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Optimal Ship Deployment and Sailing Speed under Alternative Fuels

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Abstract: The European Union (EU) has implemented a sub-quota of 2% for renewable marine fuels to be utilized by vessels operating within its jurisdiction, effective starting from 2034. This progressive policy signifies a significant leap towards reducing carbon emissions and promoting sustainable development. However, it also presents notable challenges for shipping companies, particularly in terms of fuel costs. In order to support shipping companies in devising optimal strategies within the framework of this new policy, this study proposes a mixed-integer linear programming model. This model aims to determine the optimal decisions for fuel choice, sailing speed and the number of vessels on various routes. Furthermore, we showcase the adaptability of our model in response to fluctuations in fuel prices, relevant vessel costs, and the total fleet size of vessels. Through its innovative insights, this research provides invaluable guidance for optimal decision-making processes within shipping companies operating under the new EU policy, enabling them to minimize their total costs effectively.

Keywords: sustainable maritime transportation; green shipping; energy efficiency; sailing speed

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1. Introduction

The global shipping industry plays a vital role in ensuring the movement of goods and commodities across the world [1–3]. However, traditional fuels used in this sector, primarily fossil fuels, have raised significant concerns due to their adverse environmental impacts, including carbon emissions and air pollution [4]. As societies worldwide strive to combat climate change and transition towards sustainable practices, the exploration and integration of renewable fuels have emerged as a pivotal solution for the maritime industry [5–7]. Renewable fuels, also known as biofuels or alternative fuels, are derived from organic matter such as plants, algae, and waste materials. Unlike traditional fossil fuels, these sources are considered sustainable as they can be replenished through natural processes, reducing dependency on finite resources [8]. The integration of renewable fuels into the maritime sector holds tremendous potential to greatly mitigate the environmental footprint of shipping operations while promoting sustainable development. Furthermore, the utilization of renewable energy sources aligns with international efforts to achieve the objectives of the Paris Agreement and the International Maritime Organization's (IMO) related emission reduction targets [9,10]. Understanding the significance of renewable fuels in maritime transportation is significant for guiding policy decisions and driving sustainable practices within the shipping industry.

According to [11], the EU has established a sub-quota of 2% for renewable marine fuels to be utilized by vessels operating within its jurisdiction, effective from the year 2034. This means that starting from 2034, at least 2% of the fuel used by vessels during voyages within the EU must be derived from renewable sources. Note that for these voyages linking the EU and non-EU areas, half of the fuel consumption generated is attributed to the EU. Undoubtedly, this exerts a crucial impact on the optimal decision-making of shipping companies.

In this paper, we put forth mathematical frameworks aimed at facilitating the attainment of optimal decision-making in the pursuit of cost minimization for shipping companies, while simultaneously ensuring compliance with the renewable fuel policy recently introduced by the EU. To the utmost extent of our understanding, our study represents a groundbreaking inquiry, uniquely incorporating this freshly established EU policy. Specifically, our investigation addresses the ensuing research inquiries:

1. What are the optimal fuel choices within different types of areas that result in the minimal overall expenditure while adhering to the renewable fuel target stipulated by EU policy?
2. What are the optimal sailing speeds, taking into account both traditional and renewable fuels, within the EU and non-EU areas, to minimize the aggregate expenses incurred by shipping companies in accordance with the recently proposed EU renewable fuel regulations?
3. What is the optimal number of deployed vessels in diverse shipping routes, including considerations for the chartering in or chartering out ships, that will culminate in the lowest total costs while simultaneously meeting the EU's 2% renewable fuel target?
4. How do the optimal fuel choices within the EU and non-EU areas, sailing speeds associated with different fuel types, as well as the optimal number of vessels to be equipped in each shipping route, including the consideration of vessels chartering in or chartering out, vary in response to fluctuations in fuel prices, relevant vessel costs, and the total fleet size of vessels?

To tackle the four research inquiries mentioned above, we initially introduce a sophisticated mixed integer nonlinear optimization (MINLP) model characterized by its intricate nature and challenging problem-solving complexity. Subsequently, we employ advanced mathematical techniques to convert the MINLP model into a mixed-integer linear programming (MILP) formulation. This transformation enables the utilization of readily available optimization solvers for solving the MILP model. Lastly, we conduct a series of comprehensive experiments and thorough sensitivity analyses to assess the model's performance in response to various parameter variations.

1.1. Literature Review

We review two streams of literature closely related to our study: (i) the renewable fuel in shipping; (ii) the optimal decisions in shipping.

1.1.1. The Renewable Fuel in Shipping

In the level of policy, many countries and organizations have shed light on the transformative potential of renewable fuels and their role in shaping the future of sustainable shipping [12]. In detail, at the IMO, there are ongoing deliberations regarding the implementation of Market-Based Measures (MBMs) to enhance the economic desirability of low- and zero-carbon fuels compared to fossil fuels. The proposed MBMs encompass a range of approaches, including the imposition of global levies on marine fuels, the establishment of an Emissions Trading System (ETS), and the exploration of other hybrid mechanisms [13]. Moreover, the FuelEU Maritime Directive exemplifies a joint endeavor to decrease the greenhouse gas (GHG) of energy employed aboard maritime vessels, elucidating a profound ambition of achieving a 75% reduction by 2050 [14]. This multipronged objective can be actualized by means of actively advocating and extensively embracing renewable and low-carbon fuels [14]. In addition, a comprehensive overhaul of the European Energy Taxation Directive (EU ETD) looms on the horizon, enacting thresholds for the minimum taxation rates on bunker fuel. Noteworthy is the fact that fossil fuels bear the brun of the highest minimum tax rate, valiantly standing at EUR 10.75/GJ, while renewable fuels are subject to the lowest rate, valiantly striking at EUR 0.15/GJ [15]. In addition, the revised renewable energy directive (RED II) propounds an exacting target of a minimum 13% reduction in GHG intensity within the transport sector by 2030 [15]. Moreover, it establishes sub-targets, tailored specifically to advance biofuels and non-biological renewable fuels [16].

In the aspect of renewable fuel utilization, various studies have explored the potential of different alternatives. Hydrogen fuel, due to its notable efficiency and environmental advantages, stands as a paramount sustainable fuel option. In practical applications, methanol is commonly employed to generate hydrogen. The alcohol–hydrogen fuel mixed by a series of high-temperature catalytic reactions can be used in the shipping industry [17]. Moreover, biodiesel emerges as a sustainable energy source that exhibits exceptional biodegradability and possesses low toxicity, making it an excellent alternative to fossil fuels across various sectors [18]. Additionally, a comprehensive study [19] focused on evaluating the environmental and economic aspects of using Liquefied Natural Gas (LNG) as a ship fuel. The results from this extensive life-cycle analysis and cost assessment demonstrated that LNG generates lower greenhouse gas emissions, up to 28% less than heavy fuel oil, while producing slightly higher nitrogen oxide emissions. From the prospective of technology, LNG, Liquefied Petroleum Gas (LPG), and methanol are considered more mature technologies, along with biodiesel, hydrogen, and ammonia fuels, which exhibit greater potential for future development [10]. However, the present utilization of a diverse array of low-carbon fuels presents certain drawbacks that impede their immediate substitution for conventional fossil fuels. Addressing this challenge entails the establishment of multi-period energy planning, which not only facilitates adaptation to demand fluctuations and evolving emission restrictions at distinct stages, but also aids in energy projection and future investment strategizing [20]. What is more, from an economic standpoint, the dual fuel propulsion system stands out as the most viable and cost-efficient alternative for container vessels in the present. By ingeniously alternating between conventional fossil fuels and renewable energy sources, this system optimally adheres to forthcoming regulatory requirements and standards [21].

1.1.2. The Optimal Decisions in Shipping

In the realm of maritime transportation, the pursuit of attaining the optimal trajectory, sailing speed, fuel consumption, and other pertinent optimal decisions constitutes the focus in cost minimization. Within this context, the exploration of optimal decisions has been undertaken to curtail operational expenses [22–25].

Several studies have been conducted to optimize sailing speed and fuel consumption for the purpose of reducing shipping costs. For the relationship between fuel consumption and sailing speed, the prevailing consensus posits that there exists a cubic relationship between fuel consumption and sailing speed [26]. Laporte et al. [27] conducted a comprehensive study on speed optimization problems within the liner transportation network, taking into account time window constraints. Arijit et al. [28] and other researchers extensively investigated the implementation of a slow streaming policy as a means to minimize fuel consumption and associated costs. The adoption of slower speeds has proven effective in reducing fuel consumption; however, it can also result in delivery delays. Moreover, reducing the sailing speed necessitates deploying more vessels for the service, thereby augmenting the operational expenses of the ships [29]. In addressing this trade-off, He et al. [30] proposed a speed optimization problem where a set of speeds for each segment of a given route is determined to minimize costs while considering time windows and speed limits for each segment. Aydin et al. [31] conducted an assessment of speed optimization in liner shipping, incorporating stochastic port times into their model. Their objective was to minimize total fuel consumption while upholding schedule reliability. Li et al. [32] proposed an innovative approach that combines the optimization of sailing routes and speeds, taking into account the interrelation between them as well as environmental factors.

In the context of model formulation involving multiple optimal decision variables, Lu et al. [33] introduce a dual-objective optimization model for ship speed, with a focus on the influence of the ECA control area, berthing costs, and AMP systems. By employing the multi-objective PSO (Particle Swarm Optimization) algorithm, the study aimed to identify the Pareto solution set that simultaneously minimizes ship operating costs and carbon emissions. Subsequently, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) algorithm was applied to evaluate and extract the optimal compromise solution from the Pareto set. Mahsa et al. [34] formulated a bi-objective programming model that addresses the joint optimization of ship scheduling and sailing speeds for a specific shipping service. This model takes into account factors such as non-identical stream flow speeds. Iris et al. [35] focused their research on the well-known berth allocation problem (BAP). They proposed a novel mathematical formulation that extends the traditional BAP to encompass multiple ports within a shipping network. Furthermore, their model implementation demonstrates that precise speed discretization can lead to significantly improved economic and environmental outcomes. Dulebenets et al. [36] introduced an MINLP model aimed at minimizing the overall cost of liner shipping routes. Meng et al. [37] evaluated an optimization model for fuel consumption and ship speed in liner transport, accounting for deviations from the scheduled speed. Lee et al. [38] investigated a dynamic planning model to determine fuel consumption under uncertain fuel costs. The trade-off between vessel quantity and speed was further elucidated in [39–41], emphasizing the significance of selecting the optimal number of ships for liner shipping. Sheng [40] investigated optimal vessel speed and fleet size considerations for services operating within emission control areas (ECAs).

In general, prior research efforts have predominantly focused on optimizing decisions related to sailing speed, fuel consumption, deployed vessels across different routes, and fleet size. These studies aim to provide more effective decision support for shipping companies by jointly considering multiple optimal decision variables. However, limited attention has been paid to the fuel selection and corresponding sailing speeds for different legs of the journey. Our research endeavors to address this gap by integrating the latest renewable fuel policies implemented by the EU with existing research findings. In this paper, we propose an MILP model, which aims to determine the optimal fuel selection, speed decisions, and the corresponding deployment quantity of vessels, simultaneously achieving cost minimization and promoting environmental conservation and sustainable development.

1.2. Research Contributions

1. Theoretical contributions. The present research addresses a significant research gap by focusing on the optimal selection of fuel, sailing speed, and the number of ships under the newly proposed EU policy. Notably, the existing literature has overlooked this specific aspect. To the best of our knowledge, this study represents the pioneering effort in establishing mathematical models aimed at minimizing the overall costs incurred by shipping companies while considering the implications of the new EU policy. The proposed approach employs an MILP model to determine the optimal decisions for shipping companies. By conducting rigorous experiments and sensitivity analyses, this study yields specific solutions while evaluating the impacts of various parameters.
2. Practical contributions. This research contributes valuable practical insights into the development of optimal strategies for shipping companies to effectively minimize costs and ensure compliance with the new EU emissions policy. The obtained results possess practical implications for fostering sustainable growth within the shipping industry, facilitating its alignment with environmental regulations. Notably, the proposed mathematical model serves as a decision-making tool, providing shipping companies with a framework to navigate the challenges presented by the new EU emissions policy effectively.

The rest of the paper is organized as follows. Section 2 describes the research problem in detail and develops the mathematical model. Section 3 proposes solution methods for addressing the initial proposed model. Section 4 conducts experiments and sensitivity analysis. Finally, conclusions are drawn in Section 5.

The main notations used in this study are summarized in Table 1.

Table 1. Notations.

Sets	
M	Set of shipping routes, $m \in M$
I^0	Set of the legs within the non-EU areas, $i \in I^0$
I^1	Set of the legs within linking the EU and non-EU areas, $i \in I^1$
I^2	Set of the legs within the EU areas, $i \in I^2$
Parameters	
c^m	The operating cost of a vessel on each liner shipping route, m
c_{out}	The revenue of chartering out a vessel
c_{in}	The cost of chartering in a vessel
K	The total fleet size of vessels
T	The service frequency of each shipping route
μ_1	The traditional fuel price per tonne
μ_2	The renewable fuel price per tonne
b^m	The total berthing time at all ports on liner shipping route m, $m \in M$
L_i^m	The total length of the shipping route m within the i type of areas, $i = 0, 1, 2$, $m \in M$
v_0^{tm}	The sailing speed on liner shipping route m within non-EU areas with traditional fuel, $m \in M$
v_1^{tm}	The sailing speed on liner shipping route m within linking the EU and non-EU areas with traditional fuel, $m \in M$
v_2^{tm}	The sailing speed on liner shipping route m within EU areas with traditional fuel, $m \in M$
v_0^{rm}	The sailing speed on liner shipping route m within non-EU areas with renewable fuel, $m \in M$
v_1^{rm}	The sailing speed on liner shipping route m within linking the EU and non-EU areas with renewable fuel, $m \in M$
v_2^{rm}	The sailing speed on liner shipping route m within EU areas with renewable fuel, $m \in M$
$v_{\min}$	The minimum sailing speed
$v_{\max}$	The maximum sailing speed
J	The integer used to discretize sailing speed, $j = 0, 1, ..., J$
Function	
$f(v^3)$	Fuel consumption rate at the sailing speed of v
Decision variables	
x^m	The number of vessels to be deployed on each liner shipping route m, $m \in M$
x_{out}	The number of chartering out vessels
x_{in}	The number of chartering in vessels
l_i^{tm}	The sailing length in the i type of areas on each liner shipping route m with traditional fuel, $i = 0, 1, 2$, $m \in M$
l_i^{rm}	The sailing length in the i type of areas on each liner shipping route m with renewable fuel, $i = 0, 1, 2$, $m \in M$
z_i^{tmj}	Binary decision variable that equals 1 if vessels sail using traditional fuel on liner shipping route m in the i type of areas with speed v_j and 0 otherwise, $i = 0, 1, 2, m \in M, j = 0, 1, ..., J$
z_i^{rmj}	Binary decision variable that equals 1 if vessels sail using renewable fuel on liner shipping route m in the i type of areas with speed v_j and 0 otherwise, $i = 0, 1, 2, m \in M, j = 0, 1, ..., J$

2. Problem Description and Model Development

In this study, we consider vessel company decisions on the sailing speeds within different areas and the choice of fuel, i.e., the choice of traditional fuel and renewable fuel. Our primary objective is to assist vessel companies in achieving cost savings while simultaneously meeting the EU's 2% renewable target requirement.

We consider a shipping network with multiple routes; M denotes the set of shipping routes, $m \in M$. The liner shipping route $m \in M$ calls at several ports in Europe and Asia. The vessel company serves these routes by employing vessels equipped with dual-fuel engines, which allows them the operation on either traditional fuel or renewable fuel (though the latter option incurs higher costs). There are three distinct types of voyages in the considered container liner service network: (1) voyages within non-EU areas; (2) voyages linking the EU and non-EU areas; (3) voyages within the EU areas. We use v_0^{tm}, v_1^{tm}, and v_2^{tm} to denote the sailing speed using traditional fuel in voyages within non-EU areas, linking the EU and non-EU areas, and within the EU areas, respectively. And v_0^{rm}, v_1^{rm}, and v_2^{rm} denote the sailing speed using renewable fuel in voyages within non-EU areas, linking the EU and non-EU areas, and within the EU areas, respectively. Referring to [42], the fuel consumption and sailing speed have a cubic relationship. Therefore, we use av^3 to denote vessel fuel consumption (note that v could be v_0^{tm}, v_1^{tm}, v_2^{tm}, v_0^{rm}, v_1^{rm}, and v_2^{rm}). We use l_0^{tm}, l_1^{tm}, and l_2^{tm} to denote the total length of voyages using traditional fuel within non-EU areas, linking the EU and non-EU areas, and within the EU areas, respectively. And l_0^{rm}, l_1^{rm}, and l_2^{rm} denote the total length of voyages using renewable fuel within non-EU areas, linking the EU and non-EU areas, and within the EU areas, respectively.

The vessel company possesses a total fleet size of K vessels. Additionally, the company has the option to charter out any surplus vessels, generating additional income represented by c_{out}. On the other hand, if the existing fleet of K vessels is insufficient to serve the shipping network, the company can charter in additional vessels at a fee denoted by c_{in}. These chartering options provide the company with flexibility in managing its vessel resources and optimizing its operations based on the specific demands and requirements of the shipping network. We have $c_{in} > c_{out}$. The operating cost of vessels on each liner shipping route m is c^m.

In order to minimize the overall total costs, the vessel company must make strategic decisions regarding the following key factors:

1. The number of vessels to be deployed on each liner shipping route m, denoted by x^m;
2. The number of chartering in or chartering out vessels, denoted by x_{in} and x_{out}, respectively;
3. The sailing speed on each liner shipping route m with different types of fuel, i.e., v_0^{tm}, v_1^{tm}, v_2^{tm}, v_0^{rm}, v_1^{rm}, and v_2^{rm};
4. The sailing length on each liner shipping route m with different types of fuel, i.e., l_i^{tm} and l_i^{rm}, $i = 0, 1, 2$.

Additionally, the vessel company needs to meet the following constraints:

1. The EU's 2% renewable target requirement;
2. The service frequency of each shipping route m, denoted by T^m. That is, the time for finishing a single trip should be within T^m days;
3. The restriction of the number of vessels;
4. The restriction of vessel sailing speed.

The optimization model is formulated as follows:

[M1]

$$\min \sum_{m \in M} c^m x^m + c_{in} x_{in} - c_{out} x_{out} + \sum_{m \in M} \sum_{i=0}^{2} (\mu_1 \frac{l_i^{tm}}{v_i^{tm}} a(v_i^{tm})^3 + \mu_2 \frac{l_i^{rm}}{v_i^{rm}} a(v_i^{rm})^3) \tag{1}$$

subject to

$$\frac{0.5a(v_1^{rm})^2 l_1^{rm} + a(v_2^{rm})^2 l_2^{rm}}{0.5a(v_1^{tm})^2 l_1^{tm} + a(v_2^{rm})^2 l_2^{tm} + 0.5a(v_1^{rm})^2 l_1^{rm} + a(v_2^{rm})^2 l_2^{rm}} \geq 0.02, \ m \in M, \tag{2}$$

$$\sum_{i=0}^{2}(\frac{l_i^{tm}}{v_i^{tm}} + \frac{l_i^{rm}}{v_i^{rm}} + b^m) \leq Tx^m,\ m \in M, \quad (3)$$

$$\sum_{m \in M} x_m = K + x_{in} - x_{out}, \quad (4)$$

$$l_i^{tm} + l_i^{rm} = L_i^m,\ i = 0,1,2,\ m \in M, \quad (5)$$

$$v_{\min} \leq v_i^{tm} \leq v_{\max},\ i = 0,1,2,\ m \in M, \quad (6)$$

$$v_{\min} \leq v_i^{rm} \leq v_{\max},\ i = 0,1,2,\ m \in M, \quad (7)$$

$$x^m \in Z_+,\ m \in M, \quad (8)$$

$$x_{in} \in Z_+, \quad (9)$$

$$x_{out} \in Z_+, \quad (10)$$

$$l_i^{tm} \geq 0,\ m \in M, \quad (11)$$

$$l_i^{rm} \geq 0,\ m \in M. \quad (12)$$

Objective function (1) consists of four parts. Firstly, $\sum_{m \in M} c^m x^m$ calculates the total operation cost of vessels on m different liner shipping routes. Secondly, $c_{in}x_{in}$ represents the cost of chartering in additional vessels when the existing fleet of K vessels is insufficient to serve the shipping network; on the contrary, the third part, $c_{out}x_{out}$, is the additional revenue of chartering out surplus vessels. As Objective function (1) calculates the minimum overall total costs, we subtract this additional income. Fourthly, $\sum_{m \in M} \sum_{i=0}^{2}(\mu_1 \frac{l_i^{tm}}{v_i^{tm}} a v_i^{tm3} + \mu_2 \frac{l_i^{rm}}{v_i^{rm}} a v_i^{rm3})$ represents the total fuel costs, including traditional fuel cost and renewable fuel cost, where μ_1 and μ_2 denote the traditional fuel and renewable fuel price, respectively. Constraint (2) meets the requirement of at least 2% of the renewable fuel utilized by vessels during voyages within the EU area starting from 2034. Constraints (3) restrict the service frequency of each shipping route m. Constraint (4) restricts the total number of vessels on m shipping routes, only involving the existing vessels and additional vessels that charter in or charter out, which is subtracted. Constraints (5) regulate the total voyage in every area on each shipping route m, consisting of the length of voyage using renewable fuel and traditional fuel. Constraints (6) and Constraints (7) give the domain of v_i^{tm} and v_i^{rm}, respectively, indicating the maximum and minimum of v_i^{rm} and v_i^{rm}. Constraint (8), Constraint (9) and Constraint (10) regulate the number of deployed vessels in route m, and the number of additional vessels should be positive integers. Constraints (11) and Constraints (12) restrict the length of each leg in different types of areas on m routes, and they should be positive. For parameters, $i = 0$ indicates areas within the EU; $i = 1$ represents the areas linking the EU areas and non-areas; $i = 2$ denotes areas within non-EU. μ_1 (USD/tonne) and μ_2 (USD/tonne) denote the fuel price of traditional fuel and renewable fuel. According to practice, $\mu_1 < \mu_2$. b^m represents the total berthing time at all ports. L_i^m denotes the total length of the shipping route m of different areas. The decision variables include v_i^{tm}, v_i^{rm}, l_i^{tm}, and l_i^{rm}.

3. Solution Methods

Model (M1) is hard to solve due to the operation of multiplying and dividing the decision variables. We next develop methods to address the nonlinear terms and transform (M1) into an MILP model, which improves computational efficiency.

We discretize sailing speed v by 0.01 knot. We define

$$J = \lfloor \frac{v_{\max} - v_{\min}}{0.01} \rfloor + 1, \tag{13}$$

and we set $j = 0, 1, ..., J$. Therefore, the sailing speed v can be discretized to v_j: $v_0 = v_{\min}$, $v_1 = v_{\min} + 0.01 \times 1$, $v_2 = v_{\min} + 0.01 \times 2$, ..., $v_J = \max\{v_{\max}, v_{\min} + 0.01 \times J\}$. We further adopt binary decision variables to indicate which discretized sailing speed is chosen on each shipping route m with different types of fuel. To be more specific, z_i^{tmj}, $i = 0, 1, 2$, $m \in M$, and $j = 0, ..., J$ denotes which sailing speed v_j is chosen on shipping route m on area i using traditional fuel; z_i^{rmj}, $i = 0, 1, 2$, $m \in M$, and $j = 0, ..., J$ denotes which sailing speed v_j is chosen on shipping route m on area i using renewable fuel. Therefore, we use the new binary decision variables z_i^{tmj} and z_i^{rmj} to replace v_i^{tm} and v_i^{rm}, and (M1) can be transformed into the following (M2).

[M2]

$$\min \sum_{m \in M} c^m x^m + c_{in} x_{in} - c_{out} x_{out} + a \sum_{m \in M} \sum_{i=0}^{2} \sum_{j=0}^{J} (\mu_1 l_i^{tm} z_i^{tmj} v_j^2 + \mu_2 l_i^{rm} z_i^{rmj} v_j^2) \tag{14}$$

subject to

$$\frac{0.5 \sum_{j=0}^{J} z_1^{rmj} v_j^2 l_1^{rm} + \sum_{j=0}^{J} z_2^{rmj} v_j^2 l_2^{rm}}{0.5 \sum_{j=0}^{J} z_1^{tmj} v_j^2 l_1^{tm} + \sum_{j=0}^{J} z_2^{tmj} v_j^2 l_2^{tm} + 0.5 \sum_{j=0}^{J} z_1^{rmj} v_j^2 l_1^{rm} + \sum_{j=0}^{J} z_2^{rmj} v_j^2 l_2^{rm}} \geq 0.02, \ m \in M, \tag{15}$$

$$\sum_{i=0}^{2} \sum_{j=0}^{J} (\frac{z_i^{tmj} l_i^{tm}}{v_j} + \frac{z_i^{rmj} l_i^{rm}}{v_j} + b^m) \leq T x^m, \ m \in M, \tag{16}$$

$$\sum_{m \in M} x_m = K + x_{in} - x_{out}, \tag{17}$$

$$l_i^{tm} + l_i^{rm} = L_i^m, \ i = 0, 1, 2, \ m \in M, \tag{18}$$

$$\sum_{j=0}^{J} z_i^{rmj} \leq 1, i = 0, 1, 2, \ m \in M, \tag{19}$$

$$\sum_{j=0}^{J} z_i^{tmj} \leq 1, i = 0, 1, 2, \ m \in M, \tag{20}$$

$$l_i^{tm} \leq W_i^m \sum_{j=0}^{J} z_i^{tmj}, i = 0, 1, 2 \ m \in M, \tag{21}$$

$$l_i^{rm} \leq W_i^m \sum_{j=0}^{J} z_i^{rmj}, i = 0, 1, 2 \ m \in M, \tag{22}$$

$$z_i^{tmj} \in \{0, 1\}, \ i = 0, 1, 2, \ m \in M, \ j = 0, \ldots, J, \tag{23}$$

$$z_i^{rmj} \in \{0, 1\}, \ i = 0, 1, 2, \ m \in M, \ j = 0, \ldots, J, \tag{24}$$

$$x^m \in Z_+,\ m \in M, \tag{25}$$

$$x_{in} \in Z_+, \tag{26}$$

$$x_{out} \in Z_+, \tag{27}$$

$$l_i^{tm} \geq 0,\ m \in M, \tag{28}$$

$$l_i^{rm} \geq 0,\ m \in M. \tag{29}$$

In Model (M2), we discretize sailing speed v to facilitate our research, improving computational efficiency. Specifically, we utilize v_i^{tmj} and v_i^{rmj} to represent the sailing speeds for different types of voyages using traditional fuel and renewable fuel, respectively. Furthermore, we set the value of W to L_i^m.

Broadly speaking, Model (M2) encompasses three categories of decision variables. The first category involves integer decision variables x_m, x_{in}, and x_{out}, which denote the number of vessels to be deployed on each liner shipping route m, as well as the quantities of vessels to be chartered in or out. The second category features binary decision variables z_i^{tmj} and z_i^{rmj}, comprising a total of $6mJ$ binary decision variables. When $z_i^{tmj} = 1$, the corresponding sailing speed v_i^{tmj} is selected for voyages utilizing traditional fuel, resulting in the adoption of traditional fuel consumption. On the other hand, when $z_i^{rmj} = 1$, the corresponding sailing speed v_i^{rmj} is chosen for voyages using renewable fuel. The renewable fuel and traditional fuel consumption are determined by expression av^3. Lastly, the third category consists of continuous variables l_i^{tm} and l_i^{rm}, totaling $6m$ continuous variables. By transforming Model (M1) into Model (M2), we can enhance computational efficiency.

Model (M2) is still hard to solve because of terms $l_i^{tm} z_i^{tmj}$ and $l_i^{rm} z_i^{rmj}$ in Objective function (14) and Constraints (16). As mentioned earlier, l_i^{tm}, l_i^{rm}, z_i^{tmj} and z_i^{rmj} are decision variables, so the multiplications of l_i^{tm} and z_i^{tmj}, l_i^{rm} and z_i^{rmj} lead to the formation of nonlinear terms within the objective function and constraint conditions, thereby transforming the model into an MINLP problem, which is inherently challenging to solve. As a nonlinear problem can encompass multiple feasible regions or sets of similar values for the decision variables that satisfy all constraints, each feasible region may contain multiple "peaks" (in maximization problems) or "valleys" (in minimization problems). Determining which peak is the tallest or which valley is the deepest lacks a general approach. Additionally, there can exist spurious peaks or valleys referred to as "saddle points." Due to these possibilities, nonlinear optimization methods offer limited guarantees in terms of identifying the "true" optimal solution. As a nonlinear problem can encompass multiple feasible regions or sets of similar values for the decision variables that satisfy all constraints, each feasible region may contain multiple "peaks" (in maximization problems) or "valleys" (in minimization problems). Determining which peak is the tallest or which valley is the deepest lacks a general approach. Additionally, there can exist spurious peaks or valleys referred to as "saddle points". Due to these possibilities, nonlinear optimization methods offer limited guarantees in terms of identifying the "true" optimal solution. We define $\eta_i^{tmj} = l_i^{tm} z_i^{tmj}$ and $\eta_i^{rmj} = l_i^{rm} z_i^{rmj}$. The following inequalities hold:

$$\eta_i^{tmj} \leq l_i^{tm},\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{30}$$

$$\eta_i^{tmj} \leq Q_i^m z_i^{tmj},\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{31}$$

$$\eta_i^{tmj} \geq l_i^{tm} - Q_i^m(1 - z_i^{tmj}),\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{32}$$

$$\eta_i^{tmj} \geq 0,\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{33}$$

$$\eta_i^{rmj} \leq l_i^{rm},\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{34}$$

$$\eta_i^{rmj} \leq Q_i^m z_i^{rmj},\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{35}$$

$$\eta_i^{rmj} \geq l_i^{rm} - Q_i^m(1 - z_i^{rmj}),\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{36}$$

$$\eta_i^{rmj} \geq 0,\ m \in M,\ j = 0, \ldots, J,\ i = 0, 1, 2, \tag{37}$$

where Q_i^m represents an exceedingly large value that bounds the upper limit of l_i^{tm} and l_i^{rm}. We set Q_i^m to be equal to L_i^m. Typically, a smaller value of Q_i^m is preferred (while still ensuring the correctness of the model), as it usually leads to shorter computational time compared to a model with larger Q_i^m.

Regarding Constraints (30), since the binary variable z_i^{tmj} can take values of either 0 or 1, when z_i^{tmj} equals 1, Constraints (30) can be expressed as $l_i^{tmj} \leq L_i^m$, $m \in M$, $j = 0, \ldots, J$, $i = 0, 1, 2$. This condition is evidently valid since l_i^{tm} is bounded by the total voyage length L_i^m. Conversely, when z_i^{tmj} equals 0, Constraints (30) become $0 \leq l_i^{tm}$, $m \in M$, $j = 0, \ldots, J$, $i = 0, 1, 2$, which is also true.

Concerning Constraints (31), given the aforementioned definition, $\eta_i^{tmj} = l_i^{tm} z_i^{tmj}$, thus transforming Constraints (31) to $l_i^{tm} z_i^{tmj} \leq Q_i^m z_i^{tmj}$, $m \in M$, $j = 0, \ldots, J$, $i = 0, 1, 2$. Consequently, Q_i^m becomes the upper bound for l_i^{tm}, equating to the total leg length L_i^m.

Regarding Constraints (32), we can discuss the case where z_i^{tmj} is equal to 1 or 0 separately. When z_i^{tmj} is equal to 1, Constraints (32) can be transformed into $l_i^{tmj} \geq l_i^{tm}$, $m \in M$, $j = 0, \ldots, J$, $i = 0, 1, 2$. It is evident that this inequality holds. On the other hand, when z_i^{tmj} is equal to 0, the inequality becomes $0 \geq l_i^{tm} - Q_i^m$, $m \in M$, $j = 0, \ldots, J$, $i = 0, 1, 2$, implying that the minimum value of Q_i^m is l_i^{tmj}, consistent with Constraints (31).

The validity of Constraints (33) is unquestionable, as both l_i^{tmj} and z_i^{tmj} are greater than or equal to 0. Similarly, Constraints (34)–(37) hold for the same reasons.

By Constraints (30)–(37), we can transform (M2) to the MILP model (M3).

[M3]

$$\min \sum_{m \in M} c^m x^m + c_{in} x_{in} - c_{out} x_{out} + a \sum_{m \in M} \sum_{i=0}^{2} \sum_{j=0}^{J} (\mu_1 \eta_i^{tmj} v_j^2 + \mu_2 \eta_i^{rmj} v_j^2), \tag{38}$$

subject to

$$0.5 \sum_{j=0}^{J} \eta_1^{rmj} v_j^2 + \sum_{j=0}^{J} \eta_2^{rmj} v_j^2 - 0.02(0.5 \sum_{j=0}^{J} \eta_1^{tmj} v_j^2 + \sum_{j=0}^{J} \eta_2^{tmj} v_j^2 + 0.5 \sum_{j=0}^{J} \eta_1^{rmj} v_j^2 + \sum_{j=0}^{J} \eta_2^{rmj} v_j^2) \geq 0,\ m \in M, \tag{39}$$

$$\sum_{i=0}^{2} \sum_{j=0}^{J} \left(\frac{\eta_i^{tmj}}{v_j} + \frac{\eta_i^{rmj}}{v_j} + b^m\right) \leq T x^m,\ m \in M, \tag{40}$$

$$\sum_{m \in M} x_m = K + x_{in} - x_{out}, \tag{41}$$

$$l_i^{tm} + l_i^{rm} = L_i^m,\ i = 0, 1, 2,\ m \in M, \tag{42}$$

$$\sum_{j=0}^{J} z_i^{rmj} \le 1, i = 0,1,2,\ m \in M, \tag{43}$$

$$\sum_{j=0}^{J} z_i^{tmj} \le 1, i = 0,1,2,\ m \in M, \tag{44}$$

$$l_i^{tm} \le W_i^m \sum_{j=0}^{J} z_i^{tmj}, i = 0,1,2,\ m \in M, \tag{45}$$

$$l_i^{rm} \le W_i^m \sum_{j=0}^{J} z_i^{rmj}, i = 0,1,2,\ m \in M, \tag{46}$$

$$z_i^{tmj} \in \{0,1\},\ i = 0,1,2,\ m \in M,\ j = 0,...,J, \tag{47}$$

$$z_i^{rmj} \in \{0,1\},\ i = 0,1,2,\ m \in M,\ j = 0,...,J, \tag{48}$$

$$x^m \in Z_+,\ m \in M, \tag{49}$$

$$x_{in} \in Z_+, \tag{50}$$

$$x_{out} \in Z_+, \tag{51}$$

$$l_i^{tm} \ge 0,\ m \in M, \tag{52}$$

$$l_i^{rm} \ge 0,\ m \in M, \tag{53}$$

$$\eta_i^{tmj} \le l_i^{tm},\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{54}$$

$$\eta_i^{tmj} \le Q_i^m z_i^{tmj},\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{55}$$

$$\eta_i^{tmj} \ge l_i^{tm} - Q_i^m(1 - z_i^{tmj}),\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{56}$$

$$\eta_i^{tmj} \ge 0,\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{57}$$

$$\eta_i^{rmj} \le l_i^{rm},\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{58}$$

$$\eta_i^{rmj} \le Q_i^m z_i^{rmj},\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{59}$$

$$\eta_i^{rmj} \ge l_i^{rm} - Q_i^m(1 - z_i^{rmj}),\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2, \tag{60}$$

$$\eta_i^{rmj} \ge 0,\ m \in M,\ j = 0,\dots,J,\ i = 0,1,2. \tag{61}$$

With the help of Constraints (30)–(37) and discretization, the original optimization model is transformed into an MILP programming model, which can be solved by the off-the-shelf optimization solvers, such as CPLEX and Gurobi. To validate our models, we design a shipping network involving four shipping routes for the experiment, setting the parameters, e.g., c^m, c_{in}, c_{out}, μ_1, and μ_2 according to practice.

4. Experiments

4.1. Experiment Settings

The experiments were run on a laptop computer equipped with 2.60 GHz of Intel Core i7 CPU and 16 GB of RAM, and Model (M3) was solved by Gurobi Optimizer 10.0.2 via Python API.

4.1.1. Selected Shipping Routes

We select four routes from Asia to northern Europe[1] to test the performance of Model (M3). Details are shown in Table 2.

Table 2. Summary of shipping routes.

Route ID	Port Rotation (City)
1	Tianjin → Dalian → Qingdao → Shanghai → Ningbo → Singapore→ Piraeus → Rotterdam → Hamburg → Antwerp → Shanghai → Tianjin
2	Busan → Ningbo → Shanghai → Yantian → Singapore → Algeciras → Dunkerque → Le Havre → Hamburg → Wilhelmshaven → Rotterdam → Port Klang → Busan
3	Shanghai → Ningbo → Xiamen → Yantian → Singapore → Felixstowe→ Zeebrugge → Gdansk → Wilhelmshaven → Singapore → Yantian → Shanghai
4	Qingdao → Shanghai → Ningbo → Yantian → Vung Tau → Singapore→ Rotterdam → Southampton → Antwerp → Le Harve → Jeddah → Singapore → Qingdao

4.1.2. Parameter Settings

We first set the values of parameters for drawing the basic results, and we conduct sensitivity analysis to examine the impacts of these parameters.

1. The operation cost c^m. Referring to [43], we first set c^m = USD 180,000 per week for a 5000-TEU (Twenty-foot Equivalent Unit) container ship.
2. The fee of chartering in a vessel c_{in}. Referring to [44], we set c_{in} = USD 120,000 per week.
3. The fee of chartering out a vessel c_{out}. Referring to [44], we set c_{out} = USD 100,000 per week.
4. The traditional fuel price μ_1. Referring to [45], we set μ_1 to be an average value of 600 (USD /tonne).
5. The renewable fuel price μ_2. Referring to [45], we set μ_2 to be an average value of 1000 (USD /tonne).
6. A company's total fleet size K. Referring to [46], we set K to be an average value of 60.
7. Referring to [43], We set $v_{\max}$ = 18 knots and $v_{\min} = 13$ knots.
8. Referring to [42], we set $f(v^3) = 0.00043 \times v^3$, a = 0.00043.

4.2. Basic Results

Based on the routes presented in Table 2 and the parameter settings, we conducted numerical experiments and obtained the results in Table 3. As outlined in Section 2, the decisions regarding vessel sailing speeds and fuel choices play a significant role. Therefore, we analyzed the sailing speeds with traditional and renewable fuels, as well as voyages in different types of areas. Specifically, during the course of the experiments, as we mentioned earlier, Model (M1) entails nonlinear terms and divisions between variables, rendering it a nonlinear model that poses significant challenges for solving. However, by discretizing the sailing speed and introducing variables z_i^{tmj} and z_i^{rmj}, η_i^{tmj} and η_i^{rmj}, we transformed the MINLP model (M1) into the MILP model (M3), facilitating the determination of optimal values during the experiments process. Hence, we employ Model (M3) to ascertain the optimal decisions for sailing speed, travel distance, fuel selection, and other relevant factors.

The optimal value of the objective function for Model (M3) is denoted as "OBJ," and distances are measured in nautical miles (nm). From Table 3, we observe that the number of deployed vessels is comparable across the four routes. However, Route 1 has slightly more ships (13) compared to the other routes, primarily due to its longer total voyage distance among the four routes. Additionally, the existing fleet of vessels is sufficient, leading to the chartering out of 11 ships. In general, vessels use traditional fuel in all types of areas, including those within the EU, those connecting the EU and non-EU regions, and non-EU areas. However, renewable fuel consumption is concentrated within the EU areas. As mentioned earlier, vessel companies must consider the EU's 2% renewable fuel target requirement. For voyages linking the EU and non-EU areas, half of the fuel consumption is attributed to the EU, while for voyages within the EU areas, all fuel consumption is attributed to the EU. To meet the 2% renewable fuel requirement at a lower cost, vessel companies prioritize using renewable fuel predominantly within the EU areas. This approach minimizes fuel consumption while still meeting the renewable target requirement, considering that renewable fuel prices are higher than traditional fuel prices. Additionally, a vessel exhibits a slower speed when using sustainable energy compared to its speed when utilizing traditional fuel.

Table 3. Basic results.

Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ ($)	x_{in}	x_{out}
1	I^0	3876.00	3876.00	0	14.78	NA	12	11,917,802.38	0	15
	I^1	16,137.00	16,137.00	0	14.44	NA				
	I^2	3552.00	3294.65	257.35	14.12	13.62				
2	I^0	5089.00	5089.00	0	15.02	NA	11			
	I^1	15,020.00	15,020.00	0	14.99	NA				
	I^2	2269.00	2068.16	200.84	14.95	14.78				
3	I^0	4885.00	4885.00	0	15.21	NA	11			
	I^1	16,704.00	16,704.00	0	15.18	NA				
	I^2	1736.00	1532.40	203.60	15.18	15.11				
4	I^0	5047.00	5047.00	0	15.27	NA	11			
	I^1	12,609.00	12,609.00	0	15.25	NA				
	I^2	4553.00	4332.35	220.65	15.21	15.11				

4.3. Sensitivity Analysis

The unit traditional fuel price and renewable fuel price may change as more policies are issued to promote the use of renewable fuel. In addition, in the basic analysis, some important parameters, e.g., the total fleet size of vessels, the operating cost per ship and the revenue of chartering out a vessel, are set to be deterministic. However, these parameters often fluctuate in real life. Therefore, sensitivity analyses on these parameters are conducted to investigate the influences of these parameters on the operation decisions. In the sensitivity analysis, the parameters are divided into three sorts. The first one is the fuel price, including traditional fuel price and renewable fuel price; the second one is the relevant cost of the vessels, involving the operating cost of a vessel, the revenue of chartering out a vessel as well as the cost of chartering in a vessel; the third one is the total fleet size of vessels.

4.3.1. Impact of the Fuel Price

Given the implementation of the EU's 2% renewable fuel policy, the selection and pricing of different fuel types have significantly impacted optimal operational decisions of vessel companies. Consequently, in this section, we specifically explore the effects of traditional and renewable fuels on such decision-making processes. In our initial analysis, the unit price of traditional fuel (μ_1) is established at 600 dollars per tonne. In sensitivity analysis, we set μ_1 varying between 500 and 800 dollars per tonne. The computational results are reported in Table 4.

According to the findings presented in Table 4, the objective value exhibits an upward trend as the price of traditional fuel increases. Furthermore, an increased allocation of vessels is observed across the four shipping routes, accompanied by a decrease in sailing speeds as traditional fuel prices soar. Given the cubic relationship between fuel consumption and sailing speed, it follows that higher vessel speeds result in greater fuel consumption. Consequently, in response to the rising unit price of traditional fuel, shipping companies are inclined to reduce sailing speeds to mitigate traditional fuel consumption and thereby achieve cost savings in their operations. Additionally, if the unit price of traditional fuel (μ_1) reaches excessively high levels, shipping companies may opt to deploy additional vessels to maintain the desired weekly service frequency.

In basic analysis, the unit price of renewable fuel (μ_2) is set at 1000 dollars per tonne. However, as stated in [21], the growing emphasis on green and sustainable development has led to the formulation of favorable policies aimed at promoting the utilization of renewable fuel. This suggests the potential future decline in renewable fuel prices. Thus, we set the range of μ_2 to span from 800 to 1000 dollars per tonne. Computational findings are presented in Table 5.

Regarding renewable fuel prices, similar patterns emerge as with traditional fuel prices, albeit to a lesser extent. Specifically, the total cost increases as the price of renewable fuel rises. However, due to the minimal proportion of renewable fuel in the overall fuel consumption, the impact of changing renewable fuel prices is relatively minor compared to the effects observed with traditional fuel.

Table 4. Impact of the unit price of traditional fuel.

μ_1 (USDton)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
500	1	I^0	3876.00	3876.00	0	16.39	NA	11	11,024,279.65	0	16
		I^1	16,137.00	16,137.00	0	16.14	NA				
		I^2	3552.00	3308.22	243.78	15.60	15.60				
	2	I^0	5089.00	5089.00	0	15.12	NA	11			
		I^1	15,020.00	10,520.00	0	14.97	NA				
		I^2	2269.00	2046.60	222.40	14.94	14.02				
	3	I^0	4885.00	4885.00	0	15.24	NA	11			
		I^1	16,704.00	16,704.00	0	15.21	NA				
		I^2	1736.00	1516.89	219.11	14.85	14.53				
	4	I^0	5047.00	5047.00	0	15.30	NA	11			
		I^1	12,609.00	12,609.00	0	15.24	NA				
		I^2	4553.00	4334.62	218.38	15.20	15.18				

Table 4. *Cont.*

μ_1 (USD/ton)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
600	1	I^0	3876.00	3876.00	0	14.78	NA	12	11,917,802.38	0	15
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3294.65	257.35	14.12	13.62				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	10,520.00	0	14.99	NA				
		I^2	2269.00	2068.16	200.84	14.95	14.78				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.40	203.60	15.18	15.11				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4332.35	220.65	15.21	15.11				
700	1	I^0	3876.00	3876.00	0	14.46	NA	12	12,727,432.18	0	12
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3316.27	235.73	14.42	14.33				
	2	I^0	5089.00	5089.00	0	13.53	NA	12			
		I^1	15,020.00	10,520.00	0	13.49	NA				
		I^2	2269.00	2067.93	201.07	13.25	13.25				
	3	I^0	4885.00	4885.00	0	13.73	NA	12			
		I^1	16,704.00	16,704.00	0	13.68	NA				
		I^2	1736.00	1528.63	207.37	13.68	13.49				
	4	I^0	5047.00	5047.00	0	13.68	NA	12			
		I^1	12,609.00	12,609.00	0	13.67	NA				
		I^2	4553.00	4325.54	227.46	13.67	13.35				
800	1	I^0	3876.00	3876.00	0	13.11	NA	13	13,451,977.30	0	11
		I^1	16,137.00	16,137.00	0	13.09	NA				
		I^2	3552.00	3316.43	235.57	13.09	13.00				
	2	I^0	5089.00	5089.00	0	13.49	NA	12			
		I^1	15,020.00	15,020.00	0	13.47	NA				
		I^2	2269.00	2072.56	196.44	13.47	13.44				
	3	I^0	4885.00	4885.00	0	13.69	NA	12			
		I^1	16,704.00	16,704.00	0	13.69	NA				
		I^2	1736.00	1533.46	202.54	13.67	13.66				
	4	I^0	5047.00	5047.00	0	13.76	NA	12			
		I^1	12,609.00	12,609.00	0	13.74	NA				
		I^2	4553.00	4326.19	226.81	13.39	13.30				

Table 5. Impact of the unit price of renewable fuel.

μ_2 (USD/ton)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
800	1	I^0	3876.00	3876.00	0	14.46	NA	12	11,901,015.30	0	15
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3316.27	235.73	14.42	14.33				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	15,020.00	0	14.99	NA				
		I^2	2269.00	2061.50	207.50	14.97	14.54				
	3	I^0	4885.00	4885.00	0	15.29	NA	11			
		I^1	16,704.00	16,704.00	0	15.16	NA				
		I^2	1736.00	1531.07	204.93	15.16	15.04				
	4	I^0	5047.00	5047.00	0	15.25	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4335.24	217.76	15.23	15.22				
900	1	I^0	3876.00	3876.00	0	14.65	NA	12	11,909,871.43	0	15
		I^1	16,137.00	16,137.00	0	14.62	NA				
		I^2	3552.00	3276.59	275.41	14.41	13.22				
	2	I^0	5089.00	5089.00	0	15.03	NA	11			
		I^1	15,020.00	15,020.00	0	14.99	NA				
		I^2	2269.00	2071.01	197.99	14.91	14.89				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1533.72	202.28	15.18	15.16				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4335.19	217.81	15.21	15.21				
1000	1	I^0	3876.00	3876.00	0	14.78	NA	12	11,917,802.38	0	15
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3294.65	257.35	14.12	13.62				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	10,520.00	0	14.99	NA				
		I^2	2269.00	2068.16	200.84	14.95	14.78				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.40	203.60	15.18	15.11				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4332.35	220.65	15.21	15.11				

Table 5. *Cont.*

μ_2 (USD/ton)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
1100	1	I^0	3876.00	3876.00	0	14.75	NA	12	11,926,146.11	0	15
		I^1	16,137.00	16,137.00	0	14.41	NA				
		I^2	3552.00	3269.03	282.97	14.37	13.02				
	2	I^0	5089.00	5089.00	0	15.03	NA	11			
		I^1	15,020.00	15,020.00	0	14.98	NA				
		I^2	2269.00	2071.36	197.64	14.98	14.90				
	3	I^0	4885.00	4885.00	0	15.23	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1528.55	207.45	15.14	14.96				
	4	I^0	5047.00	5047.00	0	15.29	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4325.14	227.86	15.20	14.86				

4.3.2. Impact of Relevant Cost of Vessels

Due to the minimal impacts of fluctuations in cost of chartering in a vessel (c_{in}) and the revenue of chartering out a vessel (c_{out}) (where c_{in} resemble ship operation cost, resulting in an increase in total cost as c_{in} rises, while the total cost decreases with an upturn in c_{out}), our analysis focuses solely on ship operation cost.

In the aforementioned analysis, the c^m predetermined weekly operating cost for a vessel stands at 180,000 dollars. Nevertheless, the value of c^m is subject to fluctuation due to the impact of various unpredictable factors and risks [47], such as the global outbreak of COVID-19 in 2020, which reportedly sparked an escalation in ship operating costs [48], or the gradual impact of technological advancements, which may potentially reduce these costs. Consequently, the range of c^m is defined as 160,000 dollars to 240,000 dollars, with corresponding results meticulously documented in Table 6.

Analysis of Table 6 reveals a direct correlation between the increase in the operating cost of a vessel (c^m) and the corresponding rise in the objective value. This signifies that as the total operating costs for vessels surge, the overall objective value exhibits an upward trajectory. Furthermore, as the value of c^m intensifies, a prudent approach to saving on operating costs is witnessed through a reduction in the number of vessels deployed across the four routes.

4.3.3. Impact of the Total Fleet Size of Vessels

In the initial analysis, the total fleet size of vessels, denoted as K, is assumed to have an average value of 60. However, it is important to note that the total fleet size varies among different companies and at different stages of development. Consequently, the value of K varies according to the scale of each company. Therefore, it becomes imperative to conduct a sensitivity analysis of the total fleet size of vessels. In this experiment, we consider a range of fleet sizes, from 40 to 70 ships. It is worth mentioning that the vessel type under investigation is a 5000-TEU (Twenty-foot Equivalent Unit) container ship, which typically does not exceed 70 in number.

Table 6. Impact of the cost of operating a vessel.

c^m (USD/week)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
160,000	1	I^0	3876.00	3876.00	0	14.49	NA	12	11,012,790.23	0	13
		I^1	16,137.00	16,137.00	0	14.49	NA				
		I^2	3552.00	3318.64	233.36	14.43	13.00				
	2	I^0	5089.00	5089.00	0	15.00	NA	11			
		I^1	15,020.00	10,520.00	0	14.99	NA				
		I^2	2269.00	2072.71	196.29	14.98	13.22				
	3	I^0	4885.00	4885.00	0	13.73	NA	12			
		I^1	16,704.00	16,704.00	0	13.71	NA				
		I^2	1736.00	1524.35	211.65	13.63	13.38				
	4	I^0	5047.00	5047.00	0	13.74	NA	12			
		I^1	12,609.00	12,609.00	0	13.66	NA				
		I^2	4553.00	4331.94	221.06	13.61	13.62				
180,000	1	I^0	3876.00	3876.00	0	14.78	NA	12	11,917,802.38	0	15
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3294.65	257.35	14.12	13.62				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	10,520.00	0	14.99	NA				
		I^2	2269.00	2068.16	200.84	14.95	14.78				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.40	203.60	15.18	15.11				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4332.35	220.65	15.21	15.11				
200,000	1	I^0	3876.00	3876.00	0	14.47	NA	12	12,817,094.15	0	15
		I^1	16,137.00	16,137.00	0	14.45	NA				
		I^2	3552.00	3307.81	244.19	14.38	14.07				
	2	I^0	5089.00	5089.00	0	15.03	NA	11			
		I^1	15,020.00	10,520.00	0	14.98	NA				
		I^2	2269.00	2071.36	197.64	14.98	14.90				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.93	203.07	15.18	15.13				
	4	I^0	5047.00	5047.00	0	15.28	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4331.03	221.97	15.20	15.06				

Table 6. *Cont.*

c^m (USD/week)	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
220,000	1	I^0	3876.00	3876.00	0	16.13	NA	11	15,448,312.66	0	16
		I^1	16,137.00	16,137.00	0	16.10	NA				
		I^2	3552.00	3316.00	236.00	16.05	15.96				
	2	I^0	5089.00	5089.00	0	15.00	NA	11			
		I^1	15,020.00	10,520.00	0	15.00	NA				
		I^2	2269.00	2071.08	197.92	14.91	14.89				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.19	NA				
		I^2	1736.00	1530.73	205.27	15.08	15.04				
	4	I^0	5047.00	5047.00	0	15.28	NA	11			
		I^1	12,609.00	12,609.00	0	15.24	NA				
		I^2	4553.00	4332.58	220.42	15.23	15.12				
240,000	1	I^0	3876.00	3876.00	0	14.49	NA	11	13,706,839.57	0	16
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3316.00	236.00	14.39	14.28				
	2	I^0	5089.00	5089.00	0	15.05	NA	11			
		I^1	15,020.00	10,520.00	0	14.98	NA				
		I^2	2269.00	2071.08	197.92	14.93	14.92				
	3	I^0	4885.00	4885.00	0	13.73	NA	11			
		I^1	16,704.00	16,704.00	0	13.68	NA				
		I^2	1736.00	1530.73	205.27	13.67	13.54				
	4	I^0	5047.00	5047.00	0	13.71	NA	11			
		I^1	12,609.00	12,609.00	0	13.67	NA				
		I^2	4553.00	4332.58	220.42	13.63	13.48				

Analyzing Table 7, we observe that as the total fleet size of vessels increases, the objective value decreases. This is attributed to a shift in the vessel situation of companies, transforming it from having inadequate vessels to having surplus ships. Thus, additional revenue is generated through chartering out surplus vessels. Moreover, it is notable that the allocation of ships to the four shipping routes remains unchanged regardless of variations in the total number of ships. The shipping companies only need to determine the number of ships to be chartered out or chartered in based on the balance between the sum of ships allocated to the four routes and the company's existing total number of ships.

Table 7. Impact of the total fleet size of vessels.

K	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
40	1	I^0	3876.00	3876.00	0	14.47	NA	12	14,017,651.72	5	0
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3316.36	235.64	14.41	14.33				
	2	I^0	5089.00	5089.00	0	15.13	NA	11			
		I^1	15,020.00	10,520.00	0	14.98	NA				
		I^2	2269.00	2057.03	211.97	14.80	14.34				
	3	I^0	4885.00	4885.00	0	15.22	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.53	203.47	15.15	15.11				
	4	I^0	5047.00	5047.00	0	15.28	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4331.78	221.22	15.21	15.09				
50	1	I^0	3876.00	3876.00	0	14.47	NA	12	12,917,358.26	0	5
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3315.71	236.29	14.41	14.31				
	2	I^0	5089.00	5089.00	0	15.03	NA	11			
		I^1	15,020.00	10,520.00	0	15.02	NA				
		I^2	2269.00	2066.97	202.03	14.72	14.71				
	3	I^0	4885.00	4885.00	0	15.22	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.53	203.47	15.15	15.11				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4327.58	225.42	15.22	14.19				
60	1	I^0	3876.00	3876.00	0	14.78	NA	12	11,917,802.38	0	15
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3294.65	257.35	14.12	13.62				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	10,520.00	0	14.99	NA				
		I^2	2269.00	2068.16	200.84	14.95	14.78				
	3	I^0	4885.00	4885.00	0	15.21	NA	11			
		I^1	16,704.00	16,704.00	0	15.18	NA				
		I^2	1736.00	1532.40	203.60	15.18	15.11				
	4	I^0	5047.00	5047.00	0	15.27	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4332.35	220.65	15.21	15.11				

Table 7. *Cont.*

K	Route ID	Set of Legs	Total Distance (nm)	l_i^{tm} (nm)	l_i^{rm} (nm)	v_i^{tm} (knot)	v_i^{rm} (knot)	Number of Ships	OBJ (USD)	x_{in}	x_{out}
70	1	I^0	3876.00	3876.00	0	14.47	NA	12	10,918,026.70	0	25
		I^1	16,137.00	16,137.00	0	14.44	NA				
		I^2	3552.00	3319.10	232.90	14.41	14.32				
	2	I^0	5089.00	5089.00	0	15.02	NA	11			
		I^1	15,020.00	15,020.00	0	14.99	NA				
		I^2	2269.00	2072.07	196.93	14.95	14.75				
	3	I^0	4885.00	4885.00	0	15.25	NA	11			
		I^1	16,704.00	16,704.00	0	15.25	NA				
		I^2	1736.00	1533.01	202.99	14.46	14.22				
	4	I^0	5047.00	5047.00	0	15.29	NA	11			
		I^1	12,609.00	12,609.00	0	15.25	NA				
		I^2	4553.00	4334.11	218.89	15.22	15.08				

5. Conclusions

This research investigates the shipping company's optimal strategy regarding fuel selection, sailing speed, ship deployment, and the number of ships chartered in or chartered out, considering the EU's proposed new policy. Initially, we present an innovative MINLP model, subsequently converting it into an MILP model through the application of advanced mathematical techniques. Through rigorous experiments, our proposed model demonstrates its efficacy, leading to the following conclusions: (i) Due to the lower prices compared to those of renewable fuels, traditional fuels are employed in all three types of regions, while renewable fuels are selectively used only in specific segments within the EU area. (ii) In terms of sailing speed, given the cubic relationship between speed and fuel consumption, as well as the price disparities between the two fuel types, ships tend to operate at higher speeds when using traditional fuels, thus reducing operational costs compared to utilizing sustainable fuels. (iii) The number of vessels employed and the mileage of routes are interconnected, with decisions regarding vessel chartered in or chartered out contingent upon striking a balance between the total number of vessels employed to each route and the overall fleet size of vessels. Furthermore, we analyze the influence of variations in fuel prices, relevant costs of vessels, and the total fleet size of vessels on optimal decisions. In general, increases in fuel prices, vessel-related costs, and fleet size result in rising total costs. Specifically, when the prices of both fuel types increase, shipping companies, seeking cost reduction, tend to lower sailing speeds to minimize fuel consumption, while also employing a higher number of vessels to satisfy weekly service frequencies. Moreover, when the operational costs of vessels increase, the number of vessels employed decreases. It is worth noting that changes in the total fleet size of vessels do not affect the number of vessels employed to individual routes but rather impact decisions regarding vessel leasing and chartering.

This investigation offers valuable insights into shipping company strategies under the new policy. Overall, our study contributes to the understanding of how shipping companies can make informed decisions in response to the EU's new policy. By providing efficient solution methods and examining the sensitivity of optimal decisions to various factors, our research offers practical guidance for navigating the challenges and opportunities presented by the policy.

Despite the significant contributions of this study, there exist certain limitations that require further investigation.

Firstly, the proposed model assumes static conditions and does not account for dynamic factors such as changing market trends, weather conditions, or evolving regulations. Incorporating these dynamic elements would be valuable for a more comprehensive analysis.

Secondly, our research focuses primarily on the shipping company's perspective and optimal decision-making. However, future studies could consider the broader impact of the EU's policy on the maritime industry as a whole, including the implications for sustainability, environmental protection, and the overall supply chain efficiency.

Additionally, our study assumes perfect information availability and precise parameter estimations. In reality, uncertain data and imperfect information are common challenges. Future research endeavors could explore robust optimization techniques or apply stochastic programming to address these uncertainties and enhance the reliability of decision-making processes.

In conclusion, this study provides valuable insights into the optimal strategies for shipping companies under the new EU policy. However, addressing the aforementioned limitations and pursuing further research in the suggested directions will yield a more comprehensive understanding of the complex interplay between fuel selection, sailing speed, and fleet management, contributing to the advancement of sustainable and efficient maritime operations.

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Note

[1] https://www.cma-cgm.com/products-services/flyers, accessed on 1 August 2023.

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