Research on Continuous Berth-Quay Crane Joint Allocation Optimization Problem Based on Improved Multi-Population Genetic Search Algorithm

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Abstract. The utilization rate of port berth shorelines is directly related to the port's operational efficiency. A reasonable berthing plan can improve port operational efficiency and thereby reduce port operational costs. This paper first establishes a multi-objective optimization model based on the ship's preferred berth cost, ship delay departure cost, ship delay arrival cost and quay crane scheduling cost, and then designs an improved multi-population genetic search algorithm (Improved multi-population genetic search algorithm, IMPGA). By changing the control parameters of the genetic algorithm to increase the evolutionary diversity of the population, the tabu search algorithm is used to randomly select outstanding individuals of the population for tabu search. Under the conditions of the same length of dock berth coastline and the same ship arrival data, a numerical simulation experiment was designed. The results show that the improved multi-population genetic search algorithm can solve the joint allocation problem of continuous berths and quay cranes, and this algorithm is better than the static quay cranes. The optimization effect of scheduling is better.

Keywords: continuous berth-quay crane joint allocation; tabu search algorithm; multi-population genetic search algorithm

1 Introduction

In the process of international trade transportation, container transportation is an extremely important method. As the container throughput of ports continues to increase, there is a shortage of container ship berths in the port. Container ships need to wait a lot of time to berth at the port, which brings to corresponding losses. Effectively adjusting the resource allocation of berths and quay cranes, improving port resource utilization, and enhancing port service capabilities are issues of great concern to container ports.

Regarding the berth-quay crane allocation problem, domestic and foreign scholars have conducted a large number of studies, mainly including berth allocation and berth-quay crane allocation. Regarding the issue of berth allocation, Nishimura[1] proposed that different ships can be docked in the same berth at the same time, and there

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is a preliminary idea of continuous berth allocation. Ganji et al.[2] proposed that the ship's berth preference affects the loading and unloading operation time of the ship in the port, and established a mathematical model considering the ship's berth preference. Frojan and Alvarez et al.[3] extended the research scope from one terminal to multiple terminals and considered the comprehensive cost in the berth allocation process. In the process of studying continuous berth allocation, He Junliang[4] established a dynamic berth allocation model based on integer programming. Tang Shixuan et al.[5] aimed to minimize the ship's waiting time cost, departure delay time cost and berth offset cost, and proposed a mixed integer programming model that considers multiple types of interference events. Regarding the berth-quayside crane allocation problem, Lee et al.[6] comprehensively considered the mutual constraints of the quayside crane within the ship when the quayside crane was performing services, and solved it through a genetic algorithm. Giallombardo et al.[7] combined the quay crane and continuous berth allocation problems to establish a mathematical model and used a tabu search algorithm to solve it. In the process of studying the quay crane allocation problem, Iris[8] took into account the ship's berth preference and the impact of other quay crane work on the loading and unloading rate of the quay crane, and used a tabu search algorithm to solve the problem. Hao Yangyang et al.[9] studied the problem of ship berth allocation and quay crane allocation of service ships, and designed a two-layer genetic algorithm to solve it. Song Yunting et al.[10] established a multi-objective mathematical model for the problem of container ship berth scheduling and quay crane dynamic scheduling, with the goal of meeting the latest departure time and the lowest terminal operation cost. When Zhang Xiaoli et al.[11] studied the berth-quay crane allocation problem, they decomposed the overall research problem into the berth allocation problem and the quay crane scheduling problem, and designed a nested heuristic algorithm to solve it.

Among the algorithms for solving continuous berth-quay crane allocation, the genetic algorithm is the most widely used algorithm. However, the genetic algorithm has the problems of slow iterative optimization efficiency and premature convergence. This paper takes the container terminal berth-quay crane as the research object to establish a mathematical model, draws on the tabu search idea to design an improved multi-population genetic search algorithm to solve the continuous berth-quay crane allocation problem, and finally compares the algorithm to verify the performance effect.

2 Problem Description and Model Building

2.1 Problem Description

The continuous berth-quay crane allocation problem is shown in Fig. 1. The For ships, a1 to a8 represent quay cranes. The length of the matrix is the length of the ship, and the width of the matrix is the berthing time of the ship. For example, the berthing time of ship S1 is [t1 t2], and the length of the berth occupied is [x1 x2]. Among them, the area of rectangles S1, S2 and S3 cannot There are crossover parts. The distribution form of the quay cranes is that they are lined up on the port coastline.

The numbers of the quay cranes serving a ship must be consecutive and must meet the minimum and maximum number of quay crane constraints for the ship to call the port, such as quay cranes a2 and a3. Assigned to ship S1 for service.

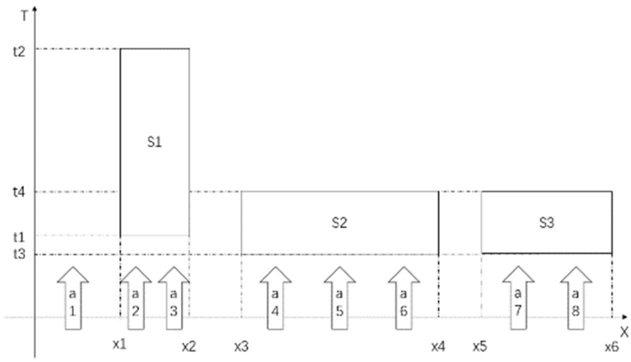

Fig. 1. Schematic diagram of berth-quay crane allocation

2.2 Model Building

This article aims to reasonably allocate berths and quay cranes for loading and unloading ships at the port, so as to minimize the total cost of port operations during the planning period. The operating costs of the port include: the scheduling cost of the quay crane, the berthing waiting cost of the ship, the increased cost of the ship deviating from the preferred berth, and the increased cost of the ship's delayed departure from the port.

Model Assumptions: ① The arrival time of the ship is fixed, and there is no delayed arrival or early arrival; ② The loading and unloading operation time of the ship is only related to the distance from the target berth location, and in the model, the loading and unloading rates of the container ship are consistent , regardless of the rummaging operation; ③ Each ship is only served once and cannot be moved; ④ The impact of berth shoreline water depth on berthing is ignored; ⑤ The process of continuous berth allocation includes reserved berths for other The safe distance used by ships; ⑥ does not consider the safe distance and its impact on the operation between quayside bridges, as well as the bay allocation; ⑦ does not consider the positional constraints of quayside bridges serving the same ship within the same time period.

Parameter Description:

$cb1$: The cost impact coefficient of ship i deviating from the ship's preferred berth, unit: 100 boxes/¥; $cb2$: The additional cost per unit time caused by ship i exceeding the expected departure time, unit: ¥/hour; $cb3$: Ship i because The additional cost per unit time caused by delayed entry into the port, unit: ¥/hour; $cb4$: the cost incurred by the port for each dispatch of the quay crane, unit: ¥/time; LB: the shoreline length of continuous berths; k_i: any The berthing position of ship i; p_i: the preferred berth of any ship i; w_i: the time for ship i to complete the loading and unloading tasks at the port; l_i: the expected departure time of ship i; d_i: the expected arrival time of ship i; E_i: the berthing operation time of any ship i; c_i: the length of any ship i; z_i: the actual packing volume of ship i; v_k: the actual loading and unloading speed of quayside crane k; t: the time period of quayside crane serving ships; m: a sufficiently large positive number; Q: the collection of quay cranes on the continuous shoreline; V: the collection of ships preparing to berth; tib_i: the actual berthing operation time of ship i; w_{iqt}: The number of times ship i dispatches quay cranes in any period of time t; x_{iqt}: ship i In time period t, if quayside crane q serves ship i, it is 1, otherwise it is 0; o_{tq}: the location of quayside crane q in time period t; q_{it}: whether quayside crane q is assigned to ship i in time period t , if assigned, it is 1, otherwise it is 0; $qmin_i$: the minimum number of quayside crane services for ship i; $qmax_i$: the maximum number of quayside crane services for ship i; f_{ti}: any time period t, if the ship If i has a quay crane for service, it is 1, otherwise it is 0; θ_{ij}: If the actual berthing time of ship i is later than the actual unberthing time of ship j, it is 1, otherwise it is 0; δ_{ij}: If the berthing position of ship i is greater than the position of ship j, it is 1, otherwise it is 0. Build the Model:

$$min\,Z = \sum_{i=1}^{V}(cb1 * |\,k_i - p_i| + cb2 * \max\big((w_i - l_i), 0\big) + cb3 * (tib_i - d_i)) + \sum_{q=1}^{Q}\sum_{i=1}^{V}\sum_{t=1}^{h} cb4 * w_{iqt} \tag{1}$$

$$k_i + \frac{c_i + c_j}{2} \leq k_j + m * \big(1 - \delta_{ij}\big), i \neq j, \forall i \in V, \forall j \in V \tag{2}$$

$$tib_i \geq d_i, \forall i \in V \tag{3}$$

$$w_i = tib_i + E_i, \forall i \in V \tag{4}$$

$$E_i = \sum_{t=1}^{T} f_{ti}, \forall i \in V \tag{5}$$

$$f_{ti} = \min\big(1, \sum_t^T \sum_{q=1}^{Q} x_{iqt}\big), \forall i \in V, \forall q \in Q, \forall t \in T \tag{6}$$

$$w_j \leq tib_i + m * \big(1 - \theta_{ij}\big), i \neq j, \forall i \in V, \forall j \in V \tag{7}$$

$$k_i + \frac{c_i}{2} \leq LB, \forall i \in V \tag{8}$$

$$k_i - \frac{c_i}{2} \geq 0, \forall i \in V \tag{9}$$

$$\theta_{ij} + \theta_{ji} + \delta_{ij} + \delta_{ji} \geq 1, i \neq j, \forall i \in V, \forall j \in V \tag{10}$$

$$\theta_{ij} + \theta_{ji} \leq 1, i \neq j, \forall i \in V, \forall j \in V \tag{11}$$

$$\delta_{ij} + \delta_{ji} \leq 1, i \neq j, \forall i \in V, \forall j \in V \tag{12}$$

$$\sum_{t=1}^{T}\sum_{q=1}^{Q} x_{iqt} * v_t \geq z_i, \forall i \in V \tag{13}$$

$$f_{ti} * qmin_i \leq \sum_{q=1}^{Q} x_{iqt} \leq f_{ti} * qmax_i, \forall i \in V \tag{14}$$

$$q1_{it} \geq q_{it} + q'_{it} - 1, \forall t \in T, \forall i \in V, q < q', q1 = q + 1 \tag{15}$$

$$o_{tq} < o_{tq'} \quad q、q' \in Q, t \in T, q < q' \tag{16}$$

$$x_{iqt} = \sum_{q=1}^{Q} q_{it} \ , \forall\, i \in V, \forall t \ \in T \tag{17}$$

$$\theta_{ij}\ ,\theta_{ji} \ \in \{0,1\}, i \ \neq j\ , \forall\ i \ \in V, \forall\ j \ \in V \tag{18}$$

$$\delta_{ij}\ ,\delta_{ji} \ \in \{0, 1\}\ , i \ \neq j\ , \forall\ i \ \in V, \forall\ j \ \in V \tag{19}$$

$$\sum_{i}^{V} q_{it} \ \leq 1\ , \forall\ q \ \in Q \tag{20}$$

$$q_{it} \ \in \{0,1\}, \forall\ i \ \in V\ , \forall\ q \ \in Q \tag{21}$$

$$k_i \ \in \ N^+, \ \ o_{tq} \ \in \ N^+, \ \ \forall i \in V, \forall q \in Q, \forall t \in T \tag{22}$$

Among them: Formula (1) represents the objective function; Formula (2) and Formula (7) represent the berthing position relationship and time relationship between ships respectively; Formula (3) represents that the ship berthing operation time should be after the ship arrival operation time; Equation (4) represents the ship's departure time; Equation (5) represents the ship's berthing operation time; Equation (6) determines whether the ship is carrying out loading and unloading operations; Equations (8) and (9) indicate that the ship should berth within the existing berth shoreline; Equation (10) to Equation (12) indicate that the ship and the ship The relationship between berthing operation time constraints and space constraints; Equation (13) indicates that the number of containers for loading and unloading operations completed during the planning period must be greater than the number of planned loading and unloading of the ship itself; Equation (14) indicates the maximum and minimum number of ship quay cranes Constraint conditions; Equation (15) indicates that the quayside crane allocation must be continuous; Equation (16) indicates that the quayside crane position with a smaller quayside crane number must be smaller than the quayside crane operating position with a larger quayside crane number; Formula (17) represents the number of quayside crane services ; Formula (18) and formula (19) represent the variable value range of the time and position constraint relationship between ships; formula (20) and formula (21) represent that a specific quay crane can only serve one ship in a time period; formula (22) indicates that the ship position and the quay crane position are positive integers.

3 Design and Analysis of Algorithms

By setting different genetic algorithm control parameters for multiple populations, the population can evolve in a diversified direction; by selecting the best individuals and replacing them with the worst individuals from other populations, the synergy of population evolution can be maintained; Increase the number of chromosomes for tabu search, and randomly select outstanding individuals in each subpopulation to perform local tabu search operations, allowing the algorithm to jump out of the local optimum, quickly converge, and find the optimal result.

3.1 Algorithmic Process Framework

The algorithm framework of this article is shown in Fig. 2. It mainly includes dividing groups, calculating the fitness of chromosomes, sub-population chromosome crossover operations, sub-population chromosome mutation operations, infeasible repair operations, and exchange operations of excellent chromosomes between populations. Each generation consists of a tabu search operation that selects a certain number of individuals.

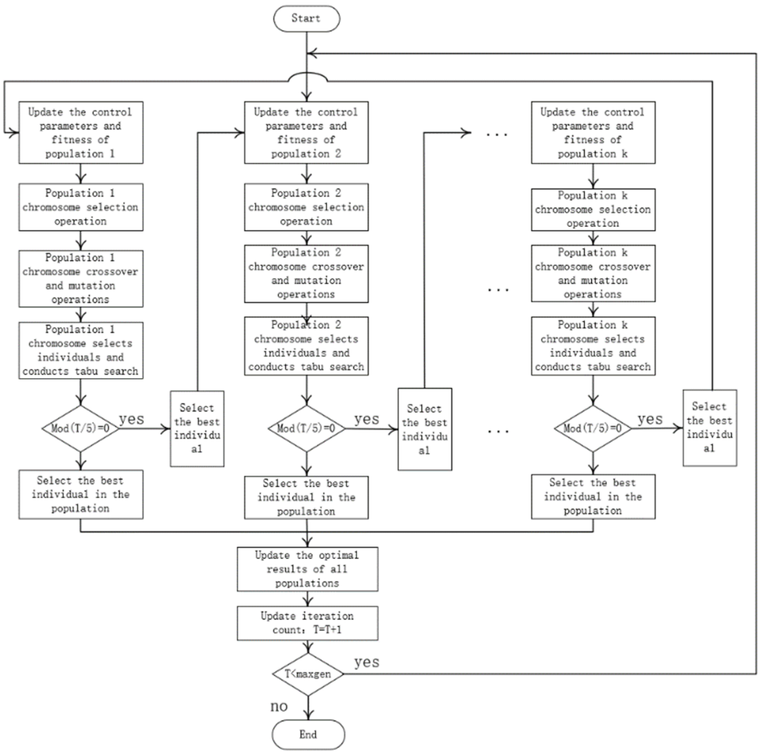

Fig. 2. Algorithm flow framework diagram

3.2 Introduction to Algorithm Process

Initial Chromosomes and Population Partitioning.

The chromosome model in this article is a five-layer chromosome coding structure. The first layer represents the number of the ship serving, the second layer represents the corresponding position of the ship, the third layer represents the berthing time of the ship, and the fourth and fifth layers represent the service. The minimum and maximum quay crane number of the ship. Divide a single population into multiple populations, assuming that the total number of populations is $Sizepop$, divided into m sub-populations, and the number of individuals in each sub-population is $Sizepop/m$.

Fitness Function Setting and Selection Operation.

In this paper, the individual fitness function is set as formula (23), and then the selection operation is performed through roulette. The probability of an individual being selected is calculated as formula (24).

$$fitness(i) = 1/sum\_cost(i) \tag{23}$$

$$R1(i) = fitness(i)/\sum_{i=1}^{sizepop} fitness(i) \tag{24}$$

Chromosome Crossover and Mutation Operations.

The crossover probability calculation method of sub-population m is shown in formula (25), and the mutation probability calculation method is shown in formula (26). $pm(m)$ and $pc(m)$ are respectively the crossover probability and mutation probability of subpopulation m under the current iteration number; $pmb(m)$ and $pme(m)$ are respectively the initial crossover probability and final crossover probability of sub-population m; $pcb(m)$ and $pce(m)$ are the initial mutation probability and final mutation probability of subpopulation m respectively; i is the current iteration number; $maxgen$ is the maximum iteration number.

$$pm(m) = pmb(m) - \frac{i}{maxgen} * (pmb(m) - pme(m)) \tag{25}$$

$$pc(m) = pcb(m) - \frac{i}{maxgen} * (pcb(m) - pce(m)) \tag{26}$$

Chromosome Tabu Search Operation.

Determine the length of the tabu search table L_tabu for tabu search, determine the algebra $Gmax$ of tabu search, and determine the number of neighborhood solutions Ca. Traverse all individuals in the subpopulation in turn and generate a random number r1. If r1<R_ts, use this chromosome as the initial solution, where $R\_ts = 0.05 + (i/maxgen) * (0.1 - 0.05)$. Neighborhood solutions are then generated. A judgment is made after each round of iterative neighborhood search, and terminates when the maximum number of iterations is reached.

Chromosome Gene Exchange.

The overall population is divided into three sub-populations, and gene exchange between populations is carried out every five generations. The best individuals of the sub-populations are completely introduced into other individuals, and the worst individuals introduced into the population are deleted.

Chromosome Repair Operations.

The chromosome repair operation is performed by shifting the chromosome ship position at the non-crossing position left and right. If it cannot be repaired, the chromosome repair operation is performed by delaying the berthing time of the ship.

4 Algorithm Case Results and Analysis

4.1 Initial Data

Assume that 12 container ships are ready to berth during the ship berth-quayside crane planning period. The length of the berth shoreline is 1,400 meters, the number of quayside cranes is 18, the loading and unloading rate of quayside cranes is 40 boxes/minute, and the scheduling of quayside cranes cost is 100¥/time. The specific information of each ship is shown in Table 1.

Table 1. Ship information sheet

Ship number	Ship length	Estimated arrival time/ minutes	Estimated departure time/ minutes	Minimum number of quay crane services	Maximum number of quay-side crane services	Berth preference/ meter	Container volume	Deviation from preferred berth cost (¥/meter)	Delayed berthing costs	Delayed departure costs
V1	210	0	240	3	6	185	900	12	12	13
V2	300	0	240	5	7	400	800	6	14	10
V3	320	0	240	5	7	960	1100	9	18	12
V4	320	240	420	5	8	460	900	10.2	20	25
V5	290	180	420	5	9	595	980	13.2	26	24
V6	380	250	430	3	9	1090	1050	7.8	14	14
V7	390	420	660	7	9	495	1350	12.6	28	22
V8	390	420	660	7	9	775	1350	18	22	16
V9	280	800	1000	5	9	240	850	12.6	14	18
V10	250	600	780	3	7	625	1100	14.4	22	26
V11	310	600	720	5	8	1155	700	9.6	20	28
V12	290	810	930	3	8	1245	600	10.8	20	27

The genetic algorithm in this paper is programmed in MATLAB R2022b and tested on a computer with an AMD Ryzen 5 5600H with Radeon Graphics 3.30 GHz processor. Algorithm parameters: population size is 120, each subpopulation size is 40, the maximum number of iterations is 500, the algorithm runs until the maximum number of iterations, $pcb = [0.15,0.1,0.05]$, $pce = [0.075,0,05,0.025]$, $pmb = [0.075,0.05,0.025]$, $pmc = [0.15,0.1,0.05]$, the probability of each population performing a neighborhood search is: 0.01 to 0.05, the length of the taboo search table isL_tabu = 8, the number of taboo search generations is $Gmax$ = 20, and the number of taboo search neighborhood solutions is Ca = 10. In this experiment, the static quay crane dispatching experiment of 12 ships was set as a control experiment.4.2Result analysis.

4.2 Result Analysis

The iteration of the improved genetic algorithm in solving berth-quay crane allocation is shown in Fig. 3. The algorithm iteratively converges quickly before 200 generations. When the algorithm iterates to the later stage, the algorithm's optimization ability decreases. However, since each population has a certain probability of neighborhood Tabu search, the algorithm still maintains the ability to explore the optimal solution.

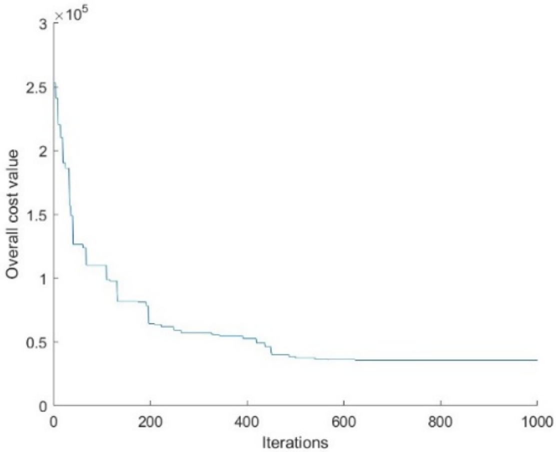

Fig. 3. Dynamic quay crane dispatching solution convergence diagram

4.3 Dynamic and Static Berth-Quay Crane Scheduling Results

The results of the 12-ship dynamic berth-quay crane dispatching experiment calculated using the improved genetic algorithm are shown in Table 2. The total deviation from the preferred berth cost is 2298¥, the delayed berthing cost is 7954¥, the delayed departure cost is 14911¥, and the shore crane cost is 14911¥. The bridge dispatching cost is 10,500¥, and the total dispatching cost during the planning period is 35,663¥. Among them, the working situation of dynamic quay crane dispatching quay crane is shown in the Fig. 4.

Table 2. Dynamic quay crane dispatching to solve ship berthing results

Ship number	Ship length	Actual berthing position	actual berthing time	Actual departure time	Deviation from preferred berth cost	Delayed berthing costs	Delayed departure costs	Quay crane dispatching cost	total cost
V1	210	183	1	306	24	12	858	600	35663
V2	300	438	1	204	228	14	0	600	
V3	320	912	1	236	18	18	0	700	
V4	320	271	307	518	397.8	1340	2450	800	
V5	290	576	205	421	13.2	650	24	1300	
V6	380	1086	251	458	31.2	14	0	1300	
V7	390	310	519	784	819	2772	2728	900	
V8	390	965	459	694	0	858	0	900	
V9	280	362	801	1023	100.8	14	414	900	
V10	250	630	601	981	72	22	5226	900	
V11	310	1155	695	826	0	1900	2968	800	
V12	290	900	827	939	594	340	243	800	

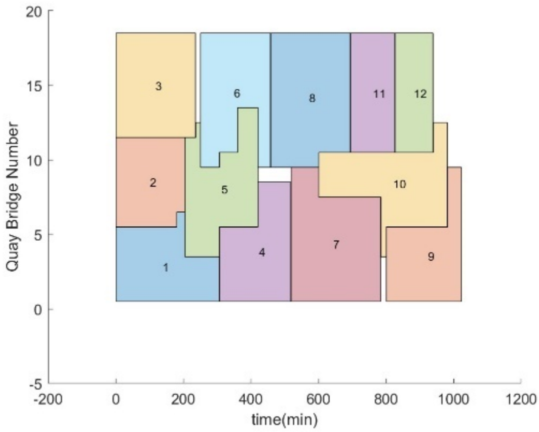

Fig. 4. Dynamic quay crane dispatching quay crane working conditions

The results of the 12-ship static berth-quay crane dispatching experiment for comparison are shown in Table 3. The total deviation from the preferred berth cost is 1374.6¥, the delayed berthing cost is 16038¥, the delayed departure cost is 23797¥, and the quay crane dispatching cost is 7,700¥, and the total dispatching cost during the planning period is 48,909.6¥. Among them, The working situation of static quay crane dispatching quay crane is shown in the Fig. 5.

Table 3. Static quay crane dispatching to solve ship berthing results

Ship number	Actual berthing position	actual berthing time	Actual departure time	Deviation from preferred berth cost	Delayed berthing costs	Delayed departure costs	Service quay crane number	Quay crane dispatching cost	total cost
V1	185	1	338	0	12	1274	1~4	400	60506.2
V2	440	1	200	240	14	0	5~10	600	
V3	912	1	236	18	18	0	12~18	700	
V4	274	339	563	367.2	1980	3575	1~6	600	
V5	579	201	494	52.8	546	1776	7~11	500	
V6	1085	251	475	39	14	0	12~18	700	
V7	375	564	788	0	4032	2816	1~9	900	
V8	965	495	719	0	1650	0	10~18	900	
V9	370	801	1055	0	14	990	1~5	500	
V10	635	789	1063	0	4158	7358	6~11	500	
V11	1156	720	869	9.6	2400	4172	12~18	700	
V12	905	870	998	648	1200	1836	12~18	700	

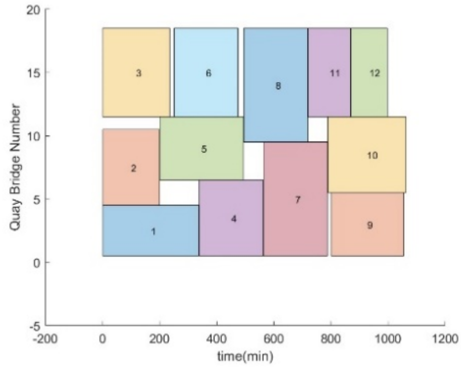

Fig. 5. Static quay crane dispatching quay crane working conditions

The cost comparison between dynamic quayside crane dispatching and static quayside crane dispatching is shown in Table 4. The delayed berthing cost and delayed ship unberthing cost of dynamic quayside crane dispatching during the planning period are better than those of static quayside crane dispatching, and the optimization rates are respectively 50.41% and 37.34%. From the overall cost point of view, the dynamic quayside crane dispatching method saves 13,246.6¥ compared with the static quay-side crane dispatching method, and the cost optimization rate is 27.08%.

Table 4. The total cost of dynamic quay crane dispatching and static quay crane dispatching

	Cost of ship deviating from preferred berth	Quay crane dispatching cost	Delayed berth-ing costs of ships	Delayed berthing cost of ship	Total cost
Dynamic quay crane dispatching	2298	10500	7954	14911	35663
Static quay crane dispatching	1374.6	7700	16038	23797	48909.6
Dynamic quay crane dispatch saves costs	-923.4	-2800	8084	8886	13246.6
Dynamic scheduling optimization rate	-67.18%	-36.36%	50.41%	37.34%	27.08%

5 Conclusion

In order to solve the shortcomings of the genetic algorithm in solving the berth-quay crane problem, this paper designed an improved multi-population genetic algorithm. Through the improved genetic algorithm, the static quay crane scheduling and the dynamic quay crane scheduling were solved separately for the numerical case of 12 ships arriving at the port. The results It is proved that the cost of dynamic quay crane dispatching is 27.08% lower than the cost of static quay crane dispatching. When multiple ships arrive at the port, the cost of dynamic quay crane dispatching is smaller and the usage efficiency of quay crane is higher.

This paper still has the following shortcomings: the mathematical model does not take into account the actual operation of container turning, and subsequent research can study such content; the search step of the taboo search algorithm has a large random exploration range, which leads to a slower convergence speed and longer calculation time when solving the problem. In the future, heuristic adjustments to control the direction of change can be considered to reduce the number of calculation steps.

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