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Speed and Fuel Ratio Optimization for a Dual-Fuel Ship to Minimize Its Carbon Emissions and Cost

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Abstract: In this study, nondominated sorting genetic algorithm II (NSGA-II) was used to minimize the cost and carbon emissions of a liquefied natural gas (LNG) dual-fuel ship for a given route. This study considered the regulations of emission control areas (ECA) and the European Union (EU) Emissions Trading System (ETS) to determine the optimal speed and LNG/oil ratio for the ship. NSGA-II used the arrival time at each port and the LNG usage ratio for each voyage leg as its genes. The time window for arrival, the fuel cost, and potential EU carbon emission regulations were used to estimate the cost of the considered voyage. Moreover, fuel consumption was determined using historical data that were divided by period, machinery, and voyage leg. The results indicated that the optimal speed and fuel ratio could be determined under any given fuel and carbon price profile by using NSGA-II. Finally, the effects of regulations and carbon price differences on the optimal speed and fuel ratio were investigated. The cost minimization solution was susceptible to being affected by the regulations of ECAs and the EU ETS. The speed profile of the cost minimization solution was found to have a tendency to travel at faster-than-average speeds outside ECAs and non-EU regions, and travel slower in ECAs and EU regions. Meanwhile, the selection of fuel type showed that 100% traditional fuel oil in all regions, but with sufficiently high EU carbon permit cost, tends to use 100% LNG in EU regions.

Keywords: maritime transportation; LNG dual-fuel ship; speed optimization; fuel ratio optimization; multi-objective optimization; carbon emission minimization; cost minimization

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1. Introduction

In 2018, the International Maritime Organization (IMO) set a goal to reduce greenhouse gas (GHG) emissions from ships by at least 50% by 2050 relative to the corresponding level in 2008 [1]. This goal is known as the IMO's Initial GHG Strategy. However, the IMO is currently revising its Initial GHG Strategy and expects to finalize the revised strategy in 2023 [2]. To help meet the aforementioned goal, the IMO [3] has introduced several new measures, including the Energy Efficiency Existing Ship Index and Carbon Intensity Index (CII), for assessing the GHG emissions of ships and providing a basis for comparing the efficiency of different ships.

The European Union (EU) is also taking action to reduce GHG emissions from ships [4]. The EU is currently considering including the maritime sector in its Emissions Trading System (ETS). This inclusion would result in ship owners being required to pay for their GHG emissions at EU ports. This policy is expected to incentivize ships to become more efficient and emit less carbon [5]. In addition to the aforementioned measures, the IMO has introduced regulations to manage sulfur emissions from ships. These regulations have established sulfur emission control areas (ECAs) in which ships must use fuel with a sulfur content of no more than 0.1%. Outside of ECAs, ships can use fuel with a sulfur content of up to 0.5% [6]. In general, shipping companies tend to use cheap fuels unless relevant restrictions (e.g., ECAs and CII thresholds) or taxes (e.g., the EU ETS) exist. Overall, the aforementioned measures are creating new challenges for ship companies, which must now find methods to reduce their GHG emissions and comply with the new regulations while minimizing the impact on their profits.

Available alternative fuels for ships include liquefied natural gas (LNG), methanol, ammonia, and hydrogen. Smith et al. [7] predicted the fuel types that will be used in the future to achieve the goal of net-zero emissions by 2050, as shown in Figure 1. LNG is expected to replace traditional fuels, such as low-Sulfur fuel oil (LSFO) and marine diesel oil (MDO), and become the primary fuel in the near future. The use of ammonia is expected to grow considerably after 2030, and ammonia will become the dominant maritime fuel by 2050. According to Burel et al. [8], the usage of LNG may reduce carbon emissions by up to 25%. Therefore, an LNG dual-fuel ship was considered in the present study. An assumption was made that such a ship can be set to sail with any fuel ratio between 100% fuel oil and 100% LNG in the dual-fuel mode [9].

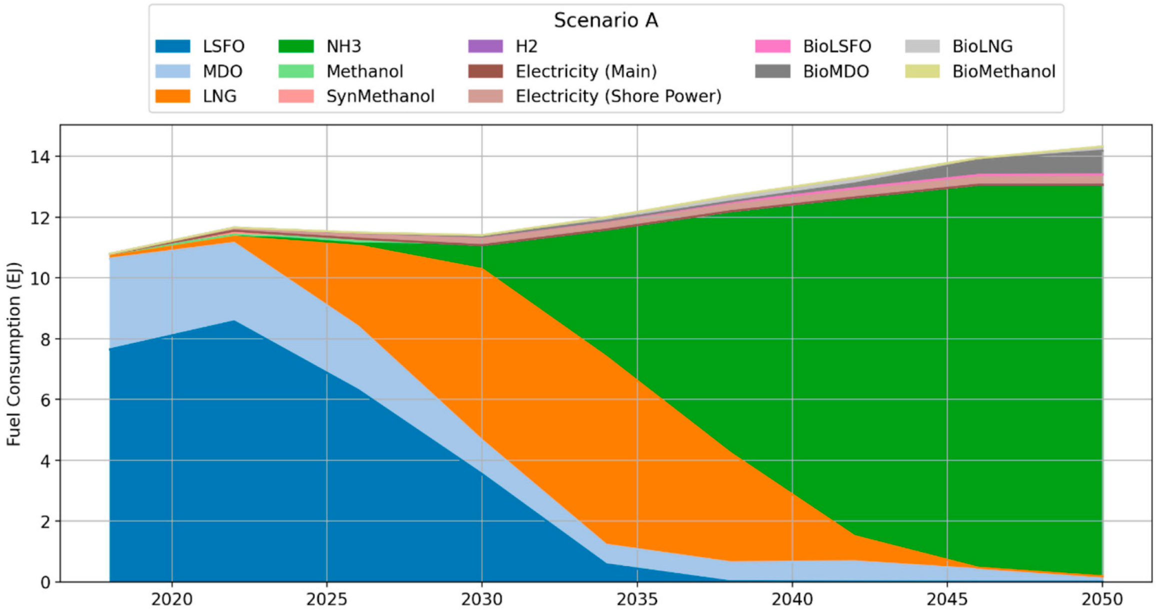

Figure 1. Types of fuel predicted to be used to reach the goal of net-zero GHG emissions by 2050 [7].

According to Faber et al. [10], 44 methods exist for making ships more efficient. These methods can be divided into four groups: those involving the use of energy-saving technologies, the use of renewable energy, the use of alternative fuels, and speed reduction. In addition to these methods, operation optimization is crucial. Zis et al. [11] reviewed studies on weather routing and the conditions considered in these studies. In the aforementioned studies, the method used for estimating fuel consumption under a specific sailing speed involved three steps: environment impact prediction, power consumption prediction, and fuel consumption prediction. In the present study, the speed–fuel consumption relationship was obtained through the regression of historical data. Speed optimization is also a potential method for reducing GHG emissions from ships [12–24]. Ma et al. [12] investigated ship speed and route optimization by considering the rules of ECAs. De et al. [15] proposed a method to minimize the carbon emission and maximize the profit of the shipping company. The optimization variables considered in [15] were the ship routing and scheduling, loading/unloading operations, the time window concept at ports, and vessel draft restrictions. Fagerholt et al. [16] explored the speed optimization of single-fuel ships in a soft time window for a certain route. Wu et al. [17] linearized the complex, nonlinear cost minimizing problem by optimizing the fleet deployment, ship refueling strategies, and sailing speed of an LNG dual-fuel ship. Lu et al. [18] investigated the speed optimization while considering ECAs by Multiple Objective Particle Swarm Optimization (MOPSO). Han et al. [19] developed a speed optimization model that considered various policies and strategies, including the ECA policy, carbon tax policy, Vessel Speed Reduction Incentive Program, and virtual arrival strategy. Dulebenets [20] introduced speed and route optimization to minimize the cost while considering the carbon tax policy. Zhen et al. [21] established a bi-objectives optimization model to minimize the fuel cost and SO_2 emission. The variables in the study were the ship route and speed. Li et al. [22] used the speed optimization to minimize the operating cost and the fuel consumption. Gao and Hu [23] optimized the speed and fleet deployment to minimize the total sailing cost. Zhuge et al. [24] introduced speed, path, and fleet deployment optimization to minimize the sailing cost by a dynamic programming-based algorithm. De et al. [25] discussed the bunker strategy and route optimization.

In summary, recent ship operating optimization research often combined speed with other variables, and the optimization objectives were often set to be carbon emission and sailing cost, as shown in Table 1. However, few papers considered the fuel ratio of the dual-fuel ship as an optimization variable. To fill this research gap, the present study applied the speed and fuel ratio optimization to an LNG dual-fuel ship. The optimization procedure was conducted for a given route to minimize the ship's costs and carbon emissions while adhering to the latest regulations of ECAs and the EU ETS. The effects of the regulations on the optimization results were investigated by comparing several scenarios. This study may contribute to shipping companies by proposing an optimized scientific operation mode to minimize the economic impact of complying new regulations.

Table 1. Sample of operation optimization papers and the objectives, variables, algorithms, ship types, and considered regulations in those papers.

Papers	Year	Optimization Objectives	Optimization Variables	Algorithms	SHIP TYPE	Considering ECAs/Carbon Permits
Fagerholt et al. [16]	2010	Minimizing fuel consumption	Speed	IPOPT from COIN-OR	Single-fuel	No/No
Dulebenets [20]	2018	Minimizing sailing cost	Ship scheduling	Linearized model solved by CPLEX	Single-fuel	No/Yes
Zhen et al. [21]	2020	Minimizing fuel cost and SO_2 emission	Route and speed	Two-stage iterative algorithm and fuzzy logic method	Single-fuel	Yes/No
Li et al. [22]	2020	Minimizing the main engine fuel consumption and operating costs	Speed	Constrained optimization by linear approximation (COBYLA)	Single-fuel	No/No
Ma et al. [12]	2021	Minimizing sailing cost and sailing time	Route and speed	NSGA-II	Single-fuel	Yes/No
Zhuge et al. [24]	2021	Minimizing sailing cost	Joint ship path, speed, and deployment	Dynamic programming based method	Single-fuel	Yes/Yes
De et al. [25]	2021	Maximizing the profit and lowering the cost	Ship routing and scheduling, bunkering strategy	Variable neighborhood search (VNS) algorithm	Single-fuel	No/Yes

Table 1. *Cont.*

Papers	Year	Optimization Objectives	Optimization Variables	Algorithms	SHIP TYPE	Considering ECAs/Carbon Permits
Gao and Hu [23]	2021	Minimizing cost	Speed and Fleet deployment	linear outer-approximation algorithm and an improved piecewise linear approximation algorithm	Single-fuel	No/No
Wu et al. [17]	2022	Minimizing sailing cost	Fleet deployment, ship refueling strategies, and sailing speed	Linearized model solved by Gurobi	LNG dual-fuel	No/Yes
Han et al. [19]	2023	Minimizing sailing cost	Speed	Quantum genetic algorithm	Single-fuel	Yes/Yes
Lu et al. [18]	2023	Minimizing Sailing cost and carbon emission	Speed	MOPSO	Single-fuel	Yes/No
Present study		Minimizing fuel cost and carbon emission	Fuel ratio and speed	NSGA-II	LNG dual-fuel	Yes/Yes

2. Problem Description and Model Establishment

2.1. Problem Description

The optimization process consists of three steps: voyage planning, fuel consumption estimation, and speed and fuel ratio optimization. The first step in voyage planning involves establishing the intended route of the vessel and acquiring relevant historical information about the target ship. Determining the time window for each port of call, which includes the earliest and latest acceptable arrival time at a specific port, is essential. This time window can be determined from the port's request, the current conditions, or the transportation demands of the shipping company. Other crucial factors to consider during voyage planning include the maneuvering time (the time required for the pilot to maneuver the ship in and out of the port), maneuvering distance (the distance traveled during the maneuvering time), and time at berth (the time for which the vessel is scheduled to stay at a specific berth). The maneuvering time and time at berth are assumed to be fixed, and the sailing period is the target period to be optimized.

To predict fuel consumption during a voyage, the relationship between the fuel consumption rate and ship speed must be considered. This relationship is often represented using a mathematical power curve, as shown in Figure 2. The dependence of the fuel consumption rate on different factors—such as the machinery being used (e.g., main engine, auxiliary engine, and boiler), the conditions of the voyage (e.g., sailing, maneuvering, and at berth), and the port-to-port legs of the voyage [26]—must also be considered. Moreover, the effects of weather and sea conditions on fuel consumption could be examined under different slip ratios. The different fuel consumption rates set for different voyage legs can be used to simulate differences in weather and loading conditions between these legs [27]. To account for the effect of ECAs on the LNG dual-fuel ship, the fuels considered were 0.1% sulfur fuel oil, 0.5% sulfur fuel oil, and LNG. Within ECAs, only 0.1% sulfur fuel oil and LNG were allowed, whereas outside ECAs, all three types of fuel could be used. However, in this study, the fuel options outside the ECAs were limited to either a combination of 0.1% sulfur fuel oil and LNG or a combination of 0.5% sulfur fuel oil and LNG.

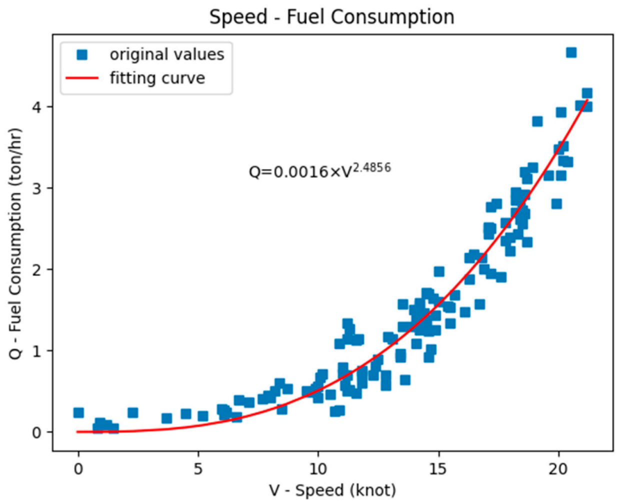

Figure 2. Results of speed–fuel consumption regression for a dual-fuel ship.

The variables of NSGA-II, which are also known as genes, were the arrival time t_n within the given time window of each port of call and the LNG/oil ratio r_n of each leg. The two objectives of this algorithm were cost minimization and carbon emission minimization. After the arrival times and LNG/oil ratios of each voyage leg were determined, the fuel consumption was estimated. Finally, the two objectives were achieved using the estimated fuel consumption, current fuel prices, carbon permits, and fuel carbon factor (Figure 3). The nomenclature and abbreviations used to establish the numerical model are shown in Table 2.

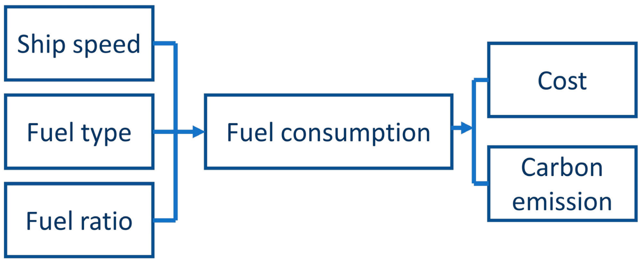

Figure 3. Process for evaluating the costs and carbon emissions of a dual-fuel ship.

Table 2. Nomenclature and list of abbreviations.

Symbol	Unit	Explanation
Abbreviations		
EU		European Union
ETS		Emissions Trading System
LNG		Liquefied natural gas
NSGA-II		Nondominated sorting genetic algorithm II
GHG		Greenhouse gas
IMO		International Maritime Organization
ECA		Emission control area
PF		Pareto front
Indices and sets		
N		set of all ports of call (legs) on the ship route, $n \in N$
I		set of all fuel types on the ship route, $i \in I$ (In this study, $I = 3$, $i = 1$ represents 0.1%-sulfur-containing fuel oil, $i = 2$ represents 0.5%-sulfur-containing fuel oil, and $i = 3$ represents LNG)

Table 2. *Cont.*

Symbol	Unit	Explanation
Parameters		
CF_i	t-CO_2/t-fuel	Carbon factor of fuel i defined in MEPC.308(76) [20]
$FC_{i,n}$	ton	Calculated consumption of fuel i for leg n
P_i	USD/ton	Price of fuel i
C_{EU}	ton	Carbon emission calculated using the rules of the EU
P_c	USD/ton-CO_2	EU carbon permit price
ts_n	hr	Accumulated acceptable earliest arrival time at port n
te_n	hr	Accumulated acceptable latest arrival time at port n
$FC_{i,n\ \mathrm{sailing}}$	ton	Fuel consumption of fuel i for leg n in the sailing period
$FC_{i,n\ \mathrm{maneuvering}}$	ton	Fuel consumption of fuel i for leg n in the maneuvering period
$FC_{i,n\ \mathrm{at-berth}}$	ton	Fuel consumption of fuel i for leg n in the at-berth period
$as_{i,n}$		Main engine fuel consumption coefficient of fuel i for leg n in the sailing period
$cs_{i,n}$		Main engine fuel consumption power coefficient of fuel i for leg n in the sailing period
Vs_n	knot	Ship speed for leg n in the sailing period
$ds_{i,n}$	ton/hr	Auxiliary engine fuel consumption coefficient of fuel i for leg n in the sailing period
$es_{i,n}$	ton/hr	Boiler fuel consumption coefficient of fuel i for leg n in the sailing period
ts_n	hr	Sailing period for leg n
$am_{i,n}$		Main engine fuel consumption coefficient of fuel i for leg n in the maneuvering period
$cm_{i,n}$		Main engine fuel consumption power coefficient of fuel i for leg n in the maneuvering period
Vm_n	knot	Ship speed for leg n in the maneuvering period
$dm_{i,n}$	ton/hr	Auxiliary engine fuel consumption coefficient of fuel i for leg n in the maneuvering period
$em_{i,n}$	ton/hr	Boiler fuel consumption coefficient of fuel i for leg n in the maneuvering period
tm_n	hr	Maneuvering time for leg n
$db_{i,n}$	ton/hr	Auxiliary engine fuel consumption coefficient of fuel i for leg n in the at-berth period
$eb_{i,n}$	ton/hr	Boiler fuel consumption coefficient of fuel i for leg n in the at-berth period
tb_n	hr	At-berth period for leg n
$\gamma_{i,n}$		binary, equals 1 if and only if the i = 1 or i = 2 in leg n; 0 for i = 3.
β_n		binary, equals 1 if and only if the 0.1% sulfur-containing fuel oil is used in during leg n; 0 for 0.5% sulfur-containing fuel oil.
δ_n		The EU carbon coefficient. 0 for legs out of EU. 1 for legs inside EU. 0.5 for legs between EU and non-EU.
$\alpha_{i,n}$		binary, equals 1 if and only if the i = 1 in leg n; 0 for i = 2 or 3.
Decision Variables		
t_n		Accumulated arrival time of port n
r_n		LNG/oil ratio for leg n

In summary, the assumptions in this study are as follows:

- 0.1% sulfur fuel oil only was always used in maneuvering and at berth periods;
- The ship speed was constant in a leg n;
- The fuel consumption and time in maneuvering and at berth periods were deterministic;
- In ECAs, 0.1% sulfur fuel oil and LNG could be used in any ratio;
- Outside ECAs, the combination of 0.1% S fuel oil and LNG or 0.5% S fuel oil and LNG could be chosen and used in any ratio;
- Fuel type index: i = 1 represented 0.1% sulfur fuel oil, i = 2 represented 0.5% sulfur fuel oil, and i = 3 represented LNG.

2.2. Optimization Algorithm

Nondominated sorting genetic algorithm II (NSGA-II) is an algorithm commonly used to find the set of optimal solutions, which is also known as the Pareto front (PF) or trade-off curve, for multi-objective optimization problems [28]. The procedure of NSGA-II comprises selection, crossover, mutation, nondominated sorting, and crowding distance calculation, as shown in Figure 4. The selection, crossover, and mutation are procedures of standard genetic algorithms. NSGA-II is famous for its high accuracy and convergence speed, and is validated by other studies [29–32]. In the present study, the NSGA-II of the pymoo package developed by Blank and Deb [33] in Python was used to solve the considered problem of simultaneous cost and emission minimization. In the case of single-fuel ships, cost and carbon emissions can be integrated into one objective, namely fuel consumption, because no trade-off exists between these objectives. Thus, a single optimal solution can be obtained. However, in the context of LNG dual-fuel ships, conflicting objectives exist because the use of LNG results in higher costs but lower emissions than does the use of traditional fuel oil. NSGA-II can find optimal solutions that optimize the conflicting objectives of cost and carbon emission for LNG dual-fuel ships. For these ships, the PF is a set of possible optimal solutions, one of which should be selected by the decision maker on the basis of additional information.

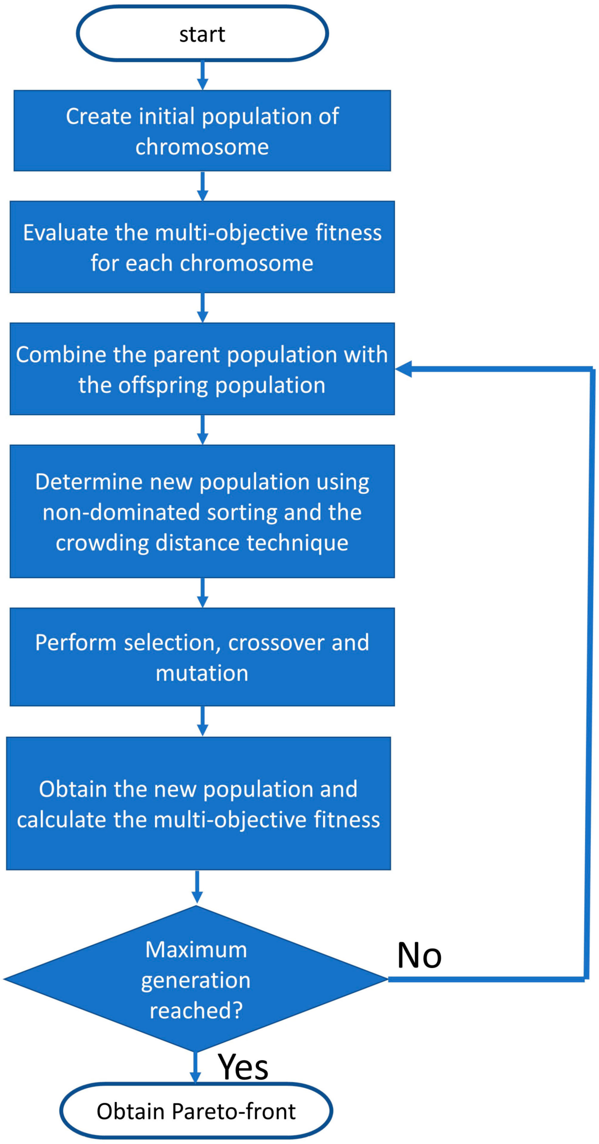

Figure 4. Flowchart of NSGA-II [28].

As a genetic algorithm, NSGA-II comprises two crucial parameters: population size and number of generations. The population size is the number of agents that search for the optimal solution in the possible solution space, and the number of generations is the number of iterations for which the agents have searched the entire search space. The termination condition is usually set by limiting the number of generations. Increases in the population size and number of generations result in more accurate solutions; however, the computation process becomes longer. Therefore, for a complex problem with a larger possible solution space, NSGA-II with longer evaluation time is required to obtain acceptable optimized solutions. Determining an appropriate population size and number of generations for a problem can be challenging.

2.3. Mathematical Model

First, the fuel consumption model of each leg n and each fuel i should be established, as shown in Equations (1)–(6).

$$ts_n = t_{n+1} - tm_n - tb_n - t_n \ \forall n \in N \tag{1}$$

$$Vs_n = \frac{D_n}{ts_n} \ \forall n \in N \tag{2}$$

$$FC_{i,n} = FC_{\mathrm{i},n\ \text{sailing}} + FC_{i,n\ \text{maneuvering}} + FC_{i,n\ at-berth} \ \forall n \in N,\ i \in I \tag{3}$$

$$\begin{gathered} FC_{i,n\ \text{sailing}} = (as_{1,n} \cdot Vs_n^{cs_{1,n}} + ds_{1,n} + es_{1,n}) \cdot ts_n \cdot \gamma_{i,n} \cdot \beta_n \cdot \tfrac{r_n}{100} + (as_{2,n} \cdot \\ Vs_n^{cs_{2,n}} + ds_{2,n} + es_{2,n}) \cdot ts_n \cdot \gamma_{i,n} \cdot (1 - \beta_n) \cdot \tfrac{r_n}{100} + (as_{3,n} \cdot Vs_n^{cs_{3,n}} + ds_{3,n} + \\ es_{3,n}) \cdot ts_n \cdot (1 - \gamma_{i,n}) \cdot \tfrac{100 - r_n}{100} \quad \forall n \in N,\ i \in I \end{gathered} \tag{4}$$

$$FC_{i,n\ maneuvering} = (am_{1,n} \cdot Vm_n^{cm_{1,n}} + dm_{1,n} + em_{1,n}) \cdot tm_n \cdot \alpha_{i,n} \ \forall n \in N,\ i \in I \tag{5}$$

$$FC_{\mathrm{i},n\ at-berth} = (db_{1n} + eb_{1,n}) \cdot tb_n \cdot \alpha_{i,n} \ \forall n \in N,\ i \in I \tag{6}$$

The ship's speed and time of maneuvering period as well as the at-berth period were determined in the route planning process. The ship's duration and speed of each leg of the sailing period were obtained from the estimated arrival time at each port of call, as shown in Equations (1) and (2). Equation (3) was used to calculate the fuel consumption of fuel i and leg n by summing up the fuel consumption of sailing, maneuvering, and at berth period of leg n. Equation (4) describes the three fuel types consumption of sailing period. Equations (5) and (6) represent the 0.1% sulfur fuel oil consumption of the maneuvering and at berth period for leg n, respectively.

Finally, the aforementioned constrained bi-objective problem can be expressed using Equations (7)–(13).

$$\mathrm{x} = [\mathrm{t}_1, \mathrm{t}_2, \cdots, \mathrm{t}_N, \mathrm{r}_1, \cdots, \mathrm{r}_n] \tag{7}$$

$$min\ \mathrm{Carbon}(\mathrm{x}) = \textstyle\sum_{i \in I} \sum_{n \in N} CF_i \cdot FC_{i,n} \tag{8}$$

$$\mathrm{C}_{\mathrm{EU}} = \textstyle\sum_{i \in I} CF_i \cdot \sum_{n \in N} (FC_{i,n} \cdot \delta_n) \tag{9}$$

$$min\ \mathrm{Cost}(\mathrm{x}) = \textstyle\sum_{i \in I} \sum_{n \in N} P_i \cdot FC_{i,n} + C_{EU} \cdot P_c \tag{10}$$

$$s.t.\ t_{n+1} - t_n > 0 \quad \forall n \in N \tag{11}$$

$$ts_n \leq t_n \leq te_n \qquad \forall n \in N \tag{12}$$

$$0 \leq r_n \leq 100 \qquad \forall n \in N \tag{13}$$

Equation (7) consists of arrival times and LNG/oil ratios for each leg. Equation (8) minimizes the total carbon emission. Equation (9) was used to obtain the carbon emission in the EU jurisdiction. Equation (10) was used to minimize the total sailing cost by summing up the fuel cost and the carbon permit cost. Equation (11) was used to guarantee that the arrival time of a port is later than the arrival time of the previous port. Equation (12) ensured the arrival time of a port was within the set time window. Equation (13) guaranteed that the LNG/oil ratio was between 100% fuel oil usage and 100% LNG usage.

3. Results and Discussion

The methodology outlined in the aforementioned text was adopted for a 4600-TEU container ship conducting a complete voyage. The itinerary considered commenced in Western Europe and proceeded to the eastern coast of North America through the Atlantic Ocean. The ship subsequently sailed back to Europe and concluded its journey at the starting port of call. The trip comprised nine ports of call, which included the initial and final ports, and four waypoints where oil changes occurred between ECAs and non-ECAs. Consequently, 12 legs had to be traversed, with 12 arrival times and 12 LNG/oil ratios to be determined. Data on the considered journey are presented in Tables 3–5, and a map of the considered route is displayed in Figure 5. The orange regions in Figure 5 indicated the ECAs.

Table 3. Time windows and route in the considered example.

Leg No.	Arrival Port/Waypoint	Acceptable Earliest Arrival Time	Acceptable Latest Arrival Time	Sailing Distance (nm)
	P1-EU	1 January 15:52	1 January 15:52	
1	P2-EU	2 January 07:35	2 January 13:35	241
2	P3-UK	4 January 09:15	4 January 15:15	60
3	Out ECA	6 January 23:56	7 January 05:56	395
4	In ECA	12 January 18:42	13 January 00:42	1786
5	P4-US	19 January 00:45	19 January 06:45	1931
6	P5-US	21 January 13:30	21 January 19:30	190
7	P6-US	23 January 14:28	23 January 20:28	154
8	P7-CA	26 January 17:32	26 January 23:32	580
9	Out ECA	30 January 05:22	30 January 11:22	667
10	In ECA	5 February 05:44	5 February 11:44	1858
11	P8-EU	6 February 10:00	6 February 16:00	364
12	P1-EU	7 February 16:52	7 February 19:52	204

Table 4. Assumed fuel properties: price, carbon factor, and lower calorific value for three different fuels.

Fuel Type	Price (USD/ton)	Carbon Factor, CF ($t\text{-}CO_2$/t-Fuel) [1] [34]	Lower Calorific Value, SE (kJ/kg) [1] [34]
0.5% S Fuel Oil	785	3.151	41,200
0.1% S Fuel Oil	1095	3.151	41,200
LNG	2000	2.750	48,000

Note: [1] Data from MEPC.308(73) [34].

Table 5. Available fuel types in all legs and EU carbon permit costs set in four scenarios.

Leg No.	Arrival Port/Waypoint	Scenario 1: General Single Fuel	Scenario 2: General Dual Fuel	Scenario 3: Considering ECAs	Scenario 4: Considering EU ETS
1	P2-EU	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
2	P3-UK	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
3	Out ECA	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
4	In ECA	0.1% S	0.1% S & LNG	0.5% S & LNG	0.1% S & LNG
5	P4-US	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
6	P5-US	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
7	P6-US	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
8	P7-CA	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
9	Out ECA	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
10	In ECA	0.1% S	0.1% S & LNG	0.5% S & LNG	0.1% S & LNG
11	P8-EU	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
12	P1-EU	0.1% S	0.1% S & LNG	0.1% S & LNG	0.1% S & LNG
EU carbon permit (USD/t-CO_2)		0	0	0	100/200

Note: Scenario 1: General single fuel with 0.1% sulfur fuel oil only for all legs. Scenario 2: General dual fuel with 0.1% sulfur fuel oil and LNG available for all legs. Scenario 3: Considering ECAs with 0.5% sulfur fuel oil and LNG available for outside ECAs and other legs with 0.1% sulfur fuel oil and LNG. Scenario 4: Considering EU ETS with Scenario 2 with EU carbon permit 100 or 200 USD/t-CO_2.

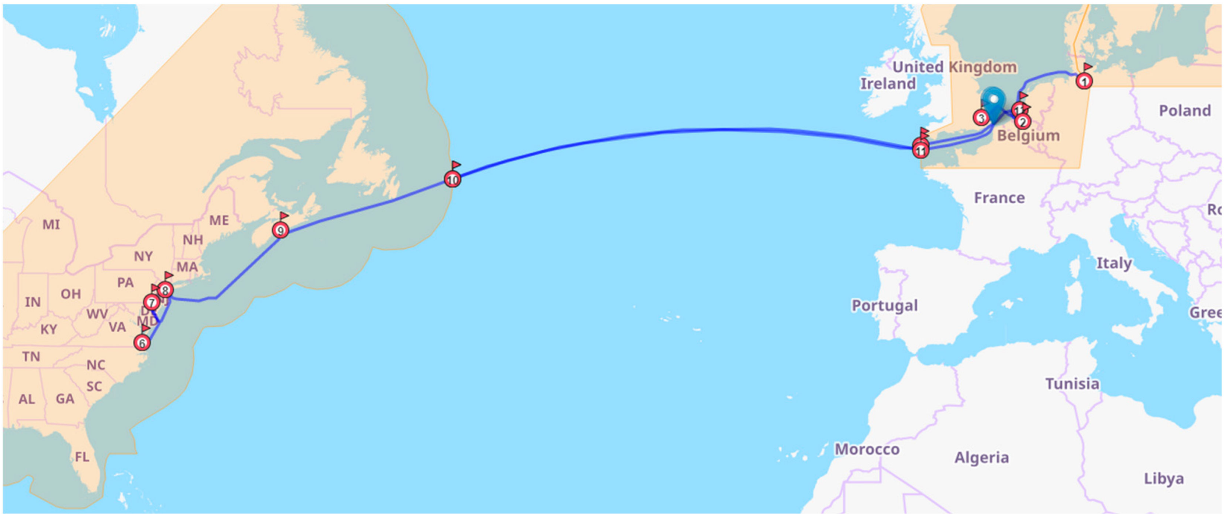

Figure 5. Map of the considered route. Orange regions were considered ECAs.

In order to investigate the different optimal results of each consideration, the four scenarios were demonstrated and expressed in Table 5.

1. General single fuel: using 0.1%-sulfur-containing fuel oil only in all legs and considering no EU ETS rules;
2. General dual fuel: using 0.1%-sulfur-containing fuel oil and LNG in all legs and considering no EU ETS rules;
3. Considering ECAs: using 0.1%-sulfur-containing fuel oil and LNG in ECAs, 0.5%-sulfur-containing fuel oil and LNG outside ECAs, and considering no EU ETS rules;
4. Considering EU ETS: using 0.1%-sulfur-containing fuel oil and LNG in all legs and considering EU carbon permit of 100 or 200 USD/t-CO_2;

All legs except leg 4 and 10 were assumed to be in ECAs, and legs 1–5 and 9–12 were assumed to be under the jurisdiction of EU ETS. The EU ETS was assumed to consider the 100% of carbon emission for legs 1–2 and 12, while considered 50% of carbon emission for legs 3–5 and 9–11. By comparing Scenario 1 with Scenario 2, the effects of using dual-fuel ships could be demonstrated. By comparing Scenario 2 with Scenario 3, the impacts of ECAs could be investigated. By comparing Scenario 2 with Scenario 4, the effects of the EU ETS could be determined. In these comparisons, Scenario 1 served as the control group when compared with Scenario 2, while Scenario 2 served as the control group when compared with Scenarios 3 and 4. The optimal speeds of Scenario 1 and 2 were also compared with the theoretical optimal speeds (average speed) for validation. Since Scenario 1 represented a general single-fuel ship, speed was the only variable being optimized.

3.1. Results for a General Single-Fuel Scenario and General Dual-Fuel Scenario

The set of optimal solutions could be presented in a two-objective figure and explained by the PF. In this study, the X-axis and Y-axis were set as cost and carbon emissions, respectively. The PF represents a set of optimal solutions for a problem. Each solution, which is represented by a point in the PF figures (Figure 6), comprised an arrival time and LNG/oil ratio. Because both minimization objectives were achieved simultaneously, solutions located further toward the bottom-left of the PF figures were better. For single-fuel ships, the PF was a single point (Figure 6a) because no trade-off existed between cost and carbon emissions. In this case, the optimal solution was the set of arrival times that minimized fuel oil consumption.

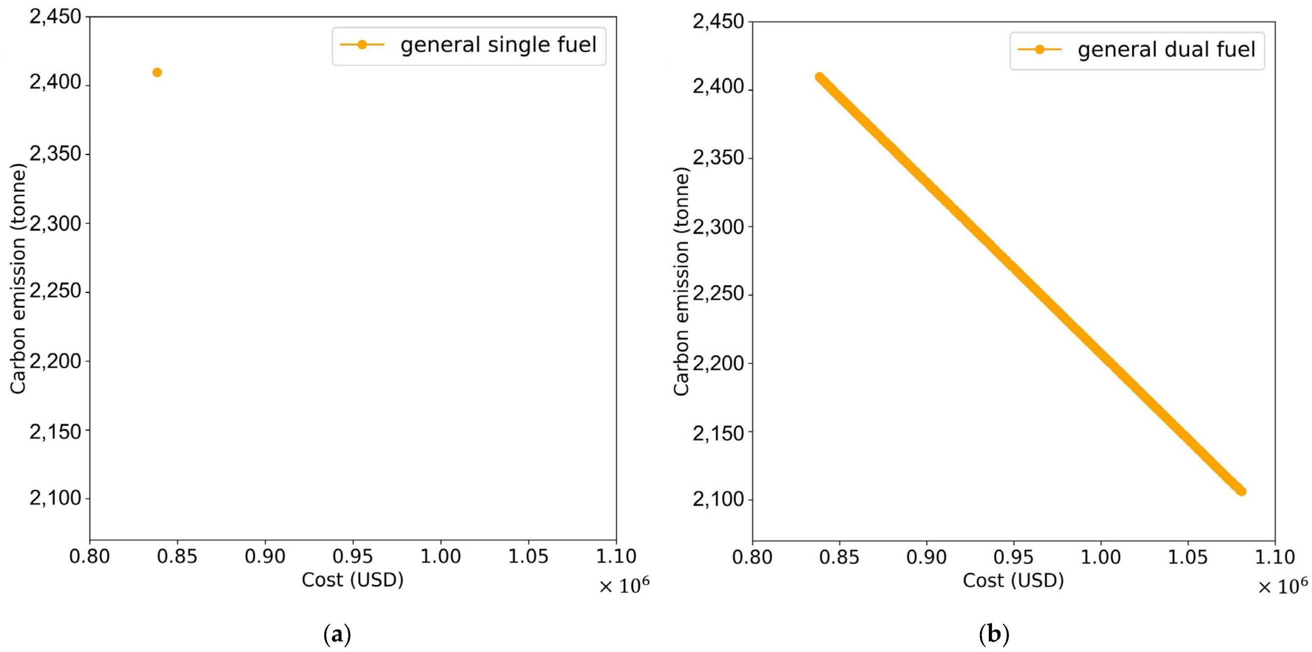

Figure 6. PF figures for a (**a**) general single-fuel ship and (**b**) general dual-fuel ship. (**a**) The carbon emission and the cost had no trade-off on single-fuel ship; thus, it was one optimal solution and a single point on PF figure. (**b**) For the general LNG dual-fuel ship, the two objectives had conflicts, and the optimal solutions would become a straight line.

In contrast to the PF of a single-fuel ship, the PF of a general LNG dual-fuel ship was a straight line (Figure 6b) when the regulations of ECAs and the EU ETS were not considered. For an LNG dual-fuel ship, all solutions had similar arrival times but different LNG/oil ratios. The optimized solution that achieved the lowest cost, which was located in the top-left corner of the PF, corresponded to the use of fuel oil but no LNG (100% fuel oil). By contrast, the optimized solution that achieved the lowest carbon emission, which was located in the bottom-right corner of the PF, corresponded to the use of LNG but no fuel oil (100% LNG).

In the considered examples, the weather conditions and fuel consumption in a journey leg were assumed to be constant; therefore, the theoretical optimal sailing speed of the general single-fuel ship and general dual-fuel ship were the average speed for all the legs. However, NSGA-II is an evolutionary algorithm and can only search for the approximate optimal solution, as shown in Figure 7. It theoretically takes infinite time to obtain the exact average speed profile.

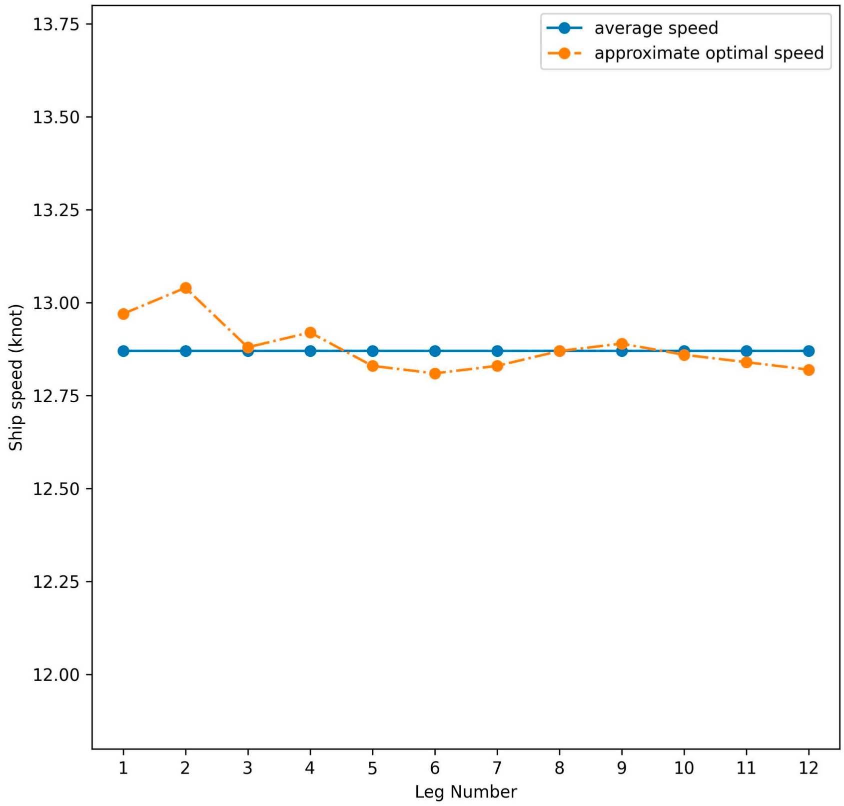

Figure 7. Theoretical average speed (blue, solid line) and approximate optimal speed (orange, dash-dotted line) in all legs for both a general single-fuel ship and a general dual-fuel ship.

3.2. Effects of Emission Control Areas

When the regulations of ECAs were considered, available fuel oil could be divided into two categories: fuel oil with 0.1% and 0.5% sulfur. In the considered example, a mixture of 0.1%-sulfur-containing fuel oil with LNG could be used in the ECAs, whereas a mixture of 0.5%-sulfur-containing fuel oil with LNG could be used outside the ECAs (as shown in legs 4 and 10 of Scenario 3, Table 5). The optimization results indicated that the PF was bilinear when the aforementioned regulations were considered (Scenario 3, green solid line in Figure 8). The cost minimization solution corresponded to the use of only 0.1%-sulfur-containing fuel oil in the ECAs and only 0.5%-sulfur-containing fuel oil outside the ECAs. By contrast, the carbon minimization solution corresponded to the use of only LNG inside and outside the ECAs. The aforementioned results were obtained because the price of LNG is considerably higher than the prices of 0.1%-sulfur-containing fuel oil and 0.5%-sulfur-containing fuel oil. At the bending point of the bilinear PF (green-frame arrow in Figure 8), the solution corresponded to the use of only 0.5%-sulfur-containing fuel oil in non-ECAs and only LNG in ECAs. The optimal strategy involved substituting LNG with 0.1%-sulfur-containing fuel oil in the ECAs first, since 0.5%-sulfur-containing fuel oil is more cost-effective than is 0.1%-sulfur-containing fuel oil.

The speed profile also changed when considering the regulations of the ECAs (Figure 9). The cost minimization solution contained a marginally higher sailing speed outside the ECAs than did the carbon minimization solution. This result was obtained because 0.5%-sulfur-containing fuel oil is cheaper than 0.1%-sulfur-containing fuel oil. The carbon minimization solution had an average speed profile.

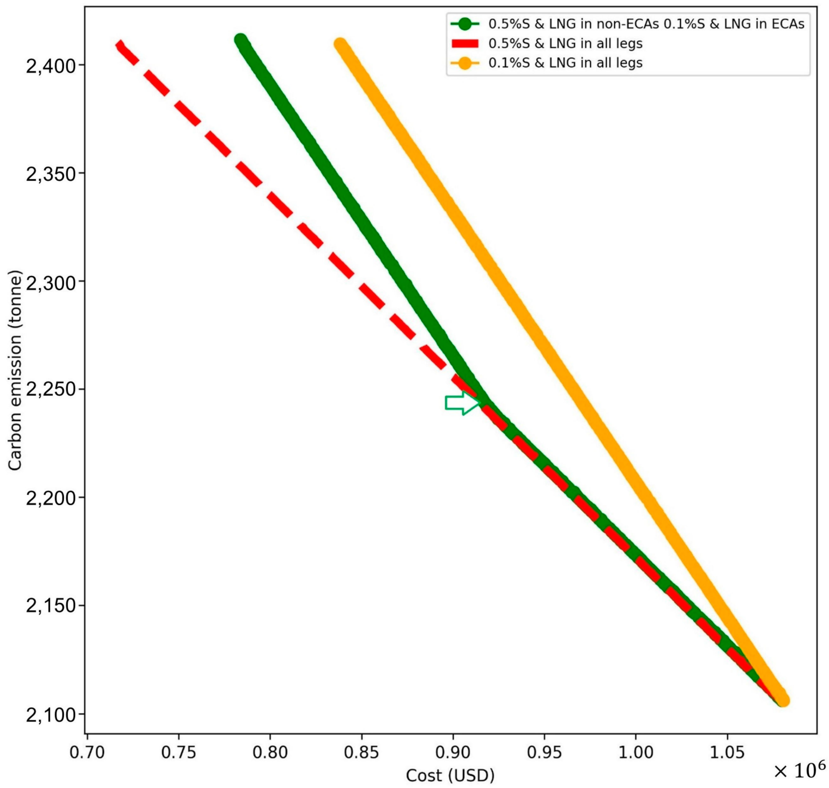

Figure 8. PFs (green solid, orange solid, red dashed) represent Scenario 3, Scenario 2, and considering 0.5% sulfur oil and LNG available in all legs, respectively. The green-frame arrow indicates the bending point of green PF.

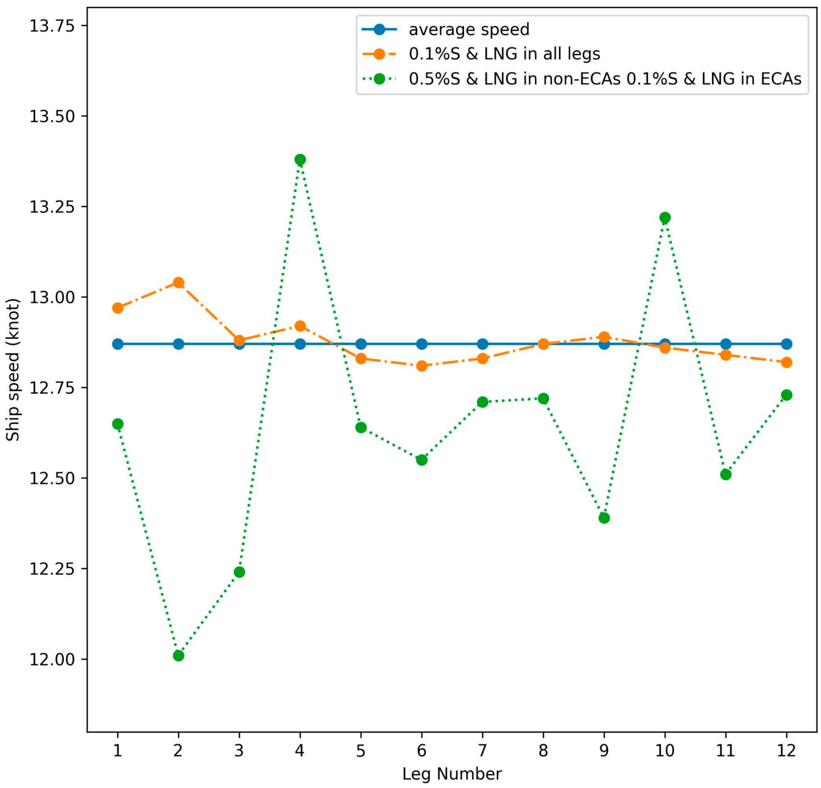

Figure 9. Theoretical average speed (blue, solid line), cost minimization optimal speed (orange dashed dotted line and green dotted line) in all legs represent the Scenario 2 and Scenario 3.

3.3. Effects of the European Union Emissions Trading System

The rules of the EU ETS might also affect the optimal speed profile and fuel ratio. The EU carbon permit is assumed to be 100 or 200 USD/ton; as a result, the PFs were moved to the right, as shown in Figure 10. Consideration of these rules might result in marginal reductions in ship speed in areas under the 100% jurisdiction of the EU ETS (legs 1, 2, and 12 in Table 5) to reduce the cost incurred for EU carbon permits. Therefore, the cost optimal ship speed outside the EU would increase to comply the set time window, as shown in Figure 11. The bottom-right solution was the carbon emission minimization solution and thus still represented the average speed profile. Moreover, the cost minimization solution still involved the use of 100% fuel oil, whereas the carbon minimization solution involved the use of 100% LNG.

These effects may vary with the costs of each fuel and the EU carbon permit. For example, if the EU carbon permit cost is considerably higher than its current cost, the cost minimization solution would not exclude the use of LNG. This solution would involve the use of 100% LNG near EU ports and 100% fuel oil outside EU ports because the EU carbon permit cost is sufficiently high to cover the price gap between fuel oil and LNG. Equation (14) was used to determine whether the cost minimization solution involves the use of LNG. This equation compares the costs (including the costs for the fuel and carbon permit) of producing one unit of energy with fuel oil and LNG. If the carbon permit cost is sufficiently high to cause the cost of LNG to be less than that of fuel oil for producing one unit of energy, the cost minimization solution includes the use of LNG.

$$\frac{P_{oil} + CF_{oil} \cdot P_C}{SE_{oil}} \geq \frac{P_{LNG} + CF_{LNG} \cdot P_C}{SE_{LNG}} \tag{14}$$

NSGA-II can be used to determine the optimal solutions under all conditions.

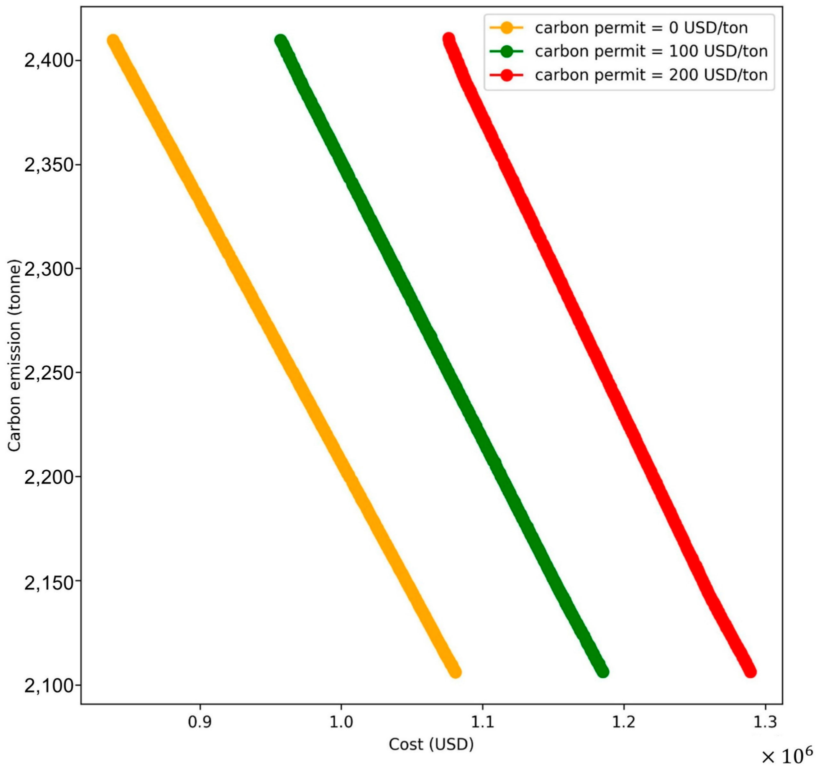

Figure 10. PFs (orange, green, red) represent scenario 2, scenario 4 with a 100 USD carbon permit, and scenario 4 with a 200 USD carbon permit, respectively.

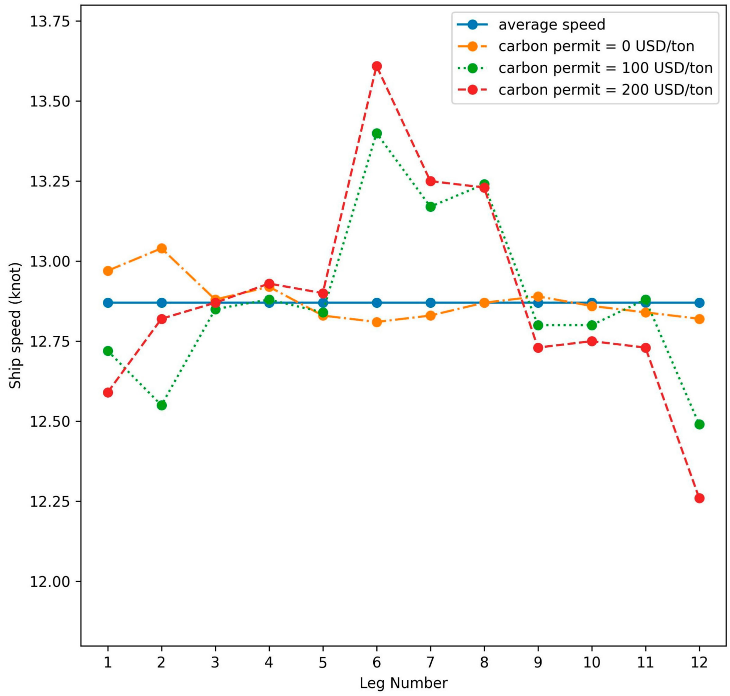

Figure 11. Theoretical average speed (blue solid line), cost minimization optimal speed (orange dashed dotted line, green dotted line, and red dashed line) in all legs represent Scenario 2 and Scenario 4 with a 100 USD carbon permit, and Scenario 4 with a 200 USD carbon permit, respectively.

3.4. Convergence Analysis

NSGA-II obtained the approximate optimized solutions of the considered problem. Without a sufficient number of generations, the solutions might not converge and might be unsatisfactory. Many methods have been proposed to evaluate the convergence of solutions for multi-objective optimization problems. The simplest method involves comparing the PF of the current generation with that of the previous generation and examining whether the PF has shifted to the bottom-left of the PF figures. The shift of the PF can be represented as a hypervolume index [35]. When no considerable improvement occurs in the solution quality of the algorithm after an iteration, the results are considered to have converged. As displayed in Figure 12, the solutions of the considered problem converged after 250,000 function evaluations (500 generation and 500 population size) when using NSGA-II.

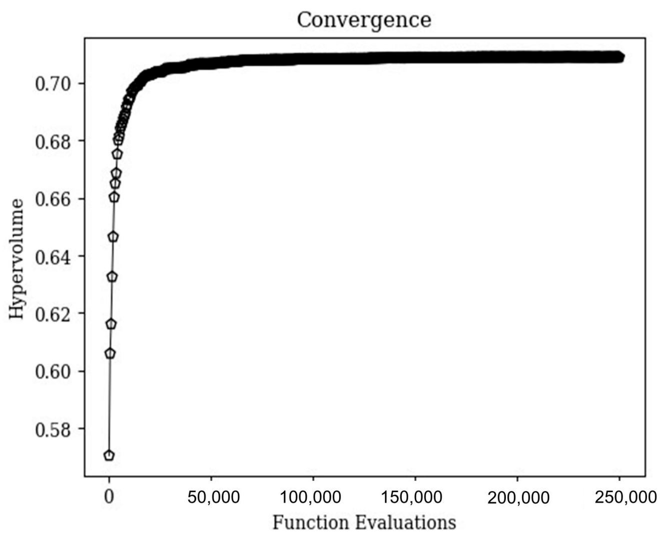

Figure 12. Hypervolume analysis of the considered problem.

3.5. Sensitivity Analysis

A sensitivity analysis was performed on Scenarios 2, 3, and 4 by changing the price of 0.1% sulfur fuel oil, and the cost and carbon emission of the cost minimization solutions were compared and are demonstrated in Table 6. It was observed that with the higher or lower price of 0.1% sulfur fuel oil, the cost of the cost minimization solution would increase or decrease. However, the carbon emission remained the same. In Scenarios 3 and 4, the fuel price would influence the optimal speed of the route. As the speed adjusted itself, the cost would then be affected and would not change as much as that of Scenario 2.

Table 6. Sensitivity analysis conducted with respect to the 0.1% sulfur fuel oil price.

Scenarios	0.1%Sulfur Fuel Oil Price (USD/ton)	Cost Minimization Solution		Percentage Increase or Decrease in Cost
		Carbon Emission (ton)	Cost (USD)	
Scenario 2: General dual fuel	1642.5 (+50%)	2408.13	1,254,885	49.93%
	1368.8 (+25%)	2408.32	1,046,333	25.01%
	1095	2408.48	836,967	0
	821.3 (−25%)	2408.95	627,657	−25.01%
	547.5 (−50%)	2408.31	418,836	−49.96%
Scenario 3: Considering ECAs	1642.5 (+50%)	2413.27	1,100,230	31.45%
	1368.8 (+25%)	2412.43	941,600	12.50%
	1095	2409.30	782,634	0
	821.3 (−25%)	2409.00	621,496	−25.74%
	547.5 (−50%)	2409.90	458,149	−45.26%
Scenario 4: Considering EU ETS	1642.5 (+50%)	2408.25	1,374,311	43.81%
	1368.8 (+25%)	2408.93	1,165,014	21.91%
	1095	2408.38	955,644	0
	821.3 (−25%)	2408.20	746,324	−21.90%
	547.5 (−50%)	2408.66	537,958	−43.71%

3.6. Managerial Implications

Shipping companies need to be aware of the importance of corporate social responsibility. While striving to increase revenues, it is important to maintain an appropriate trade-off between carbon emissions incurred and profits earned, taking into account the sustainability aspects of maritime transport. The methodology presented in this paper captured the trade-off between the two objectives of a shipping company, operating costs, and carbon emissions, and provided a set of optimal sailing speeds and LNG/oil ratios for operators. Shipping companies operate and schedule according to the optimized results as much as possible to reduce operating costs and carbon emissions while complying with international and regional regulations.

Meanwhile, the IMO, regional legislators, and individual government authorities continue to work on improving the relevant rules and regulations. Appropriate carbon reduction regulations may be considered to prevent companies from evading carbon emission monitoring by changing routes and ports of transshipment, or to prevent ships from taking detours to avoid regional regulations, or increasing speed outside the region to slow down in the region, which may increase overall carbon emissions.

4. Conclusions and Prospects

In this study, NSGA-II was used to optimize the cost and carbon emissions of a dual-fuel ship for a given route. This algorithm was used to determine the optimal sailing speed and LNG/oil ratio for each voyage leg of the considered route. The set of optimal solutions included cost minimization and carbon emission minimization solutions.

The carbon emission minimization solution obtained when not considering the differences between voyage legs involved traveling at an average-speed profile and using 100% LNG as fuel for all legs with or without the consideration of the regulations. The cost minimization solution was susceptible to being affected by the regulations of ECAs and the EU ETS. Thus, the following results were obtained for the cost minimization solution:

- When the regulations of ECAs and the EU ETS were not considered, the cost minimization solution involved traveling at an average-speed profile and using 100% fuel oil as fuel;
- When the regulations of ECAs were considered, for all voyage legs, the cost minimization solution involved traveling at faster-than-average speeds outside ECAs, traveling slower in ECAs, and using 100% fuel oil as fuel. At the bending point of the bilinear PF, the solution involved the 100% use of LNG in ECAs and 0.5%-sulfur-containing fuel oil in non-ECAs;
- When considering the regulations of the EU ETS, for all voyage legs, the cost minimization solution involved traveling at faster-than-average speeds in non-EU regions and using 100% fuel oil as fuel. When the EU carbon permit cost was sufficiently high to cover the price difference between LNG and fuel oil, the cost minimization solution involved the use of 100% LNG in EU regions and 100% fuel oil in non-EU regions;

To make the analysis conditions more realistic, this study took into account ECA and EU ETS regulations, as well as real-time fuel prices and carbon permits. However, accurate estimation of fuel consumption is also important, and the historical data used for this purpose can be affected by external factors such as weather and sea surface conditions, leading to scattered results. In addition, actual operating conditions may differ from predicted fuel consumption because of external environmental factors. Therefore, accurate estimation of fuel consumption remains a challenge.

In addition, predicting time windows at each port can be challenging, as the timeline is adjusted according to the actual situation during the voyage, which affects the optimal speed distribution for the entire voyage. While actual time and fuel consumption can be updated to reflect changes, deviations from optimal solutions are inevitable. Shipping company decision makers should consider these factors when selecting the most appropriate solution from a set of optimal solutions.

In the future, shipping industry models can integrate advanced techniques such as weather routing and stochastic analysis to optimize fuel savings and reduce carbon emissions. This includes considering the combined route analyses and the stochastic nature of weather and sea surface condition parameters. Additionally, models can incorporate life cycle assessment of fuel and other carbon reduction methods. It is important to not only monitor and control the cost and carbon emissions of each vessel, but also to plan the entire fleet in a coordinated and integrated manner. By doing so, a more effective optimization model can be developed to provide better solutions for carbon reduction analysis in shipping.

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