing effective government regulatory agency strategies to encourage the use of green fuels by ships and achieve positive GHG emissions reduction in the shipping industry is a matter of urgency [20].

In this paper, we propose a game-theoretic model to study how regulatory agencies can incentivize clean fuel adoption in the shipping industry. The model involves subsidies for ship retrofits and penalties for emissions. The proposed model helps the regulatory body devise effective emission mitigation policies and instruments while taking into account shipping companies' interests in reducing operational costs and emissions fines. We establish a bi-level formulation for the proposed model where multiple shipping companies make retrofit decisions, and the regulatory agency adjusts subsidies and penalties in response.

### 1.2. Literature Review

The importance of adopting green alternative fuels has gained considerable recognition in the existing literature, signifying a pivotal shift towards environmentally sustainable practices within the maritime industry. For instance, [21] studied shipowners' emission reduction solutions through a multi-nominal logit model and found that alternative fuels, such as liquefied natural gas, are the most attractive option for gas carriers. While the benefits of these green alternatives are evident, their widespread adoption by ships remains a complex challenge. [22] noted that even in leading countries like Norway, the adoption of alternative fuels in the shipping industry is still in its early stages. Therefore, it is still necessary to support alternative fuel innovation through technology-push mechanisms, such as research and development funding. [23] pointed out that stricter emission regulations will be applicable to cruise ships visiting the Norwegian fjords. In response, numerous Norwegian ports have taken a proactive stance of imposing fees on vessels calling at the ports to incentivize the adoption of alternative fuels. [24] conducted a comprehensive assessment of the overall potential of green fuels and their ability to decarbonize international shipping from a technical, environmental, and policy perspective. The results showed that liquefied natural gas is economically feasible and offers moderate environmental benefits, making it a short-term prospect requiring minimal policy intervention. However, deeper decarbonization in the long term will require strong financial incentives.

While existing research has offered valuable perspectives into decarbonizing the maritime industry through clean fuel adoption, it suffers from two main drawbacks: First, most retrofitting studies are primarily focused on the technical aspects of how to make appropriate facility upgrades and ship layout changes to integrate storage and supply systems for green fuels. However, what has often been overlooked is the equally critical task of retrofitting ships to accommodate the use of these alternative fuels. Retrofitting is not merely a technical challenge but also an economic and logistical one, as shipowners and operators must carefully plan and execute retrofitting projects to ensure compliance with evolving environmental standards while minimizing downtime and financial implications. Therefore, it is imperative for us to investigate how ships can be modified, upgraded, or replaced over time to embrace the use of alternative fuels in a sustainable and cost-effective manner. As each vessel type, route, and operational context may demand a unique retrofitting strategy, a holistic approach becomes necessary that not only focuses on the development and viability of green fuels but also on the practical aspects of integrating these fuels into existing maritime infrastructure.

On the other hand, existing policy-level instruments, such as emission incentive policies and mandatory measures (e.g., carbon pricing and carbon tax), are commonly developed without taking the shipping lines' initiatives and reactions into account when regulators make policies that promote the use of low/zero-emission fuels. This can be problematic. In charting the course for the future development of maritime decarbonization, it becomes increasingly apparent that all stakeholders must redirect their focus toward addressing this challenge. Their collective commitment and concerted efforts are pivotal in aiding the IMO in realizing its ambitious decarbonization goals for the shipping industry. Since both regulator and shipping companies play pivotal roles in the decarbonization process and engage in dynamic interactions, it becomes clear that they must understand the implications of their choices. This understanding serves as the foundation for identifying potential coordination or cooperation strategies to ensure that the transition to greener, more sustainable shipping practices is not only environmentally sound but also economically feasible and operationally viable.

### 1.3. Our Contributions

In this paper, we aim to bridge these important gaps in the literature and propose a game-theoretic formulation to study how regulatory agencies can interact with shipping lines and stimulate clean fuel adoption by providing subsidies for ship retrofits and implementing penalties for ship emissions. In the proposed formulation, the regulator aims to develop the best emission mitigation policies that lead to the anticipated climate outcome. Shipping lines, on the other hand, want to minimize operating costs, as well as reduce fines for pollutant emissions. We develop a bi-level structure in which multiple shipping liners act at the upper level to take the initiative toward reducing their carbon emissions and make retrofit decisions (i.e., the optimal retrofitting time for all vessels), and the regulatory agency, at the lower level, reacts to all the retrofitting decisions made by different ship lines (SLs) and adjusts retrofit subsidy, operation and maintenance (O&M) subsidies, and pollutant penalty rates according to the shipping lines' retrofitting plans. The above formulation results in a multi-leader–follower game, and we transform the bi-level problem for a single shipping line into a single-level-equivalent MPEC problem using the Karush–Kuhn–Tucker (KKT) conditions for the follower problem. Then, by considering multiple SLs, we have an equilibrium problem with equilibrium constraints, which is solved by diagonal algorithms (Das).

The contributions of this paper can be summarized as follows:

(1) This paper studies the decision-making hierarchy of two key stakeholders, shipping lines and regulators, involved in the ship retrofitting planning process toward the 2030/2050 climate goals set by the IMO. To the best of our knowledge, this is the first work to study this important problem.

(2) This paper presents a novel bi-level structure to capture how multiple shipping lines' ship retrofitting plans interact with the regulator's emission control policies. The interaction is a multi-leader–follower game that can be formulated and solved as an EPEC problem.

(3) Comprehensive experimental results are provided to validate the effectiveness of the proposed approach. The impact of government subsidies, fuel selection, and the size of the shipping lines on optimal retrofitting decisions is studied through comparative experiments.

It is worth noting that the above modeling structure may not capture the full complexities of the vessel retrofitting problem. However, we believe it is necessary to provide a simplified framework that enables us to reasonably explore the core dynamics and interactions between regulators and shipping companies during the maritime transportation system's transition.

The rest of this article is organized as follows: Section II introduces an overview of the current industrial efforts in promoting green fuels and the proposed modeling methodology. Section III describes the solution methodology, and section IV provides a summary and recommendations for future work.

## 2. Problem Description and Modeling

### 2.1. Current Practice of Vessel Retrofitting

As previously mentioned, the process of retrofitting vessels encompasses a broad spectrum of actions, ranging from enhancing engine efficiency to installing exhaust gas cleaning systems (scrubbers) and integrating infrastructure for storing and supplying alternative fuels, as shown in Figure 1. For instance, when converting a ship to operate on methanol, the transformation involves repurposing existing ballast tanks to serve as fuel tanks and creating separate compartments for transfer and high-pressure pumps. Additional components, such as fuel injectors and pumps, must be added to the main engine to facilitate the delivery of fuel to the cylinders [25].

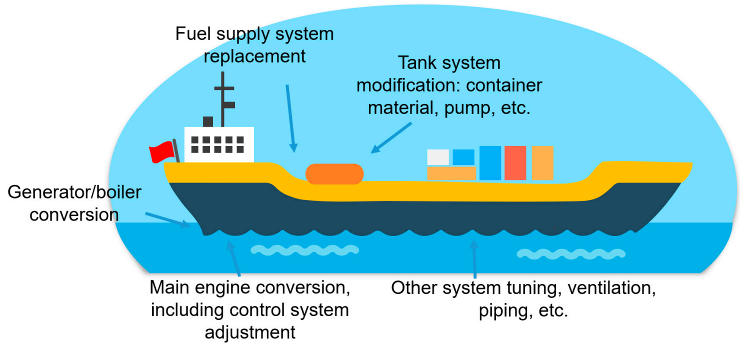



**Figure 1.** Representative key retrofitting considerations for a ship to be "alternative fuel-ready": modifications are necessary for the fuel tanks, main engine, generator/boiler, fuel supply system, and other system components.

In the case of hydrogen-powered ships utilizing an alkaline electrolysis system, specific modifications like the construction of dedicated pure water tanks may not be necessary if the vessel is equipped with a freshwater generator. Alternatively, a freshwater tank could be repurposed for storing pure water in the absence of a generator. Within the engine room, space allocation becomes crucial for housing alkaline electrolysis cells and control units, with minor adjustments such as the incorporation of double-arm piping possibly being required [26].

For ships utilizing LNG and LPG (liquefied petroleum gas) fuel systems, the primary focus centers on the construction of storage tanks and their associated safety systems. LNG-fueled vessels necessitate specially designed LNG tanks and dedicated spaces for managing LNG within the tanks. Additionally, considerations include gas ventilation zones, double-walled gas piping, secure refueling stations, and the separation of the main engine from the engine room. LPG-fueled ships require the installation of new storage and supply systems, encompassing tanks, pumps, pipelines, and heating equipment. Engine modifications become imperative to accommodate liquefied gas fuel, potentially involving adjustments to the injection system and ignition system [26,27].

In the case of ammonia-fueled ships, the retrofitting process involves the addition of ammonia storage and supply systems, which entail high-pressure hydrogen storage tanks, ammonia pipelines, compressors, and other components. Necessary alterations include modifications to fuel control and injection systems, alongside the incorporation of safety mechanisms like ammonia leak detectors. Ensuring the implementation of proper ventilation systems is of paramount importance to enhance vessel safety [28]. Engine adjustments are necessary to accommodate liquefied gas fuel, including modifications to the injection system and potential ignition system changes [26,27]. Ammonia-fueled ships demand the addition of ammonia storage and supply systems, which encompass high-pressure hydrogen storage tanks, ammonia pipelines, compressors, and more. Modifications to fuel control and injection systems are essential, as well as the inclusion of safety equipment such as ammonia leak detectors. Ensuring proper ventilation systems is also crucial for vessel safety [28].

### 2.2. Problem Description and Assumption

As shown in Figure 2, the proposed bi-level programming model in this paper can be interpreted as follows:

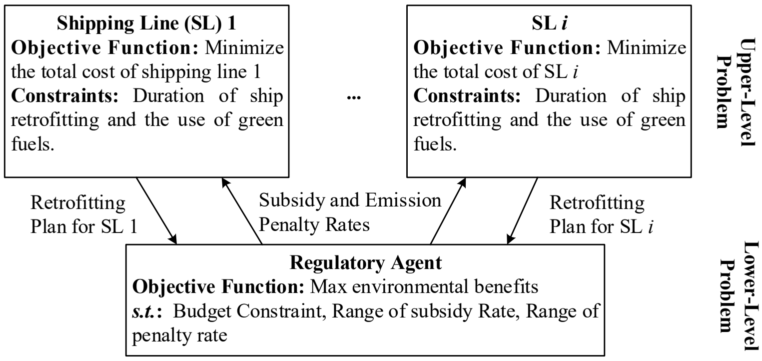



**Figure 2.** Schematic of bi-level model structure.

On the shipping line level, as profit-driven organizations, shipping liners need to ensure that using green fuels for their ships has long-term economic benefits. Their goal is to minimize the costs of transitioning to, and maintaining, the use of green fuels. Meanwhile, they also aim to pay the least amount of pollution penalty and maximize the government subsidies they can collect, all to minimize the overall expenditure. Based on this objective, each shipping line needs to decide the optimal retrofit plan for their ships and determine the most economically advantageous time for each ship to undergo retrofitting, as it can be a lengthy process.

On the regulatory agency level, the regulator collects and responds to the shipping lines' retrofit plans collectively, based on which incentive and penalty policies are determined. The government's goal is to encourage retrofitting efforts from shipping liners, while at the same time ensuring that the decarbonization goal can be achieved. In the proposed formulation, we consider that the regulator provides subsidies, including a ship retrofit subsidy and O&M subsidies following the retrofitting. The subsidy rates vary for ships of different tonnage. The regulator also has an annual budget ceiling for the subsidies. If the total emission exceeds a cap for all SLs, the regulator will impose a penalty on SLs that fail to comply with their emission quota. The more emissions a shipping liner produces, the higher the penalty fines the shipping liner needs to pay.

In game theory terms, the proposed structure is to obtain the Nash equilibrium among multiple leaders of a Stackelberg leader–follower game, which becomes a multi-leader–single-follower game. Note that, different from the typical structure where the regulator acts as a leader and shipping liners (i.e., companies) act as followers, we consider a situation of information asymmetry in which shipping liners, as the leaders of the proposed game, need to anticipate the reaction of the follower (i.e., the regulator) to their decisions. Meanwhile, the regulator must take all the shipping liners' decisions as exogenous and use the information collectively to determine a system-wide optimal solution. In this way, our intention is to encourage all shipping liners to take the initiative in vessel retrofitting/alternative fuel adoption, and the regulator needs to evaluate different shipping liners' planned strategies and identify the equilibrium response to the leaders' decisions.

It is worth noting that our proposed modeling strategy aligns well with the current and envisioned paradigm of the maritime decarbonization pathway identified by the IMO [29]. First, our strategy emphasizes the economic viability of green fuels for shipping liners, a key concern for profit-driven organizations. By minimizing the costs associated with transitioning to and maintaining green fuel use, while also maximizing government subsidies and minimizing pollution penalties, our model ensures that shipping companies can see long-term economic benefits from their investments in sustainability. Secondly, our approach incorporates the regulatory framework established by the IMO, which includes both incentives for compliance and penalties for exceeding emissions caps. By factoring in subsidies for ship retrofitting and operations and maintenance (O&M) post-retrofit, our model addresses the financial aspects that are crucial for the widespread adoption of green technologies in the maritime sector. Moreover, our use of a game-theoretic approach to model the interactions between shipping liners and regulators reflects the complex dynamics of the maritime industry. By treating shipping liners as leaders who anticipate regulatory responses, and regulators as followers who optimize their policies based on the collective actions of the liners, our model captures the strategic behavior that is essential for achieving Nash equilibrium in this multi-leader–single-follower game. This structure not only encourages shipping liners to take the initiative in vessel retrofitting and alternative fuel adoption but also enables regulators to evaluate and respond to these strategies effectively.

The proposed game can then be solved as a generalized Nash equilibrium problem (GNEP), where each participant in solving the optimization problem must set their strategy based on the decision of their competitors, and no participant can unilaterally change their strategy to increase their profit [30].

To better study the problem, the following assumptions are adopted for the rest of the discussion: (i) the sailing time/profile of each vessel is known; (ii) the selection of green fuel for each type of vessel is fixed and remains unchanged throughout the planning horizon (i.e., a vessel can only be retrofitted once); (iii) retrofitting of a vessel always starts at the beginning of a year and can be completed at the end of the same year; (iv) retrofitting-related costs and benefits are calculated at the end of each year; (v) no vessel will retire during the retrofitting planning horizon.

### *2.3. Mathematical Formulation*

The detailed formulation of the proposed problem is provided as follows:

A bi-level optimization model is proposed in this work, and the upper-level model aims to minimize the operational cost of a shipping line as follows:

$$\min_{x,y} \sum_{i} \sum_{j} \sum_{t} \left( CA_{ijt} + CO_{ijt} + CP_{ijt} - SCP_{ijt} - BF_{ijt} - B_{ijt} \right) \tag{1}$$

The above cost comprises six terms: (1) the retrofit cost of $CA_{ijt}$, (2) the O&M cost of $CO_{ijt}$, (3) the penalty cost before retrofitting $CP_{ijt}$, (4) the economic benefit of $SCP_{ijt}$, (5) the voyage cost difference of $BF_{ijt}$, and (6) the actual budget of $B_{iji}$.

For an individual shipping line $i$, the cost associated with performing retrofitting for a ship includes the capital cost, O&M cost, and emission penalty cost. The capital cost of retrofitting a vessel is calculated based on the retrofitting cost coefficient (i.e., $CAP_{ij}$), based on (Joanne et al., 2017), a ship's propulsion power (i.e., $P_{ij}$), and a binary variable (i.e., $y_{ijt}$) indicating the retrofitting status. That is, the actual retrofitting cost of the ship is obtained by multiplying the retrofitting cost per unit power by the propulsion power of the ship, in the following form:

$$CA_{ijt} = CAP_{ij} \cdot p_{ij} \cdot y_{ijt}, \forall i, j, t \tag{2}$$

In (2), if a vessel of type $j$ belonging to shipping line $i$ uses green fuel in year $t$, then $y_{ijt} = 1$; otherwise, $y_{ijt} = 0$.

Referring to [31], the O&M cost of retrofitting a ship of type $j$ for a shipping line $i$ in year $t$ can be written as follows:

$$CO_{ijt} = p_{ij} \cdot N\_sail_{ijt} \cdot r_j \cdot L_{ij} \cdot x_{ijt}, \forall i, j, t \tag{3}$$

where $N\_sail_{ijt}$ denotes the annual sailing frequency of the ship, $r_j$ represents the average length of a single voyage, and $L_{ij}$ is the O&M cost coefficient for using green fuel. First, the propulsion power is multiplied by the sailing time, and then multiplied by the O&M cost per kWh to estimate the actual O&M cost of the vessel, and $x_{ijt}$ is a binary variable: if the vessel of type *j* is consuming green fuel in year *t*, then $x_{ijt} = 1$; otherwise, $x_{ijt} = 0$.

The emission penalty before using green fuel for a vessel of type j of can be expressed as follows:

$$CP_{ijt} = p_{ij} \cdot N\_sail_{ijt} \cdot r_j \cdot \sum_q \left( e\_aux_q \cdot \pi_q \cdot \left(1 - x_{ijt}\right) \cdot 10^{-3} \right), \forall i, j, t \tag{4}$$

where $e\_aux_q$ denotes the emission coefficient of pollutant *q* for the original fuel (e.g., Marine gas oil (MGO)), and $\pi_q$ is the penalty cost coefficient for pollutant *q*. First, the power is multiplied by the sailing time, then multiplied by the pollutant emissions per kWh to obtain the total pollutant emissions of the ship, and finally multiplied by the amount of emissions per kg to obtain the ship's emission penalty. Similarly, we can calculate the emission penalty after a vessel is switched to green fuels as follows:

$$CPF_{ijt} = p_{ij} \cdot N\_sail_{ijt} \cdot r_j \cdot \sum_q \left( fuel\_aux_q \cdot \pi_q \cdot x_{ijt} \cdot 10^{-3} \right), \forall i, j, t \tag{5}$$

where $fuel\_aux_q$ denotes the emission coefficient of pollutant *q* using green fuel. Comparing the emission penalty before and after retrofitting, we can obtain the economic benefit gained by switching to green fuel in terms of avoiding the emission penalty:

$$SCP_{ijt} = p_{ij} \cdot N\_sail_{ijt} \cdot r_j \cdot \sum_q \left( e\_aux_q \cdot \pi_q \cdot x_{ijt} \cdot 10^{-3} \right) - CPF_{ijt}, \forall i, j, t \tag{6}$$

Lastly, when we evaluate the cost of the fuels, the difference in fuel cost between using green and fossil fuels can be calculated as follows:

$$BF_{ijt} = \left( p_a / h - p_{sj} / HOT_j \right) \cdot p_j \cdot N\_sail_{ijt} \cdot r_j \cdot x_{ijt}, \forall i, j, t \tag{7}$$

where *h* is the calorific value of raw fuel, and the $HOT_j$ is the calorific value of new fuel used in ship *j*. The sum of the subsidies provided by the government for retrofitting and O&M is as follows:

$$B_{ijt} = SU1_{ijt} + SU2_{ijt}, \forall i, j, t \tag{8}$$

The corresponding constraints regarding the ship modification time and the use of green fuel are as follows:

$$\sum_t x_{ijt} \le \sum_t y_{ijt} \cdot M, \forall i, j \tag{9}$$

$$y_{ijt} \le x_{ij(t+1)} \cdot M, t = 1, 2, \ldots, T-1, \forall i, j \tag{10}$$

$$y_{ijt} \le 1 - x_{ijt}, \forall i, j, t \tag{11}$$

$$x_{ij(t-1)} \le x_{ijt}, t = 2, 3, \ldots, T, \forall i, j \tag{12}$$

Equation (9) ensures that green fuel can only be used after the ship has been retrofitted. Equation (10) indicates that the use of green fuel starts in the year following the retrofit, i.e., if *y* is equal to 1 in year *t*, *x* must be 1 in year *t+1*. Equation (11) ensures that retrofitting and green fuel use cannot occur in the same year, i.e., if *y* is equal to 1, *x* must be 0. Equation (12) ensures the continuing use of green fuel every year after its adoption.

In the regulator model on the lower level, according to the retrofitting plans of all shipping lines, the regulator determines the subsidy rate (retrofit subsidy and O&M subsidies) and penalty rate for each ship under a limited subsidy budget. The regulator aims to maximize environmental benefits by maximizing pollution fines for ships using green fuels as follows:

$$\max_{\alpha,\pi} \sum_i \sum_j \sum_t \left( EB_{ijt} \right) \tag{13}$$

First, the environmental benefits obtained by the regulator can be represented as follows:

$$EB_{ijt} = N\_sail_{ijt} \cdot r_j \cdot p_{ij} \cdot \sum_q \left( fuel\_aux_q \cdot sc_q \cdot x_{ijt} \cdot 10^{-3} \right), \forall i, j, t \tag{14}$$

where $sc_q$ is the external cost of pollutant $q$. The government regulatory agency's subsidy for retrofitting a ship is as follows:

$$SU1_{ijt} = CAP_{ij} \cdot p_{ij} \cdot \alpha_{1t} \cdot y_{ijt}, \forall i, j, t \tag{15}$$

where $\alpha_{1t}$ denotes the subsidy coefficient for retrofitting. Moreover, the operating and maintenance subsidies for using green fuel for a vessel can be described:

$$SU2_{ijt} = p_{ij} \cdot N\_sail_{ijt} \cdot r_j \cdot L_{ij} \cdot \alpha_{2t} \cdot x_{ijt}, \forall i, j, t \tag{16}$$

where $\alpha_{2t}$ refers to the operating and maintenance subsidies coefficient for using green fuels for a ship.

The corresponding constraints include subsidy limits and penalty limits as follows:

$$\sum_i \sum_j \left( SU1_{ijt} + SU2_{ijt} \right) \le B \quad : \lambda_t \quad \forall t \tag{17}$$

$$\beta_g^1 \le \alpha_{gt} \le \beta_g^2 \quad (\overline{\mu_{gt}}, \underline{\mu_{gt}}) \quad \forall t, g = 1,2 \tag{18}$$

$$0 \le \pi_q \le \sigma \quad : (\overline{\mu_q}, \underline{\mu_q}) \quad \forall q \tag{19}$$

Equation (17) ensures that the total amount of subsidies provided by the government regulatory agency to the three lines does not exceed the total budget. Equation (18) gives the upper and lower bounds of the subsidy proportion provided by the government regulatory agency authorities to shipping lines. Meanwhile, the penalty cost coefficients should always be positive and subject to an upper bound, as shown in (19).

Note that in the above formulation, the Lagrangian multipliers for each constraint, i.e., $(\lambda_t, \overline{\mu_{gt}}, \underline{\mu_{gt}}, \overline{\mu_q}, \underline{\mu_q})$, are included after the colon for future reference.

Combing the upper- and lower-level problems, we have a bi-level optimization for a single shipping line interacting with the regulator in the following form:

Upper Level: Solve (1) and (9)-(12) for an individual shipping line.

Lower Level: Solve (13) and (17)-(19) for the regulator.

## 3. Solution Methodology

### 3.1. EPEC

To solve the above bi-level problem, we can reformulate the lower-level problems (13) and (17)–(19) by replacing it with its KKT conditions. As the lower-level problem is non-empty and convex, its KKT conditions are necessary and sufficient for optimality. In this way, the bi-level model for an individual shipping line can be expressed as a single-layer MPEC model. Specifically, the KKT conditions for (13) and (17)–(19) can be derived as follows:

$$\lambda_t \cdot \sum_i \sum_j \left( CAP_{ij} \cdot y_{ijt} \cdot p_{ij} \right) + \overline{\mu_{gt}} - \underline{\mu_{gt}} = 0, \forall g, t \tag{20}$$

$$\lambda_t \cdot \sum_i \sum_j \left( p_j \cdot D_{ijt} \cdot L_{ij} \cdot x_{ijt} \right) + \overline{\mu_{gt}} - \underline{\mu_{gt}} = 0, \forall g, t \tag{21}$$

$$\overline{\mu_q} - \underline{\mu_q} = 0, \forall q \tag{22}$$

$$0 \le \lambda_t \perp \left( \sum_i \sum_j \left( SU1_{ijt} + SU2_{ijt} \right) - B \right) \ge 0, \forall t \tag{23}$$

$$0 \le \underline{\mu_{gt}} \perp \left( \beta_g^1 - \alpha_{gt} \right) \ge 0, \forall g, t \tag{24}$$

$$0 \le \overline{\mu_{gt}} \perp \left( \alpha_{gt} - \beta_g^2 \right) \ge 0, \forall g, t \tag{25}$$

$$0 \le \underline{\mu_q} \perp \pi_q \ge 0, \forall q \tag{26}$$

$$0 \le \overline{\mu_q} \perp \left( \pi_q - \sigma \right) \ge 0, \forall q \tag{27}$$

For a constraint in the form of $0 \le \mathrm{A} \perp B \ge 0$, we expand it to $0 \le \mathrm{A} \le \delta \cdot M$, $0 \le B \le (1-\delta) \cdot M$, where $M$ is a sufficiently large constant and $\delta$ is a binary variable. The above complementarity conditions (23)–(27) can then be replaced by a set of linear constraints using the binary expansion approach described above. After performing this operation, we obtain the following linearized constraints:

$$0 \le \lambda_t \le iSU_t \cdot M, \forall t \tag{28}$$

$$0 \le \left( \sum_i \sum_j \left( SU1_{ijt} + SU2_{ijt} \right) - B \right) \le \left( 1 - iSU_t \right) \cdot M, \forall t \tag{29}$$

$$0 \le \underline{\mu_{gt}} \le iSC_{gt} \cdot M, \forall g, t \tag{30}$$

$$0 \le \beta_g^1 - \alpha_{gt} \le \left( 1 - iSC_{gt} \right) \cdot M, \forall g, t \tag{31}$$

$$0 \le \overline{\mu_{gt}} \le iSF_{gt} \cdot M, \forall g, t \tag{32}$$

$$0 \le \alpha_{gt} - \beta_g^2 \le \left( 1 - iSF_{gt} \right) \cdot M, \forall g, t \tag{33}$$

$$0 \le \underline{\mu_q} \le iPC_q \cdot M, \forall q \tag{34}$$

$$0 \le \pi_q \le \left( 1 - iPC_q \right) \cdot M, \forall q \tag{35}$$

$$0 \le \overline{\mu_q} \le iPF_q \cdot M, \forall q \tag{36}$$

$$0 \le \pi_q - \sigma \le \left( 1 - iPF_q \right) \cdot M, \forall q \tag{37}$$

where $iSU_t$, $iSC_{gt}$, $iSF_{gt}$, $iPC_q$, and $iPF_q$ are binary variables.

Overall, we convert the bi-level problem formulation for shipping line $i$ into the following mixed-integer linear programming (MILP) optimization problem:

Objective: (1);

Subject to (9)–(12), (20)–(22), and (28)–(37).

Then, considering that we have multiple shipping lines involved in the decision-making process, we need to consider all the individual MPEC problems simultaneously to form an equilibrium problem with EPEC problem. The EPEC formulation ensures that a

Nash equilibrium can be achieved among multiple shipping lines, as all shipping lines' MPEC problems are solved concurrently. Based on the above discussion, we can have the corresponding EPEC as $\{(1), (9)–(12), (20)–(22), (28)–(37)\}_{i=1}^{k}$, where $k$ is the total number of shipping lines considered in the problem.

Figure 3 depicts how the original problem shown in Figure 2 can be reformulated into its EPEC form and solved as a set of MILP problems.

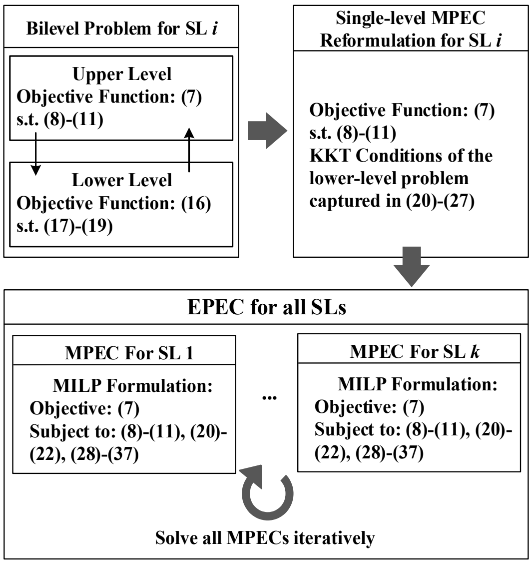



**Figure 3.** EPEC formulation of the proposed retrofitting problem involving multiple shipping lines and a common regulator.

### 3.2. Diagonalization Method to Solve the EPEC Problem

Once the EPEC problem for the ship modification problem has been formulated, we solve it using the diagonalization method (DM). The DM is applied to iteratively solving each individual bi-level programming problem, where players update their own strategies in a cyclic or parallel fashion, while the strategies of other players are considered fixed [30]. When applied to our problem, the way to find the equilibrium solution is by iteratively solving the MPEC model for each SL given the optimal solution of the other SLs as a parameter. A detailed DM process used in this paper is illustrated in Algorithm 1.

We denote by $Y$ the entire retrofit strategy of set $y$. First, we solve the MPEC for SL1 by initializing the values of the other lines' decisions $Y'_{2,\dots,k}$, as an expected retrofit schedule. We then proceed to solve the MPEC problems for the other SLs and check the convergence and stopping condition: if $|Y_i^*\text{-}Y_i'| < \varepsilon$, then we accept the solution and stop; else if $|Y_i^*\text{-}Y_i'| \geq \varepsilon$, set $Y_i' = Y_i^*$, and solve MPEC$_i$ again. Otherwise, the cycle stops when the maximum number of cycles is reached, and no output is produced as no equilibrium point can be found. The detailed DM algorithm is illustrated in Algorithm 1.

**Algorithm 1: DM-based solution methodology**

Step 1. Input parameters $Y'_{2,\dots,k}$, let cycle = 0.

Step 2. For shipping line $i$ = 1 to $k$, solve line $i$'s MPEC:

$$\min_{x,y} \sum_i \sum_j \sum_t \left( CA_{ijt} + CO_{ijt} + CP_{ijt} - BF_{ijt} - SCP_{ijt} - B_{ijt} \right)$$

subject to: (8)–(11), (20)–(22), (28)–(37);

cycle = cycle + 1;

Derive an optimal solution $\left( \alpha_{1t}^*, \alpha_{2t}^*, x_{ijt}^*, y_{ijt}^*, Y_i^* \right)$.

Step 3. If $\left| Y_i^* - Y_i' \right| < \varepsilon$, or $cycle > MaxCycle$, go to step 4; else go to Step 2; let $Y_i' = Y_i^*$

Step 4. Output $Y_{1,\ldots,k} = Y'_{1,\ldots,k}$ .

## 4. Numerical Experiments

In the following simulation study, we consider three shipping lines and analyze their retrofitting decision over a ten-year planning horizon. The specific ship information, including ship tonnage, propulsion power, number of ships, voyage time, and frequency, is modified according to [31–33] and provided in Table 1 and Figure 4. We assume that all vessels under study are currently using MGO as their fuel.

**Table 1.** Shipping lines' vessel information.

| Shipping Line | Tonnage of Ship (t) | Propulsion Power (kW) | Amount of Ship | Green Fuel Selection |
|---|---|---|---|---|
| 1 | 10,000 | 1000 | 2 | Methanol |
| | 20,000 | 2200 | 1 | Hydrogen |
| | 30,000 | 3500 | 2 | LPG |
| 2 | 20,000 | 2200 | 2 | Hydrogen |
| | 30,000 | 3500 | 2 | LPG |
| | 50,000 | 5600 | 1 | Ammonia |
| 3 | 30,000 | 3500 | 2 | LPG |
| | 50,000 | 5600 | 1 | Ammonia |
| | 70,000 | 7000 | 2 | LNG |

In terms of fuel selection, we adhere to the following criteria. Methanol is deemed suitable for small-to-medium-sized vessels with propulsion power ranging from 500 kW to 20,000 kW. Hydrogen fuel has higher adaptability to existing vessels compared to methanol, but its technological maturity is lower, and it is commonly used in coastal and inland waters. LPG is suitable for small-to-medium-sized vessels with propulsion power between 1000 kW and 20,000 kW. Ammonia is suitable for large vessels with propulsion power between 5000 kW and 50,000 kW. Although its technological maturity is relatively low, the infrastructure for ammonia is relatively well-established, providing a foundation for its future application in ships. LNG is applicable for various types of vessels with propulsion power ranging from 1000 kW to 100,000 kW, and it is a well-established alternative fuel for large vessels [34].

Figure 4 illustrates the representative sailing profile for each type of vessel under different shipping lines within the planning period. Without loss of generality, we assume that vessels of similar tonnage also have similar sailing durations. We also make the assumption that with the continuing growth of the global maritime industry, the annual number of voyages for all types of vessels is anticipated to increase throughout the planning period.

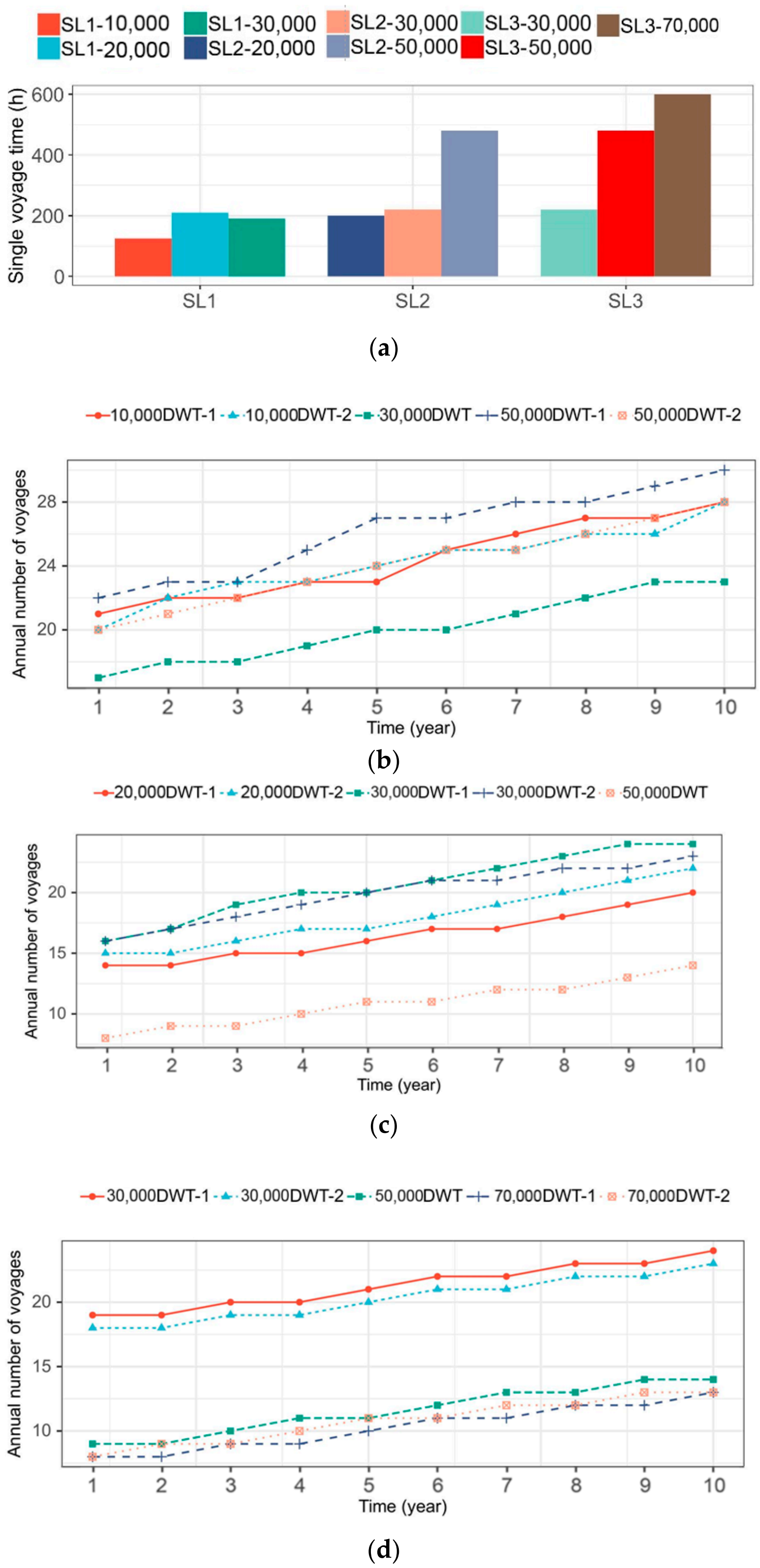



**Figure 4.** Mission profiling of ships for all shipping lines, adapted from [31]. (**a**) Average voyage durations for different types of vessels. (**b**) Sailing frequency of different vessels owned by SL1. (**c**) Sailing frequency of different vessels owned by SL2. (**d**) Sailing frequency of different vessels owned by SL3

Furthermore, Table 2 presents the retrofitting cost coefficient for retrofitting vessels that use different types of fuels. The retrofitting costs include the system components of the alternative fuel system, engine conversion, and engine room modifications. The engine conversion costs depend on the type and size of the vessel. Methanol fuel requires engine conversion and safety modifications in the engine room. Hydrogen fuel requires fewer system components and does not require major engine modifications. LPG and LNG fuels, on the other hand, require extensive engine modifications. Ammonia requires specialized ammonia engines or fuel cells.

**Table 2.** The retrofitting cost coefficient for retrofitting vessels [26,35,36].

| Green Fuel | Retrofitting Cost Coefficient (USD/kW) |
|---|---|
| Methanol | 392 |
| Hydrogen | 100 |
| LPG | 500 |
| Ammonia | 525 |
| LNG | 664 |

When measuring the ships' environmental impacts, we considered four types of pollutants, namely, $NO_X$, $SO_2$, $CO_2$, and PM. Table 3 presents the emission factors of five types of pollutants for different fuels. The environmental costs associated with these pollutants are 10.687 USD/kg, 12.329 USD/kg, 0.029USD/kg, and 76.867 USD/kg, respectively. The data are organized and modified based on [31]Yu (2019).

**Table 3.** The emission factors for different fuels [35,37].

| Operational Fuel Emission Factors (g/kWh) | $NO_X$ | $SO_2$ | $CO_2$ | PM |
|---|---|---|---|---|
| MGO | 7.91 | 0.13 | 646 | 0.37 |
| Methanol | 3.05 | 0 | 522 | 0 |
| Hydrogen | 0 | 0 | 0 | 0 |
| LPG | 3 | 0.003 | 430 | 0.027 |
| Ammonia | 0 | 0 | 0 | 0 |
| LNG | 1.17 | 0.003 | 412 | 0.027 |

For the regulatory agency, we assume that it has an annual budget of USD 1 million during the ten-year planning period to promote the early adoption of green fuels. The fixed subsidy rate granted by the regulator for ship retrofitting ranges between 10% and 46%. Additionally, the O&M subsidies granted by the regulator for clean fuels to shipping lines range between 0.01 USD/kWh and 0.2 USD/kWh [28]. The pollution fine coefficients, based on environmental costs, are set as follows: $NO_X$: 5 USD/kg~15 USD/kg; $SO_2$: 10 USD/kg~15 USD/kg; $CO_2$: 0.01 USD/kg~0.03 USD/kg; PM: 60 USD/kg~80 USD/kg.

All computational experiments were carried out on a PC with an AMD Ryzen 7 5800U CPU and 16 GB of memory. The Branch-And-Reduce Optimization Navigator (BARON) solver within GAMS was used to solve the optimization model.

### *4.1. Performance Evaluation: Shipping Lines*

We first analyze the results from the perspective of shipping lines involved in the decision-making process.

Table 4 shows the retrofitting plans for different vessels owned by three shipping lines. From the table, it can be seen that the retrofitting priorities for different vessels vary based on their deadweight tonnage (DWT), fuel type, and voyage profiles. However, all the vessels are successfully retrofitted within a period of six years. Specifically, for SL1, a 20,000 DWT vessel and a 30,000 DWT vessel are retrofitted in the second year, another 20,000 DWT vessel is retrofitted in the third year, and two 10,000 DWT vessels are retrofitted in the fifth and sixth years, respectively. For SL2, two 30,000 DWT vessels are retrofitted in the first year, while the remaining two 20,000 DWT vessels and one 50,000 DWT vessel are retrofitted in the fifth year. SL3 retrofits a 50,000 DWT vessel with the longest voyage duration and a 70,000 DWT vessel in the first year, followed by two 30,000 DWT vessels in the third year, and the remaining 70,000 DWT vessel in the fourth year. These results indicate that the retrofitting sequence for each shipping line is closely related to the duration of the voyage and the DWT of the vessel. Vessels with longer voyage durations and higher DWT are usually prioritized for retrofitting. Additionally, retrofitting is also influenced by the cost and technology of the green alternative fuel used. For example, the 50,000 DWT vessel of SL2 and the 50,000 DWT vessel of SL3, which switch to ammonia fuel, undergo retrofitting at a later stage due to the higher technology cost associated with using ammonia fuel.

**Table 4.** The retrofitting strategies of shipping lines.

| SL | Tonnage of Ship (ton) | Whether to Be Retrofitted (Y/N) | First Year to Be Retrofitted |
|---|---|---|---|
| 1 | 10,000 | Y | 5 |
| | 10,000 | Y | 6 |
| | 20,000 | Y | 3 |
| | 20,000 | Y | 2 |
| | 30,000 | Y | 2 |
| 2 | 20,000 | Y | 5 |
| | 20,000 | Y | 5 |
| | 30,000 | Y | 1 |
| | 30,000 | Y | 1 |
| | 50,000 | Y | 5 |
| 3 | 30,000 | Y | 3 |
| | 30,000 | Y | 3 |
| | 50,000 | Y | 4 |
| | 70,000 | Y | 1 |
| | 70,000 | Y | 1 |

### *4.2. Performance Evaluation: Regulator*

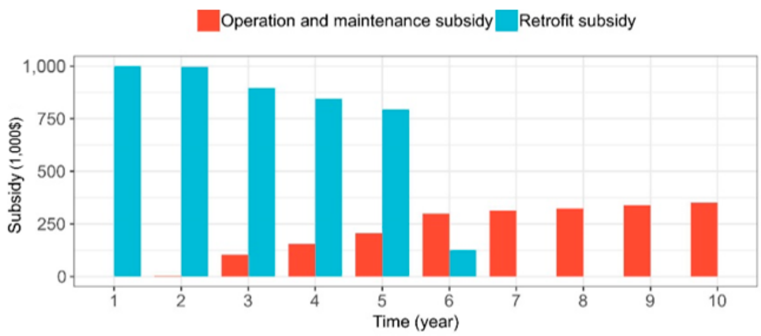
As the other crucial player in the decision-making process, we analyze the results for the regulator in the following discussion.

Table 5 displays the subsidy design results by the regulatory agency for retrofitting and operation. The table shows that the annual ship retrofitting subsidy coefficient varies each year, influenced by the number and cost of ship retrofits. In the first year, there is a larger number of retrofits for large vessels, resulting in a relatively lower retrofitting subsidy coefficient due to budget constraints. The number of retrofits decreases in the second year, leading to an increase in the retrofitting subsidy coefficient. Similarly, in the fourth year, only one large vessel undergoes retrofitting, resulting in a high subsidy coefficient. All vessels complete their retrofitting plans within six years, after which the regulatory agency ceases to allocate retrofitting subsidies. Regarding O&M subsidies, the government starts providing them in the second year. However, due to a significant portion of subsidies being allocated for ship retrofits initially, the O&M subsidy rate is relatively low. As more retrofits are completed, the subsidy rate shows an increasing trend, and after the sixth year, all subsidies are utilized for operating and maintaining the vessels, stabilizing at the maximum subsidy rate.

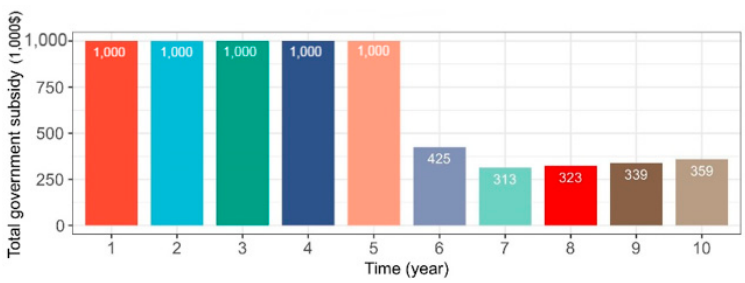
**Table 5.** The subsidy coefficients for ships.

| Time (Year) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Retrofitting subsidy coefficients (USD/kg) | 0.112 | 0.407 | 0.344 | 0.460 | 0.328 | 0.460 | | | | |
| Operation and maintenance (O&M) subsidy coefficient (USD/kg) | | 0.010 | 0.153 | 0.196 | 0.200 | 0.200 | 0.200 | 0.200 | 0.200 | 0.200 |

Figure 5 presents the details of subsidies provided by the regulatory agency. Consistent with our previous analysis, we can observe from Figure 5a that over 80% of the subsidies are allocated for ship retrofitting in the first five years. As the number of retrofitted ships increases, the retrofitting subsidies show a declining trend, while O&M subsidies exhibit an upward trend. Once all ships have been retrofitted (starting from the seventh year), the regulatory agency's budget is fully allocated to O&M subsidies. On the other hand, Figure 5b displays the total expenditure of the regulatory agency each year. It can be observed that the subsidy budget is completely utilized in the first five years, reflecting the high amount of retrofitting subsidies. In the sixth year, only one ship undergoes retrofitting, leading to a decrease in overall subsidies. Starting from the seventh year, when all ships have completed their retrofits, only O&M subsidies are provided, accounting for approximately 30% of the budget. Additionally, as the voyage duration increases, corresponding to higher O&M costs, the O&M subsidies slightly increase.




(a)




(b)

**Figure 5.** Annual retrofitting and O&M subsidies provided by the regulator. (**a**) Annual retrofitting and O&M subsidies. (**b**) Annual regulator spending.

For emission penalties, the regulatory agency applies different penalty coefficients for different pollutants, as shown in Table 6. We can observe that the penalty coefficients for $NO_x$, $SO_2$, $CO_2$, and PM are set at 8 USD/kg, 15 USD/kg, 0.01 USD/kg, and 80 USD/kg, respectively. It is worth noting that pollutants with higher emission levels have lower penalty coefficients, while pollutants with lower emission levels have higher penalty coefficients. This economic incentive mechanism encourages ship operators to adopt green alternative fuels.

**Table 6.** Pollutant results.

| Pollutants | $NO_X$ | $SO_2$ | $CO_2$ | PM |
|---|---|---|---|---|
| Emission penalty coefficients (USD/kg) | 8 | 15 | 0.01 | 80 |

Figure 6 shows the emission reduction effect of the proposed approach for the regulator. We can clearly observe that in year 0 (before the retrofitting starts), the shipping lines have a high level of emissions. During the retrofitting process, the total emissions drop as many vessels are no longer in service, resulting in less emissions. When all the vessels are retrofitted (after year 6), we can observe that vessel retrofitting for green fuels can result in a roughly 50% reduction in emissions, compared with the business-as-usual case where the vessels continue using MGO as their fuel. This observation is in line with our anticipation that switching to green fuels can be an effective way to decarbonize the maritime industry. Note that in Figure 6, we calculate the overall emissions based on the Greenhouse Gas Equivalencies Calculator provided by the [38].

In addition, we calculated and compared the annual operational carbon intensity indicator (CII) for all shipping lines before and after retrofitting in Table 7. It can be observed that following retrofitting, the CIIs for all vessels drop significantly, especially when a vessel switches to hydrogen fuel, which is considered carbon-free when combusted.

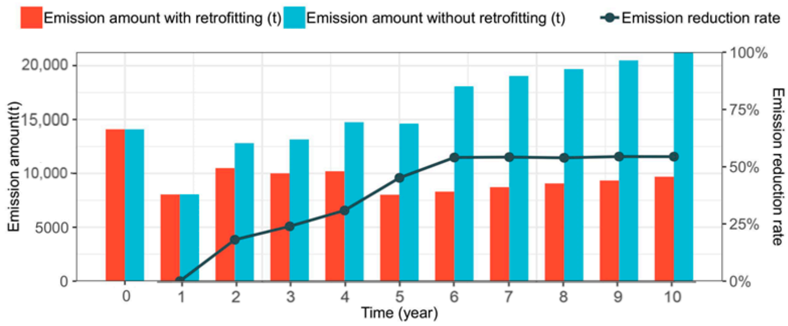



**Figure 6.** Emission reduction due to vessel retrofitting.

**Table 7.** The change in CII before and after retrofitting for different SLs.

| SL | Tonnage of Ship (Ton) | CII (before Retrofit) | CII (after Retrofit) |
|---|---|---|---|
| 1 | 10,000 | 2.98 | 2.76 |
| | 10,000 | 3.38 | 2.76 |
| | 20,000 | 4.76 | 0.00 |
| | 20,000 | 9.00 | 0.00 |
| | 30,000 | 7.78 | 5.88 |
| 2 | 20,000 | 0.74 | 0.00 |
| | 20,000 | 1.37 | 0.00 |
| | 30,000 | 1.43 | 0.81 |
| | 30,000 | 0.99 | 0.81 |
| | 50,000 | 0.86 | 0.85 |
| 3 | 30,000 | 0.86 | 0.47 |
| | 30,000 | 0.94 | 0.49 |
| | 50,000 | 0.59 | 0.58 |
| | 70,000 | 0.58 | 0.44 |
| | 70,000 | 0.57 | 0.45 |

*4.3. Government Regulatory Agency Subsidies*

Tables 8 and 9 demonstrate how the budget of the regulatory agency impacts the retrofitting plans of the shipping lines. We assess the retrofitting strategies when the annual budget increases from USD 1 million to USD 1.5 million and USD 2 million, respectively, and the results are presented in Tables 8 and 9. It is evident that as the budget increases, the pace of ship retrofitting accelerates. In particular, when the budget is USD 1 million, it would take six years for the three shipping lines to retrofit all their vessels. With a budget of USD 1.5 million, it would only take four years. And with a budget of USD 2 million, all the vessels can be retrofitted in just three years. Therefore, it is apparent that the increase in subsidies from the regulatory agency can expedite the retrofitting process for all participating shipping lines.

**Table 8.** The retrofitting strategy under a USD 1.5 million annual budget.

| SL | Tonnage of Ship (Ton) | Whether to Be Retrofitted (Y/N) | First Year to Be Retrofitted |
|---|---|---|---|
| 1 | 10,000 | Y | 4 |
| | 10,000 | Y | 3 |
| | 20,000 | Y | 2 |
| | 20,000 | Y | 2 |
| | 30,000 | Y | 1 |
| 2 | 20,000 | Y | 3 |
| | 20,000 | Y | 3 |
| | 30,000 | Y | 2 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 4 |
| 3 | 30,000 | Y | 3 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 4 |
| | 50,000 | Y | 1 |
| | 70,000 | Y | 1 |

**Table 9.** The retrofitting strategy under a USD 2 million annual budget.

| SL | Tonnage of Ship (Ton) | Whether to Be Retrofitted (Y/N) | First Year to Be Retrofitted |
|---|---|---|---|
| 1 | 10,000 | Y | 3 |
| | 10,000 | Y | 3 |
| | 20,000 | Y | 2 |
| | 20,000 | Y | 1 |
| | 30,000 | Y | 1 |
| 2 | 20,000 | Y | 2 |
| | 20,000 | Y | 1 |
| | 30,000 | Y | 2 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 3 |
| 3 | 30,000 | Y | 3 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 3 |
| | 50,000 | Y | 1 |
| | 70,000 | Y | 1 |

### *4.4. Original Fuel Types*

In the following analysis, we analyze how shipping lines react to emission regulations when different fossil fuels are used in their existing vessels before retrofitting. This can be a practical challenge, as many shipping lines currently use heavy fuel oil (HFO), as a representative dirty but cheap fuel, and low-sulfur heavy fuel oil (LSHFO), as a representative cleaner but more expensive fuel than HFO, to power their vessels.

Figure 7 illustrates the emissions generated by the three shipping lines when using different initial fuels. As shown in Figure 7, when using HFO as the initial fuel, the total pollution emissions are significantly higher compared to MGO and LSHFO fuels [39,40]. This is because HFO fuel combustion results in high emissions of $SO_2$, $CO_2$, and PM. Faced with higher pollution fines, shipping lines would actively participate in retrofitting and adopt greener alternative fuels with lower pollutant emissions. This is why the overall emissions are the lowest in the first year when using HFO as the initial fuel. The emissions from LSHFO fuel are lower than those of HFO but still slightly higher than those of MGO fuel, resulting in a slightly shorter retrofitting period compared to using MGO fuel, and correspondingly lower emissions during the retrofitting period. In the later years, emissions are the same for all three fuel scenarios, as all vessels are retrofitted and all emissions come from green alternative fuels.

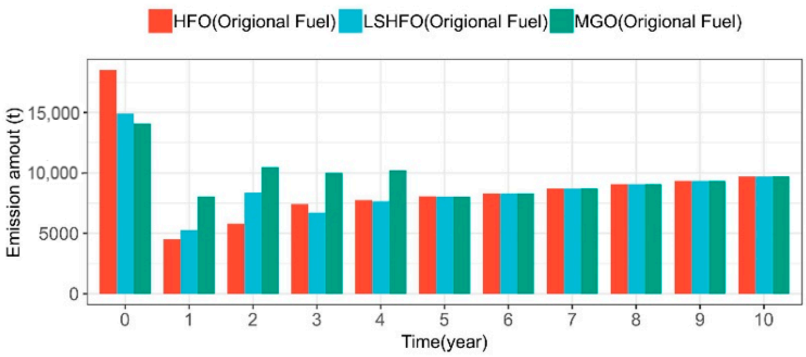



**Figure 7.** Comparison of pollutant emissions of three original fuels.

As shown in Tables 10 and 11, the enthusiasm for retrofitting ships significantly increases when the original fuel is HFO, and all vessel retrofit plans are completed within four years. Furthermore, large-scale ships with longer voyages choose to undergo retrofitting in the first year. This is because although the price of HFO is lower than that of MGO, the high emission of pollutants, especially SOx emissions, has led to a significant increase in the cost of pollution emissions, which has prompted shipping lines to increase their willingness to retrofit vessels. When the original fuel is LSHFO, all vessel retrofit plans are completed within five years, similar to MGO, but the overall retrofitting time is slightly higher than that of the original fuel MGO. This is because although LSHFO fuel reduces $NO_x$ emissions compared to MGO fuel, PM, $SO_2$, and $CO_2$ emissions increase, and the total pollutant fines are slightly higher than those for MGO fuel, which slightly increases the retrofitting enthusiasm of ships.

**Table 10.** The retrofitting strategies using HFO fuel.

| SL | Tonnage of Ship (Ton) | Whether to Be Retrofitted (Y/N) | First Year to Be Retrofitted |
|---|---|---|---|
| 1 | 10,000 | Y | 4 |
| | 10,000 | Y | 3 |
| | 20,000 | Y | 2 |
| | 20,000 | Y | 2 |
| | 30,000 | Y | 1 |
| 2 | 20,000 | Y | 2 |
| | 20,000 | Y | 1 |
| | 30,000 | Y | 1 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 3 |
| 3 | 30,000 | Y | 2 |
| | 30,000 | Y | 1 |
| | 50,000 | Y | 1 |
| | 50,000 | Y | 1 |
| | 70,000 | Y | 1 |

**Table 11.** The retrofitting strategies using LSHFO fuel**.**

| SL | Tonnage of Ship (Ton) | Whether to Be Retrofitted (Y/N) | First Year to Be Retrofitted |
|---|---|---|---|
| 1 | 10,000 | Y | 5 |
| | 10,000 | Y | 5 |
| | 20,000 | Y | 3 |
| | 20,000 | Y | 1 |
| | 30,000 | Y | 1 |
| 2 | 20,000 | Y | 2 |
| | 20,000 | Y | 1 |
| | 30,000 | Y | 4 |
| | 30,000 | Y | 2 |
| | 50,000 | Y | 3 |
| 3 | 30,000 | Y | 2 |
| | 30,000 | Y | 1 |
| | 50,000 | Y | 2 |
| | 50,000 | Y | 1 |
| | 70,000 | Y | 1 |

### *4.5. Number of Ships*

In this study, we investigate how shipping lines of different sizes react differently to retrofitting initiatives. As shown in Table 12, we consider five different scenarios when the size of the shipping lines varies. The results obtained show that under the same regulatory policy, when the size of the shipping line grows, it takes longer to complete all the retrofitting. However, in the last case (Case #5), we can see that the retrofitting slows down. This can be attributed to the fact that when the number of vessels increases to a certain extent, the high cost of shipping retrofitting and limited regulator budget can greatly reduce the motivation for vessel retrofitting. In fact, under Case #5, 40% of the vessels are not retrofitted and the shipping lines prefer to pay the emission penalties instead. This important observation shows that the regulator needs to carefully balance the sizes of the fleet and their budget to ensure the effectiveness of the retrofitting plan, as penalty alone may not be sufficient to ensure the successful low-carbon transition of the maritime industry.

**Table 12.** Retrofitting timeline with varying sizes of shipping lines.

| Cases | Case #1 | Case #2 | Case #3 | Case #4 | Case #5 |
|---|---|---|---|---|---|
| The number of SL1 | 3 | 5 | 8 | 12 | 14 |
| The number of SL2 | 3 | 5 | 8 | 10 | 13 |
| The number of SL3 | 2 | 5 | 8 | 10 | 13 |
| the total retrofit time (year) | 4 | 6 | 8 | 9 | 7 |

## 5. Conclusions and Future Work

Decarbonizing the maritime industry is of paramount importance to combat climate change, meet international commitments, and ensure the sector's long-term sustainability. To contribute to this important goal, this paper investigated the policy instruments to coordinate the decision-making process and accelerate vessel retrofitting with green fuels. We propose a bi-level structure to capture the multi-leader–single-follower game formulation involving an environmental regulator and multiple shipping lines. The equilibrium of the resulting EPEC model is obtained via the diagonalization method. Simulation results showed that the proposed approach is effective in stimulating shipping lines to take action and complete the retrofitting for their whole fleet within the first six years of the 10-year-long planning horizon. The proposed approach is also capable of helping the regulator meet the emission reduction objective by cutting emissions down by roughly 50%. The sensitivity analysis has shown that (1) subsidies play an important role in stimulating prompt retrofitting initiatives; (2) the original fuel used by vessels can also affect the retrofitting plan, especially fuels with higher polluting factors; (3) when the size of the vessel fleets grows, the shipping lines may choose to not retrofit all their vessels without proper financial incentives. Overall, the simulation results have shown that by capturing the dynamic interactions between shipping lines and the regulatory agency, the proposed approach can help both parties determine the most economical and feasible investment decisions and achieve a win–win situation.

This work can be expanded in various ways. For instance, one can incorporate a more detailed model to capture the duration and cost of the retrofitting process for different types of vessels. As many new fuels require dual fuel combustion, the complexities associated with engine technologies can also be incorporated in the modeling process. Last, while our paper focuses on investigating the operational emissions, future works can be conducted to perform the evaluation based on the life cycle emissions of the alternative fuels to provide a more comprehensive assessment of the effects of vessel retrofitting.

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## Nomenclature

| **Indices** | | **Parameters** | |
|---|---|---|---|
| $i$ | Index for shipping lines, $i$ = {1,2,3} | $p_{ij}$ | The power of a ship with ship $j$ of shipping line $i$, kW |
| $j$ | Index for ship types measured by Dead Weight Tonnage (DWT), $j$ = {1,2,…5} | $r_j$ | Time of a ship's single sailing with ship $j$ |
| $t$ | Index of the time, $t$ = {1,2,…,10} | $N\_sail_{ijt}$ | Frequency of sailing in a year with ship $j$ of shipping line $i$ at the $t^{th}$ year |
| $q$ | Index of the pollute, $q$ = {$NO_X$, $SO_X$, $CO_2$, PM} | $p_a$ | Price of marine diesel oil, USD |
| $g$ | Index of the types of subsidies, $g$ = {1, 2} | $p_{sj}$ | Price of alternative fuel $s$ for ship $j$ using green fuel, USD |
| **Variables** | | $sc_q$ | The external cost of pollutant $q$, USD/kg |
| $y_{ijt}$ | A 0–1 variable, if a ship with ship $j$ of shipping line $i$ to retrofitted in the $t^{th}$ year, $y_{ijt}$ =1; otherwise $y_{ijt}$ =0 | $N\_vessel_{ijt}$ | The number of ships of type $j$ for shipping line $i$ |
| $x_{ijt}$ | A 0–1 variable, if a ship with ship $j$ of shipping line $i$ can use green fuel in the $t^{th}$ year, $x_{ijt}$ =1; otherwise $x_{ijt}$ =0 | $\beta_g^{\min}, \beta_g^{\max}$ | The lower and upper bounds of subsidies g |
| $\alpha_{1t}$ | The subsidy coefficients provided for ship owners to retrofit ships at the $t^{th}$ year, considered as a percentage of the capital investment | $M$ | A large number |
| $\alpha_{2t}$ | The subsidy coefficients for operation and maintenance at the $t^{th}$ year | $\sigma$ | The lower bound of the cost of penalizing pollutants |
| $\pi_q$ | The penalty cost coefficients of the pollutant $q$, USD/kg | $B$ | Annual government subsidy |
| $EB_{ijt}$ | The environmental benefit of the government for a ship with ship $j$ of shipping line $i$ at the $t^{th}$ year, USD | | |
| $SU1_{ijt}$ | The government's capital cost of retrofitting a ship with ship size ship $j$ of shipping line $i$ at the $t^{th}$ year, USD | | |
| $SU2_{ijt}$ | The government's operation and maintenance cost for using green fuel of a ship with ship $j$ of shipping line $i$ at the $t^{th}$ year, USD | | |

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