

Berth Allocation Optimization with Priority based on Simulated Annealing Algorithm**Wang Yuping¹, Hao Yangyang^{2,*}, Zhang Yuanhui³, Huang Youfang² and Gu Tianyi⁴**¹Information Office, Shanghai Maritime University, Shanghai 201306, China²Logistics Research Center, Shanghai Maritime University, Shanghai 201306, China³Construction and Installation Branch Company, Laigang Construction Co. Ltd, Laifu 271104, China⁴Department of Computer Science, University of New Hampshire, Durham, NH 03824, United States

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Abstract

Existing berth–quay crane (QC)-integrated allocation models aim to minimize the total time of vessels at port or the total cost of vessels' berthing and handling. The service fairness of vessels is considered, but service priority to VIP customers is overlooked, thereby causing poor service satisfaction from berthing operations. A multi-objective continuous berth allocation model with priority was proposed in this study to address this problem. The proposed model explored the relationship among penalty cost, fairness, and priority of VIP customers and designed weight vectors for penalty cost and fairness on the basis of an analysis of berth waiting time, preference berth allocation, and QC allocation. A two-factor neighbourhood searching strategy was then implemented for berthing sequence and berthing position through the simulated annealing algorithm with considerations for priority, thereby solving the model rapidly. Different parameter strategies in the model were compared and verified by experiments. Results demonstrate that the continuous berth allocation model with priority ensures fairness of overall service in berth allocation and priori berthing of VIP customers. The simulated annealing algorithm can be superior to other heuristic algorithms in solving the model. Conclusions in this study offer theoretical bases for berthing service satisfaction on the port side and are conducive to the optimization of berth allocation.

Keywords: complex berth–QC, fairness, VIP customer service, neighbourhood searching, simulated annealing algorithm

1. Introduction

The Port of Shanghai, the largest container port in the world, suffered serious congestion in April 2017. The congestion lasted for a long time and expanded to surrounding ports continuously. Experts in the industry determined that this congestion was the consequence of shipping alliance adjustment, severely overloaded operation in the port, and system adjustment. As important nodes in water transportation, container terminals are important in operation efficiency. The berth–quay crane (QC) allocation of vessels after arrival at port is a primary task of ports. A reasonable berthing plan can reduce the berthing time of vessels effectively and thereby relieve congestion at the port. Berthing operation at port benefits multiple parties. Therefore, the formulation of high-efficiency and high-service-fairness berthing plans has become the key research content in the academe.

Current studies on berth–QC integrated allocation aim to minimize the total berthing time of vessels and service cost of ports and construct an optimization model that uses berthing time, berthing position, and allocated QC quantity as key factors, thus formulating an optimal scheduling scheme for vessels and resource allocation. Most continuous berth optimization models maximize the utilization of QC and berths by constructing berth and QC allocation models [1] or minimize the berthing cost of vessels in terms of fuel

consumption and carbon emission [2]. These two methods emphasize the benefits of single parties and overlook the overall balance of benefits among different parties, general service fairness, and overall service satisfaction. A recent study constructed a continuous berth–QC allocation model that is based on fairness maximization [3]. This model emphasizes the benefit fairness between vessels and ports but overlooks the berthing priority of VIP customers in practical situations. Therefore, evaluating the benefit pursuit of vessels and ports realistically and comprehensively, improving service satisfaction, analyzing penalty costs and fairness of berthing operations, reflecting the appeal of overall service satisfaction of all parties, protecting the priority of VIP customers, and optimizing continuous berth arrangement are practically significant.

2. State of the art

Existing studies on continuous berth allocation optimization mainly concentrated on models and algorithms. Models were theories constructed with consideration for multiple factors, such as berth waiting time, berthing sequence, and quantity of QC allocation. Algorithms were processes of optimally solving the proposed models. With respect to modeling, all studies focused on optimizing the three key factors of berthing, namely, optimization of berthing time, optimization of berth allocation, and maximization of QC allocation. The optimization goals were generally set as minimization of berthing time and total operation cost of vessels and maximization of operation efficiency of ports. Fan [4] studied the continuous berth allocation of vessels

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under dynamic arrival conditions. A model that regards the minimization of total berthing time as the objective function was constructed and solved by the genetic algorithm. Zhu et al. [5] constructed a berth allocation model that treats the cost of deviation from the preference berth as the objective function and solved it by the genetic algorithm, thus reducing the extra cost of the deviation from the preference berth. Meisel et al. [6] expressed the handling time of vessels by the handling efficiency of QC and discussed the berth-QC integrated allocation problem. However, the authors did not consider the benefits for ship owners. Liang et al. [7] believed that the handling time of vessels is closely related to the handling efficiency of QC and discussed berth-QC combined allocation. Han et al. [8] studied a two-stage model. In the first stage, a space-time continuous berth allocation model of vessels was constructed. In the second stage, the operation efficiency of the model was increased by reducing the movement of the bridge crane and minimizing the crane distribution interval. Han et al. [9] studied the QC scheduling problem from the uncertainty in the arrival and operation times of vessels, proposed a mix integer model, and solved the optimal scheduling by the genetic algorithm. The above studies have implied that minimizing the berthing time of vessels is another goal of optimization. Gui et al. [10] conducted an integral study of QC allocation and berthing schedule. The researchers constructed a continuous berth allocation model that is based on priority and solved it by a hybrid genetic algorithm to achieve the shortest total berthing and workloading times of vessels. He [11] proposed an integrated simulation-optimization method from the perspective of energy saving and emission reduction to reduce the penalty cost caused by delayed departure and decrease energy consumption cost. Qin et al. [12] discussed the berth allocation model from the perspective of water level changes. Ursavas [13] proposed a new bridge crane that can solve the problem of ordinary QC restriction by power supply and operation control cables. This new bridge crane could move freely on the port but showed poorer handling efficiency than ordinary QC did. Therefore, the bridge crane can only be a supplementation under special situations. Emde et al. [14] designed a portable mobile QC that can be placed on vehicles to serve as supplementation to ordinary QC. Nam and Lee [15] proposed a QC with floating platforms that can operate at two sides of vessels simultaneously, thus increasing handling efficiency. Ku and Arthanari [16] suggested synchronous loading and unloading. This operation mode unloads goods from the vessels to the port and then loads goods to vessels, thus avoiding non-occupation operation. In summary, these studies have analyzed the penalty cost for delayed arrival, delayed departure, and deviation from the preference berth. However, the use of fairness in berth waiting, departure waiting, and QC quantity of vessels as the evaluation standards has rarely been explored.

With an increase in service level, the satisfaction and fairness of vessels and ports during service become important factors in scheduling optimization. Relevant studies have mainly used heuristic algorithms. Shan [17] constructed a dynamic continuous berth allocation model with priority by considering the effects of handling efficiency on berthing time and priority of vessels in actual operations. Golias et al. [18, 19] proposed grading berthing services for vessels according to priority agreements and solved the multi-objective optimization problem by the heuristic genetic algorithm. Sahin and Kuvvetli [20]

considered berth allocation as a continuous spatial allocation problem, proposed a dynamic berth arrangement strategy, and solved their model by the differential evolution algorithm. Kim et al. [21] constructed a hybrid integer linear programming model to study the continuous berth allocation problem and solved it by the simulated annealing algorithm on LINDO. Liu et al. [22] focused on secondary berth allocation after accidental interruption of vessel operation to optimize berth allocation, reduce cost, and increase service satisfaction. Golias and Portal [23] studied a robust berth arrangement strategy that aims to reduce the total service time span and average service time of vessels in the port. The authors defined the problem of secondary optimization and proposed the use of a heuristic algorithm to solve this problem. However, the overall description was ambiguous. Lee et al. [24] defined port as a continuous space and optimized it through the neighborhood searching algorithm. First-come-first-service, waiting time, and dislocation of vessels were considered in service strategies. Lai and Shih [25] studied the berth utilization in the Hong Kong International Terminals and found that the organization proposed the concept of berthing priority to enhance competitiveness. Akio Imai [26,27] introduced the Lagrange relaxation algorithm to guarantee the shortest total berthing time of vessels and analyzed the importance of berthing priority in port operation with consideration for service priority factors. Fan et al. [28] discussed the fair allocation of QC resources and constructed a berth-QC scheduling model that considers the minimization of total berthing time as the objective function. This model was solved by the improved genetic algorithm and verified by a case study. Wang et al. [3] discussed continuous berth allocation that is based on fairness maximization and proposed a three-factor neighborhood searching algorithm. The optimal solution was searched rapidly by the simulated annealing algorithm. However, the researchers neglected the berthing priority of VIP customers.

Berthing service involves the benefits of multiple parties; therefore, optimizing berth allocation by considering the benefit of only one party is disadvantageous for improving service satisfaction. Most existing optimization models for berth arrangement do not consider the general benefit balance and service satisfaction of VIP customers. The contradictions of berth allocation still exist. Hence, a multi-objective continuous berth allocation model with priority was constructed by the present work to achieve berthing fairness. The proposed model analyzes berth waiting time, berth location, QC resource allocation, and influencing factors of berthing priority. The model solves the benefit balance among different parties and service satisfaction of VIP customers.

The remainder of this study is organized as follows. Section 3 describes the problems and hypotheses, constructs the studying model, designs the simulated annealing algorithm, and defines the neighborhood searching strategy. Section 4 explains the experimental design and result analysis. Results are compared with those of the neighborhood searching algorithm. Section 5 concludes the study.

3. Methodology

Dispatchers formulate berthing plans according to relevant information and distribute berth and QC to vessels. Shipping companies desire the shortest time of vessels in port and

berthing at the preference berth. The port pursues the maximum container throughput and utilization of port resources. Therefore, berth-QC allocation optimization should distribute berth and QC resources reasonably according to arrival time, increase utilization, reduce the operation cost of the port, minimize berthing time, and improve customer service.

This study discussed the continuous berth arrangement problem. Vessels berth according to terminal markers. If the vessel length is less than the terminal length, then vessels are allowed to berth. Multiple vessels can be served simultaneously. In this study, fairness (that is, fairness of order, service time, and resource allocation and priority of VIP customers) of vessel service in the port was evaluated comprehensively according to expected arrival time (EAT), priority, and handling demands. A continuous berth allocation model was constructed.

This study cited the partial definition from the Study of Continuous Berth Allocation Algorithm based on Fairness Maximization of Wang and expanded the original model. Reasonable hypotheses were proposed.

(1) Each vessel must berth, and repeated berthing is not allowed.

(2) The arrival time of vessels is not earlier than the expected time. The starting time of vessel berthing must be later than the arrival time.

(3) Adequate QC resources are available to meet vessel berthing. Therefore, berthing time is only related to cargo carrying capacity.

(4) Many berthing units are divided continuously along the terminal. Many vessels can berth at the same time.

(5) To reduce distance between berths and rear storage yard, each vessel is assigned one optimal preference berth, and deviation from the preference berth will increase the operation cost.

(6) Each vessel has one priority attribute that represents the importance level of the VIP. The higher the attribute value, the higher the priority given to the berthing of the vessel.

Factors unrelated to this study are omitted.

3.1 BA model

3.1.1 Symbol descriptions

1) $sv = \{1, 2, \dots, sv_s\}$ is the set of vessels waiting for berth, where $v \in sv$.

2) $sp = \{1, 2, \dots, sp_s\}$ is the set of berth, where $p, \rho, \beta \in sp$.

3) $st = \{1, 2, \dots, st_s\}$ is the set of time quantum in one service period, where $t, \tau, \gamma \in st$.

4) e_v is the EAT of vessel v .

5) a_v is the total berthing time of vessel v , that is, the total container loading and unloading time of the vessel (per QC*h).

6) b_v is the length of vessel v .

7) d_v is the expected departure time (EDT) of vessel v .

8) s_v is the preference berth of vessel v .

9) c_v^1 is the penalty cost unit for the deviation from the preference berth of vessel v .

10) c_v^2 is the penalty cost unit for the delayed berthing of vessel v .

11) c_v^3 is the penalty cost unit for the delayed departure of vessel v .

12) l_v is the quantity of QC allocated to vessel v .

13) M is a sufficiently large positive integer.

14) w_v is the priority parameter of vessel v ; the higher this value, the higher the priority.

15) X_{vpt} is the operation sign of vessel v in position (p, t) in the space-time matrix. A value of 1 means that the vessel operates at this position.

16) Z_{vpt} is 1 if point (p, t) is the reference point; otherwise, it is 0. Reference point refers to the left bottom of the rectangle, that is, the leftmost position at the initial berthing time and berthing position.

17) $V_{v,t}$ is 1 if vessel v is operating at t ; otherwise, it is 0.

18) $U_{v,t}$ is 1 if vessel v berths at p ; otherwise, it is 0.

19) C_v is the spanning time of cargo loading and unloading.

20) BL_v is the leftward deviation length of vessel v from the preference berth.

21) BR_v is the rightward deviation length of vessel v from the preference berth.

22) TL_v is the delay between the actual arrival of vessel v and the EAT.

23) DL_v is the delay between the actual departure of vessel v and the EDT.

24) $B_v = \sum_{p,t} (Z_{vpt} \cdot p)$ is the occupied berth of vessel v .

25) $T_v = \sum_{p,t} (Z_{vpt} \cdot t)$ is the occupation time of vessel v .

26) $POS_{p,t} = \sum_v (Z_{vpt} \cdot v)$ means that point (p, t) is occupied by vessel v .

3.1.2 Objective functions and model

The objective function of the continuous berth-QC allocation model with priority is:

$$g = w_\theta \cdot \frac{\theta^{\max} - \theta}{\theta^{\max} - \theta^{\min}} + w_f \cdot \frac{f - f^{\min}}{f^{\max} - f^{\min}} \quad (1)$$

where f is the sum of functions f^1, f^2 , and f^3 in the model. f^{\max} and f^{\min} are the maximum and minimum values of the function. θ^{\max} and θ^{\min} are the maximum and minimum values of the fairness function. Penalty cost and fairness measures synthesize one independent objective function (g) through Equation (1). Under this circumstance, $w_\theta + w_f = 1$, $w_\theta \geq 0$, and $w_f \geq 0$.

(1) Penalty cost (f)

The optimization goal of berth-QC allocation covered two aspects. One was the optimization of service time. Vessels should berth as soon as possible after arrival, accomplish loading and unloading in the regulated time of shipping companies after berthing, and then depart on schedule. The other aspect was the optimization of berths. The berth should be as close as possible to the preference to reduce the movement time of containers from QC to the rear storage yard. These two aspects had to consider the priority given to VIP customers. These two goals established an objective function of minimizing total penalty cost, which involved the priority. This function aimed to increase the satisfaction of VIP customers, reduce the penalty cost of berthing, and

shorten the berth waiting time and delayed departure time. The objective function is defined by Equations (2)–(5), and relevant constraints are defined by Equations (6)–(24).

Minimize:

$$f = (f^1, f^2, f^3) \quad (2)$$

$$f^1 = \sum_v (BL_v + BR_v) c_v^1 \quad (3)$$

$$f^2 = \sum_v TL_v \cdot c_v^2 \cdot w_v \quad (4)$$

$$f^3 = \sum_v DL_v \cdot c_v^3 \cdot w_v \quad (5)$$

Constraints:

$$BL_v \geq B_v - S_v, \forall v \quad (6)$$

$$BR_v \geq S_v - B_v, \forall v \quad (7)$$

$$TL_v \geq T_v - e_v, \forall v \quad (8)$$

$$T_v \geq e_v, \forall v \quad (9)$$

$$DL_v \geq C_v - d_v, \forall v \quad (10)$$

$$C_v \geq V_{st} \cdot (t + 1), \forall v \quad (11)$$

$$\sum_v X_{vpt} \leq 1, \forall p, t \quad (12)$$

$$V_{vt} \leq \sum_p X_{vpt}, \forall v, t \quad (13)$$

$$V_{vt} \cdot M \geq \sum_p X_{vpt}, \forall v, t \quad (14)$$

$$U_{vp} \leq \sum_t X_{vpt}, \forall v, p \quad (15)$$

$$U_{vp} \cdot M \geq \sum_p X_{vpt}, \forall v, p \quad (16)$$

$$(\beta - \rho + 1) \leq \sum_{p, \sigma \geq p \geq 0} U_{vp} + M(2 - U_{v\sigma} - U_{v\sigma}), \forall v, \rho < \beta \quad (17)$$

$$(\gamma - \tau + 1) \leq \sum_{p, \gamma \geq t \geq \tau} V_{vt} + M(2 - U_{v\gamma} - U_{v\tau}), \forall v, \tau < \gamma \quad (18)$$

$$V_{vt} \leq \sum_{p, t \leq t} Z_{vpt}, \forall v, t \quad (19)$$

$$\sum_{p, t} Z_{vpt} = 1, \forall v \quad (20)$$

$$\sum_{p < \rho, t} X_{vpt} + \sum_{p \geq \rho + b_v, t} X_{vpt} \leq M(1 - \sum_t Z_{vpt}) \quad (21)$$

$$\forall v, \rho \geq 2, \rho \leq sps - b_v$$

$$\sum_{p > b_v, t} X_{vpt} \leq M(1 - \sum_t Z_{v,1,t}), \forall v \quad (22)$$

$$\sum_{p > sms - b_v, t} X_{vpt} \leq M(1 - \sum_t Z_{v, sms - b_k + 1, t}), \forall v \quad (23)$$

$$b_k - \sum_p X_{vpt} \leq M(1 - V_{vt}), \forall v, t \quad (24)$$

The penalty cost function is shown as Equation (2). The smaller the penalty cost, the better the fairness. This function covered the total cost for the deviation from the preference berth (Equation (3)), the total penalty cost for delayed berthing (Equation (4)), and the total penalty cost for delayed departure (Equation (5)). Equations (7) and (8) restrict the deviation distances from the preference berth. Equation (8) defines the delayed berthing time of the vessel. Equation (9) imposes the restriction that vessels can only berth after arrival at the port. Equation (10) shows the delayed departure time. Equation (11) determines that vessels can depart only after loading and unloading. Equation (12) restricts that each time-space point can be occupied by only one vessel. Equations (13) and (14) establish the relationship between $V_{k,j}$ and X_{kij} . Equations (15) and (16) establish the relationship between $U_{k,i}$ and X_{kij} . Equations (17), (18), and (19) ensure the time-space continuity of berth occupation by vessels. Equation (20) determines that one vessel can occupy only one time-space point at a time. Equations (21), (22), (23), and (24) determine that grids in the rectangle are valued 1 and non-occupied grids out of the rectangle are valued 0.

(2) Fairness measures (θ)

The priority of vessel berthing is expressed by w_v . The default value of w_v is 1. The higher the value, the higher the priority. The priority was linearly related to delayed berthing and departure times, which are against service fairness.

Vessels are ordered according to EAT as follows: $e_1 \leq e_2 \leq \dots \leq e_{svs}$. The service time of vessel v is calculated by $\Psi_v = C_v - T_v, v \in sv$. By arrival time, the basic fairness of berthing order is as follows:

$$\theta(\pi) = \frac{\sum_{n < m} (I(\pi_n^a) \leq I(\pi_m^a)) \wedge (e_{\pi_n} \leq e_{\pi_m})}{(svs + 1)svs / 2} \quad (25)$$

The order of vessels that are waiting for berths in the port service system was defined as π . π^a and π^d were generated according to EAT and EDT. The element orders of π^a and π^d are $\pi^a = \langle \pi_1^a, \pi_2^a, \dots, \pi_{svs}^a \rangle$ and $\pi^d = \langle \pi_1^d, \pi_2^d, \dots, \pi_{svs}^d \rangle$. On this basis, the fairnesses of delay against EAT and EDT were explored.

Delay from EAT:

$$\theta_{da}(\pi) = \frac{\sum_{n+1=m} ((I(\pi_n^a) \leq I(\pi_m^a)) \wedge (a_n \leq a_m)) \cdot w_v}{svs - 1} \quad (26)$$

Delay from EDT:

$$\theta_{dd}(\pi) = \frac{\sum_{n+1=m} ((I(\pi_n^d) \leq I(\pi_m^d)) \wedge (a_n \leq a_m)) \cdot w_v}{svs - 1} \quad (27)$$

Fairness of berth arrangement was discussed according to whether the berth was a preference one.

Non-preference berth:

$$\theta_{rd}(\pi) = \frac{\sum_{n < m} ((DL(\pi_n^a) \leq DL(\pi_m^a)) \wedge (a_n \leq a_m))}{(svs + 1)svs / 2} \quad (28)$$

Preference berth:

$$\theta_{r\psi}(\pi) = \frac{\sum_{n < m} ((\psi(\pi_n^a) \leq \psi(\pi_m^a)) \wedge (a_n \leq a_m))}{(svs + 1)svs / 2} \quad (29)$$

The overall fairness function is the sum of the above fairness functions.

$$\theta(\pi) = \sum_* (w_* \cdot \theta_*(\pi)) \quad (30)$$

3.2 Simulated annealing algorithm

The simulated annealing algorithm was discussed in the Study of Continuous Berth Arrangement based on Fairness Maximization. This heuristic algorithm simulates the physical annealing process, which is composed of the heating, isothermal, and cooling processes. This algorithm is extremely effective in obtaining the optimal solution to continuous berth-QC allocation. The simulated annealing algorithm is different from other algorithms because it accepts new states with a certain probability, thus avoiding local optima.

In the simulated annealing algorithm, a new solution is mainly generated by the neighborhood searching algorithm. First, the neighborhood searching algorithm expands the searching range by changing the neighboring domain structure set systematically and finds the locally optimal solution. Second, the searching range is expanded again by changing the neighboring domain structure set on the basis of the locally optimal solution, and another locally optimal solution is determined. In this study, the neighborhood searching algorithm was divided into two stages. The first stage involved arranging the berthing time, and the second stage involved finding the best berth position.

3.2.1 Strategy of neighboring domain generation

In this study, the neighborhood searching algorithm required several parameters.

(1) Set of vessels (sv), set of berths (sp), and set of available berthing times (st)

(2) Relevant information of vessel v : EAT (e_v), working hours of QC (a_v), vessel length (b_v), EDT (d_v), deviation from the preference berth (s_v), penalty cost unit for the deviation from the preference berth (c_v^1), penalty cost unit for delay from EAT (c_v^2), penalty cost unit for delay from EDT (c_v^3), and priority of vessel (w_v)

These parameters were integrated into the berth allocation function. The berthing time (T_v) and berth positions (B_v) of all vessels were generated after m_p iterations.

Two neighborhood domains were generated using the verified interchange sequence. The indices of two vessels in the interchange sequence (π) are i_1 and i_2 . Under this circumstance, the distribution of i_2 is $i_2 \sim N(i_1, b^2)$, where $b = \max\{i_1, sv - i_1\}$.

The normal distribution $N(A, B^2)$ can be generated by two uniform distributions $a \sim U(0,1)$ and $b \sim U(0,1)$. $x = A + B(\sqrt{-2 \ln a}) \sin(2\pi b)$ when $x \sim N(A, B^2)$.

i_1 is calculated by random positioning. However, the random positioning has to be verified again when w_v is involved. First, two adjacent vessels in the order (π) are defined as v and v_n , whose values are rB_v and rB_{v_n} under the corresponding value of rB . According to the relative positioning strategy, the position of vessel v is expressed by B_v and the position of v_n (B_{v_n}) is expressed by $B_{v_n} \leftarrow (B_n + b_v + rB_{v_n} - BL_v + BR_v)$.

The acceptable adjustment probability of berth position is expressed by m_p , where $0 \leq m_p \leq 1$.

A random value was generated in the range of $[0,1]$ whenever the vessel moved to the preference berth. If this random value was smaller than m_p , then the adjustment was accepted.

3.2.2 Cooling scheduling and initial temperature T_0

Cooling scheduling is the cooling management table from one high-temperature state (T_0) to the low-temperature state in the simulated annealing algorithm. In this study, the classical cooling mode was selected. The temperature at t

was supposed to be $T(t)$, $T(t) = \frac{T_0}{\ln(1+t)}$. This classical

cooling mode makes the simulated annealing algorithm converge at the globally minimum point.

The experiment demonstrated that the higher the initial temperature, the higher the probability of gaining a high-quality solution. However, computation consumed considerable time. Therefore, the initial temperature should be determined by compromises between optimization quality and efficiency. Common approaches include uniform sampling and random sampling. Here, 50 groups of states were generated randomly, and the maximum difference of target values between two states ($|\Delta_{\max}|$) was determined.

The initial temperature was determined according to $|\Delta_{\max}|$

on the basis of function $T_0 = \frac{-\Delta_{\max}}{p_r}$, where p_r is the initial probability of acceptance.

4 Result analysis and discussion

4.1 Experimental design

This study applied the random data in Table 1 as the experimental data to verify the accuracy of the model and the validity of the proposed algorithm. In Table 1, 18 vessels are waiting for berthing, and 600 length units of available berths exist. A contrast analysis on objective function values under different strategies and parameters was conducted.

(1) Objective function: The smaller the objective function, the more optimal the berth allocation and the better the fairness of the overall benefit distribution.

(2) Delayed berthing time of vessel with priority: The priority strategy became increasingly effective as 0 was approached. Vessels could berth on schedule.

(3) Iteration times at minimum objective function: The fewer the iterations, the higher the reasonability of the parameter and the higher the solving efficiency of the algorithm.

Experimental contents of this algorithm mainly include the following.

(1) The minimum objective function value was estimated and the iteration times were recorded to evaluate the overall fairness of the model and solving efficiency of the algorithm.

(2) The objective function values and delayed berthing time of a vessel with and without priority were recorded to analyze the effects of priority on the berthing of the vessels.

(3) m_d was determined in the range of [1,100] at an adjustment interval of 5. A reasonable value range of m_d was observed.

(4) The probability of berth position acceptance was adjusted in the range of [0,1] to evaluate its impacts on the solving efficiency of the algorithm.

(5) The efficiencies of the neighborhood searching algorithm and the simulated annealing algorithm with priority of vessels were compared. The condition for terminating iterations in the neighborhood searching algorithm was set as 3,000 iterations. The condition for terminating iterations in the simulated annealing algorithm was set as 1,000 iterations or over 30 rejections of the new solution. The solving qualities and efficiencies of the two algorithms were compared.

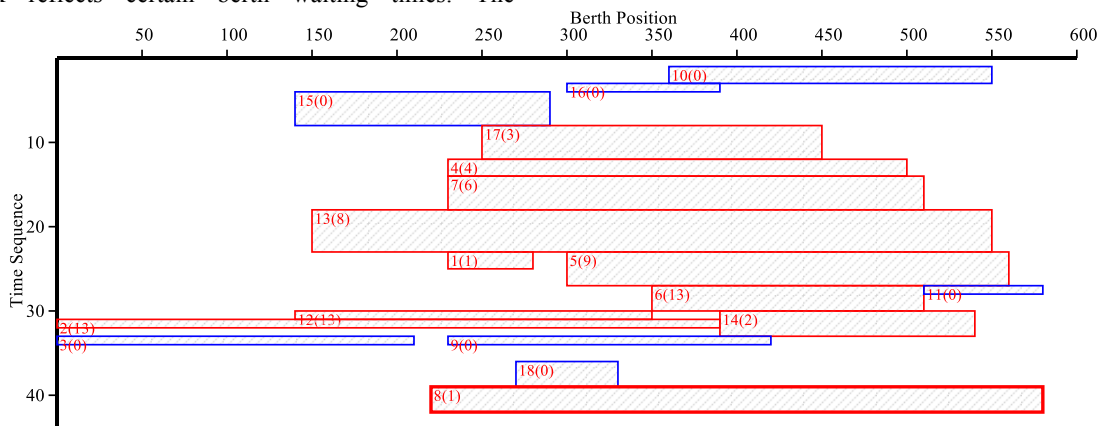
Table 1. Data of original berthing vessels

Vessel	Length	Arrival Time	Cranes	Workload(QC*h)	Preferred Berth Position	EDT	Priority
1	347	13	9	4	226	24	1
2	382	13	10	21	15	23	1
3	169	13	4	6	350	27	1
4	219	8	5	20	37	21	1
5	175	39	4	3	238	51	1
6	64	13	2	5	212	23	1
7	216	15	5	20	137	28	1
8	199	19	5	20	333	30	99
9	344	12	9	12	136	25	1
10	344	18	9	6	29	33	1
11	259	5	6	20	183	15	1
12	248	34	6	16	145	44	1
13	327	21	8	18	273	32	1
14	92	40	2	5	219	50	1
15	186	13	5	8	153	23	1
16	318	36	8	12	249	48	1
17	161	13	4	9	308	25	1
18	301	33	8	24	142	47	1

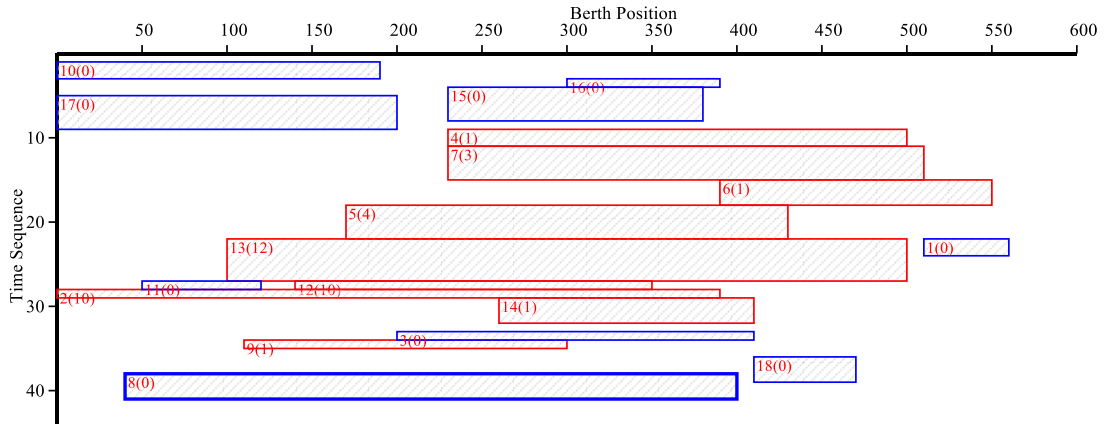
4.2 Experimental results and analysis

The results of continuous berth arrangement based on data in Table 1 are shown in Fig.1. Numbers in the vessel rectangle reflect the serial number of vessels and the waiting time. The upper left corner shows the berth position and berthing time of vessels. Width refers to the length of vessels, and height is the operation time of the vessels after berthing. The blue border reflects zero berth waiting time, and the red framework reflects certain berth waiting times. The

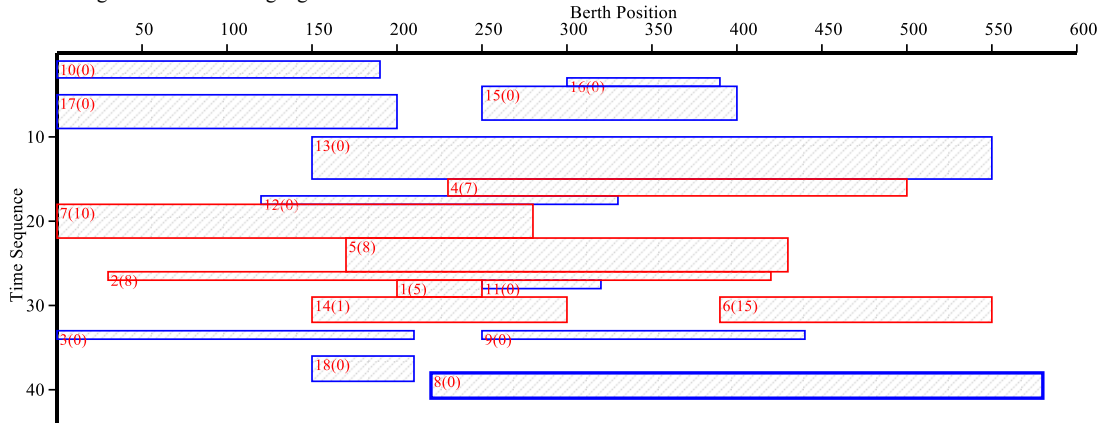
rectangle with thick borders shows certain priorities of the vessels. Fig.1(a) depicts a random solution. Fig.1(b) illustrates the optimal solution of the neighborhood searching algorithm. Finally, Fig.1(c) shows the optimal solution of the proposed algorithm and demonstrates that this solution optimized the berth position and waiting time of the vessel.



(a) Random solution



(b) Solution of neighborhood searching algorithm

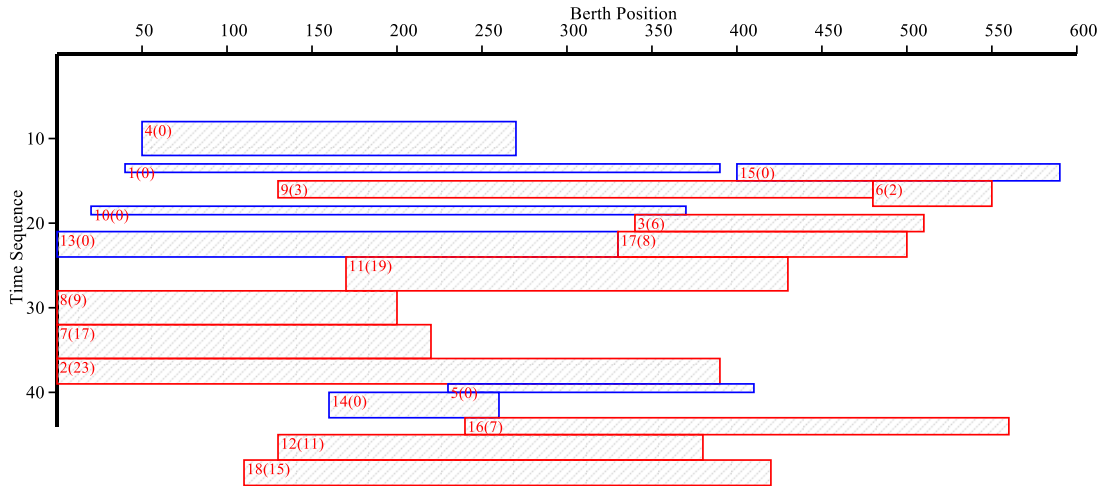


(c) Solution of simulated annealing algorithm

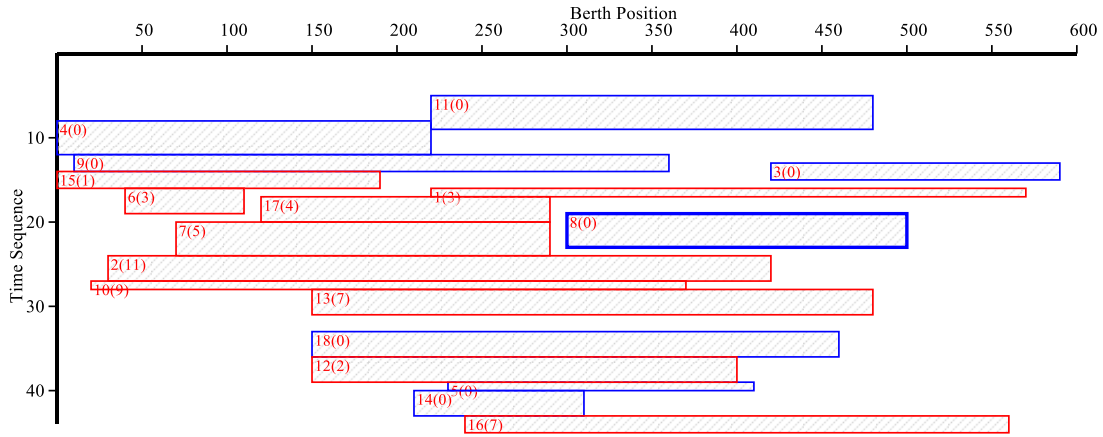
Fig. 1 Comparison of continuous berth allocation among different algorithms

The berth allocation results of the 8# vessel in the simulated annealing algorithm with and without priority are shown in Fig.2. The berth allocation of the 8# vessel in the simulated annealing algorithm without priority is shown in Fig.2(a), in which the 8# vessel has to wait for 9 unit time before berthing. The berth arrangement of the 8# vessel in

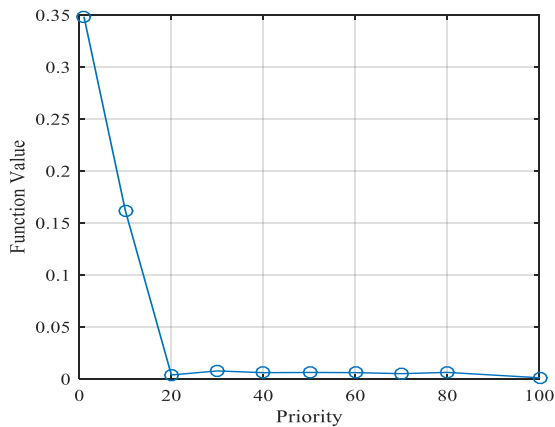
the simulated annealing algorithm with 99 priority is shown in Fig.2(b), in which the 8# vessel can berth immediately upon arrival. This comparison shows that important customers could be served first in a long queue by increasing their priority.



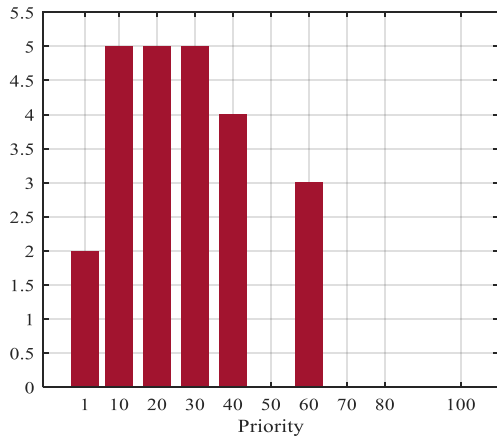
(a) No priority to 8# vessel



(b) Priority to 8# vessel
Fig. 2 Comparison of optimal scheduling programs with and without priority



(a) Objective function values under different degrees of priority



(b) Delay time under different levels of priority
Fig. 3 Influence of priority on berth allocation

The berth allocation under different levels of priority is shown in Fig.3. Fig. 3(a) depicts that a high priority was conducive to increasing the probability of prompt service. In Fig.3(b), vessels with priority >70 can berth immediately upon arrival. The independence of the optimal objective function value from priority was thus validated. Priority was a given condition and the premise to obtain the optimal solution. The objective function values under different levels of priority were incomparable. In practical port operation, only VIP customers with >70 priority can be served immediately after arrival.

The process of the simulated annealing algorithm is shown in Fig.4. The solution sequence was generated according to iteration times, which recorded the acceptable minimum, thus forming the sequence of acceptable values. The minimum of this sequence was the solution of the simulated annealing algorithm. In this experiment, the optimal solution (0.0025) was acquired at nearly 50 iterations. On this basis, the overall fairness was determined.

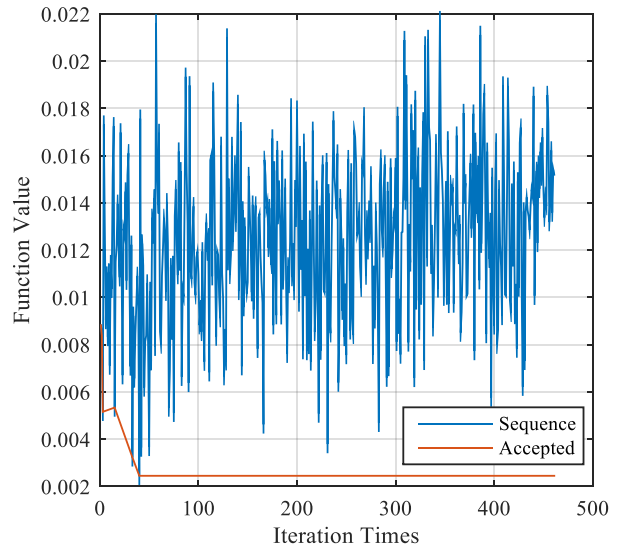


Fig. 4 Iteration process of simulated annealing algorithm

In the solving process of the simulated annealing algorithm, m_d refers to the iteration times in the solving process. m_d is a key parameter that influences the solving efficiency of the algorithm. Fig.5 indicates that with an increase in m_d in the range of [1,100], the overall reduction of the objective function value was insignificant. However, the objective function value with priority fluctuated considerably. Therefore, the reasonable value range of m_d was determined to be within [20,100] with reference to the original algorithm. Moreover, the range of m_d was insensitive to priority. In actual calculation, any value in the range of [20,100] is acceptable and will not affect the solution.

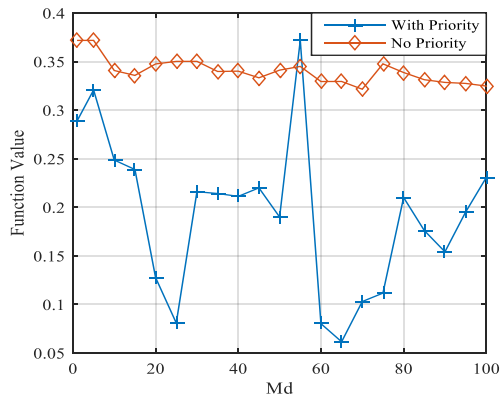


Fig. 5 Effect of priority on m_d

Solutions from the neighborhood searching and simulated annealing algorithms are shown in Fig.6. Significant differences were observed between these two algorithms. The optimal solution of the neighborhood searching algorithm was kept at 0.005 after 1,000 iterations. Meanwhile, the solution of the simulated annealing algorithm reached 0.004 after 190 iterations. The simulated annealing algorithm could produce the optimal berth allocation faster. The berth allocation based on the simulated annealing algorithm achieved better fairness and saved 5/6 of time than that based on the neighborhood searching algorithm did.

5. Conclusions

Reducing the time of vessels stay in port and increasing port operation efficiency can only provide benefit for single party but for every party. To improve the service satisfaction of VIP customers, and balance the benefits of every party, this study established a multi-objective continuous berth-QC integrated allocation model with priority and based on service fairness. The model involved weight coefficients of priorities and fulfilled the priori berth allocation of VIP customers. The following conclusions could be drawn:

(1) VIP customers can gain berth allocation and preference berth as much as possible by increasing the priority parameter, thus enhancing the service satisfaction of these customers.

(2) The simulated annealing algorithm is applicable to the fast solving of the berth allocation model with priority. This algorithm can achieve the optimal solution after only a few iterations and has higher efficiency than other heuristic algorithms have.

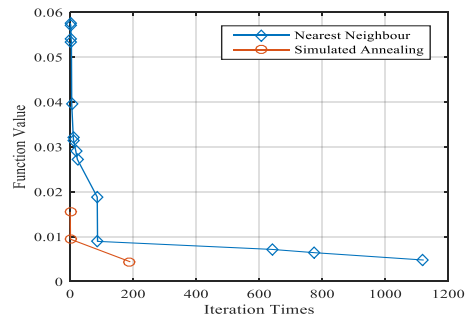


Fig. 6 Comparison between neighborhood searching and simulated annealing algorithms

The constructed multi-objective continuous berth-QC allocation model with priority ensures the service priority of VIP customers. However, theoretical support for the setting of priority weights is lacking. Future studies should discuss the relationship between priority weight and number of vessel sequences and the influence of this relationship on overall service fairness in berth allocation to further increase the accuracy and matching degree of the model in practical situations.

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