



Optimization of River-Sea-Going Ship Type Scheme and Operation Strategy Under Emission Control Area in China

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Abstract. Throughout Chinese existing river-sea-going ships, there are wide-spread problems such as chaotic ship types, small average tonnage, serious aging of ships, and low energy efficiency. In order to cater to the requirements of ship emission control areas implemented in China on January 1, 2016, research is carried out on optimization of river-sea-going ship type scheme and operation strategy under emission control area. The lowest cost model of single-ship round-trip voyage is constructed and the ship operation strategies under the emission control zone in China are analyzed. Through discussing the effects of different operation strategies on ship speed, cost and emissions, some suggestions are put forward for the operation of existing river-sea-going ships. At the same time, combining the optimization of design speed with the optimization of ship form schemes, a design speed model of river-sea-going liner based on penalty cost is proposed, and a comprehensive evaluation index system of river-sea-going liner form schemes based on technological advancement, environmental protection and economy is constructed. Systematic optimization of river-sea-going ship type scheme provides an effective way for the preliminary design of the river-sea-going ship, in line with the current river-sea-going shipping background of energy saving and emission reduction in China.

Keywords: River-sea-going ship · Emission control area · Ship type optimization · Optimal speed · Carbon emission

1 Introduction

River-sea-going transportation is a transportation mode that directly transports goods to the destination port without reloading between river vessels and sea vessels. Due to the high efficiency, low cost and small cargo damage of river-sea-going transportation, river-sea-going ships occupy an important position in the development of freight transportation in the Yangtze River [1]. The large-scale and standardization of river-sea-going ships have become the main trend of development [2]. However, in view of China's current river-sea-going ships, there are various problems such as ship clutter, small average tonnage, low overall technical level, serious ship aging, and serious

pollution, hence it is hard to meet the requirements of today's energy conservation and emission reduction [3].

Since 2008, International Maritime Organization (IMO) has discussed the application of the carbon emission reduction market mechanism in shipping industry for many times. At present, seven different carbon emission reduction mechanisms have been implemented in many countries [4]. In order to comply with the current trend of energy conservation and emission reduction, China's "Guidelines for the Evaluation of Energy Efficiency Design Index (EEDI) for Inland Ships", "Inland Green Ship Specification" and other policies and regulations have been issued. These regulations put forward higher requirements on ship design standards and energy efficiency levels. On January 1, 2016, "Implementation Plan for Ship Emission Control Areas (ECA) in the Pearl River Delta, Yangtze River Delta, and Bohai Sea (Beijing-Tianjin-Hebei) Waters" was promulgated to gradually reduce the emission of major pollutant gases such as nitrogen oxides and sulfur oxides in these regions. In view of the ECA implementation above, how to meet its demands depends on proper operation and forward-looking design.

The carbon emissions and fuel consumption of a ship depend to a large extent on ship speed. At present, there are three main methods to deal with ship carbon emissions in combination with speed optimization: (i) controlling the total amount of carbon emissions; (ii) adopting a carbon emission reduction market mechanism; (iii) combining relevant norms and policies. For the first method, Wang optimized the speed of different legs in voyage by constructing the main engine fuel consumption model to realize energy saving and emission reduction for ship transportation [5]. Xue et al. and Xu et al. considered the impact of speed, and constructed a dual-objective optimization model with the lowest cost and the lowest carbon emissions [6, 7]. Referring to the second method, Wang and Xu adopted three different carbon emission reduction market mechanisms to study the speed optimization model based on the lowest ship transportation cost [8]. Regarding the third method, Kjetil Fagerholt et al. considered the problem of ship routing selection and speed optimization in the ECA. This research pointed out that in the ECA, the ship speed is lower in order to reduce the consumption of low-sulfur oil; while in the non-ECA, the ship will accelerate the navigation to meeting the time constraints of the shift, which may lead to an increase in carbon emissions [9]. For the problem of ship speed optimization in the ECA, Chinese researchers and scholars have not started relevant research, and there is still a lot of work to be carried out.

Under the implementation of China's ECA policy, an empirical analysis of operational countermeasures in the ECA for existing river-sea-going ships was conducted to discuss the influence on the ship's speed, cost and emissions, and eventually suggestions were proposed to guide the existing river-sea-going ship operation. On the other hand, a design speed model of river-sea-going liner based on penalty cost is proposed, combined with the comprehensive evaluation index system of river-sea-going ship type scheme to systematically optimized, which provides an effective way for the preliminary design of river-sea-going ship, and conforms to the current background of river-ship-going shipping in China.

2 Problem Description and Assumptions

With the continuous promotion of ECA policy, the price gap between low-sulfur oil and heavy fuel oil will become larger and larger, resulting in a continuous increase on fuel cost and the substantial increase of the total cost of ship operations. However, incorrect operational strategies will contradict the original intention of the ECA implement. For example, a ship may bypass the ECA and sail a longer distance, which will cause the ship to consume more fuel and lead to higher carbon emissions. When a ship must pass through the ECA, due to rising transportation cost, it may led to a cargo transportation mode conversion from sea to land, which will also increase CO₂ emissions [9]. Therefore, for the existing river-sea-going ship, specific measures must be taken to deal with the ECA. In the following, the lowest cost model of single-ship round-trip voyage is constructed to explore the relationship between speed, cost and emissions under different operation strategies, and provide appropriate advices for the operational of existing river-sea-going vessels.

For newly-built ships, design should be forward-looking. River-sea-going container transportation belongs to liner transportation, in which routes, ports and schedules are fixed. The stability of the schedule directly determines the service quality of the route, and maintaining a high standard rate is significant for realizing long-term profitability of the route. When ship is sailing in the ECA, proper deceleration can reduce the consumption of low-sulfur oil and reduce the fuel cost. However, a ship cannot reduce its speed without considering lower limit of speed and timeliness to guarantee the efficiency in liner transportation.

In order to determine the speed of river-sea-going ships, a speed model based on the penalty cost is proposed. At the same time, the implementation of the ECA has improved the environmental performance requirements for new ships, and the optimization of the design speed needs to be synchronized with the optimization of ship type scheme. This paper proposes a comprehensive evaluation index system for ship type schemes based on combination weighting method, and systematically introduces the development and optimization process of ship type schemes for river-sea-going ships.

2.1 Assumptions

The following assumptions are made in this paper:

- (1) The cost of the installation of exhaust gas treatment device is a pre-investment, not included in the voyage operating costs, and will be considered separately in subsequent calculations.
- (2) Under the two strategies, the fixed cost of round-trip voyage is the same, the optimization objective can be simplified to the lowest voyage fuel cost.
- (3) Since fuel consumption of auxiliary engines is independent of the speed, only fuel consumption of main engines is considered.
- (4) Calculation of fuel consumption per unit time of the ship's main engine is simplified to the cube of the ship speed [11].

- (5) As the ship is in actual operation, only part of fuel consumption at discrete speeds can be obtained (see Fig. 1). Based on three data points, this paper uses a weighted linear combination method to fit the fuel consumption at a certain actual speed to realize the linear transformation of nonlinear optimization problems [12].

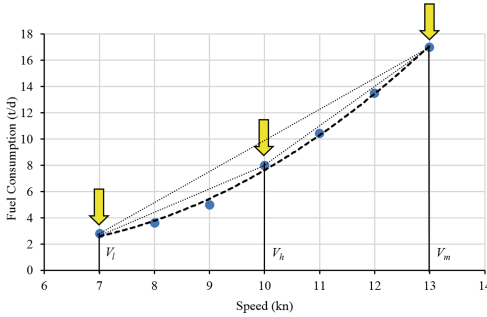


Fig. 1. Diagram of fuel consumption data and weighted linear combination method of 424TEU container ship.

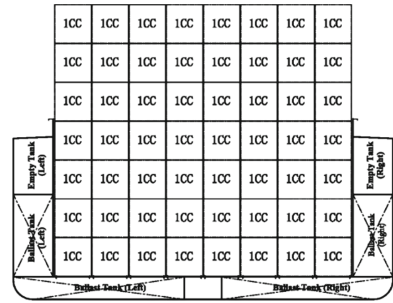


Fig. 2. Cross section of a certain river-sea-going container ship.

2.2 Load Capacity Calculation Model

Ship’s container capacity is related to the ship’s principal dimensions and can be estimated at the preliminary design stage. In order to increase the amount of containers, river-sea-going container ships generally adopt a back-loading arrangement to eliminate the impact of containers on driving sight. Besides, the hatches of most ship types are set to an open form, which can maximize the use of the cabin space and load more containers (see Fig. 2).

2.3 Fuel Cost Calculation Model for River-Sea-Going Ship

The fuel consumption of river-sea-going ships varies with the sailing season: during the dry season (December to March) and the flood season (April to November), the loading condition of the ship changes with the change of water depth conditions, and the fuel consumption situation also changes. Due to the different water depth conditions during the dry season (December to March) and the flood season (April to November), the ship loading conditions will change, and so that causes the change of fuel consumption. The calculation formula of the fuel consumption per unit time of a ship is given by Chao Liu [13], so the detailed process will not be described here. What’s more, the difference in water flow velocity during the dry season and the flood season will also affect the ship’s speed. When calculating the fuel cost of river-sea-going vessels, the influence of sailing season on fuel consumption should be considered. The key steps are shown as follows:

On one hand, the fuel consumption of a ship is:

$$e_V = 10^{-6} \times k \cdot P_S \cdot g_0 \cdot f_V \quad (1)$$

where, e_V represents the fuel consumption (t/h), k is a factor for considering the fuel consumption of all fuel units, and can be taken as 1.1 to 2, P_S represents the power of main engines, g_0 represents the fuel consumption rate (g/kwh) of the ship at rated power, and f_V is a correction coefficient of specific fuel consumption and load of engine, which is given by Chao Liu [13].

On the other hand, considering the channel flow velocity, the container handling efficiency, and the port berthing time, the round-trip voyage time of the ship is:

$$t_V = t_s^1 + t_s^2 + 2 \left(\frac{Teu_V}{100} + \frac{Teu_V}{50} \right) + 36 \quad (2)$$

where, with regard to the channel flow velocity, t_s^1 and t_s^2 represent the time of ship sailing downstream and countercurrent (h) respectively. With regard to the container handling efficiency and the port berthing time, they vary from port to port. Take a container ship sailing on a river-sea-going route between Wuhan Port and Shanghai Yangshan Port as an example, the container handling efficiency of Wuhan port is 50 TEU/h, while Shanghai Yangshan port is 100 TEU/h, and the fixed port berthing time is taken as 36 h. Teu_V represents ship's container capacity.

In summary, the fuel cost of a ship's round-trip voyage is:

$$C_V = 10^{-4} c_f \cdot e_V \cdot t_V \quad (3)$$

where, C_V denotes the cost of the ship's round-trip voyage (ten thousand yuan), and c_f denotes the fuel price (yuan/ton).

The above calculations are carried out on river-sea-going ships in different seasons, and finally the fuel cost of the whole year's navigation can be obtained by adding the fuel cost of each season.

In addition, transport efficiency indicator to measure the speed of ship transport turnover is defined as the transport task completed by the ship in a unit time:

$$EFF = \frac{Teu_V}{t_V} \quad (4)$$

3 Model Construction

On one hand, in order to cope with the ECA policy, for the active ships, the minimum cost model of single-ship round-trip voyage is constructed in "Strategy 1" and "Strategy 2" respectively. On the other hand, for the purpose of improving the stability of liner transportation, considering the transportation economy and liner transportation efficiency, a punishment mechanism is proposed to impose a penalty cost on delayed vessel, which characterizes the series of losses caused by the voyage delay. Based on this, a speed optimization model based on penalty cost is constructed.

3.1 Construction of the Lowest Cost Model for Single-Ship Round-Trip Voyage

There are three main strategies for the ECA policy [10]:

Strategy 1: Fuel conversion. That is, the ship uses low-sulfur oil in the ECA area and heavy fuel oil in the non-ECA.

Strategy 2: Add an exhaust gas treatment device. The exhaust gas treatment device can filter out the sulfur oxides in the ship's exhaust gas, so ships can continue to use heavy fuel oil in the ECA.

Strategy 3: Use clean energy such as LNG. As a clean energy source, LNG can greatly reduce emissions. Using LNG as a fuel naturally enables ships to meet ECA's emission requirements.

Since LNG technology is not yet mature, and the use of LNG as a fuel requires sufficient filling stations as support, such measures have not yet been popularized. For active ships, the first two strategies are more feasible.

Objective function of Strategy 1:

$$\min Z_1 = \sum_{v \in V} (P^{nE} \cdot F_v^{nE} \cdot \omega_v^{nE} + P^E \cdot F_v^E \cdot \omega_v^E) \quad (5)$$

Constraints of Strategy 1:

$$\begin{aligned} \sum_{v \in V} \omega_v^{nE} &= 1 \\ \sum_{v \in V} \omega_v^E &= 1 \\ 0 \leq \omega_v^{nE} &\leq 1 \\ 0 \leq \omega_v^E &\leq 1 \\ t_V &\leq t_{\max} \end{aligned} \quad (6)$$

Objective function of Strategy 2:

$$\min Z_2 = \sum_{v \in V} P^S \cdot F_v^S \cdot \omega_v^S \quad (7)$$

Constraints of Strategy 2:

$$\begin{aligned} \sum_{v \in V} \omega_v^S &= 1 \\ 0 \leq \omega_v^S &\leq 1 \\ t_V^S &\leq t_{\max} \end{aligned} \quad (8)$$

where, Z_1 and Z_2 indicate the round-trip voyage cost under Strategy 1 and Strategy 2 respectively, ω_v^{nE} and ω_v^E represent the weight set of ship speed v when sailing in the non-ECA and the ECA under the Strategy 1 respectively, and ω_v^S represents the weight set of the speed v under the Strategy 2. $v \in V = \{V_l, V_m, V_h\}$ represents the speed interpolation point, which is taken as the minimum, median and maximum value of the ship operating speed respectively. P^{nE} and P^E represent the fuel price for the non-ECA and the ECA under Strategy 1 respectively, which is taken as 2,500 yuan/ton and 4,500 yuan/ton respectively, and P^S represents the fuel price under Strategy 2, which is taken as 2,500 yuan/ton. F_v^{nE} and F_v^E indicates the fuel consumption at the speed v in the non-ECA and the ECA under Strategy 1 respectively, and F_v^S indicates the fuel consumption at the speed v under Strategy 2. t_V and t_V^S represent the round-trip voyage time under Strategy 1 and Strategy 2 respectively, which can be calculated by the following:

$$\begin{aligned}
 t_V &= \sum_{v \in V} (\omega_v^{nE} \cdot t_v^{nE} + \omega_v^E \cdot t_v^E) \\
 t_V^S &= \sum_{v \in V} (\omega_v^S \cdot t_v^S)
 \end{aligned}
 \tag{9}$$

where, t_v^{nE} and t_v^E respectively indicate the time taken by the ship for round-trip voyage at the speed v in the non-ECA and the ECA under Strategy 1, and t_v^S indicates the time taken by the ship for round-trip voyage at speed v under Strategy 2.

3.2 Construction of Speed Model Based on Penalty Cost

One concept related to the penalty cost is the ‘‘time window’’, which can be understood as the time limit for ship’s arrival. At present, the most used is the hard time window constraint, that is, the ship must satisfy the time window constraint, and the soft time window constraint is opposite.

The soft time window constraint allows the ship to violate the time window constraint to a certain extent, and imposes a certain fee on the ship as a punishment. Studies have shown that using soft time window constraint can reduce the ship transportation cost while maintaining high transportation efficiency [14]. Several commonly used penalty cost functions are shown in Fig. 3. Where $[0, t_a]$ is the internal time window, indicating the best time for the ship to arrive at the port; $[0, t_b]$ is the outer time window, which the ship must not violate; $[t_a, t_b]$ is the allowed time interference, within which the ship is subject to the penalty fee.

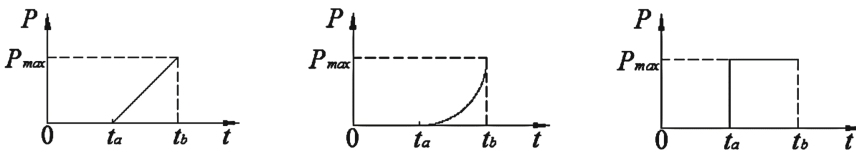


Fig. 3. Graphics of several penalty cost function.

Referring to the above several penalty cost functions, the penalty cost function in this paper is constructed as follows:

$$P(t_s) = \begin{cases} c \cdot \frac{t_s - t_a}{t_b - t_s} & t_a \leq t_s < t_b \\ 0 & 0 < t_s < t_a \end{cases} \quad (10)$$

where, c is the penalty cost coefficient, which is taken as 50,000 yuan, the soft time window $[t_a, t_b]$ is mainly determined according to the schedule of river-sea-going ships. Nowadays, ships are generally required to reach Shanghai within 72 h of departure from Wuhan. Considering the influence of downstream and upstream flow velocities and the uncertainties of navigation at sea, a certain margin of navigation time is reserved as follow:

$$(t_a, t_b) = \begin{cases} (48, 60) & \text{Wuhan port to Shanghai Yangshan Port} \\ (72, 84) & \text{Shanghai Yangshan Port to Wuhan port} \end{cases} \quad (11)$$

Combined with the fuel cost calculation model established before, the Required Freight Rate (RFR) of the liner based on the penalty cost can be established as follow:

$$RFR_P = \frac{1}{Q} [Y + P + CR \cdot (I - PW \cdot R)] \quad (12)$$

where, Q represents the number of containers carried by the ship each year, Y indicates the annual operating cost of the ship, which consists of fixed costs such as crew fees, insurance premiums, and variable costs such as fuel costs and port charges. P indicates the annual penalty cost, which can be accumulated from the penalty costs of all voyages, CR represents the capital recovery factor, I is the cost of the ship, PW denotes the present value factor, and R denotes the residual value of the ship, which is taken as 10% of the ship price.

4 Solution Method

The optimal design speed of a ship is determined by economy, environmental protection performance, and technological advancement. Therefore, the optimization of design speed should be synchronized with the optimization of ship type scheme. The comprehensive evaluation index system of river-sea-going ship type based on combination weighting method will be introduced below.

Comprehensive Evaluation and Optimization of Ship Type Scheme Based on Combination Weighting Method

After calculating the relevant parameters of river-sea-going vessel series schemes with different container capacity classes, it is necessary to evaluate the feasibility of the ship type schemes and select the feasible schemes for subsequent comprehensive evaluation and optimization. Feasibility evaluation indicators include ship type safety indicators and technical indicators (Table 1).

Table 1. Feasibility evaluation indicators of ship type scheme.

Feasibility evaluation indicators	Evaluation contents
Weight check	Gravity and buoyancy balance
Initial stability	Initial stability height GM > 0.3 m
Rolling period	Rolling period > 8 s
Freeboard	Meeting the specification requirements
Container capacity	Within the range of ship’s container capacity at different container capacity classes
Sailing time	Satisfying time window constraints

For the feasible schemes, the system engineering idea is used to construct a comprehensive evaluation index system to optimize the ship type scheme. Considering the characteristics of ship type and liner shipping of river-sea-going vessels, the comprehensive evaluation of the series of ship type schemes is carried out in terms of technological advancement, environmental protection and economy. The comprehensive evaluation index system frame is shown in Fig. 4.

Regarding the comprehensive evaluation index system proposed above, the weight of each evaluation index is determined by the combination weighting method, which combines subjective weights with objective weights. It reflects a compromise between the subjective preferences of the designers and the objective distribution of each index. The key steps are shown as follows:

Determine the Subjective Weight Vector by Analytic Hierarchy Process (AHP).

Firstly, the hierarchical structure model is established. The decision-making system is divided into the target layer, the criteria layer and the scheme layer. Then, the index weights of each layer are calculated, and the subjective weight vector of each index can be obtained, as shown in Table 2.

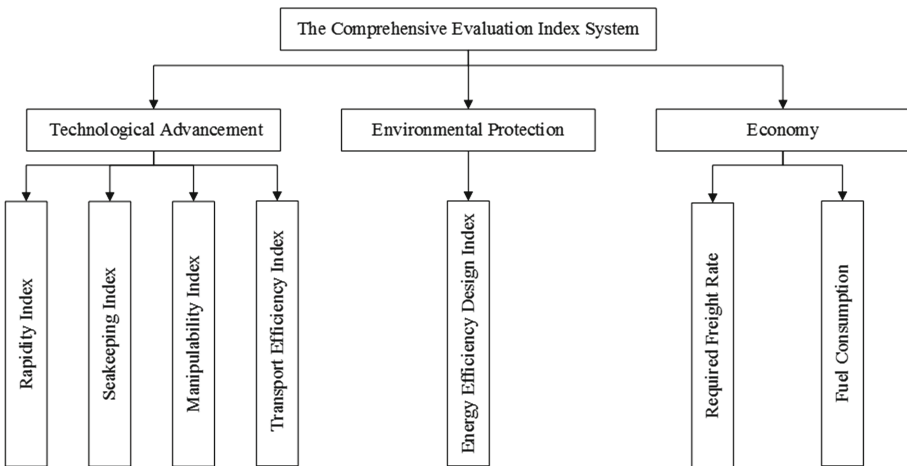


Fig. 4. The comprehensive evaluation index system for river-sea-going container ship.

Table 2. Subjective weight of comprehensive evaluation indexes.

Criteria layer	Weight	Sub-criteria layer	Weight	Subjective weight ω_1
Technological advancement	0.261	<i>C</i>	0.435	0.113
		<i>R</i>	0.063	0.016
		<i>D_{to}</i>	0.132	0.035
		<i>EFF</i>	0.37	0.096
Environmental protection	0.633	<i>EEDI</i>	1	0.633
Economy	0.106	<i>RFR_p</i>	0.833	0.088
		<i>RFD</i>	0.167	0.018

Determining the Objective Weight Vector by Variation Coefficient Method.

Calculations are as follow:

$$V_i = \frac{\sigma_i}{\bar{x}_i}$$

$$\omega_2(i) = \frac{V_i}{\sum_{i=1}^n V_i} \tag{13}$$

where, V_i , σ_i , and \bar{x}_i respectively represent the variation coefficient, the standard deviation, and the mean value of index i ; n represents the number of indexes; ω_2 represents the objective weight vector.

In this paper, the river-sea-going ship type scheme of 500TEU-capacity-class is selected as the objective weight calculation sample, and the objective weight vector ω_2 is calculated (Table 3).

Table 3. Objective weight of comprehensive evaluation indexes.

Evaluation index		Variation coefficient	Objective weight ω_2
Technological advancement	<i>C</i>	0.024	0.102
	<i>R</i>	0.043	0.185
	<i>D_{to}</i>	0.009	0.041
	<i>EFF</i>	0.021	0.088
Environmental protection	<i>EEDI</i>	0.059	0.251
Economy	<i>RFR_p</i>	0.019	0.082
	<i>RFD</i>	0.059	0.251

Determining the Combination Weight Vector by Combination Weighting Method. Combination weight vector is calculated as follow [15]:

$$\begin{aligned} \omega &= \alpha_1\omega_1 + \alpha_2\omega_2 \\ \alpha_1 + \alpha_2 &= 1 \end{aligned} \tag{14}$$

where, α_1 and α_2 represent the combination coefficients of subjective and objective weights respectively. If the decision maker is an empiricist, take $\alpha_1 > \alpha_2$; if the decision maker is a non-preferred neutral person, take $\alpha_1 = \alpha_2$; if the decision maker is a conservative, take $\alpha_1 < \alpha_2$. Since the experience of designers plays a significant role in river-sea-going ship design, it can be considered that the comprehensive evaluation index system is largely dominated by designer’s experience, take $\alpha_1 = 0.6, \alpha_2 = 0.4$.

Eventually, the combined weights of the comprehensive evaluation index system for river-sea-going container vessels can be obtained (Table 4).

Table 4. Combination weight of comprehensive evaluation indexes.

Evaluation index		Subjective weight ω_1	Objective weight ω_2	Combination weight ω_3
Technological advancement	<i>C</i>	0.113	0.102	0.109
	<i>R</i>	0.016	0.185	0.083
	<i>D₁₀</i>	0.035	0.041	0.037
	<i>EFF</i>	0.096	0.088	0.093
Environmental protection	<i>EEDI</i>	0.633	0.251	0.480
Economy	<i>RFR_P</i>	0.088	0.082	0.086
	<i>RFD</i>	0.018	0.251	0.111

After the establishment of key technical models and the comprehensive evaluation index system, it enables to optimize the series ship type schemes of river-to-sea vessels at each container capacity class and obtain the optimum ship type scheme (Fig. 5).

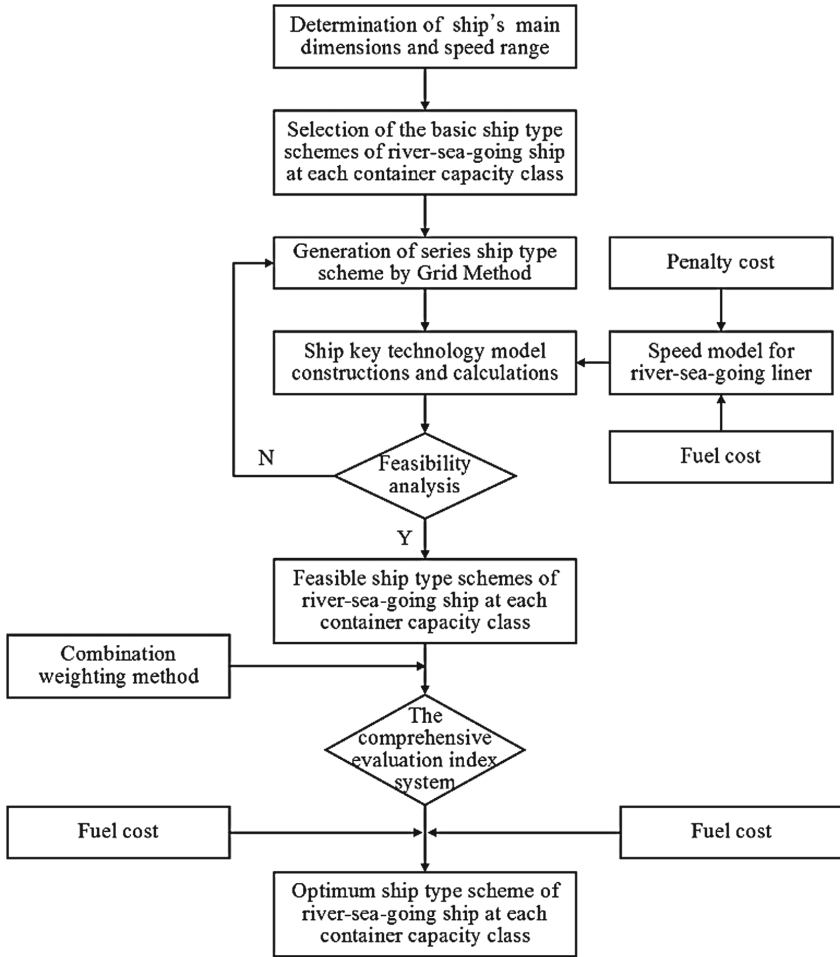


Fig. 5. Optimization process of river-sea-going ship type scheme.

5 Case Study and Analysis

For existing ships: a typical active river-sea-going ship is selected as an example, and the ship speed, cost and carbon emissions under two ECA strategies are compared and analyzed. For newly-built ships: taking a certain container capacity class of river-sea-going ship as an example, the optimization process of ship type elements and speed is systematically introduced, and the rationality of the penalty cost function based on soft time window constraints and its impact on ship form optimization results are further verified according to the optimization results.

5.1 Case-Based Strategy Analysis of ECA

A 424TEU river-sea-going ship (Table 5) on route from Wuhan port to Shanghai Yangshan port (Table 6) is chosen as an example. Aiming at minimizing the operation cost of a single-ship round-trip voyage, the optimal speed of the ship under Strategy 1 and Strategy 2 is decided. Besides, the effects of these two ECA strategies on ship speed, cost and emissions are discussed below.

Table 5. Main Elements of 424TEU river-sea-going container ship.

L_{PP}	B	D	T_d	T_s	V_0	P
122.8 m	18.8 m	8.3 m	4.5 m	6.0 m	11.88 kn	1980 kW

Table 6. Legs Division on route from Wuhan port to Shanghai Yangshan port.

Leg	Area type	Navigation distance (n mile)
Wuhan to Nanjing	Non-ECA	396
Nanjing to Shanghai Yangshan	ECA	211

Table 7. Single-ship operation optimization results under different ECA strategies.

Strategy	Ship speed (kn)		Fuel cost (Ten thousand yuan)	Carbon emission (t)
	Non-ECA	ECA		
Strategy 1: fuel conversion	9.04	7	9.63	100.59
Strategy 2: exhaust gas treatment	8.33		8.02	99.85
Strategy 3: without considering the ECA policy	8.33		10.25	100.88

The optimal speed and single-ship round-trip fuel cost under two strategies are calculated by using the linear optimization method in MATLAB. On the basis of fuel consumption, the emission level of the ship under two strategies can be obtained according to the carbon conversion coefficients of different fuels.

In order to further explore the impact of ECA implementation on single vessels, a ship operates without considering the ECA policy will be considered as the third option. In this case, it is assumed that the ship sails on the route without ECA and it consumes heavy fuel oil throughout the route, so its optimal speed is the same as that of Strategy 2. In fact, the ship consumes low-sulfur oil in the ECA, thus, the actual cost of the ship under this strategy is larger than Strategy 2. The specific optimization results are shown in Table 7.

The initial investment in the installation of exhaust gas treatment equipment on ships is related to the power of the main engine. According to statistics from relevant foreign institutions, the construction cost per kilowatt of main engine power is 118

Euros [16]. Considering the initial investment, the ship’s operating costs and carbon emissions over time are in accordance with the optimal speed in Table 7 are as shown in Fig. 6 and Fig. 7 respectively.

For the results above, it can be found that:

- (1) When adopting the fuel conversion strategy, the ship will slow down sailing in the ECA to reduce the consumption of high-priced low-sulfur oil, while it will accelerate the navigation in non-ECA to make up for the loss of time.
- (2) When adopting the exhaust gas treatment strategy, the cost of ship voyage is small, but a large initial investment is required;
- (3) If the implementation of ECA is not considered and no measures are taken, the voyage cost and emissions are the largest;
- (4) In the initial stage of ship operation, the cost of Strategy 2 is greater than that of Strategy 1 (Fig. 6 and Fig. 7). When the ship operates in 2–3 years, the cost is basically the same under this two countermeasures. Thereafter, the cost of Strategy 2 will be lower than Strategy 1. Moreover, emissions of Strategy 2 are always slightly lower than that of Strategy 1.

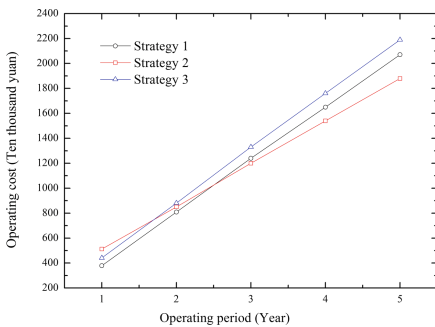


Fig. 6. Variation of single-ship operating cost with time under different ECA strategies.

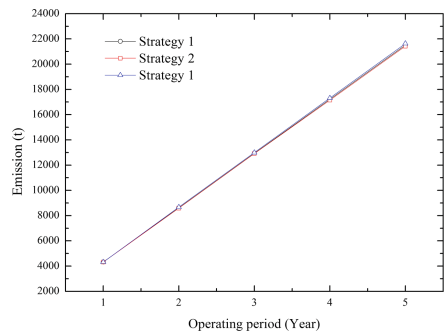


Fig. 7. Variation of single-ship carbon emission with time under different ECA strategies.

Through the case-based ECA strategy analysis above, the following recommendations can be made for the single-ship operation under the ECA policy: when the vessel is in short-term operation, fuel conversion is recommended to adopt; if the vessel has a longer service life, exhaust gas treatment should be adopted. With the passage of time, the ship can achieve better economic benefits, and be conducive to achieve energy conservation and emission reduction.

5.2 Case-Based Ship Type Scheme Optimization Analysis of River-Sea-Going Ship

A 900TEU-capacity-class river-sea-going container ship is chosen as an example, the optimization process of its ship type elements and speed is introduced. Finally, the optimal results of each container capacity class of ship type scheme are analyzed. The key steps are as follows:

Select the Base Scheme. Since currently there are no 900TEU-capacity-class river-sea-going ships on the route from Wuhan port to Shanghai Yangshan port, it is necessary to carry out its preliminary design. The ship type parameters of the basic scheme are shown in Table 8.

Table 8. Principal dimension of 942TEU river-sea-going ship.

L_{PP}	B	D	T_d	T_s	C_b	V_0	P
139 m	25.6 m	10.05 m	4.5 m	6.0 m	0.8	11.5 kn	2*1103 kW

Generate a Series of Schemes. Based on the scheme above, grid method is used to generate a series of ship type schemes (Table 9). The ship length L_{PP} varies with the gradient of standard container length plus clearance. According to the waterway restriction and related specification requirements, the upper limit is taken as 150 m. The ship breadth B varies with standard container width as step length, and the upper limit is taken as 30 m. The breadth-depth ratio B/D ranges from 2.2 to 2.6. The design draught mainly considers the seasonal variation of the minimum maintenance depth of the waterway, ranging from 4.5 m to 6.0 m. The block coefficient C_b mainly considers the hypertrophy characteristics of the river-sea-going ship type, ranging from 0.76 to 0.8. The speed range is set from 11 to 14 kn, according to the design speed of existing typical river-sea-going vessels.

Choose the Optimal Scheme. A series of schemes are obtained by free combination of the above main dimension variables. The relevant technical indicators of each scheme are calculated by MATLAB programming, and the feasible schemes are obtained by analyzing the feasibility according to Table 1. Eventually, based on the comprehensive evaluation index system, the ship type schemes are evaluated comprehensively, and the top 10 schemes are obtained as shown in Table 10.

In addition, in order to verify the rationality of the penalty cost function based on the soft time window constraints and its impact on the ship type optimization results, the preferred results of river-sea-going vessels at different container capacity classes under no constraint and the hard time window constraint ($t_s \in (0, t_a)$) are compared with that under soft time window constraint (Fig. 8, 9, 10 and 11).

Table 9. Partition of principal dimension variables based on the grid method.

L_{PP} (m)	B (m)	B/D	T_d (m)	C_b	V_0 (kn)
120.4	20.6	2.2	4.5	0.76	9
126.6	23.1	2.3	5.0	0.77	9.2
132.8	25.6	2.4	5.5	0.78	...
139	28.1	2.5	6.0	0.79	13.8
145.2	30	2.6	-	0.80	14

Table 10. Optimum selection results of 942TEU river-sea-going ship type schemes.

Ranking	L_{PP} (m)	B (m)	D (m)	T_d (m)	C_b	V_0 (kn)	P (kW)
1	145.2	25.6	10.24	4.5	0.8	11.4	2*1140
2	145.2	25.6	10.24	5.5	0.8	11.0	2*1030
3	145.2	25.6	10.24	6.0	0.8	11.0	2*1140
4	139.0	25.6	9.85	6.0	0.8	10.8	2*1030
5	145.2	25.6	10.24	6.0	0.8	10.8	2*1030
6	145.2	25.6	10.24	5.0	0.8	11.2	2*1140
7	145.2	25.6	10.24	6.0	0.8	10.6	2*1030
8	145.2	25.6	10.24	5.5	0.8	10.8	2*1030
9	139.0	25.6	9.85	5.5	0.8	11.0	2*1030
10	145.2	25.6	10.24	5.5	0.8	11.2	2*1140

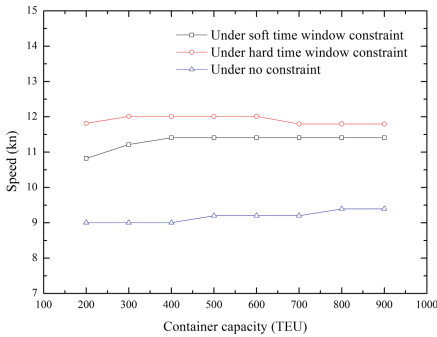


Fig. 8. Speed comparison of optimal river-sea-going ship type schemes at different container capacity classes under different time window constraints.

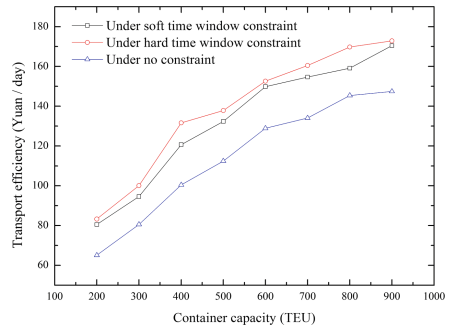


Fig. 9. Transport efficiency comparison of optimal river-sea-going ship type schemes at different container capacity classes under different time window constraints.

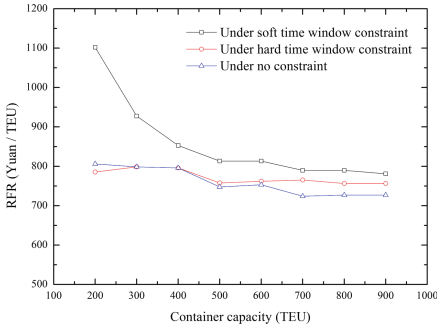


Fig. 10. RFR comparison of optimal river-sea-going ship type schemes at different container capacity classes under different time window constraints.

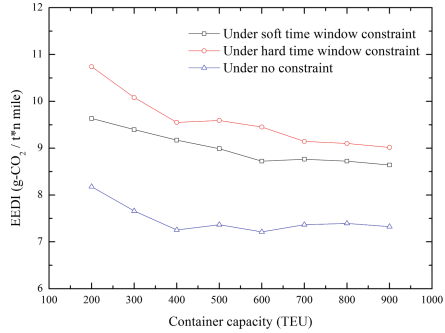


Fig. 11. EEDI comparison of optimal river-sea-going ship type schemes at different container capacity classes under different time window constraints.

It can be seen in Fig. 8, 9, 10 and 11 that:

- (1) When the soft time window constraint is adopted, the RFR of the optimal ship type scheme is slightly increased compared with the other two modes, but its transportation efficiency and energy efficiency index can reach a better level. This shows that for river-sea-going liner transportation, using soft time window constraint can well balance the three indicators of cost, emissions and transportation efficiency, and achieve more balanced results.
- (2) With the increase of the container capacity of the ship type scheme, the three major indicators have been optimized to different degrees, which also confirms the advantages of large-scale ship type.

6 Conclusion

On the basis of fully understanding the implementation of China’s ECA policy, reasonable suggestions are made for the operation of existing river-sea-going vessels by constructing the lowest single-ship round-trip voyage cost model. Penalty cost is put forward, and a speed model based on penalty cost under ECA is proposed. Additionally, as for the newly-built river-sea-going ships, the ship type schemes at different container capacity classes are evaluated and optimized, focusing on the optimization design for ships at large container capacity classes. This paper provides effective recommendations for the design, development and operation of river-sea-going ships to address the implementation of ECA policy in the Yangtze River Delta region in China. However, this paper mainly considers the optimization of ship’s main parameters in the design of river-sea-going ship, while the structure and layout of ship are ignored. In order to make the designed ship type scheme truly applicable to newly-built ship, detailed performance check and model test should be carried out for the preliminary scheme.

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