

Research Article

Combined Configuration of Container Terminal Berth and Quay Crane considering Carbon Cost

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Berths and quay cranes are scarce resources in the container terminal system. If the equipment is reasonably planned, the service quality might be improved and the operation cost of the terminal would be reduced. In addition, the competition among ports is not only the competition of the terminal service quality, throughput, and scale but also the competition of low-energy consumption and low pollution. In order to reduce carbon dioxide emissions, this paper developed a multiobjective optimization model for the joint allocation of container terminal berths and Quay cranes. The model is developed based on preference of ships for berths, and the impact of carbon emission cost on terminal operations have been considered. The carbon cost from two aspects, namely, reducing the operation cost of ships and minimizing the average waiting time and departure delay of ships, has been considered. The improved adaptive genetic algorithm has been used to solve the model. A container terminal in Ningbo has been used as a case study. The carbon emission cost of the berths and quay cranes operation system has been calculated. The influence of the variation in carbon emission cost on the berths and quay cranes configuration scheme has been evaluated. The result proves that considering the carbon cost can make the berths and quay cranes operation more green and reasonable. It can be seen that the objective function value of the joint scheme is 5.92% lower than that of the traditional scheme, and the terminal operation cost of carbon emission constraints is 11.76% lower than that of no carbon emission constraints.

1. Introduction

The resources of berths and quay cranes are scarce in the container terminal system. Reasonable allocation of berths and quay crane resources can greatly reduce the port operating cost and improve the container handling efficiency. In recent years, the container transportation volume continues to increase, causing congestion when ships enter the port, leading to increased waiting time for ships. In this process, it not only causes the waste of fuel oil and the emission of carbon dioxide, and increases the cost of fuel oil but also does not conform to the concept of green shipping. Therefore, how to optimize the joint scheduling of berths and quay cranes to reduce costs and realize low-carbon green shipping has become an important issue.

Berth allocation and quay crane allocation are two interrelated problems. The berth allocation plan needs the

cooperation of the quay crane, and the quay crane allocation plan should take the berth allocation plan as the carrier. Specifically, the berth allocation plan depends on the allocation of quay cranes, and the loading and unloading time of a ship is related to the number of quay cranes allocated. Enough quay cranes allocated to ships can help to reduce the operation time of ships and improve the service level of ships. However, due to the limited allocation of quay cranes, unreasonable allocation will increase the time cost of ships. On the other hand, the berth plan also affects the allocation and scheduling of quay cranes. Unreasonable berth allocation will increase the idle time of some quay cranes, or cause frequent dispatching of quay cranes, resulting in waste of resources. Therefore, in the context of low-carbon economy, in order to achieve the two goals of reducing the cost of wharf operation and the cost of ship's time in port, the multiobjective optimization model of joint allocation of

berths and quay cranes considering the cost of carbon emissions is more applicable than the traditional single objective optimization model.

2. Literature Review

For the research on berth allocation, Nishimura et al. [1] took the public wharf as the research object, and established the berth scheduling optimization model based on the discrete berths. The model is solved by genetic algorithm. The feasibility of the algorithm is verified with an example, and the result has been compared with the Lagrange relaxation algorithm. Imai Akio et al. [2] considered the special service of ship berthing in the model, i.e., ship priority berthing right, and designed heuristic genetic algorithm to solve the model. KAP Hwan Kim and Moon [3] designed the simulated annealing method to solve the discrete berth assignment problem, and compared it with the optimization theory.

In the aspect of configuration of the quay crane, Lu et al. [4] studied crane scheduling problems for a new type of automated container terminal system, which is based on multistory frame bridges. The scheduling of quay cranes is divided into static and dynamic modes. Omar Abou Kasm and Ali Diabat [5] systematically introduced a mixed integer programming (MIP) formulation and an exact solution approach to solve the next-generation quay crane scheduling problem. Ceng et al. [6] proposed a new transfer operation mode of dry and branch vessels in container terminals, and designed a heuristic algorithm to solve the model.

In terms of the research on joint allocation of terminals, Tian and Meng [7] studied the optimization of collaborative scheduling of berths, quay cranes, and trucks. An integer linear programming mathematical model of collaborative scheduling has been developed. This model can be used to minimize the overall logistics operation cost. The real data of a large domestic container port T is used as a case study. The commercial software ILOG CPLEX has been used to solve the model and the optimal solution is obtained in an acceptable time. In order to optimize the port terminal operation efficiency, Jiang Meixian et al. [8] applied the mode of combination of truck operation surface and operation line to the model building process. Yang Chunxiao et al. [9] studied the configuration of berths and quay cranes under the condition of continuous berths. A coupling model based on the interaction of berths and quay cranes has been proposed. A genetic algorithm based on the inner cycle and the outer cycle of the optimal solution of berths and quay cranes has been designed. Liang et al. [10] took the minimum time of ship in port and the minimum number of quay crane movements as the goal, constructed the multiobjective problem, used the genetic algorithm to solve the model, and finally combined the Shanghai port terminal to verify the model and algorithm. Park and Kim [11] firstly proposed the optimization problem of berths and quay cranes under continuous berths, and built a dynamic planning model. In the solution of the model, the two-stage solution method is mainly used. In the first stage, the sub gradient optimization method is used to solve the berth allocation, time, and quay

crane allocation of the ship. Then, according to the solution scheme in the first stage, the dynamic programming method is used to allocate the designated quay crane for the ship. Birger et al. [12] developed a mixed integer linear programming model, which considers both berth allocation and quay crane scheduling, as well as ship priority, preferred berthing position, operation time, and other factors. At the same time, the model was applied to a mixed heuristic solution process confirmed by actual data. Zhang Haiyong and Yan Wei [13] studied the joint optimization of berths and quay cranes under discrete berths, and established a dynamic model based on rolling plan, taking into account the transfer rules of berths and quay cranes. Rodriguez et al. [14] considered the berth allocation problem and the quay crane assignment problem as a representative example of scheduling problems. The problem became a multiobjective combinatorial optimization problem that aims to minimize the total service time, to maximize the buffer times, and to minimize the standard deviation of the buffer times.

In terms of relevant research on carbon cost, Dong and He [15] analyzed various technological processes of container unloading from ship to yard, and established a carbon emission model of container terminal based on loading and unloading technology. A container terminal in Shanghai has been used as a case study. Wang Wenyuan et al. [16] analyzed the energy consumption index and influencing factors of each handling equipment in the handling process of the container terminal, and proposed the theoretical formula for calculating the carbon emission of the handling equipment of the container terminal. Wang Zhiyuan et al. [17] established a dual objective optimization model with the minimum ship oil consumption and the shortest ship departure delay time, and added the quay crane allocation model to make the overall optimization of the port. Wang Tingsong et al. [18] explored the study of integrated berth allocation and quay crane assignment problem by considering two policies of different carbon emission taxation rates on port. Guo Zijian [19] studied the optimization method of Quay crane configuration of low-carbon container terminal. Based on the classic optimization method of quay crane configuration considered from the economic point of view, the CO₂ emission per handling unit throughput of Quay crane was added as the constraint condition. The effect of carbon emission constraint condition on quay crane configuration of container terminal was verified through calculation. Lang and Veenstra [20] using the ship arrival time as a decision variable minimized the fuel consumption when the ship approaches the port. Harry and Van Duin [21] took Rotterdam port as a case study, proposed a method to evaluate the carbon dioxide emission of container terminal, deeply analyzed the operation process of port container terminal and the emission generated in these processes, and put forward the most effective method to reduce carbon emission. Yi-Chih Yang [22] investigated CO₂ emissions produced by two different container terminal operating models (tire transtainers and rail transtainers) at the port of Kaohsiung, and seeks to determine energy saving and CO₂ reduction strategies for shipping companies and terminal operators in order to comply with green port requirements.

Jaehun Sim [23] proposed a model using a system dynamics approach to evaluate the total amount of carbon emissions produced in a container terminal, while calculating the required reduction amount of carbon emissions in the container terminal at a given carbon emission reduction goal from the year 2017 to the year 2030.

From previous studies, it can be seen that, the research on port operation optimization under the low-carbon background is relatively insufficient. There are few studies on container scheduling considering carbon emission reduction. And, most studies consider only one element of the container terminal configuration. We consider the joint optimization of multiple container terminal elements under the condition of carbon cost in this paper. The paper aims to reduce the terminal operation cost and the time cost of ships in port. In order to achieve this goal, an integrated scheduling of berth and quay crane considering the carbon cost has been proposed.

Therefore, based on previous studies, this paper proposed an integrated scheduling of berths and quay cranes under the condition of considering the carbon cost. In the process of berth and quay cranes being dispatched, there may be a part of carbon dioxide produced by truck transportation. Therefore, this paper will add the influence of truck on the total cost in the berth and quay crane configuration model, and finally achieve two goals of reducing the terminal operation cost and the time cost of ships in port.

3. Problem Description

The berth, quay crane, and container truck play a significant role in the production of the container terminal system. Figure 1 shows the berth and quay crane configuration flow chart. After a container ship arrives at the port, it first waits for berthing at the anchorage. If there is a free berth meeting the requirements of the ship's length and water depth, the ship will enter the berth. After berthing, it is necessary to wait for the quay crane to be ready before starting the loading and unloading of containers. The container is lifted from the ship by the quay crane and placed on the collecting truck for transportation. The whole process needs the berth, the quay crane, and the container truck cooperating with each other.

At present, most previous studies focus on berth scheduling, quay crane scheduling, or truck consolidation scheduling. But, these scheduling are linked with each other. For example, when a ship arrives at the port, the berth resources of the terminal are limited. Effectively assigning a berth to a ship arriving at the port can reduce the berthing time of the ship, thus reducing the waiting time of the ship and improving the production efficiency of the terminal. At the same time, for the berthed ships, after a certain number of quay cranes are allocated, the container transportation between the quay crane and the import and export yard is carried out by the truck.

Therefore, this paper first developed a joint configuration optimization research model of berth and quay crane, taking the berth and quay crane as a whole to plan and to ensure the efficient connection of ship operation. In practice,

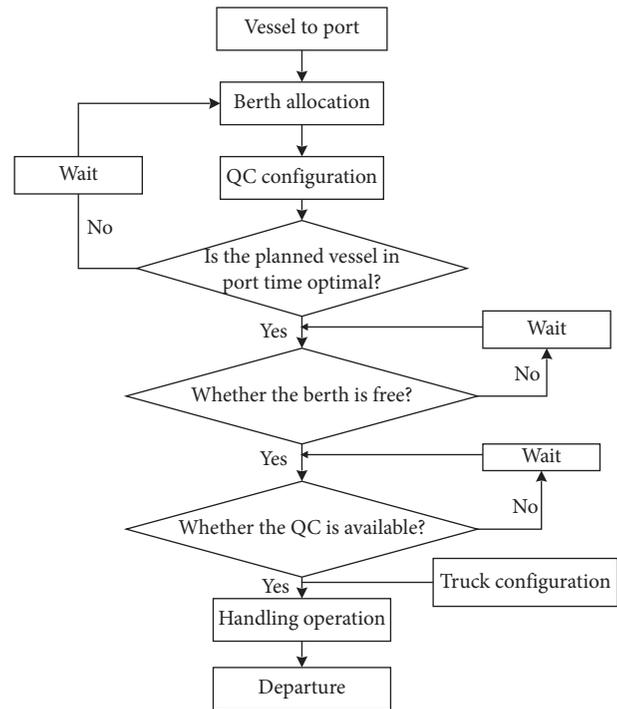


FIGURE 1: Berth and quay crane configuration flow chart.

if the ship deviates from the preferred berth, the container will be transported from the container truck to the corresponding yard and container area of the preferred berth, then the carbon dioxide emission will be generated. Because this part of energy consumption is related to the berth allocation plan, the energy consumption has been considered in the berth and quay crane allocation model. And, the berth type studied in this paper is discrete berth. Secondly, this paper quantifies the cost of carbon emission. Based on the current situation of berth and quay crane operation and the operation process of ships in port, a multiobjective optimization model of berth and quay crane joint configuration considering carbon cost is constructed to reduce the time cost and operation cost of ships in port.

4. Mathematical Model

In this paper, the arrival ship, the berth, and the quay crane operation system are taken as a research object. The time of ship in port includes the time of waiting for entering the berth, the time of waiting for quay crane, and the working time of quay crane. The berth and quay crane operation system mainly includes the berth and quay crane. Considering the current situation of berth and quay crane operation of the container terminal, the optimization model of berth and quay crane joint configuration in this paper is based on the following assumptions:

- (1) The research type of the berth is the discrete berth.
- (2) Any quay crane can only serve one ship at a certain time.
- (3) The starting time of wharf service is after the arrival of the ship.

- (4) At any time, the number of quay cranes serving the ships in berthing shall not exceed the total number of all quay cranes.
- (5) Objective factors such as sudden accidents have not been considered.
- (6) The loading and unloading efficiency of all quay cranes is the same, and the operation end time is the same.
- (7) The quay crane is located on the same parallel track, and a quay crane cannot cross another quay crane for translation, and the time of quay crane translation is ignored.
- (8) All ships shall approach the port at the most once during the plan period.

4.2. Objective Functions and Constraints. The objective function consists of two parts: the operation cost of the terminal and the time cost of the ship in port. The terminal operation cost can be divided into two parts: the transportation cost of the truck and the operation cost of the quay crane. The cost of time in port is divided into three parts: the cost of waiting for berthing at the anchorage, the cost of productive berthing of ships in port, and the cost of non-productive berthing. The weighted method is a common method to solve the multiobjective problem. In this study, F , F_1 , and F_2 are used to express the objective function, the operation cost of the wharf, and the time cost of the ship in port, respectively. Then, the objective function of the multiobjective optimization problem based on the weight coefficient can be expressed as

4.1. Parameters and Decision Variables. Table 1 presents the parameters and decision variables of the model.

$$F = \omega_1 \left\{ \min \left[(c_1 + c_{11}) \sum_{i=1}^s SC_i (TU_i - TW_i) + (c_{22} + c_2) \sum_{i=1}^s IE_i |SB_i - W_i| \right] \right\} + \omega_2 \left\{ \min \left[\sum_{i=1}^s f_{i1} \left(\frac{(Tb_i - Ta_i)}{24} \right) + \sum_{i=1}^s f_{i2} \left(\frac{(Tu_i - Tw_i)}{24} \right) + \sum_{i=1}^s f_{i3} (Tw_i - Tb_i) \right] \right\}, \quad (1)$$

$$F_1 = \min \left[(c_1 + c_{11}) \sum_{i=1}^s SC_i (TU_i - TW_i) + (c_{22} + c_2) \sum_{i=1}^s IE_i |SB_i - W_i| \right], \quad (2)$$

$$F_2 = \min \left[\sum_{i=1}^s f_{i1} \left(\frac{(Tb_i - Ta_i)}{24} \right) + \sum_{i=1}^s f_{i2} \left(\frac{(Tu_i - Tw_i)}{24} \right) + \sum_{i=1}^s f_{i3} (Tw_i - Tb_i) \right], \quad (3)$$

$$c_{22} = AD_t \times q \times EF_t \times P. \quad (9)$$

where

$$c_1 = AD_i \times P_1. \quad (4)$$

Formula (4) means operation cost per unit time of quay crane.

$$c_2 = AD_j \times P_2. \quad (5)$$

Formula (5) means unit distance transportation cost of truck.

$$AE_e = \sum AD_e \times EF_e. \quad (6)$$

Formula (6) means indirect carbon emissions from purchased electricity.

$$c_{11} = AD_c \times EF_e \times P. \quad (7)$$

Formula (7) means carbon emission cost of quay crane.

$$AE_c = \sum (AD_{j,l} \times q_{j,l} \times EF_{j,l} \times 10^{-6}). \quad (8)$$

Formula (8) means carbon dioxide emissions from fuel combustion.

Formula (9) means carbon emission cost of truck.

$$F_{QC} = (c_1 + c_{11}) \sum_{i=1}^s SC_i (TU_i - TW_i). \quad (10)$$

Formula (10) means operation cost of quay crane.

$$F_{truck} = (c_{22} + c_2) \sum_{i=1}^s IE_i |SB_i - W_i|. \quad (11)$$

Formula (11) means transportation cost of truck.

$$F_2 = f_1 t_1 + f_2 t_2 + f_3 t_3. \quad (12)$$

Formula (12) means time cost of vessel in port.

$$\frac{(Tb_i - Ta_i)}{24}, \frac{(Tu_i - Tw_i)}{24}. \quad (13)$$

Formula (13) means the nonproductive berthing time and productive berthing time of the ship.

TABLE 1: Parameters and decision variables.

Parameters	
B	Collection of berths, $B = \{1, 2, 3, 4, \dots, b\}$
C	Collection of quay crane, $C = \{1, 2, 3, 4, \dots, c\}$
I	Berth spacing
L	Length of quay line
Lb_j	Length of berth J
Db_j	Depth of berth J
C_1	Operating cost per unit time of quay crane
C_{11}	Cost of per unit time carbon emission of quay cranes
C_2	Per unit distance transportation cost of truck
C_{22}	Carbon emission cost of per unit truck transportation
P	Per unit carbon emission cost
P_1	Unit price of electricity
P_2	Unit price of diesel oil
S	Collection of arriving vessels, $S = \{1, 2, 3, 4, \dots, s\}$
Cm_i	Maximum number of quay cranes that can be configured for ship I, $i \in S$
W_i	Preferred berthing of ship I, $i \in S$
Ls_i	Master of vessel I, $i \in S$
DS_i	Depth of immersion of vessel I, $i \in S$
Decision variable	
SO	The service sequence set of ships arriving in the period
SO_i	Berthing sequence number of ship i , $i \in S$
SB	Ship berth allocation set
SB_i	Berthing serial number of ship i , $i \in S$
SC	Ship operation quay crane collection
SC_i	Number of quay cranes for ship I, $i \in S$
Ta_i	Ship I arrival time, $i \in S$
Tb_i	Ship I berthing time, $i \in S$
Tw_i	Commencement of ship i , $i \in S$
Tu_i	Departure time of ship i , $i \in S$
T	Average ship on duty time
δ_{it}^u	If quay crane u is assigned to ship i at time t , the value is 1, otherwise it is 0
Q_i	Container handling quantity of vessel I
Q_{iu}	Number of containers handled by quay crane u allocated for vessel I
X_{ijk}	$\{0, 1\}$ is a 0–1 decision variable; when ship I is served in order k on berth J, the value is 1; otherwise, it is zero
AD_i	Power consumption per unit time of quay crane
AD_j	Per unit transport distance fuel consumption of the truck
AE_e	Carbon emissions from outsourced electricity, unit: (t·CO ₂)
AD_e	Net purchased electricity usage, unit: 10 kw · h
ADc	The power consumption per unit time of the quay crane, unit: kW H
EF_e	Carbon dioxide emission factor of electric power, unit: (t · CO ₂ /10 kW h)
AE_c	The carbon dioxide emissions from fuel combustion, in (t CO ₂)
$AD_{j,i}$	The activity data for type i energy consumed by mode of transportation in j , i.e., fuel consumption, in tons (t)
q	The low calorific value of fuel, in MJ/T fuel
$EF_{j,i}$	The fuel emission factor, g CO ₂ /MJ
AD_t	The unit fuel consumption of the truck (mainly diesel oil for the truck), unit: ton/km
EF_t	The fuel emission factor, in grams of CO ₂ /MJ
f_1	The charging standard for anchorage, unit: yuan/day
f_2	The productive berthing charge standard, unit: yuan/day
f_3	The charge standard for unproductive berthing of the terminal, unit: yuan/day
ω_1	Wharf operation cost coefficient
ω_2	Time cost coefficient of ship in port

Subjected to $SC_i \leq Cm_i, \quad \forall i \in S, \quad (14)$

$$\sum_{j \in B} \sum_{k \in SO} X_{ijk} = 1, \quad \forall i \in S, \quad (14)$$

$$Ta_i \leq Tb_i, \quad \forall i \in S, \quad (18)$$

$$\sum_{i \in S} X_{ijk} \leq 1, \quad \forall j \in B, \forall k \in SO, \quad (15)$$

$$\sum_{j \in B} \sum_{k \in SO} X_{ijk} \times Db_j \geq Ds_i, \quad \forall i \in S, \quad (19)$$

$$L_{si} + SB_i \leq L, \quad \forall i \in S, \quad (16)$$

$$\sum_{j \in B} \sum_{k \in SO} X_{ijk} \times Lb_j \geq Ls_i, \quad \forall i \in S, \quad (20)$$

$$\sum_i SC_i \times \alpha_{it} \leq C, \quad \forall t, \forall i \in S, \quad (21)$$

$$\sum_u Q_{iu} \delta_{it}^u = Q_i, \quad \forall t, \forall i \in S, \quad (22)$$

$$Tu_i - Tw_i = \frac{E_i}{(V_0 \times SC_i)}, \quad \forall i \in S, \quad (23)$$

$$\sum_{i \in S} X_{ijk} = nSC_i, \quad \forall i \in S, \quad (24)$$

$$\sum_{k \in SO} \sum_{j=1}^{Tu_i-1} X_{ijk} = 0, \quad \forall i \in S, \quad (25)$$

$$\sum_{k \in SO} \sum_{Tu_i+1}^T X_{ijk} = 0, \quad \forall i \in S. \quad (26)$$

Constraint (14) means that the ship can only be serviced once at a certain berth. Constraint (15) means that one berth cannot hold multiple ships at the same time. Constraint (16) means that all vessels must be berthed in the Quay Line. Constraint (17) means that the number of quay cranes allocated by the ship cannot be greater than the maximum acceptable number of quay cranes. Constraint (18) means that the arrival time of the ship cannot be greater than the berthing time of the ship. Constraint (19) indicates that the berth allocation scheme must meet the ship draft requirements. Constraint (20) indicates that the berth allocation scheme meets the ship length requirements. Constraint (21) indicates that the number of quay cranes under operation at a certain time is less than the maximum number of quay cranes. Constraint (22) means that the required loading and

unloading tasks of each vessel must be met. Constraint (23) indicates that the operation time of the ship is directly proportional to the loading capacity of the ship and the loading and unloading efficiency of the quay crane. Constraint (24) indicates that the number of working quay cranes remains unchanged during the operation of the ship. Constraints (25) and (26) indicate that there is no quay crane working on the ship outside the specified time window.

5. Model Solution

In this paper, the improved adaptive genetic algorithm is used to improve the chromosome coding method, chromosome crossover strategy, crossover probability, and mutation probability, respectively.

5.1. Chromosome Coding. The main variables of this model are berthing of ships and the number of quay cranes for ships. Due to that there are two decision variables in this model; the chromosome group coding method is adopted instead of the traditional one-dimensional single chromosome coding. Figure 2 shows the description of the genome code in this paper. In Figure 2, the first row of chromosome 1 represents the number of ships arriving at the port, the second row of chromosome 2 represents the berthing berth of the ship, and the third row of chromosome 3 represents the number of quay cranes allocated for the ship operation.

5.2. Fitness Function. Among the common fitness function construction methods, the simplest one is the objective function mapping method, which is also the most practical method to solve the minimization problem. In order to evaluate individuals more intuitively and simply, this paper takes the objective function as the fitness function, which is given as

$$F = \omega_1 \left\{ \min \left[(c_1 + c_{11}) \sum_{i=1}^s SC_i (Tu_i - Tw_i) + (c_{22} + c_2) \sum_{i=1}^s IE_i |SB_i - W_i| \right] \right\} \\ + \omega_2 \left\{ \min \left[\sum_{i=1}^s \left(\frac{f_{i1}(Tb_i - Ta_i)}{24} \right) + \sum_{i=1}^s \left(\frac{f_{i2}(Tu_i - Tw_i)}{24} \right) + \sum_{i=1}^s f_{i3}(Tw_i - Tb_i) \right] \right\}. \quad (27)$$

In this paper, the objective function is taken as the fitness function. The value of the fitness function is determined by the common parameters and the operation time of the ship in the port. In this paper, the chromosome designed by the genetic algorithm only contains decision variables: berthing berth and quay crane configuration of ships. So, how to get the operation time of ships from the configuration of berths and quay cranes is the key problem in this paper.

5.3. Crossover. In this paper, the method of two-point crossover has been adopted, i.e., randomly selecting two points of chromosome gene sequence, and carrying out crossover operation on the gene sequence between the two points. Due to the limitation of the model constraints in this paper, this paper needs to adjust the crossover strategy according to the actual situation, making the feasible solution meet the constraints.

Ship no.	1	2	3	4	5	6	7	8	9	10
Berth	3	2	1	4	3	2	3	6	4	1
Number of quay cranes	4	5	3	4	4	3	5	6	3	2

FIGURE 2: Example of chromosome coding.

Figures 3 and 4 present the two-point-cross example diagram. In Figures 3 and 4, M and N represent the parent individual. Two intersections are randomly generated on the chromosome, and then the gene sequences between the intersections are exchanged to obtain M_1, N_1 , as shown in Figures 3 and 4.

Figure 5 presents the example diagram of child adjustment strategy. For the offspring $M1$ and $N1$, all ships arriving at the port can only be served once. Therefore, find out the repeated sequence of ship serial numbers in the offspring $M1$ and $N1$, and exchange them until there is no repeated ship serial number, so as to generate the offspring $M2$ and $N2$.

Finally, for the offspring $M2$ and $N2$, due to the limitation of the maximum number of working quay cranes in the model, the third chromosome should be adjusted according to the example model. Figure 6 presents cross-correcting diagram. The third chromosome of the offspring is compared with the number of quay cranes acceptable to the ship. If it is larger than the maximum number of quay cranes, it is adjusted to the maximum number of quay cranes acceptable to the ship. For example, assume that the maximum number of working quay cranes of all ships is 5, obviously, the third chromosome of offspring $M2$ and $N2$ needs to be adjusted; find out the gene with the third chromosome larger than 5, replace it with 5, and generate the final offspring P and C after adjustment.

5.4. Variation. Figure 7 presents schematic illustration of mutation operations. Mutation operation is used to simulate the structural change of chromosome caused by the mutation of a gene on the chromosome. In genetic algorithm, mutation operation refers to the mutation operation of genes randomly assigned to a certain position of chromosome according to the mutation probability. Considering the model constraints in this paper, the strategy of substituting mutation has been adopted. In this mutation, the gene sequence of a certain position in the current population has been randomly replaced.

5.5. Control Parameters. The genetic algorithm designed in this paper involves two control parameters, one is the crossover probability P_c , the other is the mutation probability P_m . f_{\max} represents the fitness of the optimal chromosome individual in the population, \bar{f} represents the average fitness in the population, and f' represents the better individual fitness value. The fitness values of the chromosome individuals requiring variation are represented by f . Then,

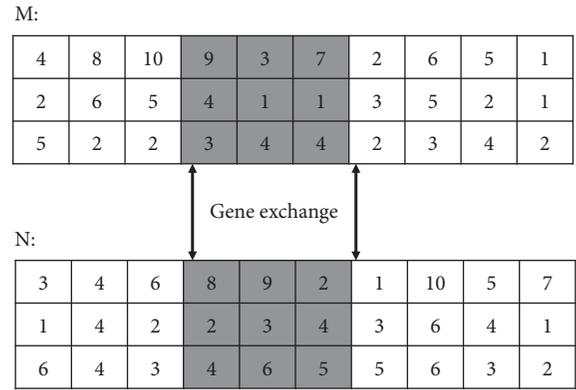


FIGURE 3: Initial two-point-cross example diagram.

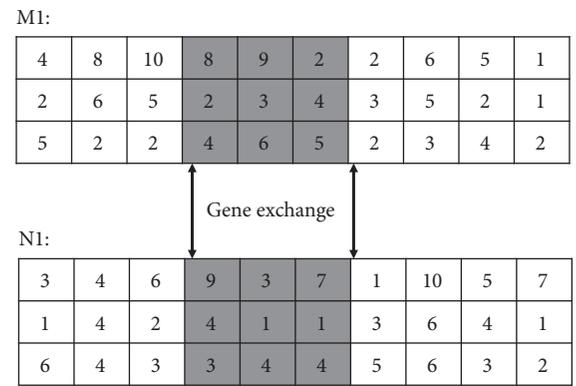


FIGURE 4: The completed two-point-cross example diagram.

$$P_c = \begin{cases} \frac{k_1 (f_{\max} - f')}{(f_{\max} - \bar{f})}, & f' \geq \bar{f}, \\ k_2, & f' < \bar{f}. \end{cases} \quad (28)$$

$$P_m = \begin{cases} \frac{k_3 (f_{\max} - f)}{(f_{\max} - \bar{f})}, & f \geq \bar{f}, \\ k_4, & f < \bar{f}. \end{cases} \quad (29)$$

The closer a chromosome individual's fitness is to the optimal fitness, the smaller its crossover probability and mutation probability are; when the fitness of a chromosome individual is equal to the optimal fitness, its mutation probability and crossover probability are equal to zero. k_1 to k_4 are less than or equal to 1. Because $f' < \bar{f}, f < \bar{f}$, we want to change the chromosome individuals as much as possible, so we need to take k_2 as large as possible. Because the mutation probability is generally small, it is necessary to take a relatively small value for k_4 .

5.6. Summary of the Basic Flow of the Algorithm. This paper summarizes the algorithm flow of model solving; the basic steps are as follows:

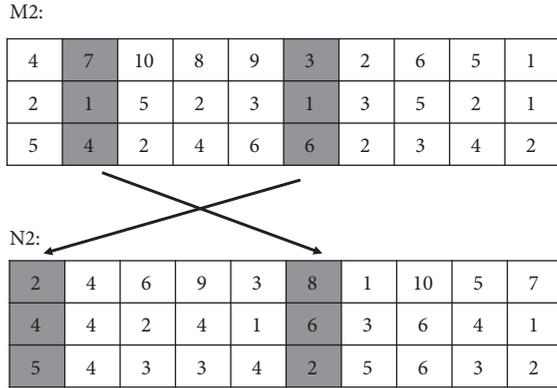


FIGURE 5: Example diagram of child adjustment strategy.

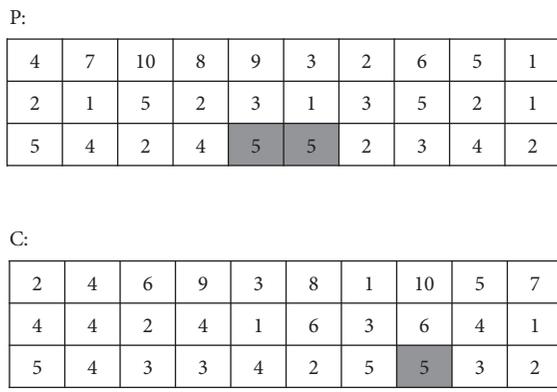


FIGURE 6: Example cross-correcting diagram.

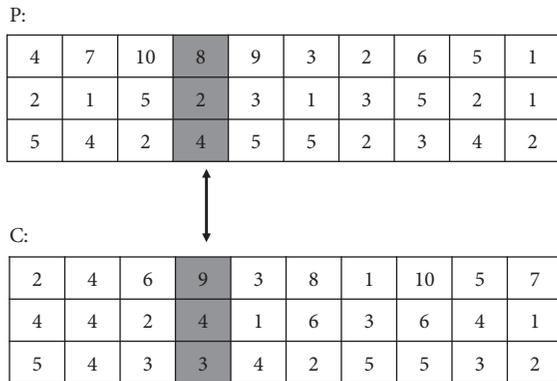


FIGURE 7: Schematic illustration of mutation operations.

- (1) Using real coding to construct multilayer chromosome structure.
- (2) Set reasonable control parameters.
- (3) Let $i=0$; according to the designed chromosome structure, the initial population $p(0)$ is generated by the random method. The population contains M chromosome individuals, and each chromosome represents a quay crane allocation scheme.
- (4) Calculate the fitness values of all chromosome individuals in population $p(i)$.

- (5) Set the termination condition of the algorithm.
- (6) If the current calculation results meet the termination conditions of the algorithm, terminate the algorithm and output the results; Otherwise, skip to step 7.
- (7) According to the best preserved individuals, the next generation of chromosome individuals was generated by roulette replication.
- (8) In addition to the best preserved individuals, the other $M-1$ individuals will be randomly paired, and then the P_c will be obtained according to the adaptive adjustment strategy.
- (9) According to the adaptive adjustment strategy, the P_m will be obtained, and then these chromosome individuals will be mutated according to P_m .
- (10) New species group $i=i+1$.
- (11) If the termination condition is satisfied, the algorithm stops; Otherwise, skip to step 4.

6. Example Analysis

6.1. Example Data. This paper selects the actual data of a container terminal in Ningbo as a case study. Based on the relevant operation data of the port freight container terminal, parameters of the terminal are calculated, which are given in Tables 2 and 3.

6.1.1. Terminal Base Data. Table 2 presents the terminal base data of this model.

6.1.2. Ship Base Data. Table 3 presents the ship base data of this model.

6.1.3. Design of Parameters. Table 4 presents the parameter data of this model.

c_1, c_{11}, c_2, c_{22} are calculated as follows:

- (1) c_1 : operating cost per unit time of quay crane

The operation cost of quay crane is equal to the price of electricity multiplied by the unit power consumption. According to the data of the container terminal, the price of electric power is about $112.9 \text{ kw} \cdot h$, and the electric energy consumption per hour per unit quay crane is about $0.824 \text{ yuan/kw} \cdot h$.

$$c_1 = \frac{112.9 \text{kw} \cdot h \times 0.824E}{\text{kw} \cdot h} = 93.03E. \quad (30)$$

- (2) c_{11} : cost of per unit time carbon emission of quay cranes

The carbon emission cost of the quay crane is equal to the unit power consumption of the quayside bridge multiplied by the power carbon dioxide emission factor multiplied by the unit carbon dioxide emission cost. The hourly power consumption of the quay crane is $112.9 \text{ kW} \cdot h$. With reference to the emission coefficient of the regional grid reference

TABLE 2: Terminal base data.

Terminal base data	
Quayline length	1800 m
Depth of channel	14 m
Channel width	250 m
Length of channel	14 m
Number of berths	6
Quay crane	22
Width of harbor basin	600 m

line, the emission coefficient of electric carbon dioxide in a container terminal area of Ningbo is 0.8959. Therefore, the cost per hour of carbon emission per quay crane is

$$c_{11} = \frac{0.8959 \times 16.5E}{\text{ton} \times 112.9kw \cdot h \times 10^{-3}} = 1.52E. \quad (31)$$

- (3) c_2 : per unit distance transportation cost of truck

The unit distance transportation cost of the truck is equal to the price of energy multiplied by the unit driving distance. According to the relevant terminal data inquired, the main energy consumption of the truck is diesel, the diesel consumption per kilometer is 0.35 L, and the unit price of diesel is about 6.3 yuan/L.

$$c_2 = 0.35L \times \frac{6.3E}{L} = 2.2E. \quad (32)$$

- (4) c_{22} : carbon emission cost of per unit truck transportation

The unit carbon emission cost of the truck is equal to the unit distance carbon dioxide emission of the truck multiplied by the diesel carbon dioxide emission factor multiplied by the unit carbon dioxide emission cost. According to the guidance of provincial greenhouse gas emission inventory issued by the national development and Reform Commission, the carbon dioxide emission coefficient of diesel oil is 3.0959 Kg/Kg, about 2.66 Kg/L. Therefore, the unit carbon emission cost of collecting card is:

$$c_2 = \frac{16.5E}{t} \times \frac{2.66Kg}{L} \times 0.35 \times 10^{-3} = 0.015E. \quad (33)$$

6.2. Results and Discussion. In this paper, it is assumed that the initial population P is 80, the number of iterations is 1000, and the crossover probability and the mutation probability are $k1=0.5$, $k2=0.7$, $k3=0.5$, $k4=0.1$.

ω_1 , ω_2 represent the weight coefficients of wharf operation cost and ship time cost in port, respectively. Considering that the wharf is the main body of service, the service quality of ships should be improved on the basis of the reduction of wharf cost. Therefore, the value of ω_1 should be higher than that of ω_2 .

In present paper, the values are taken as $\omega_1=0.6$, $\omega_2=0.4$; $\omega_1=0.7$, $\omega_2=0.3$; $\omega_1=0.8$, $\omega_2=0.2$; $\omega_1=0.9$, and $\omega_2=0.1$.

Figures 8 to 11 present convergence curves obtained by 1000 times of algorithm iteration.

It can be concluded that the higher value of ω_1 , and the lower value of ω_2 , lead to the greater value of objective function.

Therefore, the coefficients of the multiobjective problem in the following paper will be $\omega_1=0.7$, $\omega_2=0.3$.

According to the calculation results of MATLAB, the optimal solution under the joint configuration of berth and quay crane is shown in Table 5. As can be seen in Table 5, the target function value is 220972.7, and average time of vessel in port is 40.3 h.

S; berthing serial number of the ship, SO: berthing sequence of the ship, SB: berthing berth of the ship, SC: number of configured quay cranes, W_i : Ship's preferred position, F: target function value, F_1 : operating costs of quay cranes, F_2 : port time cost of the ship, T: average time of vessel in port.

According to the calculated results, the optimized berth and quay crane configuration is presented in Figure 12. The configurations are drawn in a two-dimensional coordinate system, where the abscissa represents the berth number and the ordinate represents the time.

6.3. Analysis of Calculation Results. In order to present the advantages of the optimized joint configuration scheme considering the carbon cost, this paper compares it with the traditional first come, first stop configuration scheme and the configuration without considering carbon constraints.

Table 6 shows the results of the traditional first come first served berth and quay crane configuration scheme, and Table 7 shows the comparison of the operation cost and the average operation time of the ships in the port. Figure 13 shows comparison of bar charts of the two plans.

Table 7 presents the difference between the two schemes. From Table 7, it can be found that the joint scheme configuration is superior to the traditional first come first serve configuration. From Table 7, it can be seen that the objective function value of the traditional scheme is 6.29% higher than that of the joint scheme, the operation cost of the wharf is 2.99% higher than that of the joint scheme. Also, it shows that the time cost of ships in port and the average time of ships in port are 15.76% and 13.4% higher than that of the joint scheme. The scheme of joint allocation not only reduces the cost of wharf operation but also shortens the time of ships in port, and greatly improves the overall quality and efficiency. Therefore, the scheme of joint configuration is superior.

In the present paper, the impact of considering carbon emission constraints on the joint allocation optimization scheme is analyzed, and the model optimization results without considering carbon emission constraints are listed in Table 8. Figure 14 shows the comparative chart considering carbon costs.

Compared with the optimal results before and after adding carbon emission constraints, it was found that the cost of ships in port without carbon emission constraints is lower than that with carbon emission constraints. However, the cost of carbon is higher than that with carbon emission constraints. So, the cost of wharf operation is higher, and the total objective function value is slightly lower than that with

TABLE 3: Ship base data.

No.	Length of ship	Preference berth	Loading and unloading capacity	Maximum number of quay cranes	Breadth of ship	Depth of immersion
1	263	3	4250	5	42	12.8
2	243	2	2730	4	32	9.5
3	161	4	1500	4	23	5.8
4	128	5	980	3	18	5
5	201	4	3140	5	32	8.9
6	72	6	750	2	13	3
7	213	1	2400	4	32	10
8	140	2	1690	3	20	5
9	115	4	1020	2	16	4.5
10	195	5	2060	4	37	13.5
11	147	3	1450	2	21	8
12	294	4	4300	5	32	13.5
13	128	6	1240	2	18	5
14	204	2	2980	5	32	10.4
15	153	3	1400	3	21	6.9
16	192	1	1750	4	32	12.8
17	158	2	1320	3	23	8.2
18	201	4	2470	5	40	10.1
19	115	3	1190	2	16	4.5
20	159	6	1230	2	23	1.7

TABLE 4: Parameter data.

Parameter	Parameter meaning	Parameter values
c_1	Operating cost per unit time of quay crane	93.03
c_{11}	Cost of per unit time carbon emission of quay cranes	1.52
c_2	Per unit distance transportation cost of truck	2.2
c_{22}	Carbon emission cost of per unit truck transportation	0.015
P	Per unit carbon emission cost	16.5
f_1	The charging standard for anchorage	0.05
f_2	The productive berthing charge standard	0.23
f_3	The charge standard for unproductive berthing of the terminal	0.15
v_0	Loading and unloading capacity per unit time of quay crane	35Per hour
l	Berth spacing	0.3 km
Db_j	Depth of berth J	15.5 m
Lb_j	Length of berth J	0.3 km

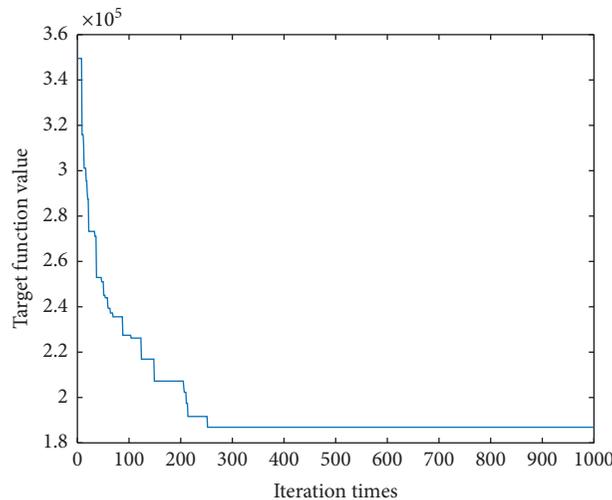


FIGURE 8: Convergence curve obtained by 1000 times of algorithm iteration when $\omega_1 = 0.6$ and $\omega_2 = 0.4$.

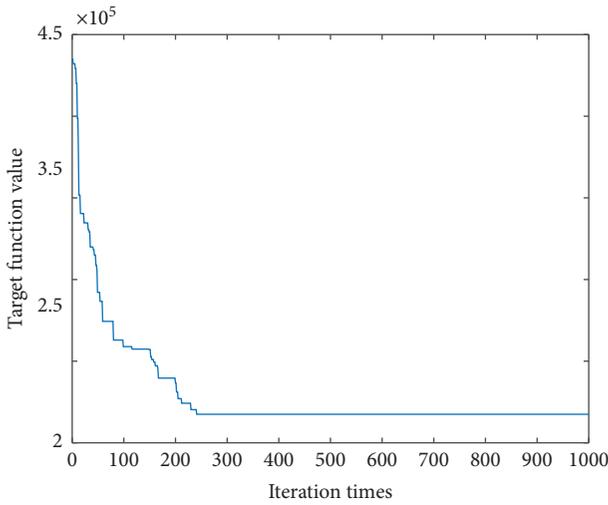


FIGURE 9: . Convergence curve obtained by 1000 times of algorithm iteration when $\omega_1 = 0.7$ and $\omega_2 = 0.3$.

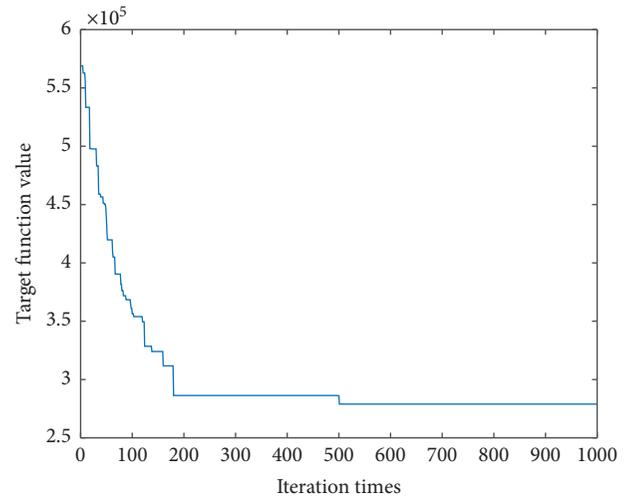


FIGURE 11: Convergence curve obtained by 1000 times of algorithm iteration when $\omega_1 = 0.9$ and $\omega_2 = 0.1$.

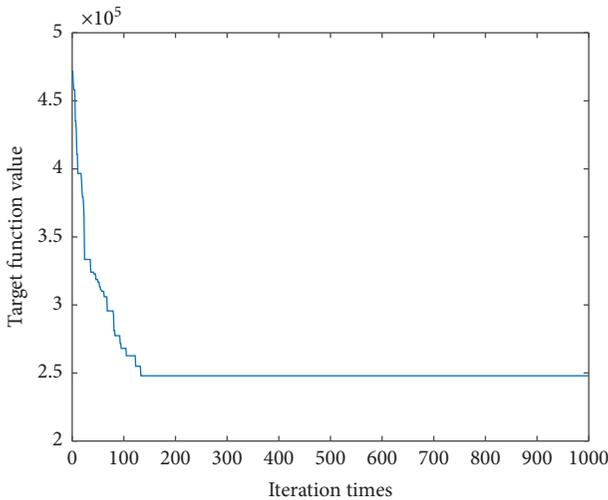


FIGURE 10: Convergence curve obtained by 1000 times of algorithm iteration when $\omega_1 = 0.8$ and $\omega_2 = 0.2$.

carbon emission constraints. To sum up, the joint allocation of terminals with carbon emission constraints is more in line with the era background of green shipping development. Although the total cost is slightly higher, carbon emissions have been reduced.

6.4. Sensitivity Analysis. In order to verify the validity of the model, the sensitivity of some parameters in the model has been analyzed. The sensitivity analysis in the present paper only discusses the impact of changes in some parameters on the model cost and average time in port, including unit carbon emission cost and operation efficiency of quay crane.

(1) Sensitivity analysis of unit carbon emission cost

According to the relevant data of the example, the carbon emission cost obtained is 16.5 yuan/ton. In addition, Beijing’s carbon trading price is about 50

TABLE 5: Model optimal solution considering carbon cost.

	Vessel assembly																					
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
SO	1	2	6	3	14	10	12	4	11	5	8	7	17	18	20	9	16	19	13	15		
SB			3	2	5	5	4	6	2	1	5	6	3	4	5	2	3	2	2	3	5	
SC			4	4	2	2	4	2	3	2	2	3	2	4	2	2	3	4	2	3	2	
W_i			3	2	4	5	4	6	1	2	4	5	3	4	6	2	3	1	2	4	3	6
F: 220972.7; F_1 : 234093.4; F_2 : 190357.7; T: 40.3																						

yuan/ton, while the foreign carbon tax charge standard is 80–200 yuan/ton. Therefore, in this study, the trading prices of carbon are assumed to be 16.5, 50, 80, 110, 140, 170, and 200 yuan/ton, respectively. Table 9 presents sensitivity analysis based on carbon cost change.

As shown in Figure 15, with the increase of carbon emission cost, the change of objective function value, wharf operation cost, and ship in port time cost tends to be relatively moderate, and the change of ship in port time is more and more obvious.

The length of the average time in port is an important factor to judge the service quality of the container terminal. It can be seen from Figure 15 that the change of carbon emission cost has a great impact on the time in port. The higher the carbon emission cost is, the more obvious the change of time in port is, and the longer the time in port is. With the development of China’s carbon trading market, China’s unit carbon emission cost will increase, which will have a greater impact on the service quality of China’s container terminals, and also have higher requirements for the operation optimization of container terminals. Container terminal operators should pay more attention to the operation and management of the terminal, actively respond to the development and implementation of carbon trading policy,

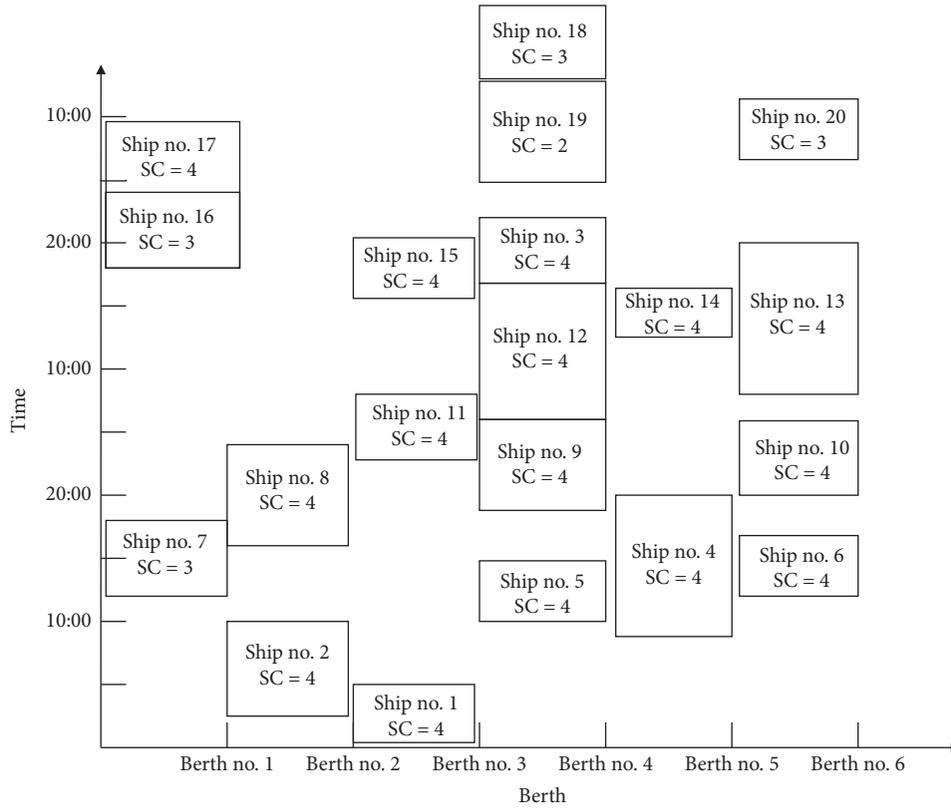


FIGURE 12: The configuration plan of berth and quay crane.

TABLE 6: Configuration scheme for first come first served ships.

Vessel assembly																				
S	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SB	3	2	4	5	4	6	2	1	5	6	3	4	5	2	3	2	2	3	3	5
SC	5	4	2	2	4	2	3	2	2	3	2	4	2	2	3	4	2	3	2	2
W_i	3	2	4	5	4	6	1	2	4	5	3	4	6	2	3	1	2	4	3	6

F: 234871.9; F_1 : 241092.1; F_2 : 220358.1; T: 45.7

TABLE 7: Model optimization comparison table.

Plan	F (yuan)	F_1 (yuan)	F_2 (yuan)	T (hour)
Joint plan	220972.7	234093.4	190357.7	40.3
Traditional plan	234871.9	241092.1	220358.1	45.7
Change rate	6.29%↑	2.99%↑	15.76%↑	13.4%↑

optimize the operation of the container terminal from the perspectives of resource allocation and management, and import and export operation optimization, etc., in order to cope with the growing carbon trading market in China.

(2) Sensitivity analysis of operation efficiency of quay crane

In this paper, the operation efficiency is assumed to be 35 cases/hour. According to the search data, the double

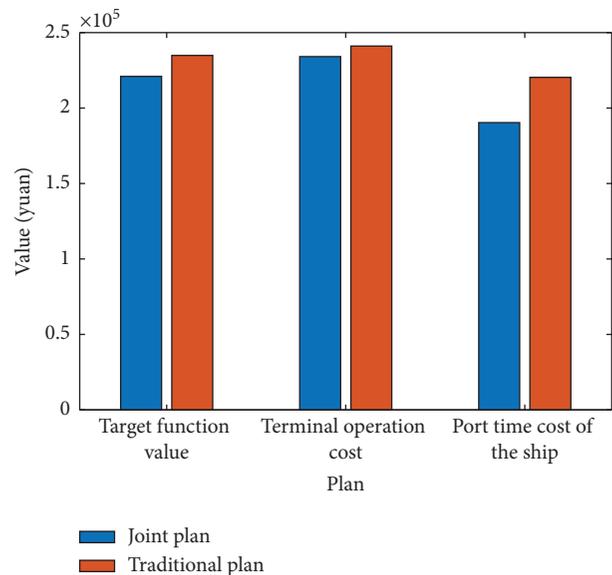


FIGURE 13: Comparison bar chart of the two plans.

trolley and double box spreader can theoretically carry out 55–60 cycles, which can be converted into 80–100 TEU/h. Therefore, the operation efficiency of quay crane is assumed to be 40, 45, 50, 55, 60, 65, 70, 75, and 80 box/hour, respectively. Table 10 presents sensitivity analysis based on unit QC operation efficiency.

TABLE 8: Comparison of models considering carbon costs.

Model	Port time cost of the ship (yuan)	Terminal operation cost (yuan)	Target function values (yuan)
No carbon emission constraints	111357.2	265281.1	219103.93
Carbon emission constraints	190357.7	234093.4	220972.7

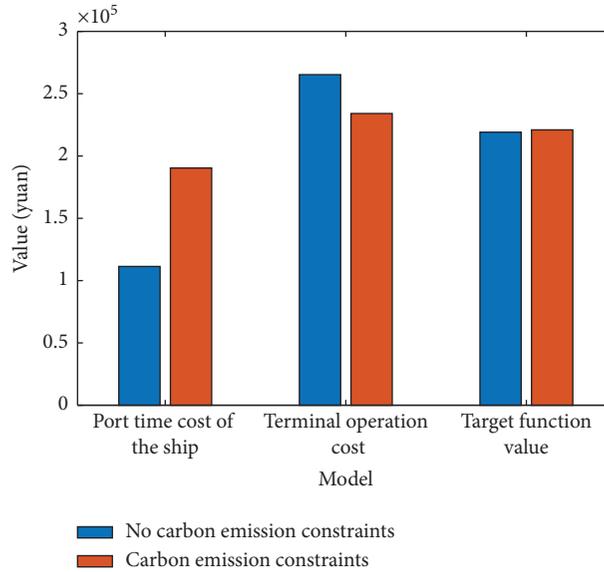


FIGURE 14: Comparative chart considering carbon costs.

TABLE 9: Sensitivity analysis table based on carbon cost change.

Carbon emission costs (yuan/tun)	Target function value (yuan)	Terminal operation cost F_1 (yuan)	Port time cost of the ship F_2 (yuan)	Average port time (hour)
16.5	220972.7	234093.4	190357.7	40.3
50	224949.6	238092.3	194283.3	40.7
80	228747.7	243083.9	195296.6	41.5
110	233672.9	249267.2	197286.2	42.7
140	241136.1	257632.8	202643.8	43.8
170	244037.1	259726.5	207427.8	45.7
200	245684.8	262080.4	207428.4	48.8

In order to express the effect of the variation in the efficiency of the QC on each index, the change of each index with the change of the efficiency of the QC operation is given in Figure 16.

With the improvement of the operation efficiency of the quay crane, the changes of the operation cost and the objective function value of the container terminal are relatively small. The changes of the average time in port and the time cost of the ship in port are relatively large, and the changes are more and more obvious. The length of average time in port is an important factor to judge the service quality of the container terminal. It can be seen from Figure 16 that with the continuous improvement of the efficiency of quay crane operation, the time in port of the ship is continuously reduced, and the decreasing range is more and more large.

6.5. *Algorithm Comparison.* In this paper, the improved adaptive algorithm is compared with the simulated annealing algorithm. Two algorithms are used to compare the cases in this paper, and the data of the objective function value (fitness value) and the convergence Algebra (the number of algorithm iterations to reach the optimal value) are recorded. The comparison results are shown in Table 11.

It can be seen that the simulated annealing algorithm needs more iterations and longer running time. Therefore, the adaptive genetic algorithm has better convergence than the simulated annealing algorithm, which can effectively shorten the running time of the algorithm and get the optimal solution of the objective function faster.

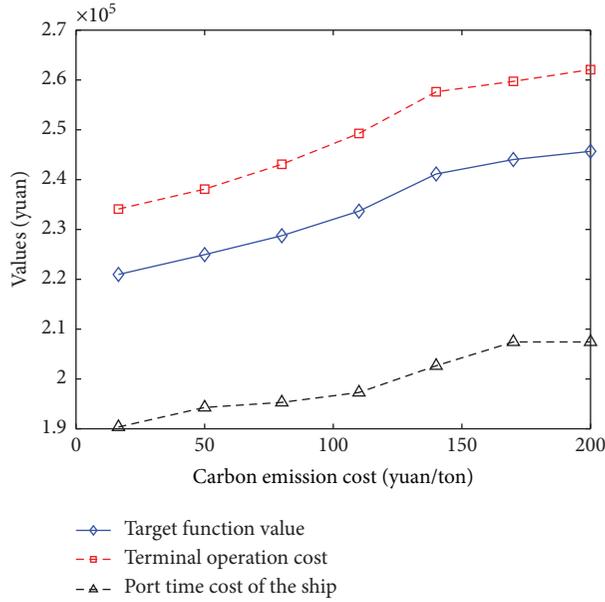


FIGURE 15: Variation of cost with variable carbon emission cost.

TABLE 10: Sensitivity analysis table based on unit QC operation efficiency.

Efficiency of quay crane operation (Box/hour)	Target function value (yuan)	Terminal operation costs (yuan)	Port time cost of the ship (yuan)	Average port time (hour)
35	220972.7	234093.4	190357.7	40.3
40	220599.2	234821.7	187413.4	39.5
45	218999.5	233528.2	185099.2	38.3
50	217733.1	232423.5	183455.5	37.2
55	216406.8	231456.6	181290.6	35.7
60	215471.6	230284.3	180908.6	32.8
65	213772.6	229085.5	178042.5	30.8
70	211961.9	228130.6	174234.9	27.3
75	209644.3	226578.1	170132.1	25.7
80	206486.4	224634.8	164140.1	21.8

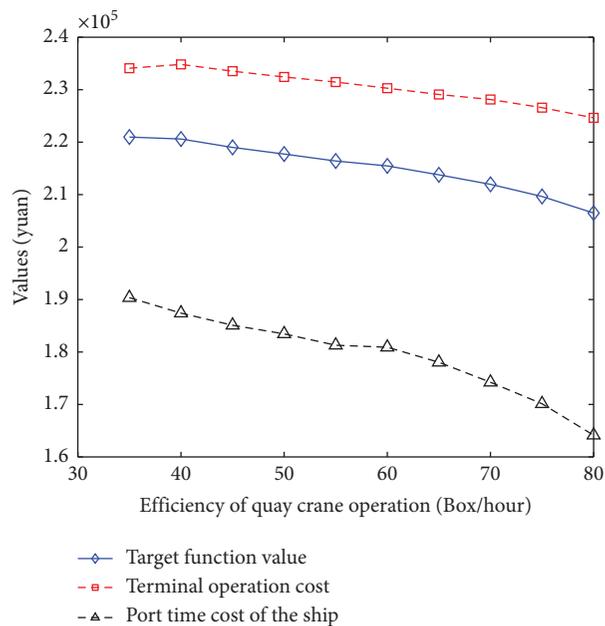


FIGURE 16: Sensitivity analysis diagram of QC operation efficiency.

TABLE 11: Comparison table of two algorithms.

Experiment no.	Target function value		Convergence algebra		Performance period/s	
	Genetic algorithm	Simulated annealing algorithm	Genetic algorithm	Simulated annealing algorithm	Genetic algorithm	Simulated annealing algorithm
1	222436	212534	340	649	297.776	1222.761
2	223065	216752	346	712	274.258	1211.997
3	224842	213358	377	676	254.700	1187.615
4	225101	212531	382	703	275.051	1187.146
5	224323	220124	374	635	310.042	1171.998
6	224786	218789	384	612	278.794	1189.324
7	225601	217329	392	683	291.274	1172.311
8	223978	214537	333	665	263.587	1183.126
9	226589	221108	405	692	262.832	1201.872
10	224589	219099	397	644	268.233	1191.113

7. Conclusions

This paper focuses on optimizing the berth and quay crane configuration of low-carbon container terminals. A multi-objective optimization model of berth and quay crane joint configuration considering carbon cost has been constructed. Taking berth and quay crane as a whole, it can more effectively reflect the relationship of mutual influence and mutual restriction, which is in line with the actual situation of terminal production organization. The model takes the minimum operation cost of the terminal and the minimum time cost of the ship at the port as the two objectives. The influence of carbon emission constraints on the quay crane configuration of the container terminal has been verified.

The results show that the optimization model of berth and quay crane configuration considering carbon emission constraints can affect the original configuration scheme. In order to achieve the purposes of energy saving and emission reduction, the container terminal can reduce the carbon emission value of handling unit throughput consumed during code head operation through the reconfiguration of berth and quay crane on the basis of the existing configuration. It can be seen that the objective function value of the joint scheme is 5.92% lower than that of the traditional scheme, the operation cost of the wharf is 2.90% lower than that of the traditional scheme, and the terminal operation cost of carbon emission constraints is 11.76% lower than that of no carbon emission constraints.

However, there are some limitations in this study. (1) The operation of the container terminal is complex and changeable, and the optimal model of joint configuration of berth and quay crane is calculated under ideal conditions. In the actual production, there are often special cases to break the assumptions of the model, or the failure of ships and quay cranes. The method of taking the emergencies into account in the model is a direction for future research. (2) At present, this paper only considers the front part of the terminal operation, but there are other parts of the container terminal operation, such as the field crane scheduling problem. In future research, it is necessary to consider the container terminal as a whole into the model. (3) In practice, the path problem of collecting cards is more complex. In this paper, the path problem of collecting cards has not been

considered in the model. Therefore, more time needs to be spent in the future to solve the above limitations to optimize the model and conduct more perfect research.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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