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Collaborative Scheduling for Yangtze Riverport Channels and Berths Using Multi-Objective Optimization

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Abstract: Efficient coordinated scheduling has long been a focal point in port research, complicated by the diverse optimization goals dictated by different port characteristics. This study focuses on Yangtze River ports, exploring coordinated scheduling amidst river–sea intermodal transportation. Our research aims to reduce berth deviation costs and shorten the total scheduling time for ships, while maximizing berth utilization rates for ports. Initially, we analyzed the operational realities of Yangtze River ports and waterways. Subsequently, we innovatively introduced three key factors influencing scheduling: berth preferences, seagoing ship inspections, and planning cycles. Finally we proposed the optimized Non-dominated Sorting Genetic Algorithm III (NSGA-III). Evaluating the model using a seven-day dataset of vessel activities at Yangtze River ports revealed significant improvements: the optimized NSGA-III enhanced objective values by 30.81%, 13.73%, and 12.11% compared to the original scheduling approach, surpassing both conventional NSGA-III and NSGA-II algorithms. This study underscores the model's efficacy in not only reducing operational costs through optimized ship and berth sequencing but also in enhancing clearance efficiency for relevant authorities.

Keywords: waterway scheduling; berth allocation; preferred berth; berth utilization; optimized NSGA-III

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1. Introduction

In recent years, the volume of river–sea intermodal transportation in the Yangtze River Basin has steadily increased, which poses great challenges to the effective utilization of port and waterway resources along the Yangtze River. How to make reasonable use of waterways, optimize the scheduling of waterways and berths, reduce ship waiting time, improve berth utilization, and reduce berth deviation costs have become hot topics in the operation management research of many ports [1].

Many scholars have conducted in-depth investigations into them. Tavakkoli Moghaddam [1] adopted a mixed-integer programming model considering factors such as ship draft, tide, and arrival during non-planned time periods to solve the problem of scheduling waterways, berths, and cranes. Tavakkoli Moghaddam [2] used a mixed-integer programming model that considers ship draft, tide, and non-planned arrival times to address scheduling issues for waterways, berths, and cranes. Jiang [3] developed a mathematical model for vessel scheduling and berth allocation under restricted channel conditions, considering carbon emissions and aiming to reduce vessel waiting times. Using the adaptive double-population multi-objective genetic algorithm NSGA-II-DP, results showed better overall convergence compared to NSGA-II. Qin [4] created an integer programming model with the objectives of total weighted turnaround time, total weighted departure delay, and completion time, considering both static and dynamic ship arrivals. Zhang [5] improved the non-denominated sorting genetic algorithm II (NGSA-II) by combining the heuristic initialization population, two-point crossover, and single-parent crossover optimization strategies, resulting in a reduction of 68.5% and 29.2% in the total waiting time and total scheduling time, respectively, compared to the original NSGA-II. Liu [6] developed a mixed-integer linear programming model for one-way waterway ports and used an adaptive large neighborhood search algorithm with a rolling plan for dual waterway ports to address the issue of large ships occupying the entire waterway. A two-stage stochastic programming model was also constructed and solved using Benders decomposition and heuristic algorithms, considering various uncertainties. Dai [7] developed a Markov decision process model for berth allocation and quay crane scheduling, considering quay loading capacity, cargo types, and switch setup times. A greedy insertion offline algorithm was used to significantly reduce waiting times, enhancing port efficiency and flexibility. Zheng [8] considered factors such as tides, entry and exit time periods, and preferred berths to establish a 0–1 integer linear programming model using the sum of the berth deviation cost and ship demurrage cost as optimization objectives to determine the entry and exit times and berthing positions of each ship. Xiang [9] investigated the berth allocation problem arising from uncertain operation times due to fluctuations in the total number of containers. It aimed to minimize the total deviation cost between the planned and expected berthing times of vessels. A comprehensive expanded robust optimization framework was developed, and a column-and-constraint generation algorithm was employed for solving it. Compared to first-come-first-served and rolling horizon planning methods, this framework significantly improves the expected costs within an acceptable computational time.

Although existing studies have considered the coordinated scheduling of waterways and berths from different perspectives,there are still some issues: Many scholars have overlooked berth preferences. Berth and warehouse locations are fixed, ports must minimize the operational time and workload while ships must quickly complete loading and unloading at preferred berths to shorten shipping schedules. Thus, ignoring berth preference imposes a burden on both parties [10]. Although the Yangtze River Economic Belt has achieved integrated transportation between the river and sea, coordination between multiple departments, such as inspection and quarantine, maritime affairs, border inspection, and port and shipping, remains difficult, and the comprehensive formation of a convenient customs clearance service environment has not yet been achieved [11]. In practice, seagoing ships selected for inspection upon arrival at port undergo inspections before and after loading and unloading operations. This contrasts sharply with domestic trade ships exempt from such procedures. Consequently, scheduling cannot be uniform for all ships. Ignoring seagoing ship inspection arrangements impacts ship waiting and departure times, potentially affecting multimodal transportation’s economy and convenience. Current ship scheduling research primarily focuses on micro-level analyses within specific daily time periods. While some researchers use random simulations of ships arriving early or late, there are still gaps in longer-term planning research [12], limiting the continuity of the scheduling plan. Most scholars use operations research solvers, traditional optimization algorithms (e.g., simulated annealing or mountain climbing), or mathematical optimization algorithms for ship scheduling. However, these models face many constraints, making it difficult to obtain effective solutions with solvers like CPLEX and Gurobi. Traditional algorithms often exhibit a low efficiency for complex multi-objective problems [13]. Mathematical optimization struggles with single-objective weights, finding optimal solutions under one weight at a time, leading to challenges in non-convex situations, inconsistent objective dimensions, and poor robustness.

In order to address the above issues, this paper proposes a mathematical model for coordinated scheduling. First, the scheduling situation of Yangtze River ports was analyzed to identify the conditions that limit ship scheduling. Subsequently, an optimization objective function was constructed with the goals of minimizing berth deviation costs and total scheduling time while maximizing berth utilization. The scheduling model fully accounted for the impacts of berth preference costs and customs inspection factors. Finally, by integrating the initial population and dynamically adjusting crossover and mutation probabilities, the conventional NSGA-III algorithm was optimized. Then, an experimental validation was conducted with a planning period of 7 days and the results showed that, compared to the port's original scheduling scheme, the optimized NSGA-III algorithm improved the three objective values by 30.81%, 13.73%, and 12.11%, respectively. Additionally, berth deviation costs were reduced by CNY 95 and CNY 362 compared to the NSGA-III and NSGA-II algorithms. The total scheduling time was also reduced by 274.3 min and 1991.22 min, respectively. Berth utilization rates were slightly improved compared to both algorithms.

The remainder of this paper is organized as follows: Section 2 discusses our port background and problem statement. Section 3 introduces the optimized scheduling model. Section 4 discusses the optimized NSGA-III algorithm. Section 5 presents the experimental setup and results. Section 6 provides the discussion and conclusion.

2. Problem Statement

The target port in this paper is a large coastal port in the Yangtze River Basin primarily engaged in the transportation of general cargo such as wood pulp, steel, machinery, and equipment.

2.1. Yangtze River Port

Figure 1 shows the target port, which comprises two basins. Both basins connect to the navigation channel, and the two basins are 200 m apart. Each basin contains eight berths, with the distance between each berth and the basin entrance varying. The berths can be divided into three types: (1) berths for barges, (2) berths for seagoing ships, and (3) berths for all types of ships.

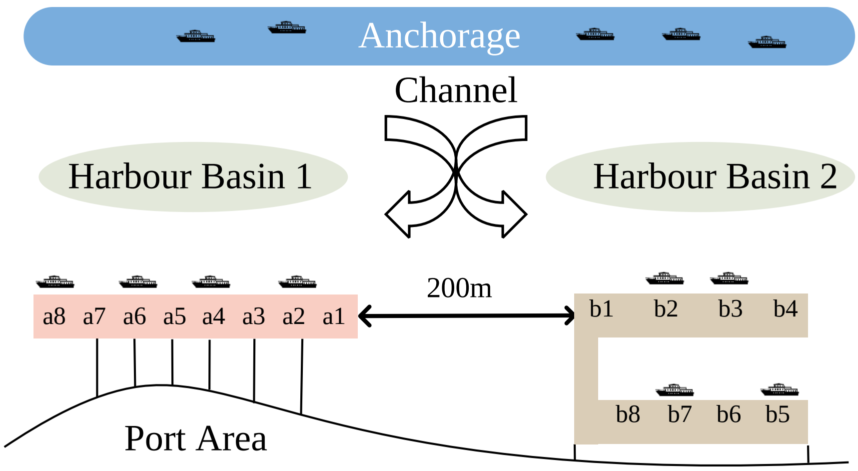

Figure 1. A port example in Yangtze River Basin.

Large coastal ports often adopt a "first come, first served" scheduling principle to serve ships. Ship entry operations require cooperation among the port, shipping agencies, and inspection departments (including customs, maritime, and inspection and quarantine). Operationally, arriving barges can be directly arranged and dispatched by the port without any declaration, whereas seagoing ships generally need to be declared by a shipping agent seven days before entering the port. Figure 2 shows the specific processes involved in entering the target port for seagoing ships. Customs receives and reviews orders two to three days before a ship enters the port, and provides cargo notification upon arrival. The port will arrange for the ship to berth, and the inspection department will perform risk assessment based on the type of cargo, current policies, ship credit, historical control frequency, and other necessary factors. The inspection department decides whether to perform further inspection on this ship according to the assessed results. If the risk parameter exceeds a given threshold, this ship is required to lift its goods to the inspection area to check whether they match the manifest. If the nature of goods cannot be determined, inspection personnel also take samples and send them to a specialized organization for testing. This process requires both time and cost, and the selected ships can only operate after they have passed the inspection. Furthermore, when all paperwork is completed, the ship must also be inspected and approved before it can be released to leave the port.

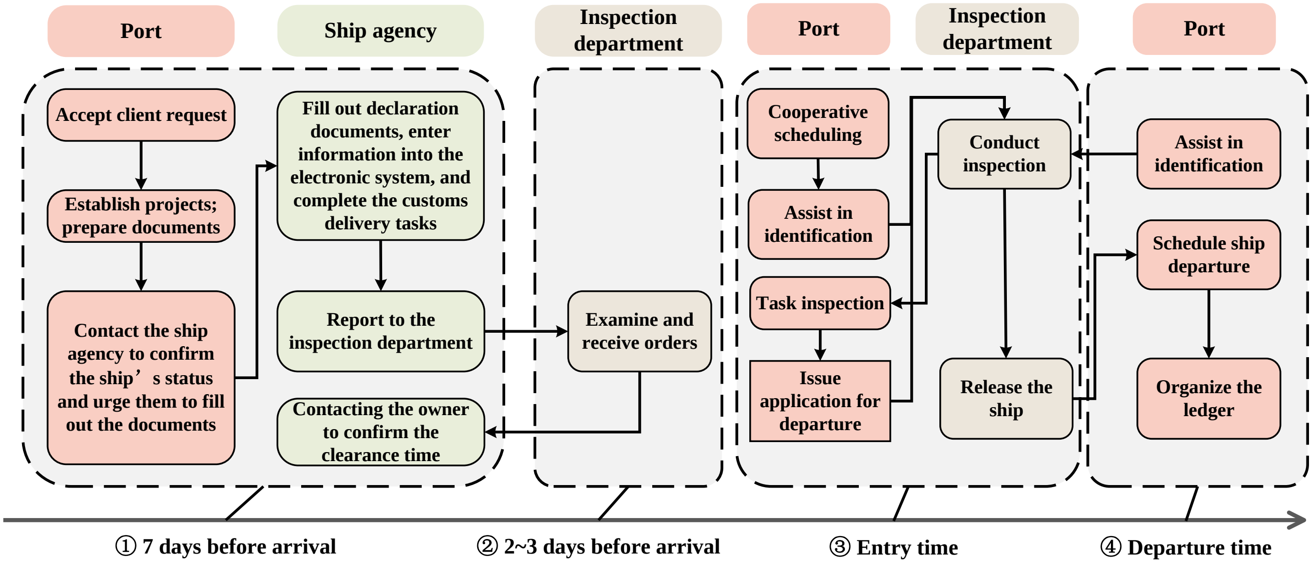

Figure 2. Operational procedures for seagoing ships subject to inspection.

Clearly, ship scheduling represents a system engineering problem involving multiple parties. The port necessarily employs a more intelligent and compact ship scheduling strategy, which can not only reduce labor costs and shore bridge resource (e.g., cranes and trucks) wastage, but also improve port throughput. Furthermore, the inspection department also requires a scheduling strategy that can help to allocate inspection tasks, rationalize work intensity, improve work efficiency, and reflect more humane work characteristics. Finally, shipping companies expect to receive timely port services, complete the loading and unloading of their goods efficiently, minimize waiting time costs, and accelerate ship turnover [14]. These various expectations necessitate that any scheduling problem be based on the actual conditions of the port. It must propose a coordinated scheduling strategy for waterways and berths that considers the interests of all three parties and their multiple objectives. The strategy should aim to complete ship inspections within the specified time frame, reduce berth deviation costs, shorten the total scheduling time for all ships, and improve berth utilization.

2.2. Considered Factors

Three factors are ignored when employing the "first come, first served" scheduling principle:

(1) Berth preference: Randomly allocating berths can increase ship operation time, resulting in disrupted berthing plans for other ships, an increased risk of waterway congestion, and reduced port operational efficiency.

(2) Seagoing ship inspections: Although the inspection itself does not charge fees, the freight forwarder must move their goods to the inspection area, split them apart, and repack them as required. The shipping company must bear the costs associated with the dock and labor resources as well as the labor utilized during this process, and, if the inspection takes too long, the shipping schedule will be delayed. For the customs, maritime, and border inspection departments, a low inspection rate may pose significant regulatory risks, whereas a high inspection rate may seriously affect customs clearance efficiency.

(3) Planning period: The port conducts preliminary scheduling based on the expected arrival time of each ship at the anchorage. Owing to various factors such as weather, manpower, and resources, ships often arrive early or late at the port, resulting in significant discrepancies between the actual and forecast arrival times [15]. The berth utilization rate is an excellent indicator of the level of port services within a certain period, and is often calculated based on a longer planning period. However, if scheduling is based on a shorter period of time, directly adjusting the original plan to accommodate the change in the arrival time of a ship may cause a chain reaction in multiple subsequent planning periods, requiring arriving ships to be rescheduled and causing considerable inconvenience to port work. Simultaneously, short-term scheduling is not conducive to evaluating berth utilization.

Therefore, this paper developed a ship scheduling optimization model using a seven-day planning period to help the port perform global control, macro-scheduling, and long-term planning. The restrictive conditions for ship scheduling, including berth preference and ship inspection factors, were determined based on the scheduling situation at the port. Next, the waterway and berth collaborative scheduling process was reconstructed and an objective function established to minimize the berth deviation cost and total scheduling time while maximizing berth utilization. Finally, the resulting optimized NSGA-III algorithm was used to solve the mathematical model and obtain an optimal solution set describing the optimal collaborative port waterway and berth scheduling scheme.

3. Optimization Model

This paper conducted an analysis of the actual ship scheduling situation in Yangtze River ports to inform relevant model assumptions, provide inductive definitions of the influencing variables in actual scenarios, and propose an objective function for the required solution.

3.1. Model Assumptions

This paper focused on the core issues of ship entry and exit sequences and berth allocation while providing a certain degree of simplification for other factors. The related modeling assumptions are as follows:

(1) The ship arrival time at the anchorage and time required for operation are known.
(2) Each ship enters and leaves the harbor only once through the waterway and berths only once.
(3) The water depth of the waterway meets the navigational needs of the ship, and the ship requires 18 min to pass through the waterway.
(4) The ship travels at a constant speed of 4.98 knots in the harbor pool.
(5) The inspection department operates from 09:00 to 16:00.

3.2. Model Variable

The variables related to ship scheduling can be categorized into input, intermediate, output, and decision variables, which are defined in Tables 1–4.

Table 1 presents the input variables, including ship number, berth number, sight range, visibility, wind, and others. These variables are primarily used to establish the context in which the scheduling model is applied.

Table 2 shows G_{ijk}, which is used to calculate the berth deviation distance.

Table 3 presents the output variables, including the arrival time of ships at the berth, the start and finish times of inspections for seagoing vessels, and the start and finish times of operations. These variables are used to determine the final scheduling plan.

Table 1. The list of input variables.

Symbol	Definition
I	The set of ships; i denotes the ship number, $i^{'}$ denotes any ship number except i, $i^{'} \neq i$, and $i, i^{'} \in I = \{1, 2, ..., n\}$
J	The set of berths; j denotes the berth number, $j^{'}$ denotes any berth number except j, $j \neq j^{'}$, and $j^{'} \in J = \{a_1, a_2, ..., a_8; b_1, b_2, ..., b_8; \}$, where a_j and b_j are the berths in harbor pools I and II, respectively
M	A sufficiently large positive number
Ts_i	Safe time interval for two ships to navigate the channel
VR_1	If range of view is less than VR_1, change to one-way navigation mode
W_0	If the wind is greater than W_0, change to one-way navigation mode
V	Current waterway visibility
W	Current waterway winds
BL_j	Length of berth j, unit: meters
SL_i	Length of ship i, unit: meters
Vh_i	Ship i speed in the harbor pool, unit: meters per minute
Ta_i	Ship i arrival time at anchorage
Te_i	Time required for the identification of seagoing ships
P_{ik}	Preferred berth k for ship i
CP_i	Vessel deviation cost factor, CNY 100 for every 300 meters deviation
SG_j	Distance of berth j from the entrance to the harbor basin in which it is located

Table 2. The intermediate variable.

Symbol	Definition
G_{ijk}	The distance between berth j, where ship i is actually scheduled to dock, and the preferred berth P_{ik}: if they are in the same pool, $G_{ijk} = \lvert SG_j - SG_k \rvert$; if they are in different pools, $G_{ijk} = SG_j + 200 + SG_k$ (if the preferred berths are in both pool I or pool II, then the actual berths are compared with the preferred berths in the same pool)

Table 3. The list of output variables.

Symbol	Definition
TP_{i1}	Time of ship to apply for entry into port
Tb_i	Actual dispatch time of ship
B_{ij}	Berthing position of ship i
Tsh_{ij}	Time spent by ship i traveling from the entrance of the harbor pool to the assigned berth
Trb_{ij}	Time that ship i actually berths at moment j
Tms_{i1}	Time of commencement of inspections prior to the operation of a seagoing ship i subject to inspection
Tme_{i1}	Completion time for pre-operational inspections of seagoing ship i subject to inspection
Tws_i	Time of commencement of operation of ship i
Tms_{i2}	Time of commencement of inspection after the operation of a seagoing ship i subject to inspection
Tme_{i2}	Completion time of inspections after the operation of a seagoing ship i requiring inspection
TP_{i2}	The time when ship i applies to leave the port when the operation is completed
Tle_i	Actual time of departure of ship i from port

Table 4 presents the decision variables, which encompass the direction of ships entering and leaving the harbor, navigation patterns, berth types, and other factors. The values of these variables are adjusted to accommodate various practical scenarios.

Table 4. The list of decision variables.

Symbol	Definition
$IO_i = 1$	Indicates the time at which the ship's direction is inbound, otherwise 0
$Mode = 1$	Indicates two-way traffic, otherwise 0
$X_i = 1$	Indicates that ship i has available berths, otherwise 0
$T_i = 1$	Indicates that ship i type is barge, otherwise 0
$S_i = 1$	Indicates that ship i should enter the harbor at the moment, otherwise 0
$H_i = 1$	Indicates that seagoing ship i is drawn for deployment, otherwise 0
$K_j = 1$	Indicates that berth j is a barge berth, otherwise 2 indicates that it is a seagoing ship berth and 3 indicates that the berth can accommodate both ship types
$BO_j = 1$	Indicates that berth j is occupied, otherwise 0
$Y_{ij} = 1$	Indicates that ship i is in service at berth j, otherwise 0
$P_i = 1$	Indicates that ship i has a preferred berth

3.3. Objective Function

The objective function of this paper considers the berth deviation cost, total dispatch time, and berth utilization rate:

$$F_1 = \sum_i \sum_j \sum_k Cp_i \times Y_{ij} \times G_{ijk}, \tag{1}$$

$$F_2 = \sum_{i=1}^{n} (Tle_i - Ta_i), \tag{2}$$

$$F_3 = \frac{\sum_i^n \sum_j^{16} Y_{ij}(Tle_i - Trb_{ij})}{161,280} \times 100\%, \tag{3}$$

where Equation (1) refers to the cost of berth deviation in CNY, Equation (2) refers to the total scheduling time in minutes, and Equation (3) refers to the utilization rate of the sixteen berths over seven days, in which the numerator is the sum of the occupied time and the denominator is the total operating time during the considered period.

3.4. Model Constraints

According to the port scheduling requirements, the model constraints include ship sequencing, berth allocation, time flow, bidirectional navigation, and seagoing ship inspection constraints.

(1) Ship sequencing constraints: Each ship entering or leaving the port passes through the waterway only once, as indicated by

$$A_{ii'} = 1, \forall i, i' \in I, \tag{4}$$

To prevent ships from pursuing each other in the waterway, the speed of two consecutive ships sailing in the same direction is limited by

$$V_i - V_{i'} > 0, \forall i, i' \in I, \tag{5}$$

The rear ship i should maintain a certain safety time interval from the front ship, given by the constraint:

$$T_{bi'} = max(TP_{i'1}, Tb_i + Ts_{i'}), A_{ii'=1}, \forall i, i' \in I, \tag{6}$$

When two ships are moving consecutively out of the harbor, the rear ship should maintain the following safety time interval from the front ship:

$$T_{bi'} = max(TP_{i'2}, Tb_i + \frac{S_{Gj}}{Vh_i} + Ts_{i'} - \frac{S_{Gj'}}{Vh_{i'}}), A_{ii'} = 1, \forall i, i' \in I, \quad (7)$$

When the front ship i is inbound and the rear ship i' is outbound and does not satisfy the two-way navigation requirements:

$$T_{bi'} = max(TP_{i'2}, Tle_i - \frac{S_{Gj}}{Vh_i} + Ts_{i'} - \frac{S_{Gj'}}{Vh_{i'}}), A_{ii'} = 1, Mode = 0, \forall i, i' \in I, \quad (8)$$

Finally, when the front ship i is outbound and the rear ship i' is inbound and does not satisfy the two-way navigation requirements:

$$T_{bi'} = max(TP_{i'1}, Tle_i + Ts_{i'}), A_{ii'} = 1, Mode = 0, \forall i, i' \in I, \quad (9)$$

(2) Berth allocation constraints: All dispatched ships must have available berths as follows:

$$\sum_{i=1}^{n} X_i = n, \quad (10)$$

The berth type must be matched with the ship type as follows:

$$M(K_j - T_i) = 0, \forall i \in I, j \in J, \quad (11)$$

The length of the ship is limited by the length of the berth according to the following:

$$MIo_i(BL_j - SL_i) > 0, \forall i \in I, j \in J, \quad (12)$$

Incoming ships must ensure that the pre-allocated berths are free before they enter the port according to

$$Io_i - MBo_j > 0, \forall i \in I, j \in J, \quad (13)$$

Each berth can only be allocated to one incoming ship as follows:

$$Y_{ij} \leq 1, \forall i \in I, j \in J, \quad (14)$$

An outgoing ship operating at the same berth immediately before an incoming ship is to be dispatched is constrained as follows:

$$A_{ii,} - MIo_i > 0, \forall i \in I, \quad (15)$$

Finally, priority should be given to arranging for ship i to berth at its preferred berth as follows:

$$P_i = 1 \overset{Bo_k=0}{\Rightarrow} Y_{ik} = 1, \forall i \in I, k \in J, \quad (16)$$

(3) Time flow constraints: The berthing time of all scheduled ships must be later than their actual arrival time at the anchorage as follows:

$$Tb_i - Ta_i \geq 0, \forall i \in I, \quad (17)$$

The departure time of all scheduled ships must be later than the completion time of their corresponding operation as follows:

$$Tle_i - Twe_i > 0, \forall i \in I, \quad (18)$$

Finally, the beginning of operation for ships that are not required to undergo customs inspections (all barges and other marine ships) is defined as later than the berthing time as follows:

$$Tws_i - Trb_{ij} > 0, \forall i \in I, j \in J, \quad (19)$$

(4) Bidirectional navigation constraints: The following conditions must be maintained if navigation occurs in both directions:

$$V \geq VR_1 \cap W \leq W_0, Mode = 1 \quad (20)$$

(5) Seagoing ship inspection constraints: The first inspection of a seagoing ship must begin after the berthing time as follows:

$$Tms_{i1} - Trb_{ij} > 0, \forall i \in I, j \in J, \quad (21)$$

Operations must begin after the first inspection completion time as follows:

$$Tws_i - Tme_{i1} > 0, \forall i \in I, \quad (22)$$

The second inspection of a seagoing ship must begin after the completion of the operation as follows:

$$Tms_{i2} - Twe_i > 0, \forall i \in I, \quad (23)$$

The application for departure from the port must occur after the completion of the second inspection as follows:

$$TP_{i2} - Tme_{i2} > 0, \forall i \in I, \quad (24)$$

Finally, the time required for the seagoing ship to enter port and undergo inspection is given by

$$8:40 < Ta_i < 14:00 \Rightarrow S_i = 1, \quad (25)$$

$$14:00 \leq Ta_i < 16:00 \wedge Te_i < 2 \Rightarrow S_i = 1, \quad (26)$$

$$Ta_i \geq 16:00 \Rightarrow S_i = 0 \quad (27)$$

where ships that cannot be scheduled to enter the port on the same day ($S_i = 0$) are required to re-apply for port entry by 08:42 the next day (based on the 18 min required for ships to pass through the waterway and the 09:00 opening time of the inspection department).

4. Optimized NGSA-III Algorithm

Multi-objective genetic algorithms typically exhibit a superior ability to handle high-dimensional multi-objective problems compared to traditional mathematical optimization algorithms [16]. Srinivas [17] first proposed NSGA-I for multi-objective optimization; Deb [18] subsequently used the crowding distance to improve this algorithm, establishing NSGA-II; finally, Deb [19] used the reference point instead of crowding degree selection to propose NSGA-III. Although the flow of NSGA-III is generally similar to that of NSGA-II; the former overcomes the problems of the latter in solving high-dimensional multi-objective optimization problems, including those associated with the difficulty of visualizing the multi-dimensional frontiers, the uneven distribution of the non-dominated layer, and the readiness to fall into a local optimum, by selecting individuals based on the reference points.

As a type of multi-objective genetic algorithm, NSGA-III evenly expands the individuals in the Pareto optimal solution front to the entire Pareto domain by setting reference points and conducting adaptive standardization of the population as well as correlation and individual retention operations to ensure population diversity [20].

4.1. Algorithm Improvement

The flowchart of the optimized NSGA-III algorithm is shown in Algorithm 1.

Algorithm 1 Generation of the Optimized NSGA-III Procedure

Require: Generate initial population P_t with 40% random individuals and 60% individuals from tabu search and H structured reference points Z
Ensure: P_{t+1}
for generation = 1 to MaxGeneration **do**
  binary tournament selection (individuals)
  $P_c = P_{c_{max}} - (P_{c_{max}} - P_{c_{min}}) \times (1 - \frac{f_i}{f_{max}})$
  $P_m = P_{m_{min}} + (P_{m_{max}} - P_{m_{min}}) \times (1 - \frac{f_i}{f_{max}})$
  generate offspring population Q_t
end for
$R_t = (P_t \cup Q_t)$
$(F_1, F_2, ..., F_w) =$ non-dominated sort (R_t)
Set F_1 as the initial non-dominated solution set
while $|S| < N$ **do**
  Move one non-dominated solution from F_1 to S
end while
Adaptive normalization:
Find ideal point Z^* and calculate nadir point
Normalize objectives using ideal and nadir points
Associate individuals with reference points
Retain individuals
if termination criterion is met (e.g., number of generations) **then**
  stop and return final population
else
  go to step 1
end if

Although NSGA-III is much better than NSGA-II in terms of population diversity, it retains the problem of premature convergence [19]. Numerous numerical experiments have shown that NSGA-III is extremely effective in solving large-scale high-dimensional problems, but its performance is poor when dealing with multi-objective optimization problems [21] and its local search ability is insufficient [22].

Therefore, this paper optimized the conventional NSGA-III by improving the population initialization method and dynamically adjusting the crossover and mutation probabilities as follows:

(1) The quality of the initial population has a significant impact on the convergence efficiency of NSGA-III [23], and random population initialization is generally applied. However, for the ship scheduling problem, random population initialization generates a large quantity of infeasible scheduling solutions that limit the evolution speed and individual quality of the population. Therefore, this paper used two methods to initialize the population:

   (a) The initial population was designed based on the problem background. First, a zero matrix was created to store the population information and each individual in the population was considered to randomly generate each ship's release status, delayed entry time, etc., record these data in the zero matrix, then calculate the fitness value of each individual and store it in the fitness matrix.

   (b) The tabu search algorithm was introduced to generate a mixed initial population. Random individuals generated based on the problem background accounted for 40% of this initial population, whereas individuals generated using the tabu search algorithm accounted for the remaining 60%. This effectively utilizes the superior local search ability of the tabu search.

(2) Crossover is critical to determining the global search capability of NSGA-III [24]. As mutation operations do not play a major role in the early stages of evolution, the solution space was explored to the extent possible by making the crossover probability relatively large. However, as the number of evolutions increases, the population becomes stable and, to escape from a local optimum, the crossover probability must be reduced by increasing the mutation probability and accelerating the convergence of the algorithm [25]. Therefore, this paper dynamically adjusted the crossover and mutation probabilities to realize optimization as follows:

$$P_c = P_{c_{max}} - (P_{c_{max}} - P_{c_{min}}) \times (1 - \frac{f_i}{f_{max}}), \quad (28)$$

where P_c is the current crossover probability; $P_{c_{min}}$ and $P_{c_{max}}$ are the minimum and maximum values of the crossover probability, respectively; f_i is the fitness of individual i; and f_{max} is the value with the largest fitness in the current population, given by

$$P_m = P_{m_{min}} + (P_{m_{max}} - P_{m_{min}}) \times (1 - \frac{f_i}{f_{max}}) \quad (29)$$

where P_m is the current probability of variation and $P_{m_{max}}$ and $P_{m_{min}}$ are the minimum and maximum values of the probability of variation, respectively.

4.2. Design of the Fitness Function

The fitness function refers to the degree to which an individual survives a measure of group dominance and is used to distinguish between "good and bad" outcomes for individuals [26]. During the solution process, the algorithm assumes that smaller individual values are better. Through iterative optimization, the final minimum result is achieved in the direction of the three solutions. In this paper, f_1, f_2, and f_3 are used to represent the fitness functions used to judge the individual's strengths and weaknesses, respectively; the three fitness functions should be set as follows:

(1) To minimize the berth preference cost, the fitness function f_1 should be equivalent to the objective function F_1:

$$f_1 = F_1 \quad (30)$$

(2) To minimize the total scheduling time, the fitness function f_2 should be equivalent to the objective function F_2:

$$f_2 = F_2 \quad (31)$$

(3) To maximize the berth utilization rate, the fitness function f_3 should be derived from the reciprocal of the objective function F_3:

$$f_3 = \frac{1}{F_3} \quad (32)$$

5. Experimental Results

5.1. Data Sources

The data for this thesis are given by the port and are divided into ship data and berth data; the ship data have a total of 69 ship-specific pieces of information, each of which includes the ship number, ship type, time required for sea ship inspection, time of arrival at anchorage (all of these ships arrived at anchorage within the planning period of 24 December 2023–30 December 2023), the preferred berths, time of passage through the channel, time of passage through the harbor basin, the speed, and operating time. The berth data have a total of 16 berth-specific pieces of information, each of which includes the berth number, berth type, and distance from the berth to the entrance of this harbor pool.

5.2. Experiment Setting

To verify the practicality of the mathematical model designed in this paper, the optimized NSGA-III, NSGA-III, and NSGA-II were applied to realize the cooperative scheduling of Yangtze River ports and berths. These algorithms were run using MATLAB R2022b on a 64-bit Windows operating system.

As compared with the other two objectives, this paper pays more attention to the berth deviation cost; the algorithm is set up to take the ship deviation cost as the optimization objective first, and the algorithm convergence process is shown in Figure 3 after 100 iterations. As in the early stage of the algorithm, most of the solutions in the population give a larger gap between the actual berth of the ship and its preferred berth, affected by the constraint; the value of the target one is larger. However, in about 20 generations, the cost of berth preference began to gradually decline, in about 55 generations there was a small jump out of the local optimum, in 80 generations it was stabilized in the range of feasible solutions, and it gradually entered convergence and ultimately stabilized at about 2620, so this paper adopts 100 for the number of iterations. Other experiments were conducted using a population size of 50, $P_{c_{min}} = 0.1$, $P_{c_{max}} = 0.9$, $P_{m_{min}} = 0.01$, and $P_{m_{max}} = 0.1$.

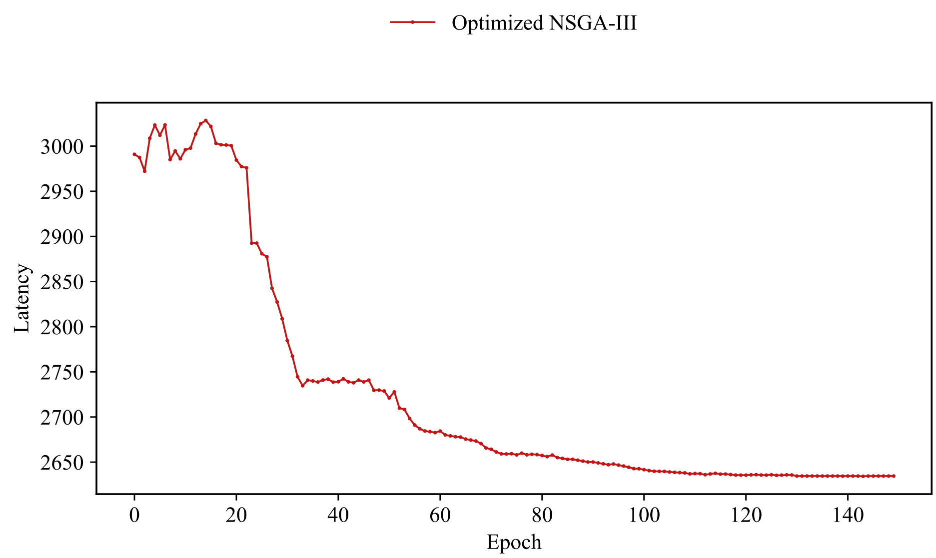

Figure 3. Convergence plot of berth deviation cost for optimized NSGA-III.

5.3. Analysis of Results

5.3.1. Schedule Results Table

The partial scheduling results generated by the optimized NSGA-III are shown in Table 5. The table records the scheduling results of the vessels, including the actual scheduling of movement control time, arrival time at the berth, berthing location, and departure time for each ship. By optimizing with the NSGA-III algorithm, the scheduling arrangement is made more efficient.

Table 5. Partial scheduling results of the proposed optimized NSGA-III.

Ship Number	Actual Scheduling of Movement Control Time	Arrival Time at the Berth to be Called	Berthing Location	Departure Time
1	24 Dec. 2023 at 11:10	24 Dec. 2023 at 11:28	a1	24 Dec. 2023 at 16:28
2	24 Dec. 2023 at 15:50	24 Dec. 2023 at 16:13	b6	24 Dec. 2023 at 20:13
3	25 Dec. 2023 at 08:42	25 Dec. 2023 at 09:10	a8	30 Dec. 2023 at 06:10
...				
21	27 Dec. 2023 at 17:05	27 Dec. 2023 at 17:27	a4	28 Dec. 2023 at 04:27
22	27 Dec. 2023 at 19:00	27 Dec. 2023 at 19:22	b5	28 Dec. 2023 at 04:22
23	27 Dec. 2023 at 19:05	27 Dec. 2023 at 19:26	b3	28 Dec. 2023 at 02:26
...				
41	29 Dec. 2023 at 08:47	29 Dec. 2023 at 09:10	a5	31 Dec. 2023 at 17:10
42	29 Dec. 2023 at 06:41	29 Dec. 2023 at 07:05	b8	29 Dec. 2023 at 15:05
43	29 Dec. 2023 at 07:25	29 Dec. 2023 at 07:46	b4	29 Dec. 2023 at 08:46

5.3.2. Compared with Original Scheduling Program

The port adopts a manual scheduling mode based on the principle of "first come, first served", which results in a berth deviation cost of CNY 3820, a total scheduling time of 311,655 min, and a berth utilization rate of 26.94% for the scheduling scenario in the experimental planning period.

The comparison between the optimized NSGA-III and the original scheduling program results is shown in Figure 4. The optimized NSGA-III program output the following optimal result: for f_1, the berth preference cost was CNY 2643; for f_2, the total scheduling time was 268,867 min; for f_3, the berth utilization rate was 0.0292 (approximately 34.25%). This comparison indicates that the optimized NSGA-III f_1, f_2, and f_3 values were 30.81%, 13.73%, and 12.11% better, respectively, than those of the original program.

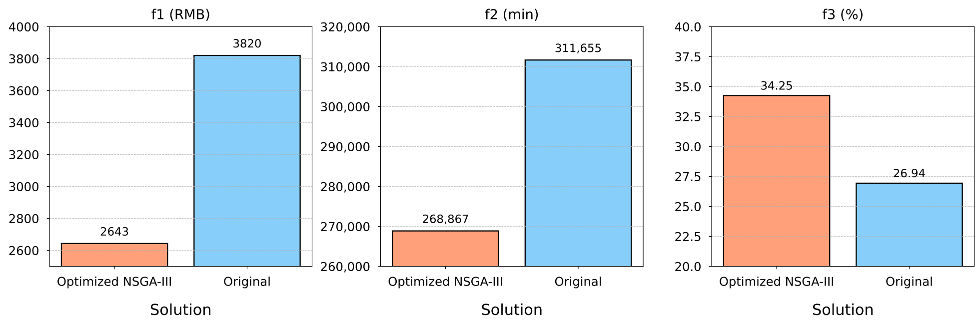

Figure 4. Optimized NSGA-III vs. original scheduling program objective values.

5.3.3. Compared with Conventional NSGA-III and NSGA-II

(1) Comparison of the mean values of the three algorithms

The mean values of the optimized NSGA-III, conventional NSGA-III, and NSGA-II outputs after 100 iterations are listed in Table 6, in which the mean values of f_1, f_2, and f_3 for the optimized NSGA-III are clearly lower than those for the conventional NSGA-III and NSGA-II, indicating that all three objectives were simultaneously improved to some extent. When using the individuals in the solution set obtained by the optimized NSGA-III, the f_1 berth deviation cost was CNY 95 and CNY 362 lower than that obtained by conventional NSGA-III and NSGA-II, respectively. The f_2 total scheduling time was 274.3 min (approximately 4.57 h) and 1991.22 min (approximately 33.19 h) shorter than the total scheduling time of the conventional NSGA-III and NSGA-II, respectively. Finally, the f_3 berth utilization rates obtained by the optimized NSGA-III, conventional NSGA-III, and NSGA-II were 33.33%, 33.31%, and 32.82%, respectively. This comparison indicates that the proposed algorithm achieved the lowest preference cost, lowest total scheduling time, and highest berth utilization.

Table 6. Objective mean of the three algorithms.

	Optimized NSGA-III	Conventional NSGA-III	NSGA-II
Mean f_1	2650	2745	3012
Mean f_2	270,264.76	270,539.06	272,255.98
Mean f_3	33.33	33.31	32.82

The comparison of the average objective values of the three algorithms is shown in Figure 5. Both the optimized NSGA-III algorithm and the conventional NSGA-III algorithm achieve significantly higher objective values than the NSGA-II algorithm. This improvement is due to the NSGA-III algorithm's enhancement of the optimization process, utilizing reference points to guide the population toward these points.

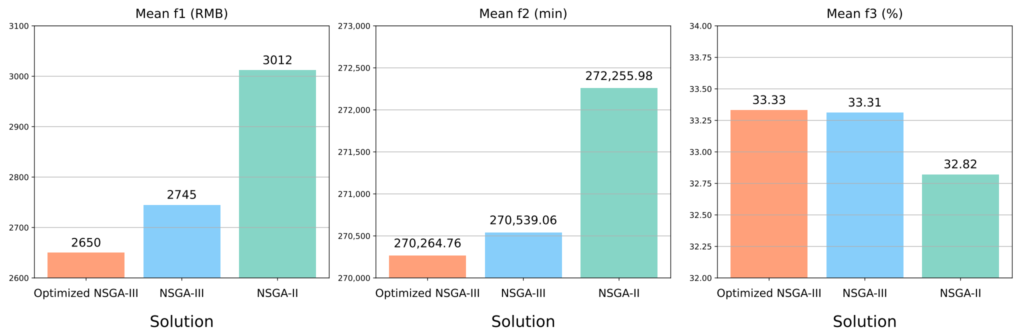

Figure 5. Comparison of the mean values of the three algorithms.

The optimized NSGA-III shows slightly better average objective values compared to the conventional NSGA-III, thanks to several enhancements. First, the quality of initial solutions is improved through a mixed initial population. Additionally, the dynamic adjustment of crossover and mutation probabilities allows the algorithm to better explore the search space and find more precise solutions. In the first 30 generations, the crossover probability remains high, between 0.8899 and 0.9, to enhance population diversity, while the mutation probability stays low, between 0.01 and 0.0111, to guide the population toward better solutions. Around the 40th generation, the crossover probability starts to decrease and the mutation probability begins to increase. By the 80th generation, both probabilities change more gradually and, by the 100th generation, they stabilize, with the crossover probability around 0.6 and the mutation probability around 0.3. This dynamic adjustment allows the algorithm to better adapt to different problems and search phases, thus improving its robustness and performance.

(2) Comparison of Gantt charts for the three algorithms

The Gantt charts displaying the optimized NSGA-III, NSGA-III, and NSGA-II algorithms are shown in Figure 6, Figure 7, and Figure 8, respectively.

The vertical axis represents berths (1 corresponds to a1, ..., 8 corresponds to a8; 9 corresponds to b1, ..., 16 corresponds to b8), and the horizontal axis represents dates, with the seven-day planning period ending on December 30, 2023, as indicated by the vertical line in the chart.

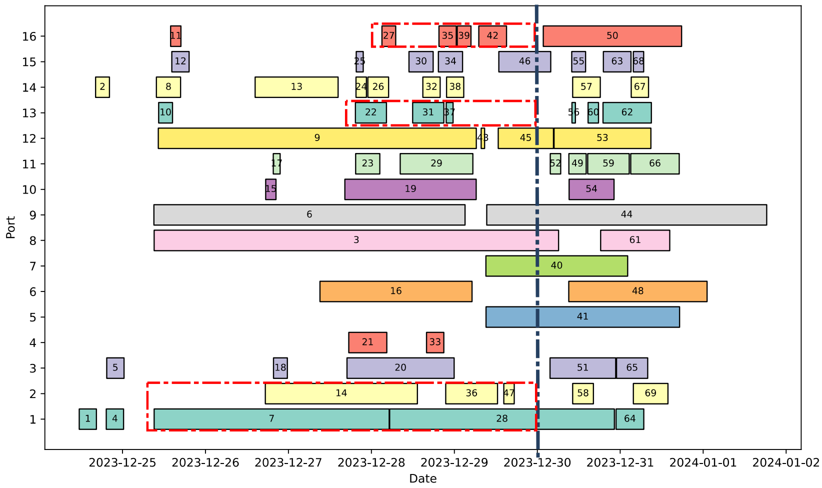

Figure 6. The Gantt chart result of the optimized NSGA-III algorithm.

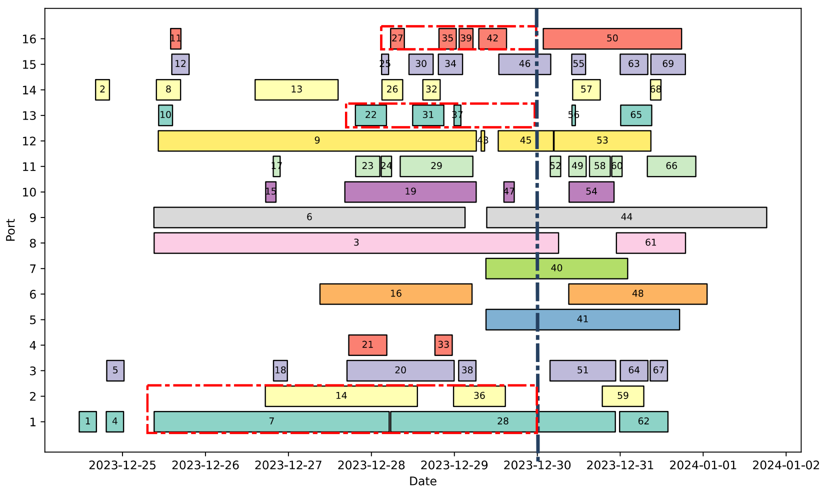

Figure 7. The Gantt chart result of the NSGA-III algorithm.

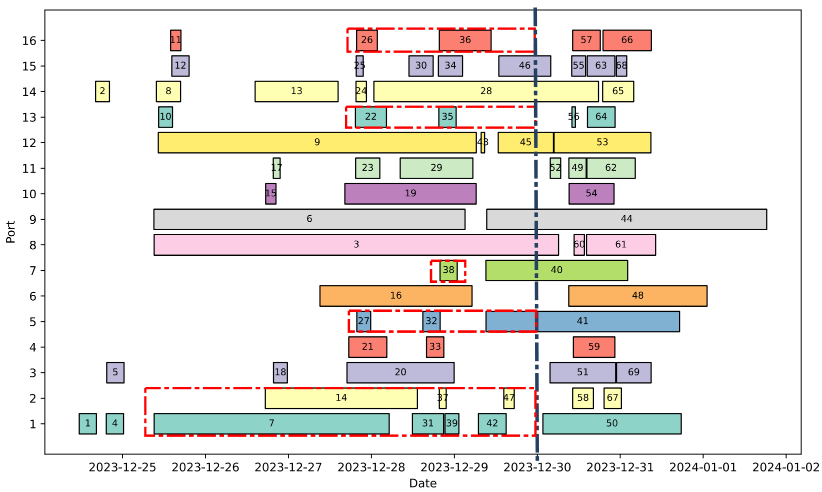

Figure 8. The Gantt chart result of the NSGA-II algorithm.

In the Gantt chart generated by the optimized NSGA-III, the rectangular blocks representing occupied hours are the most densely arranged and occupy the largest area within the planning period. For example, berth 16 (b8) is occupied by ships 27, 35, 39, and 42 under the optimized NSGA-III and NSGA-III algorithms, whereas it is occupied by ships 26 and 36 under the NSGA-II algorithm. This indicates the following: (1) The first two scheduling algorithms accommodate more ships than the latter, resulting in a higher turnover rate and berth utilization, thereby maximizing port resource utilization. (2) Although ships 26, 36, and 35 do not have preferred berths, ship 27 prefers berths b6 and b8, ship 39 prefers berth b8, and ship 42 prefers berths a8 and b8. This demonstrates that the NSGA-II algorithm does not sufficiently consider ship berth preferences, leading to higher berth preference costs. Additionally, berth 13 (b5) is more densely occupied under the optimized NSGA-III and NSGA-III algorithms compared to the NSGA-II algorithm. For berth 2 (a2), the optimized NSGA-III algorithm not only has more ship occupancy than the NSGA-II algorithm but also schedules ship 47, meeting its preferred berth requirement at a2. Similarly, for berth 1 (a1), there are more gaps in the NSGA-II chart compared to the other two algorithms. The NSGA-II algorithm schedules ships 31, 39, and 42 at a1. While ship 31 has no preferred berth, the preferences of ships 39 and 42 are disregarded. Additionally, in the NSGA-II algorithm, berth 5 (a5) and berth 7 (a7) are occupied by ships 27 and 32, and ship 38, respectively, none of which have these berths as their preferences. Furthermore, these three ships have already been scheduled in the other two algorithms within the planning period.

The optimized NSGA-III algorithm not only accommodates more ships during the planning period compared to the other two algorithms but also better meets the specific berth preferences of individual ships. This leads to increased ship turnover rates and improved berth utilization efficiencies.

These results are attributed to the optimized NSGA-III, which uses mixed initial populations, providing a solid foundation and direction for subsequent optimization search iterations, clearly defining the scope of the optimization process. By dynamically adjusting the crossover probability and mutation probability, the algorithm selects the most suitable Pc and Pm values based on current running results, preventing premature convergence or local convergence.

6. Conclusions

This paper proposes a mathematical model for ship scheduling in Yangtze River ports, taking into account berth preferences and inspections for seagoing ships. Initially, the background of the Yangtze River ports and their pressing issues were analyzed, leading to the development of a cooperative scheduling model for the waterway and berths. The model aims to minimize berth deviation costs and total scheduling time while maximizing berth utilization. An optimized NSGA-III algorithm was employed to solve the waterway–berth cooperative scheduling problem, resulting in the optimal cooperative scheduling scheme. The experimental results indicate that the optimized NSGA-III algorithm significantly outperforms the port's original scheduling scheme, achieving improvements of 30.81%, 13.73%, and 12.11% in the three objective values. Furthermore, berth deviation costs were cut by CNY 95 and CNY 362, and total scheduling time was reduced by 274.3 min and 1991.22 min, when compared to the NSGA-III and NSGA-II algorithms. Berth utilization rates saw a slight improvement over both algorithms.

The innovative aspect of this model lies in its comprehensive consideration of berth preference costs and customs inspection factors over an extended planning period. By setting relevant constraints, the scheduling process is optimized to clearly reflect the actual costs and benefits of berth allocation. In waterway scheduling, the model's optimization objectives help avoid random and disorderly berth selection, optimize ship path planning, reduce congestion risk, and enhance the port's service level. Additionally, incorporating berth preference costs allows for a more balanced distribution of berth resources, preventing prolonged occupation of some berths while others remain idle, thereby improving the overall berth utilization rate at Yangtze River ports. Furthermore, the model's scheduling process adapts to customs inspection time constraints, enhancing the efficiency of the inspection departments.

The limitation of this paper is that, despite the complex shipping operations at the target port involving both domestic and international trade, and the presence of some seagoing ships, there are still significant differences in scale, business processes, and trade volume compared to seaports. Due to the unique geographical location of the target port, the emphasis is solely on the "seagoing ship inspection factors" to highlight river–sea intermodal transportation. In the future, we plan to conduct more in-depth research on other seaports, examining additional influencing factors, such as integrating bonded warehouse scheduling, crane scheduling, and container truck scheduling, to develop a more comprehensive and effective model. We also plan to incorporate environmental concepts, enhancing the model's reliability from the perspective of ship energy saving and reducing fuel consumption, thereby promoting a green and low-carbon approach.

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