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Optimizing Route and Speed under the Sulfur Emission Control Areas for a Cruise Liner: A New Strategy Considering Route Competitiveness and Low Carbon

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Abstract: In order to reduce pollution caused by ship emissions, the International Maritime Organization (IMO) implemented sulfur emission control areas (SECAs). In comparison to ordinary vessels, cruise ships with dual attributes of transportation and tourism generate a greater amount of marine pollution, which poses a significant threat to the marine environment in both berthing ports and the sailing area. In light of the fierce competition of the cruise tourism market, cruise lines are looking for strategies, such as designing more attractive cruise routes, to maintain their core competencies under the emission control policy. In order to achieve this goal, this paper presents a mixed-integer non-linear programming (MINP) model with two objectives and is derived from the traditional route optimization problem. The primary objective is to optimize the route and speed of a cruise liner, while simultaneously enhancing route competitiveness and minimizing carbon emissions both within and outside the SECAs. Subsequently, the multi-objective particle swarm optimization (MOPSO) algorithm was used to reach the objective, and simulations were carried out to verify the effectiveness of the model and method. The results show that speed and sailing route optimization can affect carbon emissions. This paper has a certain application value and guiding significance for cruise line decision makers that will be beneficial for the environment.

Keywords: green shipping; SECAs; carbon emission; itinerary design; MOPSO; TOPSIS

MSC: 90-10

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1. Introduction

In recent decades, cruise tourism has experienced significant and swift growth, and it has been one of the fastest-growing segments of the tourism sector since 2020 [1]. According to the Cruise Lines International Association (CLIA), global cruise passengers reached 29.7 million in 2019, and reached 31.7 million in 2023, with 37.6 million expected by 2025 [2]. In 2018, the cruise fleet was composed of around 318 ships [3]. The carbon footprints of these cruise ships are causing significant environmental issues. Due to the high energy requirements for propulsion and hoteling, cruise ships are classified as one of the most fuel-intensive types of vessels [4,5]. Meanwhile, cruise ships provide an abundance of amenities that serve 2000–5000 passengers and crew, such as communications, dining, waste disposal, and recreational pursuits onboard. Cruise ships utilize diesel fuel to operate their transportation systems as well as to generate energy for their cabins and amenities [6]. With the development of the cruise industry, there has been a drastic increase in cruise demand; cruise activities generate wealth but also generate a negative externality in terms of increased pollution. Hence, the issue of cruise ship pollution cannot be disregarded. Carbon and sulfur emissions are the major sources of pollution from shipping activity, and major economies and shipping nations worldwide have implemented more stringent regulations to enhance emission reduction in the maritime sector. These policies encompass market management, technology research and development, and operational efficiency [7]. Cruise lines are progressing toward decarbonization through the use of improved technology, infrastructure, and operation practices.

The shipping sector plays a crucial role in the evolution of international trade and is responsible for nearly 90% of global trade transportation [8], while contributing 2.89% of the overall greenhouse gas emissions [9]. A decrease in these emissions is inevitable as carbon emissions from this sector are projected to match those of road transportation by 2060. Sulfur Emission Control Areas (SECAs) have been established to regulate ship emissions. To safeguard humanity from ship air pollution, certain organizations, including the International Maritime Organization (IMO), have established emission control zones. Since 2012, according to MARPOL Annex VI, the global sulfur level in marine fuel must not surpass 3.5%, and low-sulfur marine fuel oil is required in the SECAs. Ship speed plays a major role in both shipping costs and emissions, and the sulfur content should remain below 0.5% after 2020 [10]. Ref. [11] considered that there was a significant correlation among energy costs, speed reductions, and revenues, which is attributed to the substantial financial burden that energy imposes on operators and the potential for energy conservation by reducing speed.

On the one hand, the competitive pressure of cruise line products is increasing, and cruise passenger experiences are based on the attraction of the cruise port. At present, many coastal tourism destinations are investing heavily in cruise port facilities and related tourist facilities to enhance the competitive position of cruise ports, so it is important to plan optimal itineraries that maximize occupancy and expected revenue for cruise lines. On the other hand, pollution problems caused by ships, especially CO_2 emissions, should not be underestimated; the challenge of green cruise operations is imminent. Hence, cruise lines are facing a dual challenge of revenue and emission reduction. Motivated by the aforementioned concerns, this study specifically focuses on route design for the cruise liner from a sustainable perspective. To accomplish the objective of a sustainable economy with a reduced carbon footprint, this study presents the competitiveness of cruise ports as well as the compatibility of the carbon emissions with SECA regulations. Additionally, it develops a mixed-integer non-linear programming (MINP) model to optimize the cruise liner's route and speed. The challenges can be categorized into two aspects: (1) developing a competitive index system of cruise ports and (2) calculating the carbon emissions of a cruise liner during a voyage. This paper presents a summary of the primary contributions as follows:

- From the standpoint of green shipping, the sailing route design model is constructed to reduce carbon emissions under the SECAs.
- Considering the attractiveness of cruise ports, the competitiveness of the cruise port model is proposed, and a competitive index system is constructed.
- Taking into account various routes both within and outside SECAs, an actual voyage of a cruise liner is used as a case study to validate the practicability of the proposed model and approach.

2. Literature Review

2.1. Green Shipping

This study focuses on marine transportation, a subject that has garnered increasing attention over the past decade [12–15]. Maritime transport is widely regarded as the most cost-effective mode of transport, and it is the backbone of freight movement in international trade. According to the International Maritime Organization (IMO) *Fourth GHG Study 2020*, the CO_2-equivalent emissions from the global shipping sector increased from 794 million tons in 2008 to 1.076 million tons in 2018, an average annual increase of 3.1% over a decade. By 2030, CO_2 emissions from a single mission of international maritime transport should be reduced by an average of 40% or more compared to 2008 [16]. According to the report by UNCTAD, the IMO has committed to decrease greenhouse gas (GHG) emissions from the maritime sector by 50% by 2050, in comparison to the levels recorded in 2008. This commitment is in response to the detrimental environmental effects caused by shipping [17]. Extensive research has been conducted on green shipping for at least two decades. Ref. [18] discussed the motivations and concerns surrounding the shore power of stakeholders, highlighted the significant influence of vessel owners in its widespread adoption, and developed a mathematical model to show the advantages of shore power, which included an analysis of the optimal oil inventory strategy for vessels. Ref. [19] presented a method to acquire the most efficient route and speed for reducing sailing costs and time, taking into account regulations for emission control areas and environmental factors. Moreover, there is a lot of literature on strategies for mitigating CO_2 and SOx emissions to protect the marine environment, such as using liquefied natural gas, switching fuels by using MGO, and installing exhaust emission scrubbers [20–22].

Technological and operational measures are being taken for the environmental improvement of navigation. The former pertains to the implementation of enhanced ship architecture, upgraded propulsion and power systems, building of shore power systems for ship docking, and innovative fuels [23–25]. The latter includes strategies to decrease emissions during maritime activities, such as improving commercial speed and route planning, implementing energy management systems on board, managing capacity efficiently, and streamlining processes to minimize vessel turnaround times in ports. There is a significant opportunity to improve energy efficiency in shipping by decreasing speed and shortening the time in port, while maintaining the same level of transportation service and simultaneously decreasing energy consumption [26]. Ref. [27] proposed an LNG short-term delivery planning problem and constructed a model considering various constraints, including berth availability, time window, and inventory. A model for designing environmentally friendly policies was presented for coastal transportation systems, seeking to optimize the government's design of the shipping network and the regulation of canal freight rates, while also minimizing the overall cost, which includes the transportation cost and carbon emission tax in the research region [28].

Along with the increase in green shipping, the growth of cruise demand, and its economic relevance in port cities, researchers have started to analyze the impact of cruise sector activities on pollution in ports. To limit cruise ship emissions such as CO_2, SO_2, NOx, PM2.5, and wastewater, maritime policies were designed to force cruise operators to reconsider operation practices and introduce cleaner technologies [29,30]. Ref. [31] developed a bottom-up methodology to assess the amount of atmospheric pollution by cruise ships and described in-port activities of cruise ships including navigation in port both at arrival and departure, maneuvering for berthing and unmooring, and hoteling at berth and then integrated by real data to better evaluate the actual engine power applied and fuel consumption. Ref. [32] constructed a super slack-based measure model, combined a super SBM (Slacks-based Measure) with the Malmquist productivity index to measure marine environmental efficiency, and provided an objective quantification of environmental measures.

2.2. Cruise Liner Route Design

The objective of the cruise liner route problem is to design the optimal route by selecting a cruise port of call location, as cruise liners visit a sequence of ports of call [33,34]. A review of the literature on route design shows that numerous studies explore both quantitative and qualitative aspects. For example, Ref. [35] analyzed the factors motivating cruise companies to select particular ports of call, and then they introduced a factor analysis and the fuzzy AHP approach to identify the primary factors influencing the selection of cruise ports. Ref. [36] proposed a non-linear integer programming model to optimize the total profit during a planning horizon for planning cruise services, considering constraints such as the availability of berths at each port and decreasing marginal profit. According to a pre-determined schedule, a cruise liner embarked on the journey with a sequence of ports, continuously generating various types of waste during the journey. Due to the limited capacity of the waste-holding tank, a study was conducted to minimize the total cost by selecting the optimal ports for waste disposal, and dynamic programming techniques were employed to develop solutions for this issue [37]. A strategy was devised to select and prioritize the ports of call in order to make asymmetric links and find the shortest route, and the optimal profit was computed for each voyage, considering the time window and duration of the voyage [38]. A cruise itinerary design and fleet assignment methodology were developed by using a vehicle routing problem variation [39]. The problem of cruise itinerary schedule design was analyzed to maximize the profit for the cruise company, and a strategy was proposed to calculate and evaluate the cruise schedule based on a parameter optimization process [40]. Ref. [41] employed a two-stage optimization approach to design the optimal itinerary and calculated the best cabin price by combining itinerary design with revenue management methods. In order to save energy and decrease emissions, an artificial neural network model was implemented to enhance the sailing speed and minimize the fuel consumption during a journey, which is embedded into four improved particle swarm optimization algorithms, taking into account factors like station arrival time, variability in sailing speed, and load during the voyage [42]. Ref. [43] developed a mixed-integer programming optimization model to determine the optimal cruise itinerary by maximizing the overall attraction value while minimizing the total cost.

To sum up, many scholars expanded the research about green and sustainable maritime supply chain management with the development demands of the maritime sector, and a substantial amount of the literature focuses on cruise ship pollution emissions, which contributes to the continuous in-depth academic research. Relevant research methods mainly involve game theory, mathematical programming, and empirical analysis. Moreover, most of the existing research regarding route design has primarily concentrated on quantitative analysis, and limited research has been conducted on the development of a bi-objective model that takes into account economic and environmental factors for cruise route design, such as the competitiveness of cruise ports, the impact of ship speed under sulfur emission control policies, and carbon emissions. This paper will fill this gap. Ensuring a balance between environmental preservation and economic growth is a crucial goal for the cruise sector, given the environmental damage it generates in the ocean. How is it possible to strike a balance among the economic, efficiency, and environmental under the SECAs for a cruise liner to accommodate more stringent environmental policies in the future? This issue warrants further study. To answer the question, this study focuses on the route design and optimization strategies of a cruise liner and proposes a dual-objective programming model, taking into account both the maximum competitiveness of cruise ports and the minimum carbon emissions of a voyage.

3. Model

3.1. Problem Description

Due to the fuel property of ship engines, namely Heavy Fuel Oil (HFO), which is the main source of SOx, maritime transportation is a primary contributor to SOx emissions. Since 2015, the IMO regulations have mandated the use of low-sulfur diesel fuel, which must have a sulfur content below 0.1% within the SECAs. The cost of Marine Gas Oil (MGO) is higher than that of HFO, which varies based on the manufacturing procedure and market demand. The implementation of low-sulfur fuel under the SECA regulations in 2015 could potentially decrease the sailing speed of the cruise liners inside the SECAs. The network nodes of cruise routes mainly include the departure port, port of call, and destination port. Typically, the cruise liner departs from the origin cruise port and continues its route; then, it stops at various intermediate stops and finally arrives at the destination port to end its journey back at the cruise's home port. There are several alternative sailing routes between any two ports during a voyage. Disregarding other constraints, this problem can be regarded as the shortest-path problem. However, a cruise liner usually decreases its speed inside SECAs to reduce MGO costs. Due to the specific time constraints of each port of call, a cruise liner must adjust its speed outside SECAs to adhere to the limitations of time windows. To minimize costs and meet the time requirements, it is crucial to optimize the speed and route inside and outside SECAs for a cruise liner.

There is a variety of sailing plans between two adjacent ports of the cruise route, corresponding to different sailing distances inside and outside SECAs, as shown in Figure 1. Taking into account factors such as cruise port competitiveness and speed with the SECA regulations, optimizing the speed of a cruise liner and selecting the optimal sailing plan between adjacent ports can further reduce the cost of the cruise voyage.

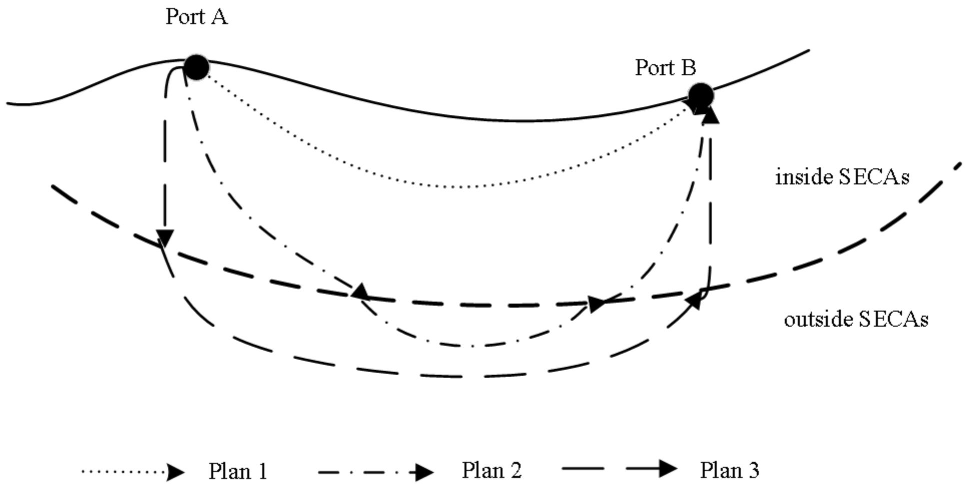

Figure 1. Navigation plan between ports.

3.2. Modelling

Model assumptions. The assumptions of the model are as follows:

(1) The trip from the cruise departure port to the next arrival at the departure port is regarded as a voyage, and the stop time at the departure port is 0.
(2) The cruise liner can only dock at each port of call once.
(3) The call time of the cruise ship at the port of call is affected by the competitiveness of the cruise port.
(4) The speed of the cruise ship is in a fixed range.
(5) The carbon emissions of cruise ships per voyage only take into account the carbon emissions arising from the use of fuel during the voyage.

The meaning of notations. In this section, a concise explanation is provided for the notation, parameter notation, and parameter notation related to the model of cruise ship routing, as shown in Table 1.

Table 1. Symbols and meanings of various parameters and variables.

Var	Type	Definition
N	Set	stands for the set of cruise ports, $N = \{1, 2, \ldots, \text{n}\}$
r	Set	represents the set of sailing plans between two adjacent ports of cruise routes, corresponding to different sailing distances inside and outside SECAs, $r = \{1, 2, 3\}$
W_i	Parameter	represents the comprehensive competitiveness of cruise port i, $i \in N$
D_{ijr}^{ECA}	Parameter	represents the sailing distance with plan r from cruise port i to j inside SECAs (n mile)
D_{ijr}^{N}	Parameter	represents the sailing distance with plan r from cruise port i to j outside SECAs (n mile)
t_{ijr}^{ECA}	Parameter	represents the sailing time of a cruise liner with plan r from cruise port i to j outside SECAs (hour)
t_j	Parameter	represents the call time at cruise port j (hour)

Table 1. *Cont.*

Var	Type	Definition
F_M^{ECA}	Parameter	represents the ship's main engine MGO consumption per hour inside SECAs (t/hour)
F_H^N	Parameter	represents the ship's main engine MGO consumption per hour outside SECAs (t/hour)
M	Parameter	represents the competitiveness of cruise ports during a voyage
Q	Parameter	represents the amount of carbon emissions from a cruise liner (t)
V_{ijr}^{ECA}	Variable	represents the sailing speed of a cruise liner with plan r inside SECAs (kn)
V_{ijr}^N	Variable	represents the sailing speed of a cruise liner with plan r outside SECAs (kn)
X_{ij}	Variable	0–1 variable, cruise ship travels from cruise port i to j; then it is 1; otherwise, it is 0

Objective function. Based on the cruise routes in Figure 1, bi-objective mathematical programming models were constructed to maximize route competitiveness and minimize carbon emissions under the SECAs during the voyage for a cruise liner.

Goal 1: Maximizing competitiveness of the sailing route for a cruise liner.

Equation (1) represents the maximum competitiveness of the sailing route for a cruise liner.

$$\max M = \frac{\sum_i^n \sum_j^n (w_i + w_j)x_{ij}}{\sum_i^n \sum_j^n x_{ij} - 2}, \tag{1}$$

Goal 2: Minimizing carbon emissions under the SECAs for a voyage.

In ship fuel consumption, the main engine's fuel accounts for 87%, the auxiliary engine's fuel accounts for 11%, and the boiler's fuel accounts for 2% [44]. Thus, in the model, the ship's CO_2 emissions originate from the combustion of fuel in both the main engine and any auxiliary engines, because the fuel consumption of the auxiliary engines G_2 accounts for 1/8 of the fuel consumption of the ship's main engine. Therefore, the total fuel consumption of a cruise liner for a voyage can be denoted as Equation (2).

$$G = G_1 + G_2 = \frac{9}{8}G_1, \tag{2}$$

Equations (3) and (4) indicate the sailing time of a cruise liner with plan r from cruise port i to j, while sailing inside and outside SECAs.

$$t_{ijr}^{ECA} = D_{ijr}^{ECA}/V_{ijr}^{ECA}, \tag{3}$$

$$t_{ijr}^{N} = D_{ijr}^{N}/V_{ijr}^{N}, \tag{4}$$

The daily fuel consumption of the main engine for a ship is a cubic ratio of speed [45]. Thus, Equations (5) and (6) represent the ship's main engine MGO consumption per hour while sailing inside SECAs and HFO consumption per hour while sailing outside SECAs.

$$F_M^{ECA} = uk\left(V_{ijr}^{ECA}\right)^3, \tag{5}$$

$$F_H^{N} = uk\left(V_{ijr}^{N}\right)^3, \tag{6}$$

where u is the ship's function coefficient, and it is a constant; k is the fuel consumption rate of a cruise ship's main engine, and $k = 195$ g(kW.h) [40].

Equation (7) represents the main engine's fuel consumption of a cruise liner from cruise port i to j.

$$G_1 = F_M^{ECA} t_{ijrv}^{ECA} + F_H^N t_{ijrv}^N = F_M^{ECA} D_{ijr}^{ECA} / V_{ijr}^{ECA} + F_H^N D_{ijr}^N / V_{ijr}^N = uk\left\{ \left(V_{ijrv}^{ECA}\right)^2 D_{ijr}^{ECA} + \left(V_{ijrv}^N\right)^2 D_{ijr}^N \right\}, \tag{7}$$

Shipping emissions are affected by ship fuel consumption and carbon emission factors within a certain period of time, and the proportionality constant is called the "carbon factor"; λ denotes the tons of CO_2 per ton of fuel, in g/kWh. The carbon emission factor has minor variations in the existing literature [46,47]. In this study, the factor value is 3.114 from the IMO *Fourth GHG Study* [16]. Therefore, Equation (8) represents the amount of CO_2 emissions from a cruise liner.

$$Q = 3.114G = 3.114 \times \frac{9}{8} uk\left\{ \left(V_{ijrv}^{ECA}\right)^2 D_{ijr}^{ECA} + \left(V_{ijrv}^N\right)^2 D_{ijr}^N \right\}, \tag{8}$$

According to Equation (8), the minimum carbon emissions under the SECAs of the sailing route for a cruise liner can be denoted as Equation (9).

$$\min Q = 3.114 \times \frac{9}{8} uk \sum_i^n \sum_j^n \left\{ \left(V_{ijr}^{ECA}\right)^2 D_{ijr}^{ECA} + \left(V_{ijr}^N\right)^2 D_{ijr}^N \right\}, \tag{9}$$

Constraints. In the model of Equations (1) and (9), the following constraints need to be met:

$$\sum_{i=1}^n x_{ij} \sum_j^n x_{ji} \le 1, \tag{10}$$

$$T_{ij} = \sum_i^n \sum_j^n t_{ijr}^{ECA} + \sum_i^n \sum_j^n t_{ijr}^N, \tag{11}$$

$$\sum_i^n x_{ij} = 1; j = 10, \tag{12}$$

$$7 \le \sum_i^n \sum_j^n \left(\frac{D_{ijr}^{ECA}}{V_{ijr}^{ECA}} + \frac{D_{ijr}^N}{V_{ijr}^N} + t_j \right) \frac{x_{ij}}{24} \le 10, \tag{13}$$

$$x_{ij} \in \{0, 1\}, \tag{14}$$

$$V_{ijr}^{ECA}, V_{ijr}^N \in V, V = \{15, 16, \cdots 21\}, \tag{15}$$

Constraint (10) ensures that the best solution has one route when a cruise liner makes a single-heading course for a voyage. Constraint (11) defines the travel time from cruise port i to j. Constraint (12) represents the port of call restriction, and the tenth cruise port is the destination. Constraint (13) guarantees that each voyage should be completed within a limited time for a cruise liner. Constraint (14) is a binary decision variable. Constraint (15) defines the value range of the sailing speed of a cruise liner.

3.3. Competitiveness of Cruise Ports

Responding to lifestyle trends, a cruise liner provides services including relaxation onboard and onshore activities and services at cruise ports of call, and it is necessary to select cruise ports of call that attract more passengers. Therefore, because determining the ports of call in cruise route design is a key decision to improve cruise line revenue, cruise lines usually select more competitive ports to improve service quality. Nevertheless, numerous factors impact the competitiveness of cruise ports, including the economy, traffic, port infrastructure, terminal construction, and politics. With the principles of comprehensiveness, scientificity, standardization, and operability, we constructed the index system of cruise port competitiveness. In the existing literature, the factors affecting a port competitiveness encompass both quantitative and qualitative aspects, such as the number of cruise tourists, the size of the berths, and the depth of the wharf, the number of star hotels, the number of cruise ships visited, and the quantity of national 4A-level scenic spots [48–52]. In the literature [38], the influential factors of cruise port competitiveness were analyzed comprehensively, and the index system was scientific and representative. Hence, this paper considers three levels of an evaluation index system. The second level contains four categories: tourism service, marina services, transport services, and customs clearance services. The third level contains detailed indices, as shown in Table 2. Many approaches have been widely implemented to obtain factor weights, such as AHP, gray clustering, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). To simplify the evaluation process of factors for future research, the weight values of each factor were cited from reference [38] due to the length limitation of the study, as shown in Table 2.

Table 2. Each factor and weight of cruise port competitiveness.

The Top Level	The Second Level	The Third Level
Cruise Port Competitiveness	Marina Service (0.0553)	Port tariffs (0.0076) Clearance capacity (0.0197) Depth of wharf (0.0165) Supply service of supplies and fuel (0.0015) Size of the berths (0.0072)
	Customs Clearance Service (0.2622)	Clearance convenience (0.0299) Staff's organizational capability (0.1958) Baggage service (0.0365)
	Transport Service (0.1175)	Accessibility to the port hinterland (0.0328) Number of parking spaces on the wharf (0.0085) Management of vehicles (0.0763)
	Tourism Service (0.5650)	Natural environment (0.0296) Local tourism resources (0.0517) Service quality of agency (0.3244) Travel support service (0.1594)

4. Methods

4.1. TOPSIS Method

The technique for the Order of Preference by Similarity to Ideal Solution (TOPSIS) is a method applied to multi-criteria decision making (MCDM) under certainty. TOPSIS was first established by Hwang and Yoon [53]. The TOPSIS method is based on the assumption that the optimal solution should be as close as possible to the positive ideal solution and as far as possible from the negative ideal solution in terms of geometric distance. The steps of the TOPSIS process are as follows:

Step 1: Determining the set of evaluation indicators.

Step 2: Creating the decision matrix.

Step 3: Normalization of the decision matrix.

Step 4: Generating the weighted normalized decision matrix.

Step 5: Determining the worst alternative and the best alternative.

Step 6: Computing the distance between alternatives to the positive and negative ideal solution.

Step 7: Ranking the scores according to distances to the ideal solution.

4.2. MOPSO Algorithm

In this study, the design of the cruise route is a challenging problem that integrates integer programming and multi-objective programming, and it is a NP-hard problem. To address this problem, we utilized multi-objective particle swarm optimization (MOPSO). MOPSO uses Pareto dominance and a novel mutation from particle swarm optimization (PSO) [54]. With its intrinsic metaheuristic methodology and geographically based adaptive grids, it efficiently identifies non-convex solutions that are both global and diversified. MOPSO comprises two primary innovations: Firstly, the adaptive grid mechanism is implemented to ensure the external population; Secondly, when solving multi-objective optimization problems, it is crucial to consider not only the convergence of solutions but also the scope and uniformity of solution distribution. Therefore, to guarantee the diversity of final solutions, a new mutation strategy is proposed to mutate the region of particle distribution. With increasing evolutionary algebra, the mutation probability gradually decreases. Among the multi-objective optimization algorithms, MOPSO can effectively tackle extensive engineering problems by utilizing a limited number of initial populations and adaptive grids based on geographical location to preserve solution diversity [55]. Hence, the MOPSO algorithm is proposed to solve the bi-objective optimization model in the cruise route design.

Pareto optimal solutions address the problem of multi-objective optimization. The assessment of solutions that are not inferior is conducted using the "crowding distance" metric. Then, the optimum solutions from each generation of particles are preserved to create a collection of globally optimal solutions, called the search set, which can be implemented by adding an external archive set to store the optimal solution set; the flowchart of the MOPSO algorithm is as shown in Figure 2. The steps of MOPSO algorithm are as follows:

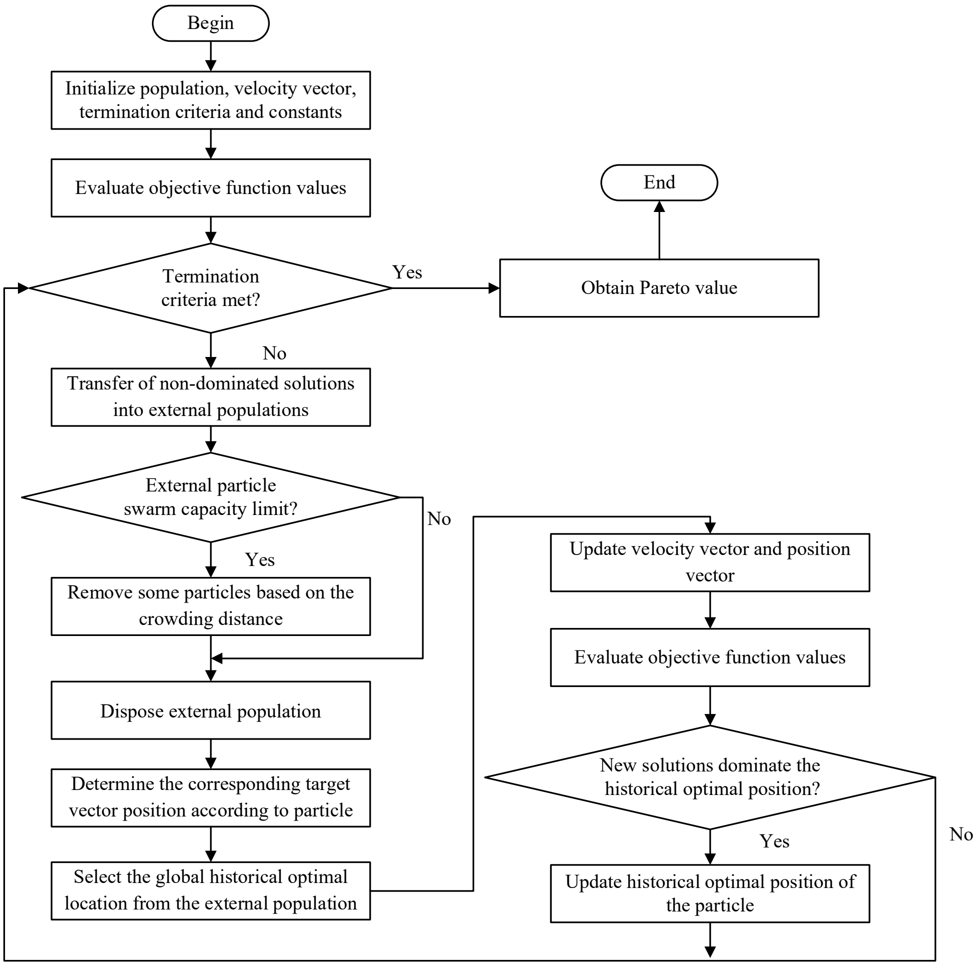

Figure 2. Flowchart of MOPSO algorithm.

Step 1: Initialize set particle number, velocity vector, and particle history position. The initial value of particle velocity is 0, and the historical optimal position of the particle is equal to the initial position of particle, and the objective function values of cruise route competitiveness and carbon emission are calculated.

Step 2: Determine the end condition of the algorithm. If the number of evolutions reaches a given number, the obtained external particle swarm is taken as the Pareto solution set to end the algorithm. If the specified number of times has not been reached, go to Step 3.

Step 3: Transfer the non-dominated solution into the external particle swarm according to the non-dominated ordering.

Step 4: Determine the external particle swarm capacity limit. If the capacity limit is exceeded, it is sorted according to the crowding distance to remove excess particles.

Step 5: Generate the global optimal position.

Step 6: Update velocity vector and position vector.

Step 7: Evaluate the objective function values of new population.

Step 8: Update the historical optimal position of the particle according to whether or not the new solution dominates the historical optimal position of the particle; if it does not, go to Step 2.

5. Case Study

5.1. Data Settings

Data of cruise port competitiveness. There are ten cruise ports: Xiamen (A), Shanghai (B), Dalian (C), Brunei (D), Bangkok (E), Cebu (F), Singapore (G), Jakarta (H), Bali (I), and Yokohama (J). When analyzing the competitiveness of cruise ports, it is very important that the data are accessible, so the qualitative factors were not considered. Table 3 provides the primary quantitative factors for contrasting several port terminal services.

Table 3. Conditions of cruise ports.

Cruise Port	Depth of Wharfs (m)	Size of Berths (1000 Tons)	Clearance Capacity (1000 Passengers)
A	12.4	150	175
B	13.0	220	600
C	12.0	165	10
D	10.0	90	38
E	11.5	200	2200
F	12.0	150	40
G	13.0	350	1850
H	12.0	70	362.5
I	9.0	150	600
J	12.0	30	234

Source: Sea Web (2018).

The cruise port competitiveness was derived using the TOPSIS approach based on the data from Tables 2 and 3. Because Shanghai (B) serves as the port of departure and Yokohama (J) serves as the port of destination, we disregard the impact of these two cruise ports in the cruise route design, because they are already the selected nodes. Thus, the competitiveness values of ports B and J were considered to be zero. The competitiveness value of ten cruise ports is shown in Table 4.

Table 4. Competitiveness of each cruise port.

Cruise Port	A	B	C	D	E	F	G	H	I	J
W_i	3	0	3.5	3	4.5	3	5.5	3.5	5	0

Data of sailing distances between cruise ports. The Automatic Identification System (AIS) data were adopted to obtain the distances between two cruise ports, to design sailing routes, and to monitor the voyages. The AIS data are available on the website http://www.shipdt.com/ (accessed on 25 December 2023). The sailing distances with three plans between different cruise ports are shown in Tables 5 and 6.

Table 5. Sailing distances with three plans inside SECAs between different ports (n mile).

Cruise Port	Plan	A	B	C	D	E	F	G	H	I	J
A	1	0	560	1280	910	1730	870	1650	2010	2630	1350
	2	0	320	730	620	850	460	680	1230	1860	860
	3	0	155	250	340	410	330	420	930	1530	630
B	1	560	0	580	1230	2280	1120	2310	2570	3170	1060
	2	320	0	310	860	1460	820	1250	1460	1950	650
	3	155	0	150	450	780	540	780	830	1490	360
C	1	1280	580	0	1790	2880	1525	2925	3175	3780	1680
	2	730	310	0	1060	2065	1125	1655	1865	1955	860
	3	250	150	0	560	980	690	980	1030	1500	480
D	1	910	1230	1790	0	1520	960	870	1280	1820	1650
	2	620	860	1060	0	1250	780	650	850	1230	1250
	3	340	450	560	0	1150	660	410	680	820	855
E	1	1730	2280	2880	1520	0	1640	1290	2060	2765	2480
	2	850	1460	2065	1250	0	1280	860	1460	1765	1890
	3	410	780	980	1150	0	860	690	1060	1270	1290
F	1	870	1120	1525	960	1640	0	1280	1860	2510	2650
	2	460	820	1125	780	1280	0	840	1260	1620	1865
	3	330	540	690	660	860	0	605	860	1210	1200
G	1	1650	2310	2925	870	1290	1280	0	870	1610	3200
	2	680	1250	1655	650	860	840	0	560	1215	2195
	3	420	780	980	410	690	605	0	475	615	1205
H	1	2010	2570	3175	1280	2060	1860	870	0	865	3445
	2	1230	1460	1865	850	1460	1260	560	0	655	2450
	3	930	830	1030	680	1060	860	475	0	465	1885
I	1	2630	3170	3780	1820	2765	2510	1610	865	0	3660
	2	1860	1950	1955	1230	1765	1620	1215	655	0	2265
	3	1530	1490	1500	820	1270	1210	615	465	0	1665
J	1	1350	1060	1680	1650	2480	2650	3200	3445	3660	0
	2	860	650	860	1250	1890	1865	2195	2450	2265	0
	3	630	360	480	855	1290	1200	1205	1885	1665	0

Table 6. Sailing distances with three plans outside SECAs between different ports (n mile).

Cruise Port	Plan	A	B	C	D	E	F	G	H	I	J
A	1	0	0	0	570	0	540	0	0	0	0
	2	0	280	610	910	960	940	990	840	790	510
	3	0	495	1190	1200	1450	1100	1270	1130	1140	720
B	1	0	0	0	760	0	710	0	0	0	0
	2	280	0	300	1140	860	1010	1075	1135	1235	435
	3	495	0	470	1570	1520	1320	1565	1780	1715	755
C	1	0	0	0	790	0	815	0	0	0	0
	2	610	300	0	1575	865	1325	1325	1345	1840	845
	3	1190	470	0	2100	1955	1695	1990	2220	2245	1245
D	1	570	760	790	0	0	0	0	0	0	250
	2	910	1140	1575	0	350	210	255	455	605	685
	3	1200	1570	2100	0	420	355	535	655	1040	1085
E	1	0	0	0	0	0	0	0	0	0	485
	2	960	860	865	350	0	375	445	615	1025	1090
	3	1450	1520	1955	420	0	415	645	1035	1545	1700
F	1	540	710	815	0	0	0	0	0	0	0
	2	940	1010	1325	210	375	0	455	615	905	805
	3	1100	1320	1695	355	415	0	705	1035	1335	1485

Table 6. *Cont.*

Cruise Port	Plan	A	B	C	D	E	F	G	H	I	J
G	1	0	0	0	0	0	0	0	0	0	0
	2	990	1075	1325	255	445	455	0	335	415	1025
	3	1270	1565	1990	535	645	705	0	435	1045	2035
H	1	0	0	0	0	0	0	0	0	0	0
	2	840	1135	1345	455	615	615	335	0	130	1015
	3	1130	1780	2220	655	1035	1035	435	0	445	1615
I	1	0	0	0	0	0	0	0	0	0	0
	2	790	1235	1840	605	1025	905	415	130	0	1415
	3	1140	1715	2245	1040	1545	1335	1045	445	0	2035
J	1	0	0	0	250	485	0	0	0	0	0
	2	510	435	845	685	1090	805	1025	1015	1415	0
	3	720	755	1245	1085	1700	1485	2035	1615	2035	0

Data of call time of each cruise port. The call time of each port was determined by its competitiveness. Because Shanghai Port is not included in the ports of call, its call time is 0. In addition, the call time of Yokohama Port is 10 h. The call time of each port is shown in Table 7.

Table 7. Call time of each cruise port.

Cruise Port	A	B	C	D	E	F	G	H	I	J
Time	6	0	6	6	10	6	10	6	9	10

The main goals of cruise lines are to raise revenue, lower costs, and generate profits. Hence, while crafting cruise ship routes, cruise lines should prioritize selecting a highly competitive route to attract more passengers. The function coefficient of the cruise ship is 1.

5.2. Results, Analysis, and Discussion

Utilizing the above model and data, we employed MATLAB to resolve the cruise liner route model using the MOPSO method. In the algorithm design, the population size is 500, the number of iterations is 200, and the learning factor is 2.05. The Pareto front, displaying the ideal results is depicted in Figure 3. Additionally, the calculation results of the optimization model included the sailing plan between various cruise ports, the sequence of the ports of call, and the speed of the cruise ship, which are presented in Table 8. Then, the result data of another route were selected for a comparative analysis, as shown in Table 9.

Table 8. Calculation results (B–A–C–E–G–J–B).

Sailing Route	Plan	Speed		M	Q
		Inside SECAs	Outside SECAs		
B-A	2	15.857	16.464	1.50	4,462,659,000
A-C	3	15.670	16.454		
C-E	3	21	21		
E-G	2	16.323	17.525		
G-J	3	15	15.314		
J-B	2	15	15		

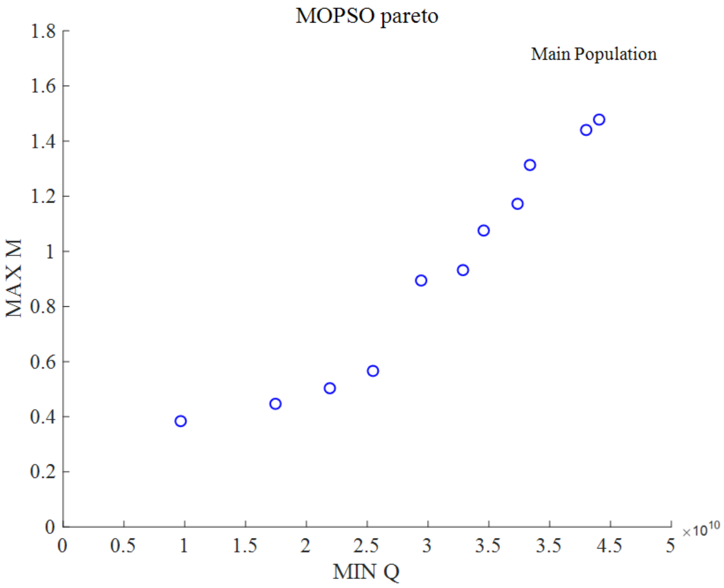

Figure 3. Pareto front of the optimal results (B–A–C–E–G–J–B).

Table 9. Calculation results (B–A–C–G–H–J–B).

Sailing Route	Plan	Speed		*M*	*Q*
		Inside SECAs	**Outside SECAs**		
B-A	2	15.100	15.400	1.47	4,029,145,000
A-C	2	21	21		
C-G	2	15.376	15.391		
G-H	2	18.361	18.888		
H-J	2	15.100	15.100		
J-B	2	16.456	16.683		

Tables 8 and 9 indicate that there is a 20.0% increase in route competitiveness when comparing the sailing route "B-A-C-G-H-J-B" to "B-A-C-E-G-J-B", along with a 9.71% increase in carbon emissions. The aforementioned findings demonstrate the practicality and efficacy of the cruise liner route and speed optimization approach proposed under the SECAs. The process of lowering carbon emissions involves reducing fuel use, resulting in substantial fuel cost savings for cruise ships operating both inside and outside SECAs. The results of this paper should provide useful information for cruise operation to strike a balance between economic and environmental factors under the SECAs.

The focus on marine environmental protection has increased significantly following the enforcement of stricter policies for maritime transport and the adoption of the carbon tax. Consequently, the importance of speed optimization will continue to escalate. When formulating sailing plans, cruise lines need to consider the impact of the SECA regulations and optimize speeds both within and outside SECAs. Providing the model and methodology facilitates quantitative assistance and decision making for cruise lines to reduce operational costs, boost profitability, and promote competitiveness, further fostering the sustainable and robust expansion of the cruise industry.

6. Conclusions

The growing recognition of marine environmental concerns among humans has led to a surge of interest in studying sustainable maritime supply chain management, making the shipping industry a prominent subject of investigation. Furthermore, the swift growth of the cruise sector has sparked heightened curiosity among scholars in studying cruise operation management, specifically about the design of cruise routes. Therefore, it is valuable to examine the influence of cruise port competitiveness and restrictions on sulfur emissions and carbon emissions on the challenges associated with planning cruise itineraries.

Cruise lines are facing a trade-off between revenue and emission reduction and would like to design more competitive routes to maximize occupancy and expected revenue for cruise lines; meanwhile, the industry is actively facing the challenge of green operations. Hence, a bi-objective programming model was constructed in this study to optimize the sailing speed and routes for a cruise liner, resulting in a reformulated voyage plan. The objectives of this model were to maximize the competitiveness of sailing routes and minimize carbon emissions inside and outside SECAs, and the MOPSO method for numerical data was designed to solve it. The validity of the model and method was verified, and an effective solution is provided for the route design for cruise lines. According to the model and method proposed in this study, cruise lines can develop sailing strategies for cruise liners in response to shifts in market conditions and environmental regulations, which enables them to preserve the market share and maximize the profits of a cruise liner. Additionally, this study offers the following significant insights:

- The implementation of the SECA policy has little influence on cruise port competitiveness; however, the cruise liner is more inclined to choose longer routes in order to decrease the sailing distance within the SECAs. In addition, the sailing speed would be reduced inside SECAs;
- Fuel consumption and carbon emissions are positively correlated; lowering carbon emissions can consequently lower fuel consumption, which can save costs and have a mutually beneficial effect. Reductions in carbon emissions might result in substantial energy savings, which could lower the operation costs of a cruise liner.

However, there are some limitations in this paper. For example, when it came to constructing the comprehensive evaluation system of cruise port competitiveness, this paper evaluated and analyzed the matter from the perspective of the marina service, customs clearance service, transport service, and tourism service, and with regard to the accessibility of data, the qualitative factors were not considered in the evaluation system. The carbon emission target was only considered in the proposed model with SECAs. In addition, in the case study, the setting of certain parameters may have been too precise because the actual sample size is insufficient. In future work, more data and parameters should be collected to verify the effectiveness of the proposed method, and future studies can combine the sulfur emissions and carbon emissions to study their impact on navigation optimization. Moreover, additional factors, such as berthing ports with on-shore power, sourcing of food and supplies (prioritizing local sourcing of food and other supplies to decrease the carbon footprint of the supply chain by reducing the distance food and supplies need to travel to reach the ships), and waste disposal, could be considered in cruise route design.

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