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Research on the Joint Organization of Ships in Inland Waterway - Lock Anchorage

Shengjian Su, Chunjian Zang, Shaoyi Guo, Haoran Wang, and Qian Gao

School of Shandong Jiaotong University, Weihai 264200, China

Abstract

This paper presents a bidirectional waterway-over-lock anchorage joint organization model to simulate ship traffic flow at a micro-level, deeply analyzing the impact of bidirectional lane-changing behavior on waterway capacity and integrating ship mooring arrangements at the anchorage. Through simulation experiments, the model evaluates waterway service levels and optimizes anchorage configurations to enhance utilization and lock efficiency. Multi-objective optimization is performed using the weighted sum and entropy weight methods to find the Pareto optimal solution and determine the weights for each objective. The model is verified wship is navigating downstream through the Qilizhou-Shiqiao lock section of the Yangtze River and anchoring at the Dingyizhou anchorage near Su Bei Lock. The results indicate improvements in total ship throughput, average flow rate, anchorage area utilization, and objective function value by 8.41%, 8.22%, 5.99%, and 7.87%, respectively.

Keywords

Inland Bidirectional Waterway; Lock Anchorage; Multi-objective Optimization Model.

1. Introduction

With the growth of global trade, inland waterway transportation has gained importance for its efficiency and safety as a mode of connecting inland regions with oceans. The joint management of inland waterways and lock anchorages is particularly critical for enhancing port operational efficiency. This study establishes a bidirectional waterway anchorage model to simulate ship traffic at a detailed level, considering the influence of lane-changing behaviors on waterway capacity. [1]. The model covers both straight and curved waterway segments and incorporates ship anchorage planning to optimize waterway and anchorage resource allocation comprehensively. Inland waterways, characterized by varied section types-straight and curved—present diverse traffic challenges due to space limitations, dense navigation, and numerous small to medium-sized ships, making curved sections more complex to manage. Additionally, optimizing anchorage configurations is essential to address resource shortages, reduce waste, and support the shift towards green water transportation.

The paper applies segmented modeling for different sections of the bidirectional waterway, incorporating rule constraints for varied conditions. Simulation experiments assess waterway capacity, calculate saturation levels, and classify service levels for complex port waterways, providing a foundation for decision-making in port planning and operational management. The study addresses multi-objective optimization using the weighted sum and entropy weight methods, yielding Pareto optimal solutions that enhance ship operation efficiency and resource allocation. Construction of Waterway Traffic Flow Model.

2. Basic Construction of Waterway Model

By constructing segmented waterway ship motion rules and conducting waterway capacity simulation experiments based on GM car following theory, the traffic flow of different sections

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of the waterway is obtained, and the actual ship capacity of the waterway is obtained[2]. Based on this, the service level of the waterway is measured and evaluated. Set the ship traffic flow in the waterway to two directions: upstream I and downstream O. The input end of the ship in the upstream I direction waterway is A and the output end is C, while the input end of the downstream O direction waterway is B and the output end is D, see Fig. 1.

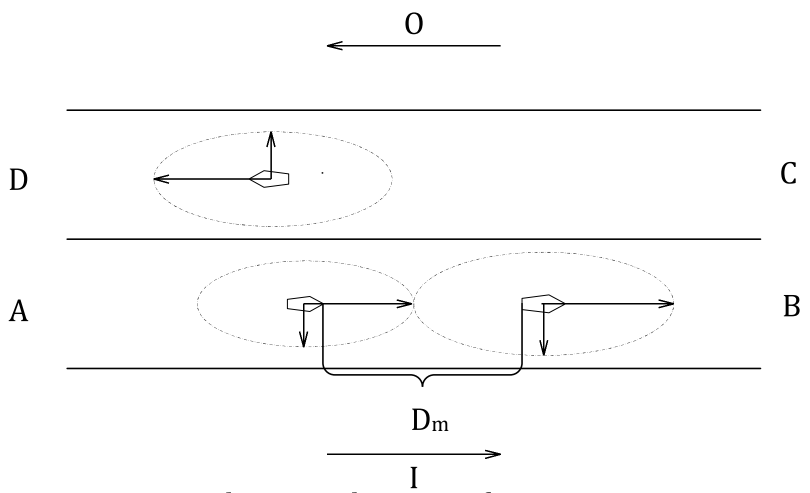

Fig. 1 Schematic diagram of waterway space

The total duration of simulation recording is T; Ts is the counting time interval for each calculation or storage of data in a time step; The total number of simulation time steps is N_t. The formula is as follows.

$$N_t = \frac{T}{t_s} \tag{1}$$

2.1. Ship Arrival

This study takes the arrival of ships following the Erlang distribution, the distance at the bow of the ship following a negative exponential distribution, and the captain and speed following a normal distribution as an example. The distance between the arrival of the preceding and following ships must not be less than the minimum safe distance, and each ship is matched with a number i according to the order of arrival[3].

The probability density function of Poisson distribution is:

$$P_a(t_s) = \frac{(\lambda t_s)^a}{a!} e^{-\lambda t_s}, t_s > 0, a = 0, 1, 2... \tag{2}$$

The probability density function of a negative exponential distribution is:

$$f(t_s) = \lambda e^{-\lambda t_s}, t_s > 0 \tag{3}$$

Where $P_a(t_s)$ is the probability of reaching a ship within the time step of t_s; The $f(t_s)$ distribution describes the time interval between the arrival of two adjacent ships, representing the probability distribution of the first ship arriving after time t_s; λ is the average arrival rate per unit time.

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2.2. Ship Safety Field

Japanese scholar Fujii Y defined the ship domain as "the area where the vast majority of subsequent ships avoid entering the vicinity of the preceding ship" and determined the boundary of the elliptical ship domain. To ensure the safe navigation of ships, a reasonable safety distance should be maintained between ships sailing in the waterway, that is, they should not invade the territory of other ships. According to the regulations on the management of inland waterway ship navigation, combined with the Fujii Y ship domain model and the three-dimensional model of inland waterway ship domain, the long axis of the ship domain is set to 3 times the length of the ship, and the short axis is set to 1 Twice the length of the ship, and there is no overlap in the ship domain between adjacent ships[4]. The formula for the minimum safe distance between the front and rear ships is:

$$D_m = 3.5L_{i(j-1)} + 2.5L_{ij} \tag{4}$$

Where D_m is the minimum safe distance between the ship and the preceding ship; $L_{i(j-1)}$is the captain of the j-1st ship currently sailing in the waterway, i.e. the captain of the previous ship; L_{ij} is the captain of the jth ship currently sailing in the waterway, also known as the captain of the rear ship. To keep the ship at a safe distance, it is necessary to make the difference in position between the front and rear ships greater than the minimum safe distance between the ships. The formula is:

$$P_{i(j-1)} - P_{ij} \geq D_m \tag{5}$$

Where $P_{i(j-1)}$ represents the position of the j-1st ship currently sailing in the waterway, which is the position of the preceding ship; P_{ij} is the position of the jth ship currently sailing in the waterway, which is the position of the rear ship.

2.3. Ship Speed Initialization

In order to make the simulation experiment more realistic, the ship in the experiment has its own initial speed, which is the speed when the ship reaches the input point A of the U-direction waterway or the input point B of the O-direction waterway. Discretize the speed v_i of each ship so that $v_i \in \{0, 1, 2, 3, \ldots, v_{im}\}$, where v_{im} is the maximum speed of ship i. During the movement, if a sufficient safe distance is maintained from the ship ahead and there are no other influencing factors, the economy speed v_{im} is maintained for navigation; When there are other ships on the front side and it is determined that they cannot be overtaken, the rear ship needs to decelerate its speed to the same as that of the front ship within the time interval t, while maintaining following navigation.

2.4. Rules for Ship Movement in Inland Waterway

The design description of the ship's motion rules is based on the example of ships in the I-direction waterway, and the same applies to ships in the O-direction waterway[5].

1.1.1 Rules for the Movement of Ships in Straight Sections

(1) Rules for Uniform Motion of Ships

When the ship is not subject to any constraints or instructions during navigation, it will sail at the economic speed.

$$V_{ij}(t) = V_{ij}(t+1) = V_{ije} \tag{6}$$

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Where $V_{ij}(t)$ is the speed of the jth i ship sailing in the waterway at time t; $V_{ij}(t+1)$ is the speed of the jth ship i sailing in the waterway at t+1; V_{ije}e is the economic speed of the jth ship i currently sailing in the waterway.

(2) Rules for Deceleration Motion of Ships

Based on the bidirectional waterway model, modularize the ship motion rules for straight sections. Ship deceleration is mainly carried out in the following two situations.

①When the ship is sailing at a speed of t in the waterway, if there is a ship ahead and it does not have the conditions to overtake the ship in the opposite waterway. It is necessary to predict and calculate the distance between the two ships before t+2 based on their current positions and speeds. The formula is as follows:

$$\left.\begin{array}{c} P_{ij}(t+1)=P_{ij}(t)+V_{ij}(t)t_s \\ P_{ij}(t+2)=P_{ij}(t+1)+V_{ij}(t)t_s \\ P_{i(j-1)}(t+2)=P_{i(j-1)}(t)+2V_{i(j-1)}(t)t_s \\ D(t+2)=P_{i(j-1)}(t+2)-P_{ij}(t+2) \end{array}\right\} \quad (7)$$

Where $P_{ij}(t)$ represents the position of the jth ship i sailing in the waterway at time t; $P_{ij}(t+1)$ is the position at t+1 where the ship continues to sail at a speed of $V_{ij}(t)$; $P_{ij}(t+2)$ is the position at t+2 where the ship continues to sail at a speed of $V_{ij}(t)$ at t+1; $P_{i(j-1)}(t+2)$ is the j-1th ship I currently sailing in the waterway, which is the position of the preceding ship at time t. $V_{ij}(t)$ continues to sail at a speed of $V_{i(j-1)}(t)$ for two time steps; D(t+2) is the distance between the ship and the preceding ship at t+2. Determine whether D(t+2) is not less than the minimum safe distance between two ships.

If $D(t+2) \geq D(t+2)$, then both ships can sail at their current speed. The formula is as follows:

$$V_j(t+1) = V_j(t) \quad (8)$$

If $D(t+2) < D_m$, the current ship needs to decelerate to the following velocity at least within the time interval of t_s, that is, at t+1, in order to ensure that the ship domains of the two ships do not overlap at t+2. The formula is as follows:

$$V_{ij}(t+1) = \frac{P_{i(j-1)}(t+1)+V_{i(j-1)}(t+1)t_s-P_{ij}(t+1)-D_m}{t_s} \quad (9)$$

②After the ship completes acceleration, if $V_{ij}(t) > V_{ie}$, it will decelerate to the economic speed at the next time step, The formula is as follows:

$$V_{ij}(t+1) = V_{ie} \quad (10)$$

(3) Rules for Acceleration Motion of Ships

At time t, there is a ship ahead of the ship, and if the ship can maintain a safe distance from the previous ship for navigation, it is a waste of its own resources. If the ship needs to reach its destination as soon as possible and maintain a minimum safe distance from the preceding ship at a speed lower than the economic speed, it may consider changing lanes to accelerate and overtake the preceding ship. However, due to the limited navigation space and the fact that the

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set waterway is only a two-way single waterway, reckless lane changing and overtaking may cause waterway blockage and increase the risk of collision between ships. Therefore, it is required that the ship complete the lane changing and overtaking process within n time steps and must meet the following conditions and corresponding organizational strategies:

①The front ship needs to maintain stable speed and heading during the overtaking process to reduce the risk of collision between the rear ship and the front ship.

②The sum of the widths of the ship's domain and the preceding ship's domain must not be less than the waterway width W, see Fig. 2.

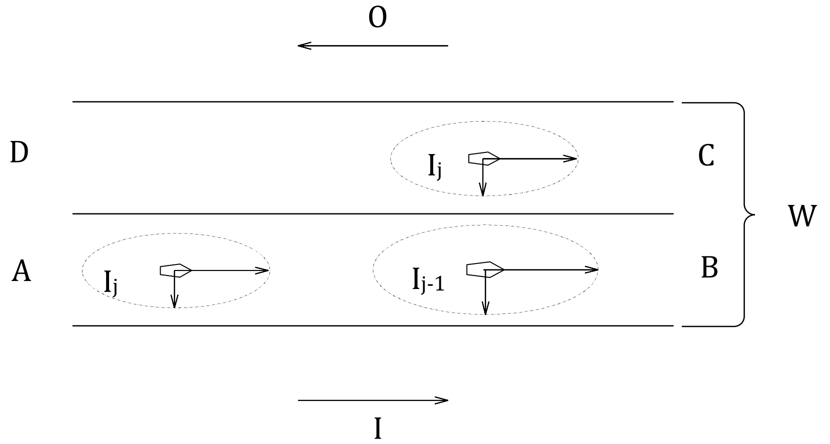

Fig. 2 Width of waterways

The formula is as follows:

$$W \geq 2.4L_{Ii(j-1)} + 2.4L_{Iij} \tag{11}$$

③At time t, the lateral distance between the ship and the leading ship in the O-direction waterway must ensure that after the ship completes the lane change and returns to the I-direction waterway, the lateral distance between the ship and the leading ship in the O-direction waterway is not less than the minimum safe distance between the two ships. The formula is as follows:

$$|P_{Iij}-(L-P_{Oij})| \geq V_{Iij}(t+1)nt_s + V_{Oij}(t)nt_s + D_m \tag{12}$$

④The lateral distance between the ship and the rear ship of the O-direction waterway at time t must not be less than the minimum safe distance between the two ships. The formula is as follows:

$$|P_{Iij}-(L-P_{Oi(j-1)})| \geq D_m \tag{13}$$

Where P_{Iij} represents the position of the ship in the I direction, and $P_{Oi(j-1)}$ represents the position of the ship behind in the O direction; L is the total length of the waterway.

⑤There is sufficient distance in front of the preceding ship, that is, the ship returns to the waterway after completing the overtaking and maintains the minimum safe distance from the original preceding ship. To meet the above conditions, the minimum speed at which the ship accelerates and overtakes should be limited, The formula is as follows:

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$$V_c = \frac{V_{Ii(j-1)}(t)nt_s + D_{m1} + D_{m2}}{nt_s} \tag{14}$$

If $V_c > V_{Iijm}$, then select V_{Iijm} as the velocity for the next time step, expressed as:

$$V_{Iij}(t+1) = V_{Iijm} \tag{15}$$

If $V_c < V_{Iijm}$, the velocity between V_c and V_{Iijm} can be selected as the velocity for the next time step, The formula is as follows:

$$V_{Iij}(t+1) \in \{V_c, V_{Iijm}\} \tag{16}$$

Where V_c is the minimum speed required for the ship to complete lane changing and overtaking in the I-direction waterway within one time step, and V_{Iijm} is the maximum speed of the ship in the I-direction waterway. $V_{Ii(j-1)}(t)$ is the speed of the ship in front of the I-direction waterway at time t; D_{m1} is the minimum safe distance between the ship that is the rear ship and the ship in front, and D_{m2} is the minimum safe distance between the ship that becomes the front ship after changing lanes and overtaking, and the ship that becomes the rear ship after being overtaken by the original front ship.

⑥After the ship has completed deceleration, if the $V_{ij}(t)$ is $<V_{ie}$ and there is enough distance from the ship in front, it will accelerate to economic speed in the next time step, The formula is as follows:

$$V_{ij}(t+1) = V_{ie} \tag{17}$$

1.1.2 Rules for the Movement of Ships in Curved Sections

In most cases, a straight waterway is connected to one or more curved sections. In curved sections, currents often form eddies or rapids due to the curvature of the waterway, and ships need to make larger steering maneuvers, which may exceed the ship's maneuvering limits, especially in the case of larger loads or longer hulls. All these may lead to frequent avoidance between ships, increase the traffic density of ships or even form a blockage, making maneuvering difficult and increasing the possibility of accidents. Therefore, in order to ensure the safety of navigation, when the ship passes through these curved segments, it can not change lanes to catch up, but reduce the speed appropriately in the actual navigation. When the ship enters the curved section, it will adjust the heading, causing the hull to tilt to form a β angle, thus increasing the rudder resistance, and the centrifugal force will consume the thrust of the propeller, which will lead to a natural slight deceleration of the ship, and the degree of deceleration will be different according to different water environments, which needs to be adjusted according to the actual situation[6].

The GPS position data of the ship is obtained from AIS and transformed into a planar Cartesian coordinate system based on a coordinate transformation under the Gauss-Kruger projection. The route can be regarded as a splicing of several straight line segments, and the mean filter algorithm is used to smooth the trajectory data, and the second-order difference method is used to calculate the angle at the splicing point, and if the angle is more than 45°, it is regarded as a sharp curve, so that the length of curved segments can be calculated[7].

Deceleration occurs when the ship enters the curved section, and the value of deceleration is obtained based on historical data analysis with the following formula:

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$$V_{ij}(t+1) = V_{ij}(t) - k \tag{18}$$

Where $V_{ij}(t+1)$ is the speed of the ship entering the curved section at t+1; $V_{ij}(t)$ is the speed of the ship before entering the curved section at t+1; k is the deceleration value of the ship.

$V_{ij}(t)$ is the speed of the ship at t+1 before entering the curved section; k is the value of ship's deceleration.

2.5. Waterway Service Level Classification

Waterway saturation refers to the ratio of the ship traffic that can safely and effectively pass through the waterway to the navigable capacity of the waterway under specific waterway conditions, which can be evaluated and calculated through the ship field model. In the simulation process, when the ship flow input increases continuously, the ship output flow no longer increases significantly, and the waterway reaches a relatively stable state, then the output flow is the maximum capacity of the waterway, and the waterway is saturated.

The evaluation of waterway saturation can help waterway managers to optimize the scheduling and commanding plan of ship navigation and effectively improve the utilization rate of waterway capacity, the formula is as follows:

$$R_t = \frac{Q_t}{C} \times 100\% \tag{19}$$

$$R = \frac{\sum_{t=1}^{N_t} R_t}{N_t} \tag{20}$$

Where R_t is the waterway saturation degree for each time step; Q_t is the actual ship flow rate in the waterway at time t; C is the maximum passing capacity of the ship in the waterway; R is the average waterway saturation degree for the whole simulation time.

Referring to international studies on the level of service of waterways, the service level of the waterway is classified according to the saturation degree, and the saturation degree of the waterway is classified into six grades from A to F, and the specific classification standards[8] ,see Table 1.

Table 1. Criteria for classifying the level of service of waterways

Saturation	Traffic flow conditions	Level of service
<0.4	Smooth, no congestion	A
0.4-0.6	Stable, no congestion	B
0.6-0.75	Stable, no significant congestion	C
0.75-0.9	Unstable, little congestion	D
0.9-1.0	Unstable, moderate congestion	E
>1.0	Unstable, severe congestion	F

3. Construction of Ship Anchoring Model for Transgressing Anchorages

Inland waterway anchorages are an important part of inland waterway navigation, they provide a place for ships to wait for berths, shelter from the wind, maintenance and other services. However, with the increase of economic development and shipping demand, inland river anchorages are facing some status quo and limitations. The shortage of inland anchorage resources, especially in busy inland waters, has become a bottleneck restricting the development of ports; due to the lack of unified planning and effective management, some

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inland anchorages have the problems of building more and using less or waiting for ships for a long time, and disorderly anchoring of ships occurs from time to time, which increases the risk of collision of ships.

Layout planning and optimal configuration of inland river anchorage is a challenge, not all of the ships arrive at the anchorage are able to directly enter the lock chamber for crossing the locks, when all the lock chambers are in operation and there is no extra space to accommodate the ships, the ships should line up and wait in the anchorage, and wait for the free lock chamber position before Receive instructions to enter the lock chambers. It is necessary to consider the actual operational point of view of the ship crossing queuing service and the limited resources of the waterway. The study of inland river crossing lock anchorage ship mooring is conducive to the optimization of anchorage configuration, which can improve the utilization rate of anchorage and reduce the waste of anchorage resources; reduce the anchorage time of the ship's anchorage position and improve the rate of ship crossing the lock. Optimizing the use of anchorage can reduce the impact on the environment, which is in line with the development trend of green water transportation[9].

3.1. Selection of Evaluation Indexes for Anchorage Operation

The utilization rate of anchorage area refers to the ratio of the sum of the safe area actually occupied by all anchored ships to the total area of the anchorage in a specific time period, which reflects the utilization of the anchorage in that time period, the higher the utilization rate of the anchorage area, the higher the efficiency of the anchorage use[10], the formula is as follows.

$$\delta_{St} = \frac{\sum_{i=1}^{M} q_i \times S_i}{S_A} \times 100\% \tag{21}$$

$$\delta_S = \frac{\sum_{t=1}^{N_t} \delta_{St}}{N_t} \tag{22}$$

where δ_{St} is the anchorage area utilization rate for each time step; q_i is the queue of all ships that are anchoring in the anchorage at time t; S_i is the area of the safe area occupied by the ship i anchoring; S_A is the anchorage area; and δ_S is the average anchorage area utilization rate over the entire total simulation time.

3.2. Rules for Allocation of Anchor Positions on Ships

In order to maximize the utilization of the lock chambers, the Bottom-Left algorithm based on breadth-first is used for ship scheduling. A schedulable point is a position calculated from the ships already in the anchorage that can be assigned to the next ship. The anchorage is simplified as a large rectangle, the coordinate system is established with the lower left corner as the origin, and the safe area occupied by the anchored ship is regarded as a small rectangle, which is 6 times the length of the ship and 2.5 times the breadth of the ship, according to the Code[11]. the formula is as follows.

$$\left.\begin{aligned} L_{iR} &= 6L_i \\ W_{iR} &= 2.5W_i \end{aligned}\right\} \tag{23}$$

where L_{iR} is the length of the safe area occupied by ship i; L_{iR} is the width of the safe area occupied by ship i.

The rules for allocation of anchorages are determined by the type of ship, the order of arrival and the rules for passing through the locks of the ship, with the following three points: ① the

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priority is according to the following order: Dangerous goods ship > official ship > passenger ship and fresh cargo ship (cargo ship carrying fresh and live cargo) > general cargo ship, etc. ② the dangerous goods ship should have a separate anchorage area; ③ ships of the same priority will be anchored first after arriving first.

3.3. Anchor Position Allocation Strategy Based on Breadth Prioritization

The application of breadth priority in the allocation of anchorages is to design the origin of the anchorage coordinate system (0, 0) as the initial schedulable point, i.e., when there is no ship anchored at this point, the subsequent ships should take this point as the preferred schedulable point[12]. For example, when ship1 and ship2 are already anchored and do not occupy the origin of the anchorage coordinate system (0, 0), and then ship3 needs to be anchored, the origin of the anchorage coordinate system (0, 0) is selected as the anchorage point of the ship, see Fig. 3.

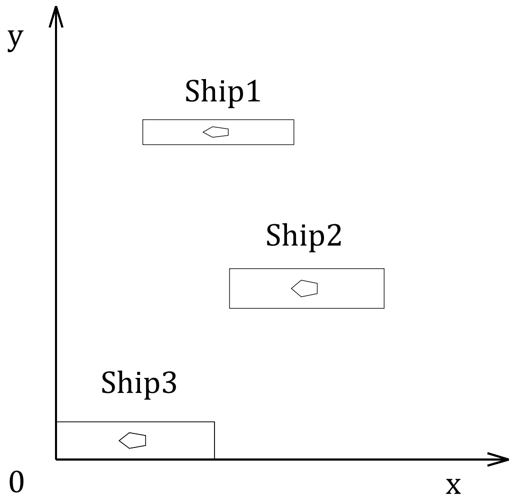

Fig. 3 Initial schedulable point

After each ship is moored, two schedulable points are generated, i.e., the upper-left schedulable point and the lower-right schedulable point of the ship's rectangle, and the newly generated schedulable points are placed into the original queue of schedulable points, the formula is as follows.

$$\left.\begin{aligned} P_{2i-1} &= (\, x_i+6L_i,\, y_i) \\ P_{2i} &= (\, x_i,\, y_i+2.5W_i) \end{aligned}\right\} \tag{24}$$

where P_{2i-1} is the lower right schedulable point position and P_{2i} is the upper left schedulable point position.

When there is already a ship anchored at the initial schedulable point, the next ship prioritizes the selection of the schedulable point along the y-axis direction of the coordinate system as the ship's anchoring position, i.e., all the schedulable points in the schedulable queue are first arranged in ascending order by the y-coordinate, and then arranged in ascending order by x when y is the same[13]. Call the first ship in the slotting queue, assign the coordinates of the head of the slotting queue to the ship, if it can pass the constraint test, put the ship at the point, and the corresponding slotting point is removed from the queue; vice versa, try to find out the next slotting point; if all the slotting points can not be put on the ship, give up the ship, take the

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next ship in the queue to try to arrange, repeat the steps until the slotting queue is empty or the anchorage has no mooring space, then the calculation stops. Stop the calculation.

4. Construction of Multi-objective Optimization Model

Multi-Objective Optimization (MOO) is an optimization problem in which multiple conflicting objectives need to be optimized simultaneously in the decision-making process. Often, these objective functions cannot reach their respective optimal solutions at the same time, because the improvement of one objective may lead to the deterioration of another objective. Therefore, the goal of solving a multi-objective optimization problem is to find a Pareto optimal solution, i.e., a solution that cannot be further optimized for one objective without compromising the other objectives[14].

4.1. Objective Function

A weighted sum method can be used to first determine the weights of each objective by assigning a weight to each objective function that reflects the importance of that objective in the total objective. The choice of weights is usually based on the decision maker's preferences or the relative importance between the objectives.

Choose to use the entropy weight method to determine the weights, the basic idea of the entropy weight method is based on the concept and nature of the information entropy, the information contained in the multiple errors of each independent prediction model is quantified, and this information is utilized to determine the weight of each independent model in the combination prediction, which in turn establishes a combination prediction model based on the entropy weight method because the information entropy is based on the original data, and the objectivity is relatively strong, so it is used to determine the weight of each sub-model of the combination prediction model by using the information entropy[15]. The weight of each sub-model in the combination prediction model is not easily affected by subjective factors. By assigning different weights to each objective, multiple objective functions are combined into one objective function to solve the single-objective problem.

When the waterway ship traffic flow is more intensive, i.e., the saturation degree is greater than 0.6, the goal should be to reduce the waterway saturation; when the waterway ship traffic flow is sparse, i.e., the saturation degree is less than 0.6, the goal should be to increase the saturation degree of the waterway by increasing the average speed of the waterway ships, the formula is as follows.

$$\left.\begin{array}{c} \min Z = w_1 R - w_2 \delta_S \\ \min Z = - w_1 R - w_2 \delta_S \end{array}\right\} \tag{25}$$

where Z is the objective function that combines the two objective functions into one; w_1 is the weight of the average waterway saturation R over the total time of the simulation; w_2 is the weight of the average anchorage area utilization δ_S over the total time of the simulation.

4.2. Constraints

The actual ship flow of the ship navigating the waterway cannot be greater than the maximum capacity of the waterway, the formula is as follows.

$$Q \leq C \tag{26}$$

Where Q is the actual ship flow in the waterway, C is the maximum passing capacity of the waterway.

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The distance between the front and rear ships cannot be less than the minimum safe distance between two ships, the formula is as follows.

$$D_m \le P_{j-1} - P_j \tag{27}$$

Where P_{j-1}-P_j is the distance between the jth ship and the previous ship j-1, and D_m is the minimum safe distance between the two ships.
The speed of a ship cannot exceed the maximum speed of that ship, and the formula is as follows.

$$v_i \le v_{im} \tag{28}$$

Where v_i is the speed of ship i and v_{im} is the maximum speed of ship i.
The sum of the area of the safe area occupied by all ships that are anchoring in the anchorage cannot exceed the anchorage area, the formula is as follows.

$$\sum_{i=1}^{M} q_i \times S_i \le S_A \tag{29}$$

The constraints that limit the ship from anchoring beyond the limits of the anchorage, prior to anchoring, are given by the following formula. the formula is as follows.

$$\left.\begin{matrix} x_i + 6L_i \le L_A \\ y_i + 2.5W_i \le W_A \end{matrix}\right\} \tag{30}$$

where x_i is the horizontal coordinate of the schedulable point where the ship i may anchor; y_i is the vertical coordinate of the schedulable point where the ship i may anchor; L_i is the length of the ship i; W_i is the length of the ship i; L_A is the length of the anchorage; and W_A is the width of the anchorage.
The constraints that restrict a ship from selecting schedulable points that cause the ship to collide with surrounding ships are such that if any of the constraints hold, then the two rectangles do not overlap. If all of these conditions do not hold, then the rectangles overlap, the formula is as follows.

$$\left.\begin{matrix} x_{1max} \le x_{2min} \\ x_{2max} \le x_{1min} \\ y_{1max} \le y_{2min} \\ y_{2max} \le y_{1min} \end{matrix}\right\} \tag{31}$$

Where x_{1max} is the x coordinate of the lower right corner of the moored ship rectangle, x_{2min} is the x of the upper left corner of the unmoored ship rectangle, indicating that the right boundary of the moored ship rectangle is less than or equal to the left boundary of the unmoored ship rectangle; x_{2max} is the x coordinate of the lower right corner of the unmoored ship rectangle, and x_{1min} is the x coordinate of the upper left corner of the moored ship rectangle, which has been anchored The left boundary of the ship's rectangle is greater than or equal to the right boundary of the unmoored ship's rectangle; y_{1max} is the y-coordinate of the lower-right point of the moored ship's rectangle, y_{2min} is the y-coordinate of the upper-left point of the unmoored ship's rectangle, and the lower boundary of the moored ship's rectangle is less than or equal to

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the upper boundary of the unmoored ship's rectangle; y_{2max} is the y-coordinate of the lower-right point of the unmoored ship's rectangle, and y_{1min} is the y-coordinate of the upper-left point of the moored ship's rectangle. y-coordinate of the upper left corner point of the moored ship rectangle, and the upper boundary of the moored ship rectangle is greater than or equal to the lower boundary of the unmoored ship rectangle.
The sum of all weights should be 1, the formula is as follows.

$$\sum_{j=1}^{n} w_j = 1, 0 \le w_j \le 1; 1 \le j \le n$$

5. Model Simulation Verification and Analysis

5.1. Model Assumption

The established model is in a relatively ideal state, without considering the influence of natural factors such as wind, waves, and currents; Not considering the impact of human factors such as crew reaction time and driving operations; Not considering the impact of ships crossing the waterway and ships encountered at intersections with the waterway on the normal navigation of the waterway; The model adopts an open boundary approach, where the ship enters the waterway model upon arrival and travels to the output point of the waterway to end the simulation; The model only considers ships arriving during the simulation time, ships already in the waterway or at anchor before the simulation time are not considered.

5.2. Simulation Results and Analysis of Model

During the period from November 1, 2023, 00:00:00 to November 7, 2023, the ships that are on the route between Qilizhou and Shiqiao locks of the Yangtze River, with the direction of downstream, and anchored in the mooring area of the North Jiangsu Lock in Dingyizhou anchorage, are selected for the validation. The maximum speed of the ship is not more than 11 knots, the total length of the selected waterway is 30 n miles, spatial and temporal maps of actual and simulated ship navigation, see Fig. 4.

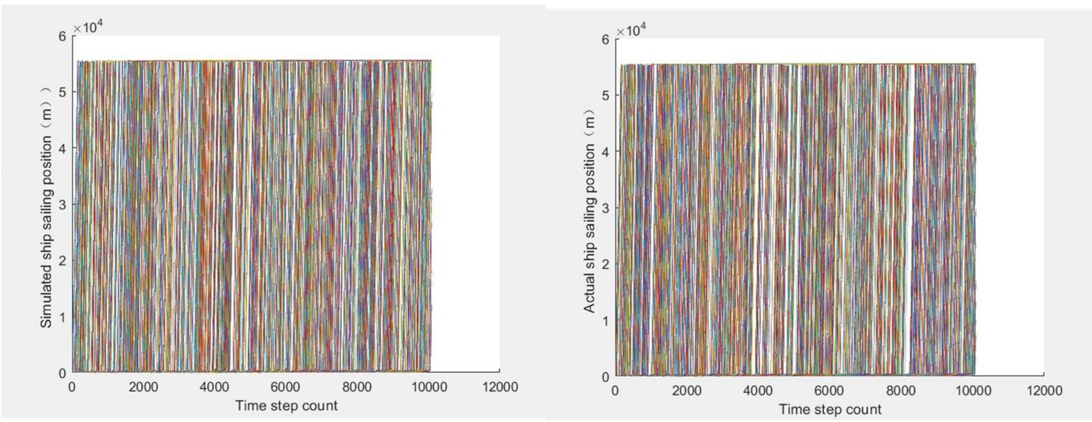

Fig.4 Spatial and temporal maps of actual and simulated ship navigation

Recorded and compared actual and simulated waterway saturation for the entire simulation time, see Fig. 5.

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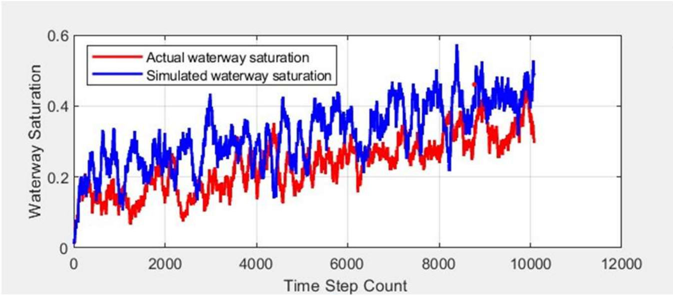

Fig. 5 Comparison of actual and simulated waterway saturation

The second-order difference method is used to calculate the length of six curved segments by taking the degree of pinch formed by the straight line of the route, and if the angle is more than 30°, it is regarded as curved, see Table 2.

Table 2. Length of curved segments of waterways

curved Segment Number	Segment length (n mile)
1	0.68
2	0.95
3	0.88
4	1.73
5	1.09
6	0.57

In accordance with the regulations of the six Wei River mouth Shiqiao locks to be lock ships, should try to choose in the north of the Su to be lock mooring area. The mooring area is about 1160m long and 370m wide, and it is stipulated that 6 rows of ships (2000 tons) can be tied up and moored, with 130m between each row as a passage.

The arrival sequence table of ship arrivals during the simulation time is substituted into the simulation to count the data related to ship waterway navigation and anchorage. The weights assigned to the two objectives by the entropy weighting method are 0.47 and 0.53, respectively. The total number of ships actually passed during the seven-day simulation time is 796, the average ship flow rate is 4.74 ships per hour, the average utilization rate of the anchorage area is 21.37%, and the value of the objective function is -2.34, while the total number of ships passed by the simulation is 863, the average ship flow rate is 5.13 ships per hour, the average utilization rate of the anchorage area is 24.81%, and the value of the objective function is -2.54, see Table 3.

Table 3. Comparison of actual situation and simulation results

Parameters	Actual situation	Simulation results	Percentage
1	796	863	8.41%
R	4.74	5.13	8.22%
δ_S	34.53%	37.82%	5.99%
Z	2.34	2.54	7.87%

From the comparison between the actual situation and the simulation results, it can be seen that the parameters such as the total number of passing ships, the average ship flow rate, the average anchorage area utilization rate and the objective function value are optimized compared with the actual statistical data during the seven-day simulation time, in which the

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total number of passing ships, the average ship flow rate, the average anchorage area utilization rate and the objective function value are improved by 8.41%, 8.22%, 5.99%, and 7.87%, respectively.

6. Conclusion

This paper establishes a bidirectional waterway-over-lock anchorage joint organization model to analyze the impact of bidirectional lane-changing behavior on waterway capacity by simulating ship traffic flow at a micro level and integrating ship mooring arrangements at the anchorage. Simulation experiments were conducted to evaluate waterway service levels and optimize anchorage configurations, thereby enhancing anchorage utilization and lock efficiency. Multi-objective optimization was performed using the weighted sum and entropy weight methods, resulting in a Pareto optimal solution and the determination of objective weights. The model was validated through simulations of ship navigation in the downstream direction along the Qilizhou-Shiqiao lock section of the Yangtze River and anchoring at the Dingyizhou anchorage near Su Bei Lock. The results indicated improvements in total ship throughput, average flow rate, anchorage area utilization, and the objective function value by 8.41%, 8.22%, 5.99%, and 7.87%, respectively.

The study confirms the model's validity and demonstrates its potential to improve the operational efficiency of waterways and anchorages. The findings provide valuable decision support for port planning and management, facilitating optimized resource allocation and enhanced ship operation efficiency, aligning with the trend towards green water transportation. Future research could further refine the model by incorporating additional practical factors, such as weather conditions, water currents, and ship maneuvering characteristics.

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