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A novel method for joint optimization of the sailing route and speed considering multiple environmental factors for more energy efficient shipping

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ABSTRACT

Energy saving and emission reduction have attracted a great deal of attention in the maritime industry. The optimization of a ship's energy efficiency can reduce energy consumption and CO_2 emissions effectively. However, most of the available studies only focus on either the sailing speed or route optimization, and the interaction between speed and route under the influence of multiple environmental factors was not accounted properly. In this paper, a novel joint optimization method of the sailing route and speed, which considers the interaction between route and speed as well as multiple environmental factors, is proposed to fully exploit the energy efficiency's potential. Moreover, a joint optimization model of the sailing route and speed, which is based on an energy consumption model that considers multiple environmental factors, is established. Next, a solution algorithm for the joint optimization model is investigated in order to achieve joint decision-making with regard to the sailing route and speed. Finally, a case study is conducted that demonstrates the effectiveness of the proposed method. The results show that the proposed method can achieve the optimal sailing route and speed under complex environmental conditions, as well as a reduction in fuel consumption and CO_2 emissions of about 4%.

1. Introduction

Maritime transport is one of the most economical and energy efficient ways of transportation. It has the advantages of large transport volume and low cost per transport volume (Zheng et al., 2019). International maritime trade has grown to 11 million tons and shows an increasing trend (UNCTAD, 2019). However, with the rapid development of shipping industry, there are also some problems, such as energy consumption and greenhouse gas emissions (Wang et al., 2018b). Air pollutants emitted from ships have been steadily growing over time and have a negative effect on human health and the environment. International shipping generates about three percent of the world's total carbon dioxide emissions, which lead to global warming and extreme weather effects (MEPC, 2014). Therefore, the energy costs and greenhouse gas emissions of ships have become important issues that require urgent solutions from the shipping industry. The International Maritime Organization (IMO) (2010) has proposed a series of mandatory rules for improving ship energy efficiency, including energy efficiency design index (EEDI) and ship energy efficiency management plan (SEEMP). For a large number of ships in service, IMO has also proposed the energy efficiency operational index (EEOI) as a monitoring tool for the ship operational energy efficiency.

At present, there are generally three methods for optimizing a ship's energy efficiency. Firstly, from the perspective of a single ship, the sailing speed or route is optimized according to the relationship between fuel consumption and speed, as well as the environmental conditions (Wang et al., 2016; Yan et al., 2015). Secondly, from the point of view of a fleet of ships and its logistics, the fleet's economic navigation schedule and overall route planning is formulated to reduce costs and emissions (Andersson et al., 2015; Song and Yue, 2016). Thirdly, from the

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perspective of a ship's design, the optimization of both the hull's shape and propulsion system's design can be adopted to reduce energy consumption and greenhouse gas emissions (Zhao et al., 2016). Compared with newly built ships, the improvement of the energy efficiency of a large number of ships in service is more urgent, and should be prioritized in order to achieve the shipping industry's goals of energy savings and emission reductions. Therefore, it is very important to adopt effective optimization measures, including the optimization of the speed and route, to improve the energy efficiency of any ships in service.

The sailing speed is one of the main factors affecting a ship's fuel consumption and it thus has an important impact on the operational economy of a ship (Meng et al., 2016; Magirou et al., 2015; Bialystocki et al., 2016; Moon et al., 2014). In recent years, sailing speed optimization models and methods have been studied widely all over the world (Psaraftis et al., 2014; Chang et al., 2014; Fagerholt et al., 2015; Kim et al., 2014b). For example, Yan et al. (2018) proposed the adoption of big data analysis in the engine speed optimization of inland river ships, which considered multiple environmental factors, to promote energy efficient shipping. Furthermore, Wang et al. (2018a) proposed a novel, dynamic optimization method that considered time-varying environmental factors, which could determine the optimal sailing speeds, to improve a ship's energy efficiency and reduce CO_2 emissions. Additionally, from the perspective of economy and logistics, Chang et al. (2014) highlighted the irrationality of the pre-set service speed in the schedule contract and proposed the adoption of a relevant speed optimization method to improve a ship's energy efficiency. Norlund et al. (2013) investigated the optimization method of the sailing schedule, frequency and speed of supply vessels, based on the oil consumption rate of various offshore facilities, in order to reduce the round-trip times and exhaust emissions, Wen et al. (2017) established a multiple objective programming model that considered the fuel consumption, fuel price, freight and inventory cost of goods in transit to achieve the route assignment and speed optimization of multiple ships. Wang (2016) focused on the sailing speed optimization of a network containership by adopting the pseudo-polynomial-time algorithm and achieved some good optimization results. Li et al. (2018) studied the speed optimization of a tanker under the influence of irregular wind and waves, and outlined the fuel consumption and operation costs of the ship during the entire voyage by establishing an economy model that considered multiple influencing factors. The above-mentioned studies on speed optimization mainly considered the environmental conditions in a given route. However, these methods do not consider the environment surrounding the sailing route when conducting the speed optimization, and thus have certain limitations. Better energy efficiency can be achieved by combining the sailing route and speed optimization according to the multiple real-time, surrounding environmental information (e.g. the wind speed, wind direction, wave height and wave direction) within the navigational area.

The sailing route optimization based on the navigational environment and sea state prediction is another effective method for improving a ship's energy efficiency. This method aims to determine the optimal sailing route by considering the navigational performance and safety, as well as the operational status and requirements, in order to improve the operational economy whilst at the same time ensuring the ship's safety (Marie et al., 2013; Kim et al., 2017). Sen et al. (2015) proposed a route optimization model based on the Dijkstra algorithm, and validated the effectiveness of this model through experiments. Shao et al. (2012) proposed a new, dynamic planning method for weather routing to minimize a ship's fuel consumption. This method jointly optimized the ship's sailing route and power, and the results showed that it can reduce fuel consumption by about 3.1%, whilst also reducing a ship's navigation time. Vettor et al. (2016) developed a ship weather routing system, which integrated a response model that considered the influence of various sea conditions. This system could obtain the optimal sailing route under different conditions. Kang et al. (2012) developed a maritime transportation planning support system by adopting a heuristic algorithm to achieve a ship's optimal sailing route. Wu et al. (2013) established a safe-economical route model based on the dynamic prediction environment, which could determine the shortest route time-wise by combining the ocean's dynamic information and route feasibility analysis. Kim et al. (2014a) proposed an angular rate-constrained path planning algorithm that is effective for global path planning of unmanned surface vehicles (USVs). Zhang et al. (2018) analyzed the connectivity of the turning point, according to a ship's trajectory, based on the turning point of the Automatic Identification System (AIS) trajectory data. Accordingly, the sailing route could be optimized by establishing the directed route network and adopting the ant colony algorithm[1] (Dorigo and Stützle, 2004). The above sailing route optimization methods mainly consider the impact of the navigational environment along the route on a ship's energy efficiency. However, the sailing speed under different navigational conditions is not fully considered when determining the optimal sailing route for optimizing a ship's energy efficiency. Therefore, these methods could not fully exploit the potential of optimizing energy efficiency.

Consequently, it makes academic and practical sense to jointly optimize the sailing route and speed by considering the influence of multiple environmental factors (e.g. the wind speed, wind direction, wave height and wave direction), in order to improve a ship's energy efficiency. However, most of the available studies only focus on either the sailing speed or route optimization, and the interaction between speed and route under the influence of multiple environmental factors was not accounted properly. Therefore, a novel joint optimization method of the sailing route and speed, which considers the interaction between route and speed as well as multiple environmental factors, is proposed in this paper to fully exploit the energy efficiency's potential. The main contributions are twofold: 1) a new joint optimization model of the sailing route and speed, which is based on the energy consumption model that considers multiple environmental factors, is established. The established joint optimization model can fully consider the interaction between route and speed and the influence of multiple environmental factors, and thus can improve a ship's energy efficiency effectively; and 2) a novel joint optimization method of the sailing route and speed that considers the multiple environmental factors is proposed. The proposed optimization method can jointly determine the optimal sailing route and speed under various navigational environmental conditions, and thus can reduce both the fuel consumption and CO_2 emissions.

The structure of the paper is as follows. Section 2 briefly illustrates the problem and the joint optimization method of the sailing route and speed. Then, a fuel consumption model, which considers multiple environmental factors is established in Section 3, and a joint optimization model of the sailing route and speed, as well as an intelligent solution algorithm are investigated in this part. On this basis, a real ship case study is carried out to verify the effectiveness of the proposed joint optimization method in Section 4. Finally, the conclusions and future work are presented in Section 5.

2. Method

Ships usually select circular navigation routes in order to shorten the sailing distance and time. However, this method may not be the most fuel-efficient due to the influence of meteorological conditions on fuel consumption. A ship's energy consumption is influenced by multiple navigational environmental factors. Therefore, it is possible to find the optimal sailing route, which has the lowest fuel consumption, by considering the real-time environmental factors. Nonetheless, a ship's

[1] Ant Colony Optimization (ACO) is a discrete optimization technique that is inspired from the behavior of ants seeking a path between food and their cave, and it has been adopted to solve various heuristic optimization problems. The detailed description of ACO can be found in Ant Colony Optimization (Dorigo and Stützle, 2004).

fuel consumption is influenced largely by a ship's speed under different environmental conditions. The energy efficiency has an approximate quadratic relationship with a ship's sailing speed. Therefore, it is also necessary to determine the optimal sailing speed under such conditions to ensure the optimal energy efficiency. The optimization degree of a single optimization method is limited, and the joint optimization of the sailing route and speed that considers their interaction and the influence of multiple environmental factors can further improve a ship's energy efficiency. Therefore, a joint optimization method of the sailing route and speed, which considers the interaction between route and speed as well as the real-time multiple environmental information, is proposed in order to achieve a better optimization result with regard to a ship's energy efficiency. An illustration of the proposed joint optimization method is shown in Fig. 1.

Data acquisition is an important aspect of the joint optimization of the sailing route and speed. A ship's energy efficiency data of is obtained by its sensors: The fuel consumption data is obtained by the fuel flow meter; the voyage data is obtained by the odometer; the shaft power data is obtained by the shaft power meter; and the longitude and latitude data is obtained by the installed Global Positioning System (GPS). Concurrently, the real-time meteorological information, including wind speed and direction as well as the wave height and direction, is obtained from the European Centre for Medium-Range Weather Forecasts. Subsequently, a fuel consumption model that considers multiple environmental factors can be established based on the obtained data. Then, the ship navigation's area is meshed according to the longitude and latitude values, and the real-time marine meteorological information for different grid positions can be obtained. Ultimately, the joint optimization model of the sailing route and speed is established. The optimization model aims to determine the optimal grid position and corresponding sailing speed within the time limit of a ship's schedule. In this way, the joint optimization of the sailing speed and route can be realized through the intelligent optimization algorithm. Finally, the proposed joint optimization method will be validated by a case study.

The joint optimization processes are illustrated in Fig. 2. When the voyage area is divided into M parts in the latitude dimension, the decisions regarding sailing route and speeds will include $2M$-3 dimensions of optimization variables. These variables include M-1 dimensions of the optimal sailing speed between the two adjacent grids, and M-2 dimensions of the sailing positions of these grids. The constraints include the ship's sailing time, position and speed. The sailing time and fuel consumption are the nonlinear function of the variables of sailing speed and sailing positions of the grids. Therefore, the joint optimization of the sailing route and speed is a multi-constraints and multi-variables nonlinear optimization problem.

In recent years, scholars have proposed a variety of intelligent optimization algorithms to solve complex nonlinear optimization problems, such as the ant colony algorithm (Yue and Chen, 2019), simulated annealing algorithm (Kosmas and Vlachos, 2012) and particle swarm optimization (PSO) algorithm. The PSO algorithm is a new intelligent optimization technology, which is suitable for solving dynamic and multi-objective optimization problem (Wang et al., 2017). Compared to other optimization algorithms, the PSO algorithm has the advantages of a faster calculation speed and better global search ability. Therefore, the PSO algorithm is adopted to solve the joint optimization model of the sailing route and speed in this paper.

3. The joint optimization model of the sailing route and speed

3.1. The ship's energy consumption model that considers multiple environmental factors

When a ship is sailing, it should receive continuous power from the main diesel engine to overcome any resistance. The power from the marine diesel engine is transmitted to the propeller through the shaft, and then to the ship's hull to overcome any sailing resistance. At a certain speed, the different environmental conditions will result in a different sailing resistance and thus lead to different propeller thrust and energy consumption values. The relationship between the propeller thrust, resistance and propeller speed can be shown as Eq. (1).

$$T_{prop} = \frac{T_{eff}}{(1-t)\cdot k} = \frac{R_{ship}}{(1-t)\cdot k} = K_T \times \rho n^2 D^4 \tag{1}$$

where, T_{prop} is the propeller thrust; T_{eff} is the effective thrust of the propeller, which is equal to the resistance exerted on the hull; t is the

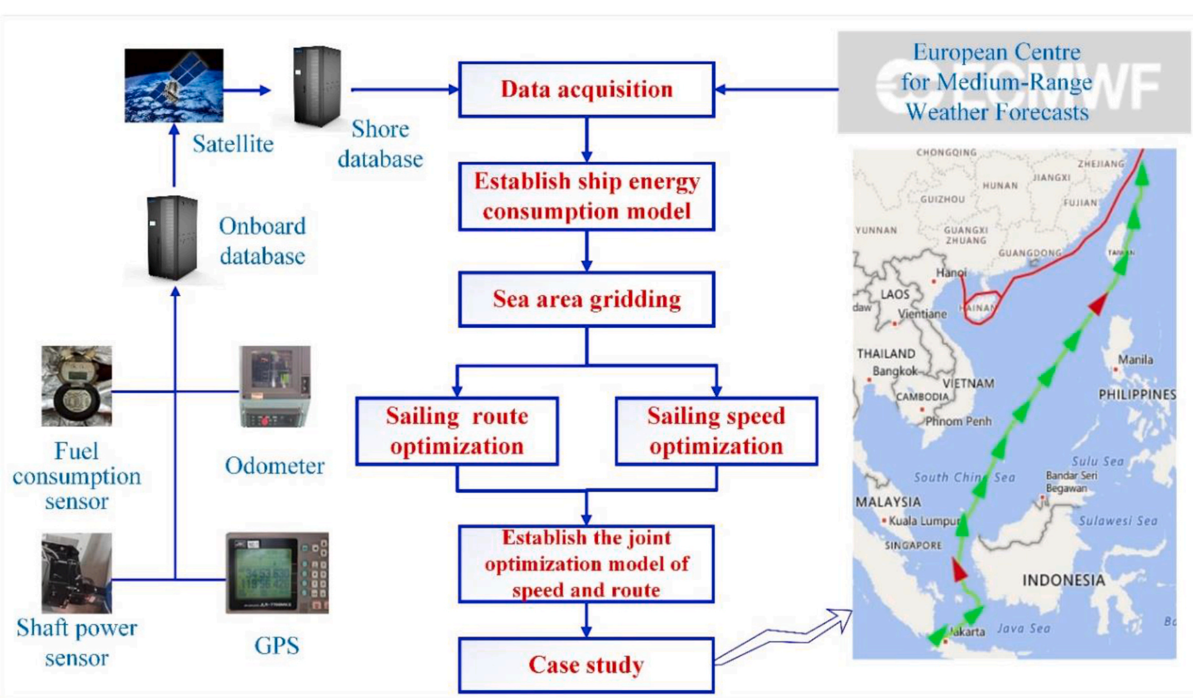


Fig. 1. An illustration of the joint optimization method.

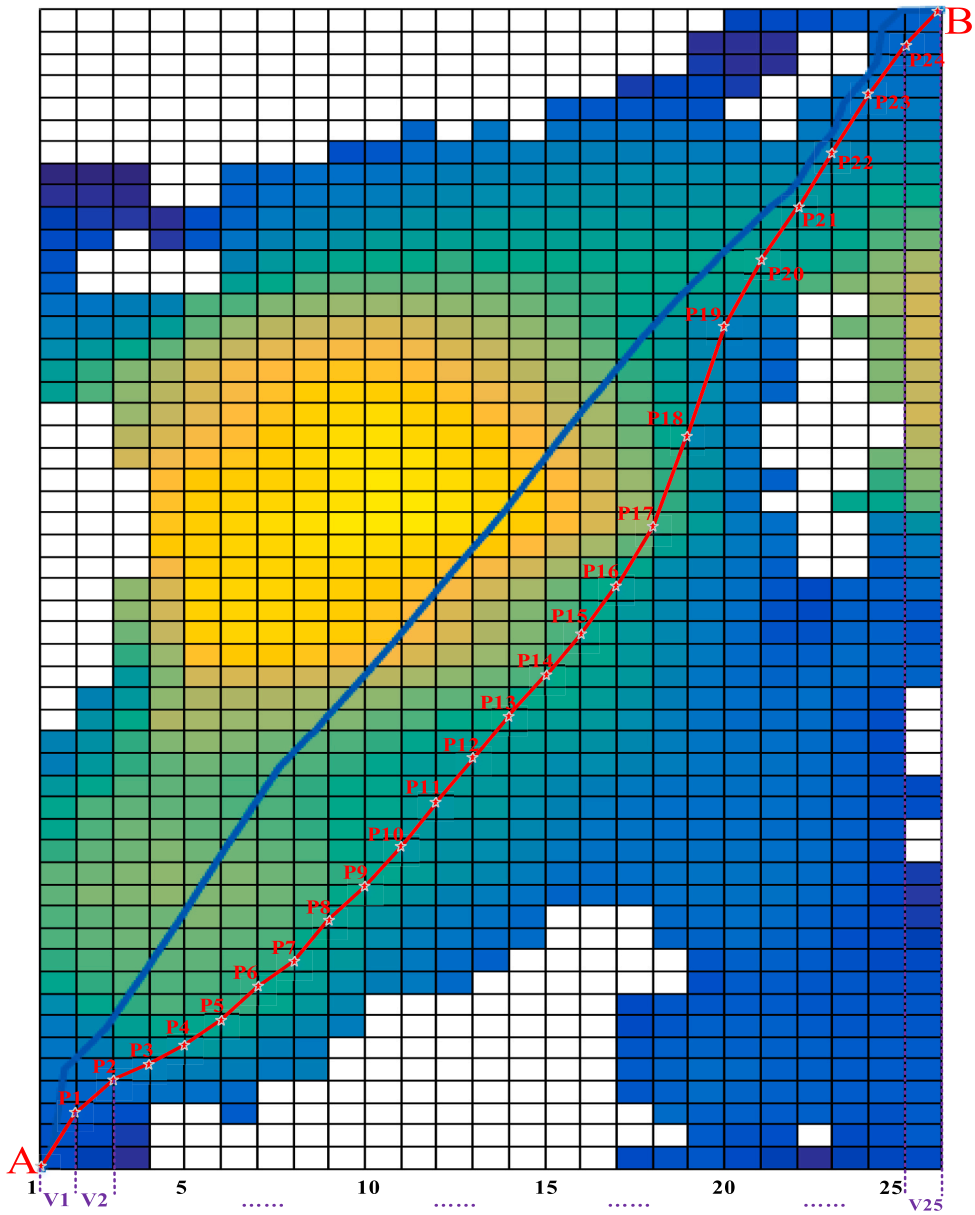


Fig. 2. Schematic diagram of joint optimization processes.

thrust deduction coefficient; k is the number of propellers; R_{ship} denotes the total ship resistance; K_T is the thrust coefficient of propeller; ρ is the density of the water; n is the propeller speed; D is the diameter of the propeller.

A ship at sea would face two main types of resistance. Above the waterline, it would face wind resistance as it cuts through the air. In addition, water resistance is unavoidable under the ship's waterline. Water resistance can further be divided into static resistance and wave added resistance. Therefore, the ship's total resistance comprises static resistance, wind resistance and wave added resistance. The static resistance of the ship can be obtained by Eq. (2) (Holtrop and Mennen, 1982).

$$R_{\text{static}} = R_{\text{F}}(1 + k_1) + R_{\text{APP}} + R_{\text{W}} + R_{\text{B}} + R_{\text{TR}} + R_{\text{A}} \tag{2}$$

where, R_{static} represents the static resistance; R_{F} represents the friction resistance; R_{APP} represents the appendages' resistance; R_{W} represents the wave making and breaking resistance; R_{B} represents the additional resistance in bulbous bow; R_{TR} represents the additional resistance in stern immersion; R_{A} represents the relevant resistance in model ship; and k_1 represents the viscous resistance factor depending on the ship type.

In addition, the wind resistance can be obtained by Eq. (3) (Kwon, 2008).

$$R_{wind} = C_a \frac{1}{2} \rho_a v_a^2 A_s \tag{3}$$

where, C_a represents the air resistance coefficient; ρ_a represents the air density; v_a represents the wind speed; and A_s represents the area of positive projection above the waterline of the ship.

Moreover, the wave added resistance can be expressed by Eq. (4) (ISO, 2015).

$$R_{wave} = 2 \int_{-\pi}^{\pi} G\left(\alpha - \chi\right) \left[\int_0^{\infty} S\left(f\right) \frac{\Delta(f, \alpha)}{\zeta_A^2} df \right] d\alpha \tag{4}$$

where, G is the directional distribution of an incident wave; α is the initial direction of an incident wave; χ is the incident angle of a wave; $S(f)$ is the frequency distribution of an incident wave, $\Delta(f, \alpha)/\zeta_A^2$ is the corresponding function of increasing resistance in a regular wave; and ζ_A is the characteristic wave height. For the common wave conditions, the wave added resistance can be calculated by Eq. (5) (ITTC, 2005).

$$R_{\text{wave}} = 0.64\zeta_A^2 B^2 C_b \rho g / L \tag{5}$$

where, B is the width of the ship; C_b is the square coefficient; and L is the length of the ship.

Finally, the total resistance of the ship can be expressed by Eq. (6).

$$R_{\text{ship}} = R_{\text{static}} + R_{\text{wind}} + R_{\text{wave}} \tag{6}$$

where, R_{ship} is the total resistance of the ship; R_{static} is the static resistance of the ship; R_{wind} is the wind resistance; and R_{wave} is the wave added resistance.

When the ship's total resistance is known, the output power of the ship's main engine can be obtained by Eq. (7).

$$P_B = \frac{R_{ship} \cdot V_s}{k_0 \cdot \eta_S \cdot \eta_G \cdot \eta_O \cdot \eta_H \cdot \eta_R} \tag{7}$$

where, k_0 refers to the number of propellers; η_S refers to the transmission efficiency of the shaft; η_G refers to the transmission efficiency of the gearbox; η_O refers to the open water efficiency of the propeller, $\eta_O = (K_T \cdot J)/(K_Q \cdot 2\pi)$; η_H is the hull efficiency, $\eta_H = (1-t)/(1-w)$, where t is the thrust deduction coefficient and w is the wake coefficient; η_R is the relative rotational efficiency of the propeller.

To sum up, the output power of the main engine can be expressed as Eq. (8).

$$P_B = \frac{R_{ship} \cdot V_s \cdot K_Q \cdot 2\pi \cdot (1-w)}{k_0 \cdot \eta_S \cdot \eta_G \cdot \eta_R \cdot K_T \cdot J \cdot (1-t)} \tag{8}$$

where, J is the propeller advance coefficient; K_T is the propeller thrust coefficient; K_Q is the propeller torque coefficient; K_T and K_Q can be expressed by the following equations.

$$K_T = f_{K_T}(J) = a_t \cdot J^2 + b_t \cdot J + c_t \tag{9}$$

$$K_Q = f_{K_Q}(J) = a_q \cdot J^2 + b_q \cdot J + c_q \tag{10}$$

In addition, the propeller advance coefficient can be expressed by Eq. (11).

$$J = \frac{V_s \times (1-w)}{n \times D} \tag{11}$$

where, D is the diameter of the propeller.

At a given ship speed, the rotational speed of the main engine and the advance coefficient of the propeller can be obtained by combining Eqs. (1), (9) and (11). Then, the output power of the main engine at different sailing speeds can be obtained by Eq. (12).

$$P_B = \frac{R_{ship} \cdot V_s \cdot K_Q \cdot 2\pi \cdot (1-w)}{k_0 \cdot \eta_S \cdot \eta_G \cdot \eta_R \cdot K_T \cdot J \cdot (1-t)} \tag{12}$$

In summary, the fuel consumption of the main engine per unit of distance travelled by the ship can be expressed by Eq. (13).

$$q = \frac{k_0 \cdot P_B \cdot g_{main}}{V_s} \tag{13}$$

where, q is the fuel consumption of the main engine per unit of distance travelled by the ship; V_s is the sailing speed of the ship; and g_{main} is the fuel consumption rate of the main engine.

From the fuel consumption model established above, it can be concluded that the fuel consumption of the main engine per unit of distance travelled by the ship varies with the ship's resistance. The ship's resistance depends on the sailing speed, wind speed and wave height. Therefore, determining the optimal sailing route within the navigational environment, which corresponds to the lowest fuel consumption and optimal sailing speeds at different segments of the route, is the key to improving a ship's energy efficiency. The ship's energy consumption and CO_2 emissions can be reduced by adopting a joint optimization decision-making method of the sailing route and speed.

3.2. The joint optimization model

For a voyage from position A to position B, the sailing distance of each segment can be obtained by Eq. (14).

$$S_{i,\,i+1} = 2 \cdot R \cdot \operatorname{asin}\left(\sqrt{\left(\sin(a/2)^2\right) + \cos(x_i \cdot \pi/180) \cdot \cos(x_{i+1} \cdot \pi/180) \cdot \sin(b/2)^2}\right) \tag{14}$$

where, $S_{i,\,i+1}$ denotes the sailing distance between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}), x means the latitude and y means the longitude; R means the radius of the earth; a and b can be obtained by Eqs. (15) and (16) respectively.

$$a = x_i \cdot \pi/180 - x_{i+1} \cdot \pi/180 \tag{15}$$

$$b = y_i \cdot \pi/180 - y_{i+1} \cdot \pi/180 \tag{16}$$

Then, the total fuel consumption between position A and B can be obtained by Eq. (17).

$$Q_{total} = \sum_{i=0}^{m} \left(q_{i,\,i+1} \cdot S_{i,\,i+1}\right) \tag{17}$$

where, Q_{total} denotes the total fuel consumption between position A and B; $q_{i,\,i+1}$ denotes the fuel consumption per unit of distance between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}), and it is the function of the sailing speed $V_{i,\,i+1}$ and the environmental factors between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}).

In addition, the total sailing time can be obtained by adding the time spent on each sections between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}), as shown in Eq. (18).

$$T_{total} = \sum_{i=0}^{m} T_{i,\,i+1} = \sum_{i=0}^{m} \left(S_{i,\,i+1} / V_{i,\,i+1}\right) \tag{18}$$

where, T_{total} denotes the total time between position A and B; $T_{i,\,i+1}$ denotes the sailing time between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}); $V_{i,\,i+1}$ denotes the sailing speed between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}).

The total fuel consumption and sailing time, which correspond to the different sailing routes and speeds under various environmental conditions, can be calculated using the established energy consumption model that considers multiple environmental factors. The joint optimization of the sailing route and speed is a nonlinear optimization model. The target and constraints of the optimization model can be expressed in Eqs. (19–22).

$$\min \quad Q_{total} = \sum_{i=0}^{m} \left(q_{i,\,i+1} \cdot S_{i,\,i+1}\right) \tag{19}$$

$$\sum_{i=0}^{m} \left(S_{i,\,i+1} / V_{i,\,i+1}\right) < T_{\text{limit}} \tag{20}$$

$$N_{\min} < f_{engine\_speed}\left(V_{i,\,i+1}\right) < N_{\max} \tag{21}$$

$$V_{\min} < V_{i,\,i+1} < V_{\max} \tag{22}$$

where, T_{limit} denotes the sailing time limitation between position A and B; $N_{\min}$ denotes the minimal engine speed and $N_{\max}$ denotes the maximal engine speed; $f_{\text{engine\_speed}}$ $(V_{i,\,i+1})$ means the engine speed between position P_i (x_i, y_i) and P_{i+1} (x_{i+1}, y_{i+1}).

Eq. (19) is the optimization objective function, in which the sailing speeds and positions of each segment are the optimization variables. The first constraint in Eq. (20) ensures that the ship can finish the entire voyage within the required time. The second and third ones in Eq. (21) and Eq. (22) are the physical limitations corresponding to the engine speed and the sailing speed respectively, which can avoid overload.

3.3. The solution method of the joint optimization model

The PSO algorithm is adopted to solve the established nonlinear joint optimization model, as shown in Fig. 3. The specific implementation processes are as follows:

Step 1: Initialization. Generate a population of particles with *M*-2 dimensions representing the positions on the grid and *M*-1 dimensions expressing the sailing speeds between every adjacent positions. Allocate a velocity to each particle randomly.

Step 2: Evaluation. Compute the optimization fitness function, namely the total fuel consumption of the voyage, according to Eq. (19), and update the best locations of the particles by selecting the optimal values.

Step 3: Velocity and location update. The location of each particle is changed by updating its velocity, and the velocity of the particle is dynamically changed by Eqs. (23) and (24). The updates of velocity and location of each particle would be continuously conducted until the constraints in Eqs. (20–22) are met.

$$V^{k+1} = w \cdot V^k + c_1 \cdot r_1 \cdot \left(p_{\text{best}}^k - X^k\right) + c_2 \cdot r_2 \cdot \left(g_{\text{best}}^k - X^k\right) \tag{23}$$

$$X^{k+1} = X^k + V^{k+1} \tag{24}$$

where, k denotes the current iteration steps; w denotes the inertia weight; p_{best} denotes the best locations of the particles; g_{best} denotes the global best locations of the particles; X denotes the locations of the particles; V denotes the velocities of the particles; c_1 and c_2 denote the learning factors; r_1 and r_2 denote the random numbers between 0 and 1.

In order to improve the accuracy of the algorithm, the dynamic method of inertia weight is adopted, as shown in Eq. (25). In this way, the larger inertia weight can ensure the strong global search ability of the algorithm at the beginning of iteration, and in later iterations, the lower inertia weight can guarantee the accurate local search of the algorithm (Wang et al., 2017).

$$w = w_{\max} - (w_{\max} - w_{\min}) \cdot it_{current} / it_{\max} \tag{25}$$

where, $w_{\max}$ denotes the maximal inertia factor; $w_{\min}$ denotes the minimal inertia factor; it_{current} denotes the current iteration times; and $it_{\max}$ denotes the maximal iteration times.

Step 4: Iteration and termination. Go to *Step 2* and continue the algorithm until the stopping criterion of the algorithm is met.

4. Case study

4.1. A description of the case study

This paper takes a Very Large Ore Carrier (VLOC) named "YU ZHONG HAI" from a Chinese shipping company as the research target, as shown in Fig. 4. This target ship mainly transports iron ore from Brazil to China. In this paper, the section from Sunda Strait in Indonesia (105° E, 6° S) to Zhoushan in China (123° E, 28° N) is selected as the research object, because of its relatively complex hydrometeorology, as shown in Fig. 5.

In addition, the basic information of the target ship is shown in Table 1.

4.2. Data acquisition and preprocessing

The onboard, installed sensors acquire the energy efficiency data, as shown in Table 2. The fuel consumption is calculated by the difference of the fuel flow meter per unit of time. The shaft power is measured and recorded by the shaft power sensor. The real-time position information is obtained by the GPS. Moreover, the voyage mileage of the ship is recorded through the odometer. All the energy efficiency data obtained by these sensors are stored in the energy efficiency system, where they can be queried and downloaded by ship managers at any time. Part of the obtained data is shown in Table 3.

The meteorological factors considered include the wave height and wave direction, wind speed and wind direction, which are obtained from the European Centre for Medium-Range Weather Forecasts (www.ecmw

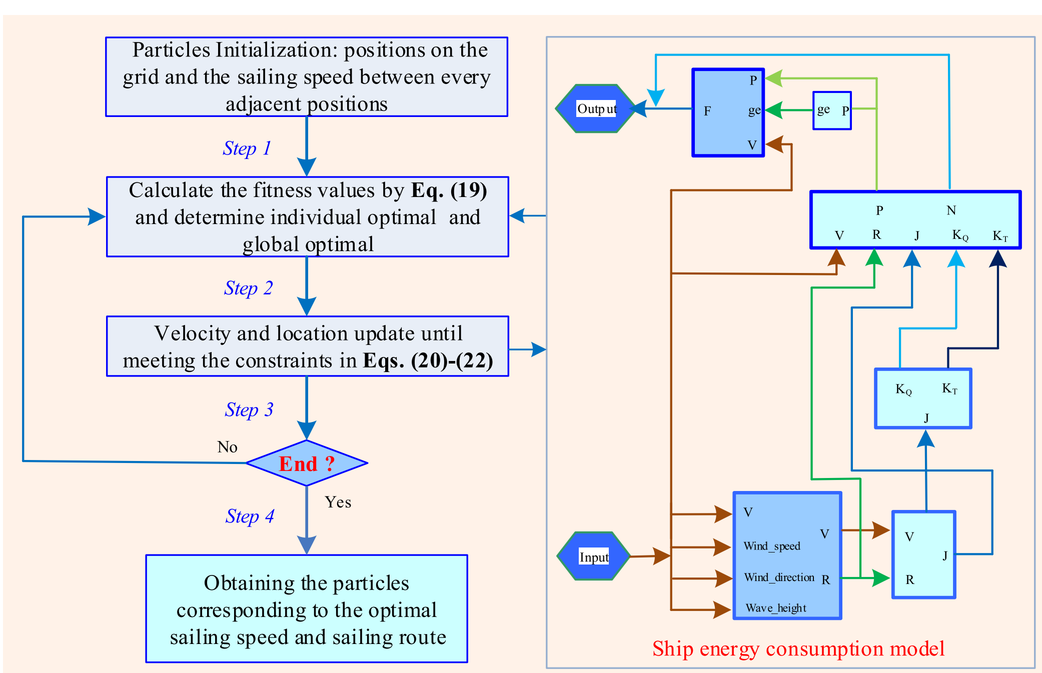


Fig. 3. Solution method based on the PSO algorithm.

Fig. 4. The carrier "YU ZHONG HAI".

Fig. 5. The navigational area of the target ship.

f.Int). The frequency of the meteorological data acquisition is four times per day and once per 0.125° in the space dimension. In this way, a total of 991,692 pieces of data were obtained. In order to ensure the validity of the obtained data and practicability of the model's application, the following data preprocessing procedures are conducted.

Table 1
Basic information of the target ship.

Item	Parameter	Item	Parameter
Length	327 m	Design speed	14.5 kn
Depth	29 m	Number of blades	5
Width	55 m	Diameter of propeller	9.7 m
Deadweight	297959 t	Engine rated power	19000 kW
Draft	21.4 m	Engine rated speed	73 rpm

1) The data preprocessing begins with the removal of low-quality datasets, including those with missing values, in order to enhance the data quality (Han, 2012). In practice, this operation does not result in a large loss of data because of the very low percentage of removed data points. Moreover, the incomplete and obviously abnormal datasets are detected and replaced by the linear interpolation methods (Yin and Zhao, 2017).
2) Secondly, the dynamic real time meteorological data at different positions and time are obtained through a three-dimensional linear interpolation of the time interval and location information, based on the acquired meteorological data and the real time data collected from the ship, which are initially separate.
3) Finally, a vector operation on the wind field components in the latitude and longitude dimensions is conducted to obtain the final data about wind speed and wind direction.

The effective data was obtained through the above preprocessing steps, and part of the energy efficiency and meteorological data is shown in Table 4.

4.3. The mesh generation of the navigational area

In this paper, the ship's navigational area is meshed according to the longitude and latitude dimensions. In this way, the optimization problem can be transformed into determining the optimal grid positions and speeds between adjacent positions, in order to reduce the fuel consumption and CO_2 emissions of the entire voyage within the given navigational time. The accuracy of the mesh generated can be fully determined by considering the ship's actual operation and situation, as

Table 2
Data acquisition form of the ship energy efficiency.

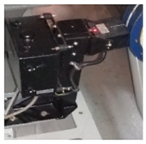
Sensor	Schematic diagram	Parameter	Remark
GPS receiving device		Ship navigation speed (kn), Longitude and Latitude (°)	Mounted on the compass deck. Acquiring ship speed to ground and the position of the ship.
Shaft power sensor		Shaft speed (r/min) and shaft power (kW)	Mounted on the shaft. Collecting real-time speed and power of the shaft.
Fuel consumption sensor		Real-time fuel consumption (m^3)	Mounted on the main oil pipe. Gathering the real-time fuel consumption.

Table 3
Part of the obtained ship energy efficiency data.

Date	Longitude/ (°)	Latitude/ (°)	Shaft power/ (kW)	Sailing speed/ (kn)	Fuel consumption/ (g/m)
2015-12-31 00:30	113.8757 E	12.3798 N	10520	9.5	126.3499
2015-12-31 00:40	113.8920 E	12.4022 N	10420	9.4	127.6940
2015-12-31 00:50	113.9077 E	12.4233 N	10420	9.4	124.4198
2015-12-31 01:00	113.9237 E	12.4438 N	10280	9.3	129.0671
2015-12-31 01:10	113.9412 E	12.4646 N	10410	9.3	129.0671
2015-12-31 01:20	113.9580 E	12.4842 N	10420	9.3	125.7577
2015-12-31 01:30	113.9748 E	12.5039 N	10230	9.3	135.6859
…	…	…	…	…	…

well as the calculation speed. In order to obtain a reasonable size of grids, the grid convergence tests were conducted. The convergence results under different grid sizes (namely 22, 26 and 30 grids in the longitude dimension with 54 grids in the latitude dimension) are shown in Fig. 6. From the grid convergence results, it can be seen that a larger grid would lead to a quick calculation speed (convergence is obtained by fewer steps) but reduce the accuracy of the optimization results (higher fuel consumption of the entire voyage) and thus the optimized percent is only about 3.5%. On the contrary, a smaller grid would improve the accuracy of the optimization results (with the optimized percent of about 4.6%) but would prolong the calculation time. In addition, more optimization parameters regarding the sailing speeds and positions for the smaller grid would result in the frequent changing of the sailing speed and route, which is not advisable in the practical application. Having taken all aspects into consideration, the reasonable size of grid is selected and the generated mesh of the navigational area is accordingly achieved for this case study, as shown in Fig. 7.

As can be seen from Fig. 7, the navigational area is divided into 26 grids and 54 grids in the longitude and latitude dimensions respectively. Therefore, there are a total of 49 variables to be determined, including 25 variables representing the sailing speeds and 24 variables representing the sailing positions. In summary, the joint optimization method proposed in this paper is verified using a case study to realize the decisional effects of the obtained variables, in order to validate its effectiveness.

4.4. *The optimization results and analysis*

In this case study, the time constraint is 179.67 h according to the real operational data, and the other required parameters for the PSO algorithm are shown in Table 5. The optimization results, including the optimal sailing positions and optimal sailing speeds between adjacent positions, based on the model and algorithm established above, are all obtained. The original and optimal sailing positions along the entire route are shown in Fig. 8. Besides, the original and optimal sailing speeds between adjacent positions along the entire voyage are shown in Fig. 9. In addition, the original and optimal fuel consumption are shown in Fig. 10.

From the optimization results, it can be seen that the optimal sailing route and speed can be determined jointly. This joint optimization method can not only optimize the sailing route, taking multiple

Table 4
Part of the obtained effective data.

Date	Longitude /(°)	Latitude /(°)	Shaft power/(kW)	Sailing speed /(kn)	Fuel consumption /(g/m)	Wind speed /(m/s)	Wind direction /(°)	Wave height /(m)	Wave direction /(°)
2015-12-31 00:30	113.876 E	12.380 N	10520	9.5	126.35	11.90	216.03	3.086	32.63
2015-12-31 00:40	113.892 E	12.402 N	10420	9.4	127.69	11.85	216.03	3.086	32.56
2015-12-31 00:50	113.908 E	12.423 N	10420	9.4	124.42	11.80	216.04	3.085	32.49
2015-12-31 01:00	113.924 E	12.444 N	10280	9.3	129.07	11.74	216.06	3.084	32.42
2015-12-31 01:10	113.941 E	12.465 N	10410	9.3	129.07	11.69	216.09	3.082	32.34
2015-12-31 01:20	113.958 E	12.484 N	10420	9.3	125.76	11.63	216.12	3.081	32.26
2015-12-31 01:30	113.975 E	12.504 N	10230	9.3	135.69	11.58	216.16	3.079	32.19
…	…	…	…	…	…	…	…	…	…

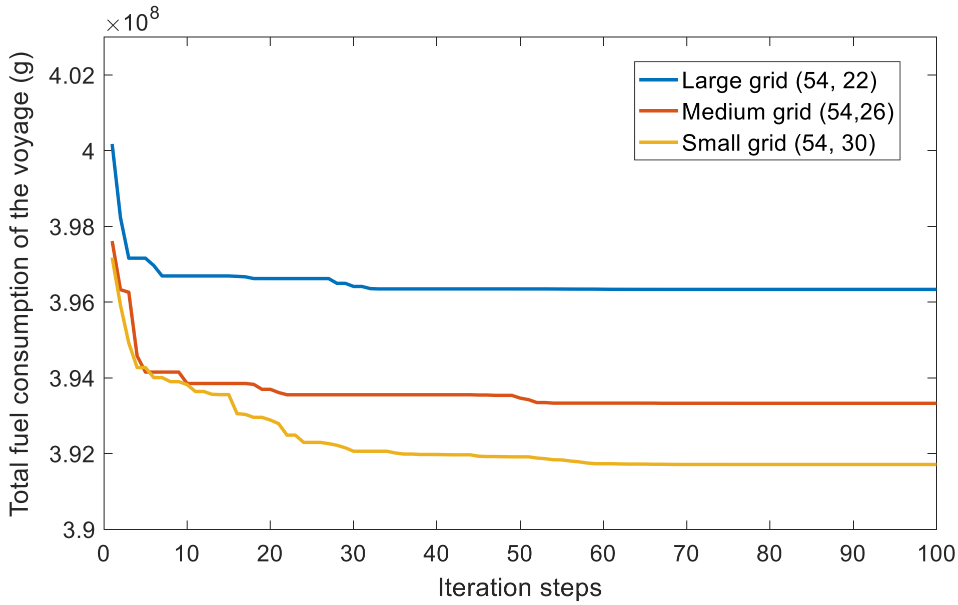


Fig. 6. The convergence results under different sizes of grids.

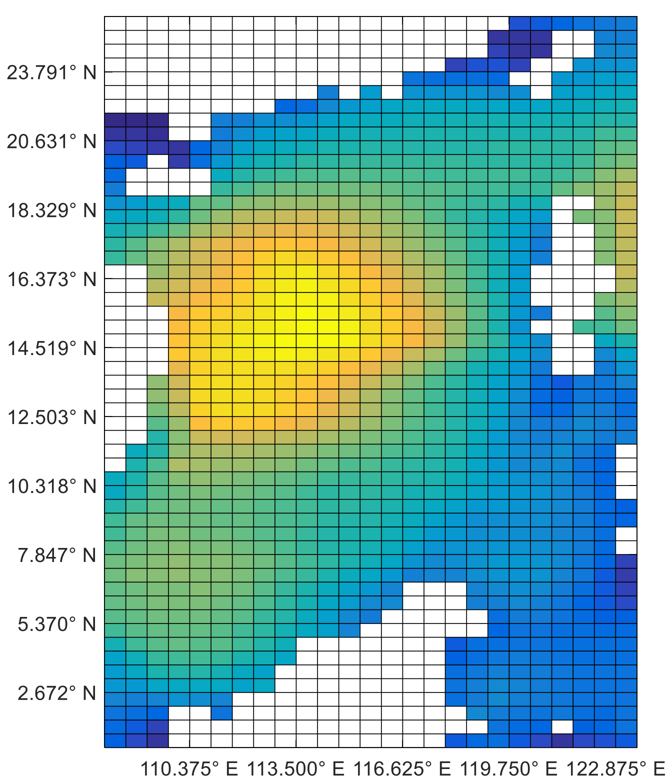


Fig. 7. Illustration of the generated mesh of the navigational area.

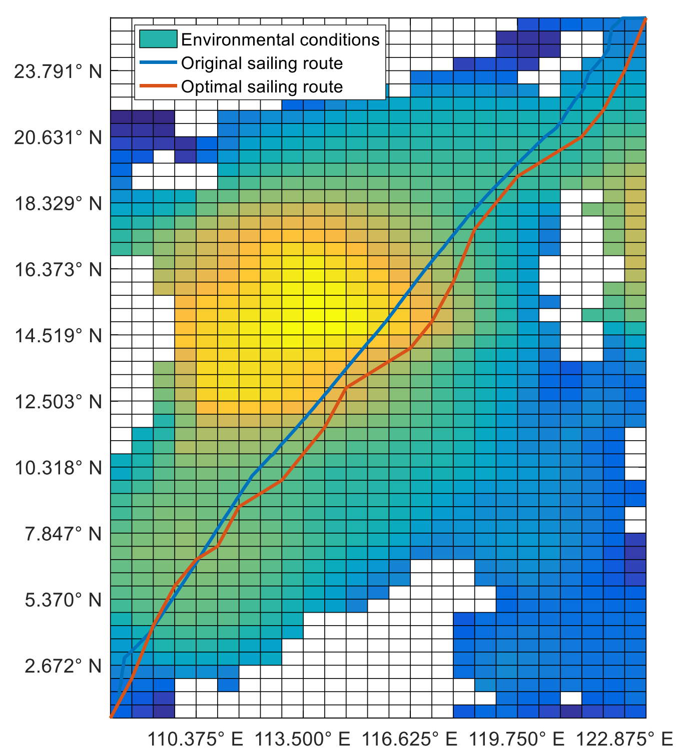


Fig. 8. The original and optimal sailing positions along the entire route.

Table 5
Required parameters for the PSO algorithm.

Parameters	c_1	c_2	w_{max}	w_{min}	$iter_{max}$
Values	2	2	0.9	0.4	100

environmental factors into consideration, but can also optimize the sailing speed of the ship in different positions along the entire route at the same time. This method can automatically avoid the worse weather conditions that would lead to greater energy consumption, although at the expense of an extended sailing distance.

It should be noted that the fuel consumption optimization for the entire voyage is a global optimization problem. The fuel consumption in most of the sailing legs under the proposed optimization method is lower than that under the original operational mode (the sailing route and speed that do not consider the multiple environmental factors). Faced with the given time constraint, a compromise on the sailing speed and thus fuel consumption has to be made in some few sailing legs, in order to achieve the optimal energy efficiency for the entire voyage. The ship has to complete the voyage within the given time constraint, in order to guarantee the in-time arriving. Therefore, the sailing speed should be

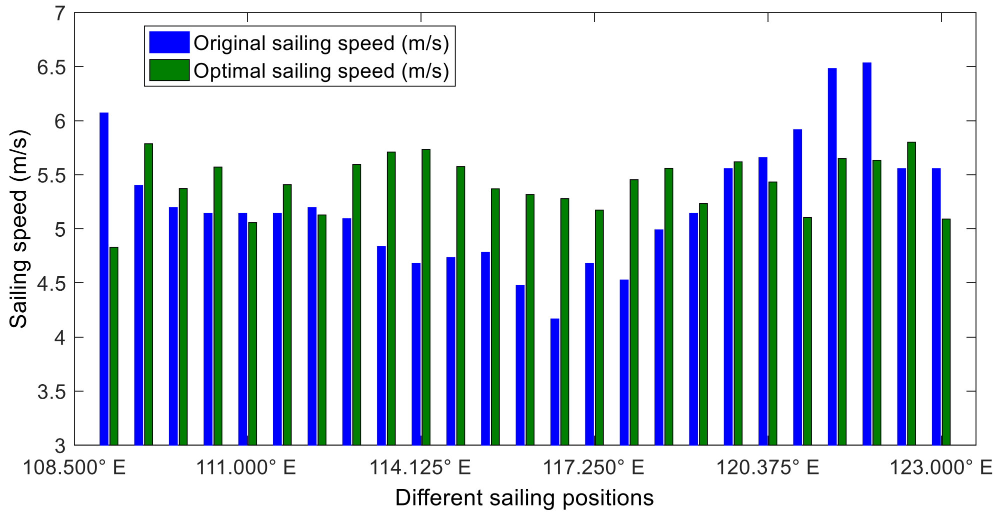


Fig. 9. The original and optimal sailing speeds between each adjacent position.

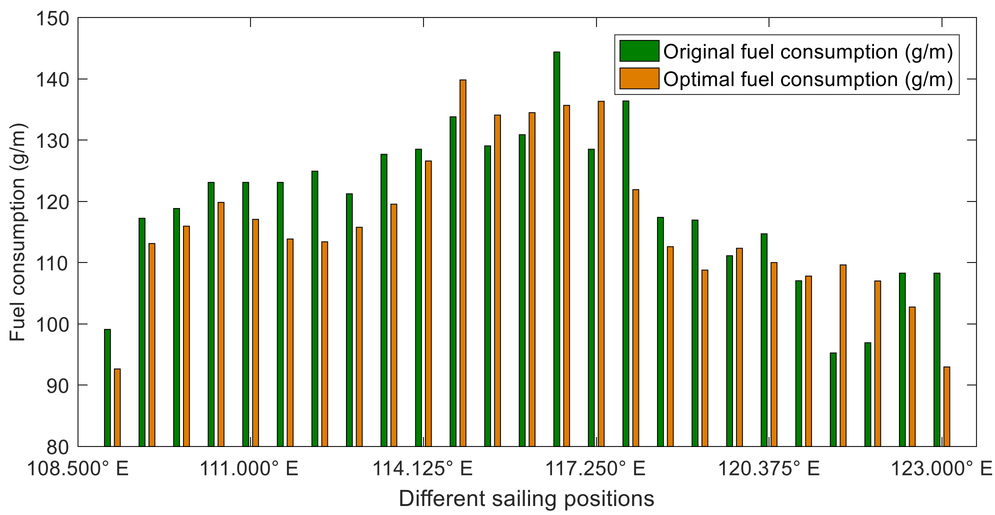


Fig. 10. The original and optimal fuel consumption at different positions.

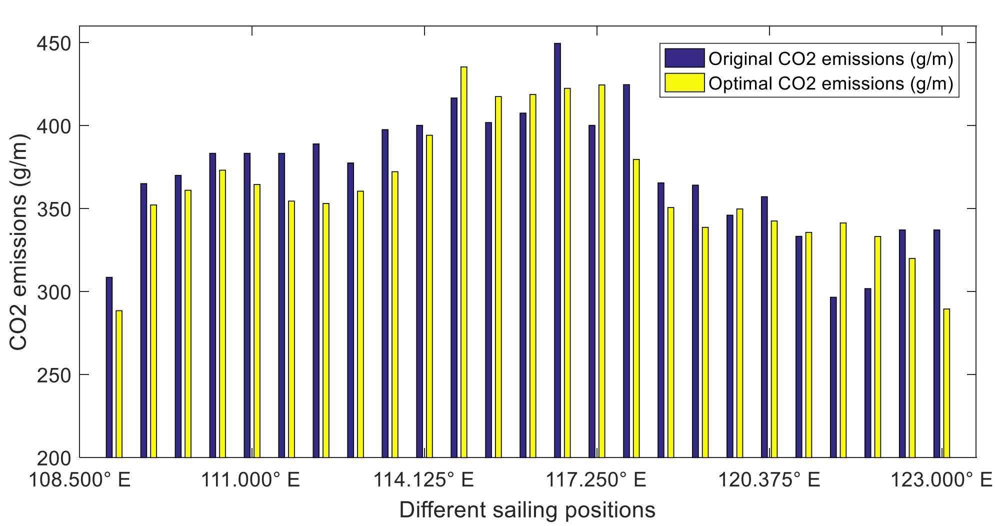


Fig. 11. The original and optimal CO_2 emissions at different positions.

increased in some sailing legs due to the longer distance of the determined sailing route compared to the original sailing route. Although the sailing distance of the original route is shorter than the determined sailing route, the fuel consumption is higher due to its more adverse environmental conditions. The fuel consumption is influenced comprehensively by the sailing speed and the multiple environmental factors. Therefore, it is possible that the higher speed would lead to a lower fuel consumption due to the milder environmental conditions, and vice versa. As can be seen from Figs. 9 and 10, taking the second leg as an example, the optimal sailing speed is higher than the original sailing speed, while the optimal fuel consumption is lower than the original fuel consumption due to the milder environmental conditions in the optimized sailing routes. That is the reason why the multiple environmental factors are fully considered to achieve the joint optimization of the sailing route and speed in this paper.

Moreover, the CO_2 emissions under the original operational mode and the proposed joint optimization method are illustrated in Fig. 11. The CO_2 emission is calculated through the fuel consumption multiplied by its CO_2 conversion rate. For the heavy fuel oil (HFO), the CO_2 conversion rate is 3.114 (Baumler et al., 2014). As can be seen from Figs. 10 and 11, the fuel consumption and CO_2 emissions under different environmental conditions and sailing speeds are different. This is the main aim of the study, to improve a ship's energy efficiency by optimizing the sailing route and speed whilst considering multiple navigational environmental factors.

In order to show the effectiveness of the joint optimization method, a comparative analysis of the fuel consumption and CO_2 emissions is conducted. The total fuel consumption and CO_2 emissions along the entire route under the original operational mode and the proposed method are shown in Table 6. As can be seen from this table, the sailing distance for the joint optimization method is longer than that for the original operational mode. However, the original sailing route does not consider the influence of the environmental factors on the fuel consumption. This shorter sailing route selected under the original operational mode is therefore not energy efficient due to its adverse environmental conditions. Consequently, the longer sailing route would result in higher average sailing speed for the joint optimization method than that for the original operational mode, with the identical voyage completion time constraint. Nevertheless, the proposed method can reduce fuel consumption and CO_2 emissions by about 4% when compared to the original operational mode. That means about 17 tons of fuel can be saved for a voyage by adopting this method. Therefore, the adoption of this method can effectively improve the market competitiveness of a shipping company through the reduction of operational costs, which are predominantly fuel costs. In addition, it can reduce a ship's CO_2 emissions by 54.4 tons for the same sailing time when compared to the original operational mode. It should be noted that a greater reduction in fuel consumption, hence saving energy, can be realized for the original sailing route under more adverse environmental conditions.

Table 6
Comparative analysis on the fuel consumption and CO_2 emissions.

Items	Sailing distance (km)	Average speed (m/s)	Fuel consumption (t)	CO_2 emission (t)
Original operational mode	3442.5	5.32	410.80	1279.23
Joint optimization method	3499.9	5.41	393.33	1224.83
Optimized percent (%)	–	–	4.25	4.25

5. Conclusions and future work

The significance of improving the energy efficiency of ships due to the urgent need to reduce energy consumption and CO_2 emissions in the shipping industry is clearly illustrated in this paper. The optimization of the sailing route and speed that considers multiple environmental factors are effective ways to improve the energy efficiency of ships in service. In this paper, a novel joint optimization method of the sailing route and speed considering multiple environmental factors is proposed in order to fully realize the potential of saving energy and reducing emissions. An energy consumption model that considers multiple environmental factors is established, by analyzing the ship's resistance and both the propeller propulsion and engine fuel consumption characteristics. On this basis, the nonlinear joint optimization model of the sailing route and speed is constructed. The corresponding optimal sailing route and speeds for a voyage are obtained by the PSO algorithm with the goal of minimizing fuel consumption and CO_2 emissions. A case study shows that the proposed method could reduce fuel consumption by about 4% when compared to the original operational mode. That means about 17 tons of fuel can be saved for a single voyage by adopting this method. This can effectively improve the market competitiveness of a shipping company. In addition, it can reduce a ship's CO_2 emissions by about 4% with an identical sailing time constraint when compared to the original operational mode. Therefore, the proposed method is of great significance for practical applications in promoting energy conservation and emission reductions in the shipping industry.

The proposed joint optimization method can be used for other types of ships, because it improves a ship's energy efficiency based purely on the optimization of sailing. Moreover, the joint optimization method for a fleet would bring more benefits for a shipping company. As a recommendation for future work, the joint optimization method can be applied to an entire fleet, whilst considering multiple dynamic influential factors. Due to the urgent need for, and strict regulations regarding energy savings and emission reductions, it will be important to explore more effective, novel energy efficiency optimization methods. The method proposed in this paper can provide shipping companies with new ways to effectively reduce fuel consumption and CO_2 emissions.

CRediT authorship contribution statement

Kai Wang: Conceptualization, Methodology, Investigation, Software, Validation, Funding acquisition, Writing - review & editing. **Jiayuan Li:** Investigation, Writing - original draft, Validation, Visualization. **Lianzhong Huang:** Methodology, Validation, Supervision, Project administration. **Ranqi Ma:** Methodology, Investigation, Writing - review & editing. **Xiaoli Jiang:** Methodology, Investigation, Writing - review & editing. **Yupeng Yuan:** Conceptualization, Methodology, Writing - review & editing. **Ngome A. Mwero:** Conceptualization, Methodology, Writing - review & editing. **Rudy R. Negenborn:** Conceptualization, Methodology, Supervision. **Peiting Sun:** Methodology, Investigation, Validation, Supervision. **Xinping Yan:** Conceptualization, Methodology, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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