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Joint Operation of Quay Cranes and Straddle Carriers in "Operation Surface" Mode

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Abstract

In order to solve the incongruity problem caused by joint operation of using straddle carrier as horizontal transportation equipment with quay crane, reduce the overall completion time of the terminal, this paper introduces the "Operation surface" scheduling mode of straddle carrier to study the joint operation sequence optimization of quay crane and straddle carrier.A mixed integer programming model is established to minimize the total completion time, considering the practical constraints of operation of quay crane and straddle carrier, the buffer capacity of quay crane and safety time. Aiming at the limitation of traditional Tabu search algorithm, an improved Tabu search algorithm is designed by the multi-neighborhood search method is added, and experiments were conducted. Experimental results verify the effectiveness of the proposed model and Algorithm. The combined scheduling model and Algorithm of quay cranes and straddle carriers under the mode of "Operation surface"provided model and algorithm reference for cooperative scheduling of multi-type equipment for operating enterprises and for realizing integrated and efficient operation of terminals.

Keywords

Container Operation; Buffer Capacity; Joint Operation; Tabu Search Algorithm.

1. Introduction

The increase of container port throughput and the development of large-scale ships also put forward higher and higher requirements for the loading and unloading capacity of the terminal container handling system.The quay crane and the straddle carrier are two important equipments at the front of the container port terminal, and the coordination problem between them directly affects the operation efficiency of the front of the terminal.[1]The container on the ship is placed in the buffer by the quay crane,and by the straddle carrier directly for handling and stacking, the quay crane and the straddle carrier are independent and non-interference each other, and the intermediate links such as waiting for truck loading and Container truck alignment can be omitted, reduce the phenomenon of congestion caused by too much mechanical equipment on the wharf, greatly improving the working speed and efficiency. Therefore, it is of great practical significance to set up a buffer area with a certain capacity under the quay crane, and to optimize the joint scheduling of the quay crane with buffer and the straddle carrier, which is of great practical significance to improve the overall loading and unloading efficiency of the container terminal and enhance the competitiveness of the port.

In order to optimize the scheduling of quay cranes, some experts optimize the operation sequence of quay cranes, the combined operation sequence of berths and quay cranes, and the combined operation sequence of quay cranes and horizontal transportation equipment, in order to improve the utilization rate of quay cranes, so as to improve the efficiency of port operations.HAN et al. [2] took the ship arrival time as the decision variable, and established the berth-quay crane joint dispatch model under

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the ship arrival time variable strategy and the ship arrival time fixed strategy respectively,and The impact of different port call schedules on ship fuel consumption and terminal carbon emissions is studied.KIM et al. [3] considered the constraints related to the control operation, studied the loading and unloading sequence of the quay crane, and designed a greedy random adaptive search method to solve it;XIE et al. [4] introduced the concept of quay crane allocation and combination, and considered constraints such as the time window of ships and berths, the number of quay cranes in the port, and the non-overlapping between ships, and adopted a globally optimal branch pricing algorithm to solve the problem.Shen et al. [5] considered the joint scheduling problem of automatic guided vehicles (AGVs) for quay cranes on grouped working surfaces under interference constraints. Establish a joint scheduling optimization model of quay crane and AGV. The dynamic scheduling mode of the quay crane and the AGV grouping operation surface scheduling mode are proposed, and the calculation examples of different scales are designed, and the genetic algorithm is used to solve the problem.LIANG et al. [6] considered the penalty time caused by the deviation of the ship from the preferred berth under the continuous berth, and absorbed the influence of uncertain factors by adding the delay time method. Zheng et al.[7] considered the influence of tidal action and the reality of dynamic scheduling in quay crane operations, and established a model with the goal of minimizing the sum of the quay crane operation cost and demurrage cost of all arriving ships during the planning period.Chen et al.[8] used a three-stage algorithm to study the integrated scheduling of quay cranes and trucks, used heuristic algorithms to generate timetables for quay crane operations, and then performed truck scheduling, and finally obtained a complete scheduling scheme. LI et al.[9] paid attention to the connection between the truck and the rail crane, and designed a two-stage tabu algorithm to solve the problem with the minimum and maximum completion time as the goal.

The above research focuses on quay cranes, trucks, and berths, which can effectively improve the operation efficiency of the terminal. However, when the straddle carrier is introduced into the terminal, the buffer area of the quay crane will greatly affect the operation efficiency of the terminal.

Under the limitation of buffer capacity, the joint scheduling problem between quay cranes and straddle carriers is less studied.TANG et al.[10] studied setting up a quay crane buffer area under the quay crane to optimize the ALV walking path.KRESS et al. [11] constructed the Manhattan Metric Straddle Carrier Routing Problem with Buffer Areas, and added the catapult chain into the tabu search method to solve it.ZHU et al. [12] made the quay crane buffer area into the quay crane off-lane under the background of the known time of the straddle carrier arriving at the terminal. Considering the fact that the quay crane trolley cannot cross the straddle carrier with boxes, they studied the A double-layer genetic algorithm is designed to solve the optimization problem of the synchronous loading of the quay crane and the straddle carrier.AN et al. [13] and others studied the application mode of container straddle carriers in small and medium-sized terminals, providing a theoretical basis for the further development and application of straddle carriers.

In the existing research on the joint operation of quay cranes and straddle carriers, under the fixed operation sequence of quay cranes or straddle carriers, the other side's operation sequence optimization is studied, without considering the operation sequence of quay cranes and straddle carriers. In both cases, the joint operation problem of both parties is not fixed. In the traditional terminal operation mode, the "operation surface" scheduling mode of straddle carriers is more conducive to resource integration. Therefore, in the case that the operation sequence of quay crane and straddle carrier is not fixed, the study of the joint scheduling problem of quay crane and straddle carrier in the ""operation surface" mode has strong theoretical significance and practical significance for integrating resources and improving overall operation efficiency.

2. Problem Description

This paper mainly studies the joint scheduling problem under the "single cycle" quay crane and straddle carrier "working face" mode.The straddle carrier scheduling mode has two modes: "operation line" and "operation surface". The "operation line" scheduling mode is shown in Figure 1, which refers to arranging a fixed number of straddle carriers for each quay crane, generally one quay is equipped with 3 straddle carriers.At this time, the straddle carrier is fixed to serve the same quay crane until the loading and unloading task of the quay crane is completed, and the no-load phenomenon of the vehicle is obvious in this mode.The “operation surface” scheduling mode is shown in Figure 2, which means that the vehicles do not serve a fixed quay crane, but all vehicles are a resource set that can serve any quay crane in the system.When the ship arrives at the port, there will be 2 to 3 quay cranes for loading and unloading at the same time, each quay crane has a fixed number of container loading and unloading tasks, in the "operation line" mode, one quay crane is equipped with 4-7 horizontal transport vehicles , when the number of tasks assigned to a quay crane is small, some vehicles will be idle while others are busy, which greatly reduces the utilization of vehicles. In the "work surface" mode, the vehicle can independently select unfinished tasks to operate according to the degree of completion of the task, which increases the utilization rate of the vehicle. At the same time, in the "work surface" mode, the vehicle's driving route becomes more complicated and higher requirements for vehicle scheduling.

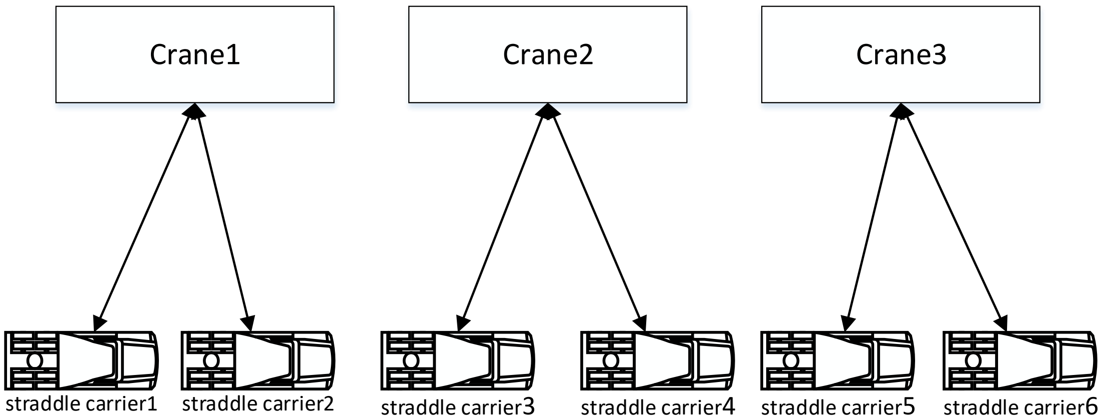

Figure 1. "operation line" mode

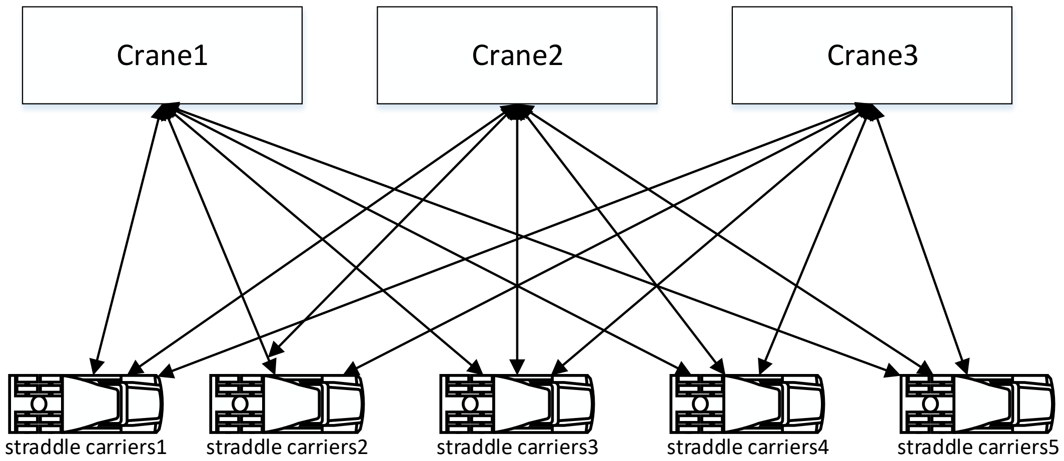

Figure 2. Joint operation flow chart of quay crane and straddle carrier

Figure 3 shows the joint operation of the quay crane and the straddle carrier in the port under the "working surface" mode. For the export container operation, the straddle carrier transports the container from the yard to the corresponding quay crane buffer area and then leaves for the next export container operation, and the quay crane will load the container in the buffer area; For the import container operation, the quay crane unloads the container from the ship and puts it into its

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buffer area for the next empty container operation, and the straddle carrier transports the container in the quay crane buffer area to the corresponding position in the yard. For small and medium-sized ships, the traditional terminal adopts the "single-cycle" quay crane operation mode. In this mode, the quay crane adopts the "unloading and then loading" operation, and the quay crane first performs the ship unloading operation and then the ship loading operation. In single cycle mode, the straddle carrier processes all the incoming cases before starting to process the outgoing cases.

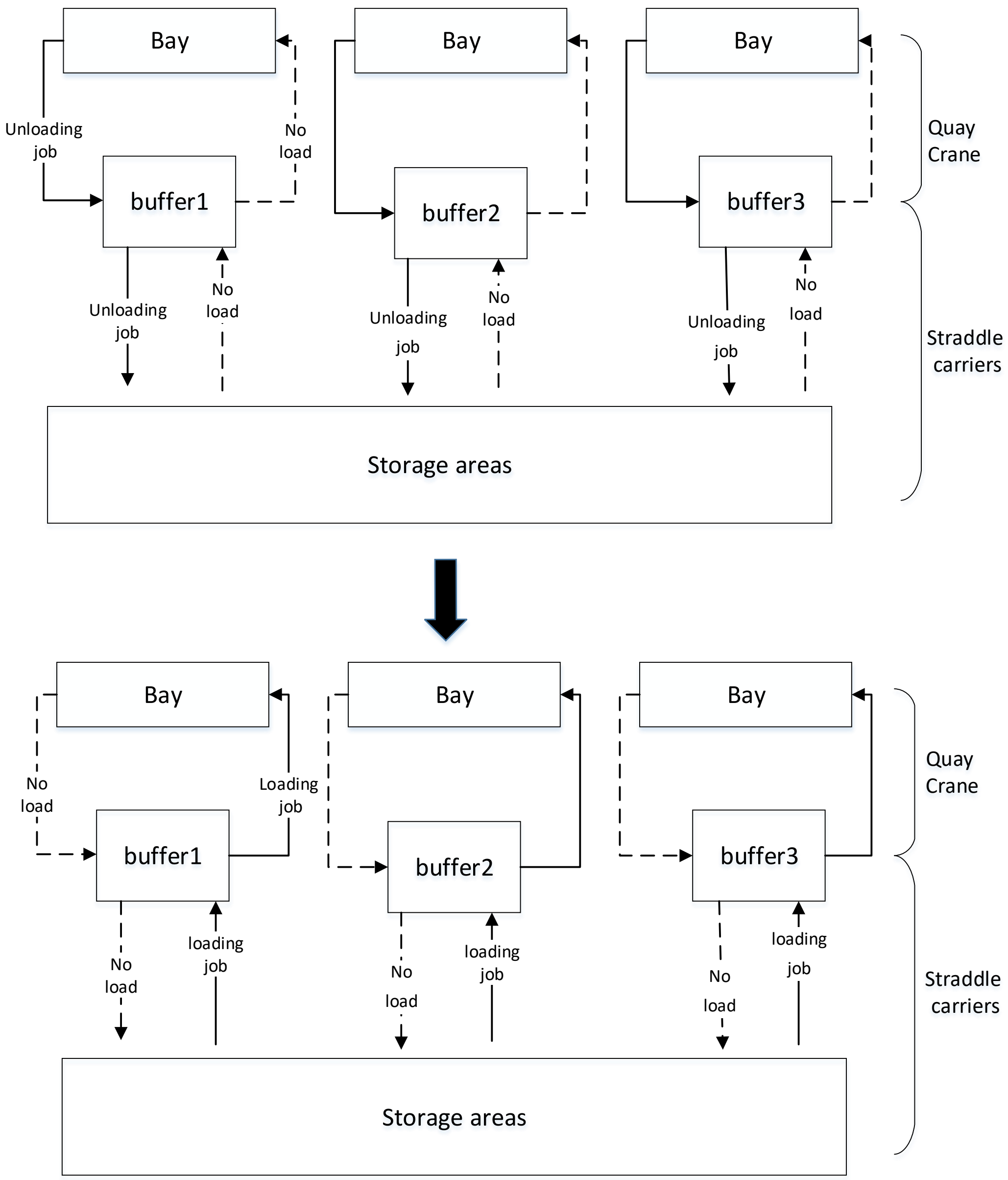

Figure 3. Joint operation flow chart of quay crane and straddle carrier

The background of this paper is the traditional “Unloading first and loading later”operation mode of wharf. This paper takes the quay crane and straddle carrier as the research object, aiming at the joint scheduling problem of quay crane and straddle carrier in the "working face" mode,Taking the minimum total completion time as the goal, considering constraints such as the capacity limit of the quay crane buffer area, the joint operation of the quay crane and the straddle carrier, and the safety time, a mixed integer programming model for the joint scheduling of the quay crane and the straddle carrier is established.Then, an improved tabu search algorithm is designed, and the validity of the model and algorithm is verified through numerical analysis of numerical examples.

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3. Model Establishment

3.1 Model Assumptions

(1) The capacity of the buffer area set under different quay cranes should be consistent;

(2) Straddle carriers work one container at a time;

(3) Do not consider the traffic jam during the movement of the straddle carrier, and do not consider the problem of turning over the container;

(4) The loading and unloading time of any container on the quay crane and the straddle carrier is the same, and the moving speed of the straddle carrier and the empty container is the same.

3.2 Notation and Insights

(1) Task parameter notations and quay crane parameter notations

Table 1 shows the task parameter notations and quay crane parameter notations used in this paper

Table 1. Task parameter notations and quay crane parameter notations

Notation	insights
J	Collection of loading and unloading tasks.
Q	Quay crane collection.
VS,VE,VC	VS represent a virtual start task, VE represent a virtual end task, VC represent a virtual task.
$Q'Q''$	$Q' = Q \cup \{VS\}$， $Q'' = Q \cup \{VE\}$
J^{q+}	A collection of loading tasks for quay crane $q, q \in Q$
J^{q-}	A collection of unloading tasks for quay crane $q, q \in Q$
J^{q}	A collection of tasks for quay crane q, $J^q = J^{q+} \cup J^{q-}$
$J^{q'}$	$J^{q'} = J^q \cup \{VC\}, q \in Q$
t_{qij}	The preparation time for the next task j after the quay crane q has processed the task $i, q \in Q, i, j \in J^q$
t_q	The time required for a quay crane to process a task, including three processes of carrying, carrying and placing the case.
t_l	represent the time it takes for a quay crane to lift or lower a container.
t_b	Safe time, represent the minimum time a container must stay in the buffer
b_q	Buffer capacity of quay crane $q, q \in Q$

(2) Straddle carrier parameter notations

Table 2. Straddle carrier parameter notations

Notation	insights
V	Number of straddle carriers
t_v	Time required to load or unload a container on a straddle carrier
N_{ki}^{lj}	No-load transportation time: the moving time of After the straddle carrier completes the i task of the quay crane k, it will go to the j task of the quay crane l.
t_{ki}^{v}	The time required for the straddle carrier to operate the i task of the quay crane k (including carrying, transporting, and unloading), $k \in Q$

Table 2 shows the parameter notations of the straddle carrier used in this paper. The transportation of the straddle carrier is divided into two parts, one part is the time to operate the container, and the other part is the empty-load transportation. Where to operate the container time $t_{ki}^{v}=2t_{v}+t^{ki^{n}}$, $t^{ki^{n}}$ Represents the moving time of the straddle carrier between the quay crane k buffer area and its corresponding end position n in the yard.

(3) Time Variable notations and Decision Variable notations Description

Table 3 and table4 show the time Variable notations and decision Variable notations used in this paper.

Table 3. Time Variable notations

Notation	insights
X_{kj}	The start moment when the straddle carrier operates the *j* task of the quay crane *k*, $j \in J^{q}, k \in Q$
Y_{kj}	The end moment when the straddle carrier operates the *j* task of the quay crane *k*, $j \in J^{q}, k \in Q$
XQ_{kj}	The moment when the quay crane *k* starts to operate the *j* task, $j \in J^{q}, k \in Q$
YQ_{kj}	The moment when the quay crane *k* ends to operate the *j* task, $j \in J^{q}, k \in Q$
Z	total completion time

Table 4. Decision Variable notations

Notation	insights
r_{ki}^{lj}	If the same straddle carrier completes the *i* task of the quay crane *k* and continues to operate the *j* task of the quay crane *l*, it is 1, otherwise it is 0. $i \in J^{k}, j \in J^{l}, k, l \in Q$
q_{kij}	After the quay crane *k* completes its task *i*,then operates the task *j* is 1, otherwise it is 0. $i, j \in J^{k}, k \in Q$
b_{ij}^{in}	It is 1 when *i* enters the buffer before *j*, otherwise it is 0. $i, j \in J^{k}, k \in Q$
b_{ij}^{out}	Before j enters the buffer, if i does not leave is 0, otherwise it is 1. $i, j \in J^{k}, k \in Q$
R_{kj}	quay crane artificial variables. $j \in J^{k}, k \in Q$

The time of container entering and leaving the buffer area is shown in Table 5. It is stipulated that the moment when the container leaves and enters the buffer area is the moment when the quay crane or straddle carrier lifts or puts down the container in the buffer area. The change in the number of containers in the buffer can be modeled by Using $b_{ij}^{in}, b_{ij}^{out}, i,j \in J^{k}, k \in K$, As shown in formulas (1)-(2),When the time when j enters the buffer area is greater than the time when i enters the buffer area, then $b_{ij}^{in}=1$.When the sum of the moment i leaves the buffer area and the time (t_s or t_v) required to pick up i is greater than the moment when j enters the buffer area, then $b_{ij}^{out}=0$.

Table 5. Decision Variable notations

task type	The moment when j enters the buffer	The moment when j leaves the buffer
$j \in J^{k+}$	Y_{kj}	XQ_{kj}
$j \in J^{k-}$	YQ_{kj}	X_{kj}

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$$b_{ij}^{in} = \begin{cases} & Y_{ki} \le Y_{kj} \quad ,i,j \in J^{k+} \\ 1, & YQ_{ki} \le Y_{kj} \quad ,i \in J^{k-}, j \in J^{k+} \\ & YQ_{ki} \le YQ_{kj} \quad ,i,j \in J^{k-} \\ 0, & 0r \end{cases}, \quad \forall k \in Q \tag{1}$$

$$b_{ij}^{out} = \begin{cases} & XQ_{ki} + t_l \ge Y_{kj} \quad ,i,j \in J^{k+} \\ 0, & X_{ki} + t_v \ge Y_{kj} \quad ,i \in J^{k-}, j \in J^{k+} \\ & X_{ki} + t_v \ge YQ_{kj} \quad ,i,j \in J^{k-} \\ 1, & or \end{cases}, \forall k \in Q \tag{2}$$

3.3 Build the model

$$min \quad Z \tag{3}$$

$$Z \ge YQ_{ki}, \forall i \in J^{k+}, k \in Q \tag{4}$$

The objective function (3) indicates that the maximum time to complete the task is minimized. The moment when the task is completed is the moment when the quayside crane places the container on the ship.Constraint (4) indicates that the total completion time is the latest time when the quay crane completes the task.

$$XQ_{kj} \ge YQ_{ki}, \forall i \in J^{k-}, j \in J^{k+}, k \in Q \tag{5}$$

$$\sum_{i \in J^{k'}} q_{kij} = 1, \forall k \in Q, \forall j \in J^{k'} \tag{6}$$

$$\sum_{j \in J^{k'}} q_{kij} = 1, \forall k \in Q, \forall i \in J^{k'} \tag{7}$$

$$R_{ki} - R_{kj} + m_k \cdot q_{kij} \le m_k - 1, \forall k \in Q, \forall i,j \in J^k, \quad i \ne j \tag{8}$$

$$XQ_{kj} - (t_{kij} + YQ_{ki}) \ge (q_{kij} - 1)M, \forall i,j \in J^k, \forall k \in Q \tag{9}$$

$$YQ_{ki} - (t_q + XQ_{ki}) \ge 0, \forall i \in J^k, \quad \forall k \in Q \tag{10}$$

$$q_{kij} = \{0,1\}, \forall i,j \in J^k, \forall k \in Q \tag{11}$$

$$m_k \ge R_{ki} > 0, R_{ki} \in N^+, \forall k \in Q, \forall i \in J^k \tag{12}$$

M represents a very large number.Constraints (5)-(12) represent constraints on the operation of the quay crane.Constraint (5) means that the “unloading and then loading” operation of the quay crane is satisfied, that is, the processing of the loading task is started after the processing of the unloading task is completed.Constraints (6)-(7) represent that the same quay crane can only handle one container at a time.Constraint (8) avoids the occurrence of sub-loops in the operation sequence of each quay crane.Constraint (9) means that the time interval between the quay crane processing two tasks is greater than the empty-load moving time of the quay crane between the two tasks.Constraint (10) means that the difference between the time at which the quay crane ends processing task i and the time at which it starts processing task i is greater than the time at which the quay crane handles the task.

$$X_{kj} \geq X_{ki}, \forall i \in J^{k-}, j \in J^{k+}, k \in Q \tag{13}$$

$$\sum_{k \in Q'} \sum_{i \in J^k} r_{ki}^{lj} = 1, \forall j \in J^l, \forall l \in Q \tag{14}$$

$$\sum_{l \in Q''} \sum_{j \in J^l} r_{ki}^{lj} = 1, \forall i \in J^k, \forall k \in Q \tag{15}$$

$$\sum_{k \in Q'} \sum_{i \in J^k} r_{VS}^{ki} = V \tag{16}$$

$$\sum_{k \in Q''} \sum_{i \in J^k} r_{ki}^{VE} = V \tag{17}$$

$$r_{VE}^{ki} = r_{ki}^{VS} = r_{ki}^{ki} = r_{VS}^{VE} = 0, \forall i = J^k, \forall k \in Q'' \tag{18}$$

$$Y_{ki} + N_{ki}^{lj} - X_{lj} \leq (1 - r_{ki}^{lj}) M, \forall i \in J^k, j \in J^l, \quad \forall k \in Q', \forall l \in Q'' \tag{19}$$

$$Y_{ki} - (t_{ki}^{v} + X_{ki}) \geq 0, \forall i \in J^k, \forall k \in Q \tag{20}$$

$$r_{ki}^{lj} = \{0,1\}, \forall i \in J^k, j \in J^l, \forall k, l \in Q \tag{21}$$

Constraints (13)-(21) represent constraints on straddle carrier operation.Constraint (13) means that the straddle carrier starts to process the loading task after processing the unloading task.Constraints (14)-(15) ensure that the same straddle carrier has only one successor task and one predecessor task.Constraints (16)-(17) indicate that the number of straddle carriers dispatched at the virtual starting point and the number of straddle carriers returning to the virtual end point is a fixed value.Constraint (18) means that the straddle carrier cannot return to the previous task from the subsequent task, cannot directly go from the virtual starting point to the virtual ending point, and cannot loop itself.Constraint (19) states that the time interval between the straddle carrier processing two tasks is larger than the time the straddle carrier moves between the two tasks.Constraint (20) means that the difference between the time when the straddle carrier ends processing task i and the time when it starts processing task i is greater than the time when the straddle carrier processes the task.

$$\sum_{i \in J^k} b_{ij}^{in} - \sum_{i \in J^k} b_{ij}^{out} < b_k, \quad \forall k \in Q, j \in J^k \tag{22}$$

$$X_{ki} - YQ_{ki} \geq t_b, \forall i \in J^{k-}, \forall k \in Q \tag{23}$$

$$XQ_{ki} - Y_{ki} \geq t_b, \forall i \in J^{k+}, \forall k \in Q \tag{24}$$

$$Y_{kj} - Y_{ki} \leq M \cdot b_{ij}^{in}, \forall i, j \in J^{k+}, \forall k \in Q \tag{25}$$

$$Y_{kj} - YQ_{ki} \leq M \cdot b_{ij}^{in}, \forall i \in J^{k-}, j \in J^{k+}, \forall k \in Q \tag{26}$$

$$YQ_{kj} - YQ_{ki} \leq M \cdot b_{ij}^{in}, \forall i, j \in J^{k-}, \forall k \in Q \tag{27}$$

$$Y_{kj} - (XQ_{ki} + t_l) \geq M(b_{ij}^{out} - 1), \forall i, j \in J^{k+}, \ i \neq j, \forall k \in Q \tag{28}$$

$$YQ_{kj} - (X_{ki} + t_v) \geq M(b_{ij}^{out} - 1), \forall i, j \in J^{k-}, i \neq j, \forall k \in Q \tag{29}$$

$$Y_{kj}\text{-}(X_{ki}+t_v)\ge M(b_{ij}^{out}-1),\forall i\in J^{k-},\ \ j\in J^{k+},i\ne j,\forall k\in Q \tag{30}$$

$$X_{ki},Y_{ki},XQ_{ki},YQ_{ki}\in N_{\ge o},\forall j\in J^{k},\forall k\in Q \tag{31}$$

Constraints (22)-(31) represent constraints on the buffer area.Constraint (22) represents that the number of containers in the buffer area does not exceed the buffer area capacity before the j task of the k-quay crane enters the buffer area.Constraints (23)-(24) represent security time constraints, which stipulate that each container task must stay in the cache for a certain time;Constraints (25)-(26) represent constraints that satisfy the decision variables b_{ij}^{in}, b_{ij}^{out}, (Equations (1)-(2)).For example, constraint (25) indicates that when i and j are both loading tasks, the time when i enters the buffer area is less than the time when j enters the buffer area, that is $Y_{ki}<Y_{kj}$, then $b_{ij}^{in}=1$. For example, constraint (28) indicates that when i and j are both export containers, the time when container j enters the buffer area is smaller than the time when container i leaves the buffer area plus the time when the quayside crane lifts container i, that is $Y_{kj}\le XQ_{ki}+t_s$,then $b_{ij}^{out}=0$.

4. Algorithm Design

4.1 Basic Idea

The calculation of the model built in this paper is relatively difficult and belongs to NP-hard problems.According to the research problem and the characteristics of the model, the tabu search algorithm is more suitable for the solution of the article.Tabu Search (TS) is a step-by-step optimization neighborhood search algorithm, starting from the initial solution, marking the local optimal solution or solution process that has been solved.The traditional TS algorithm relies on the neighborhood search. The centralized search has only the depth but not the breadth, and it is easy to obtain the local optimum. The diversity search only has the breadth but not the depth, and it is easy to measure the optimal solution.Therefore, this paper designs an "improved tabu search algorithm" to solve the model, adopts a variety of neighborhood search strategies, combines centralized search and diversity search strategies, ensures the diversity and concentration of neighborhoods, and strengthens the TS search mechanism to find the global optimal solution.

4.2 Improve the General Process of Tabu Search Algorithm

The article uses the improved tabu search algorithm to solve the model, and the algorithm flow chart is shown in Figure 4.

Step1: Randomly generate the operation sequence of quay cranes and straddle carriers that meet the requirements of "unloading before loading" as the initial solution S, and the initial value is obtained from the solution $W(S)$.

Step2: Input algorithm parameters, maximum number of iterations $r_{\max}$, Maximum number of candidate sets $n_{\max}$,candidate set N,Tabu List 1(Tabu1),Tabu length 1(T1),Tabu List 1(Tabu2),Tabu length 2(T2).

Step3: According to Tabu1, T1, using exchange, reverse order, diversity search strategy and other methods to generate candidate sequences, as the quay crane operation sequence, this sequence is added to Tabu1.

Step4: According to Tabu2, T2,Use exchange, reverse order, etc. to generate a candidate sequence as a straddle carrier operation sequence, and add the candidate solution to the candidate set N,n=n+1, if $n<n_{\max}$,then enter Step5, or return Step4.

Step5: Decode and calculate the candidate solutions in N, select the current optimal solution S', and record its fitness value $W(S')$.

Step6: If $W(S)>W(S')$,update optimal value,or enter Step7.

Step7: Update optimal solution, $S = S'$.

Step8: Tabu search algorithm iterative termination test. Check if the maximum number of iterations has been reached, if so, enter Step9; if not,enter Step3.

Step9: Output the global optimal solution.

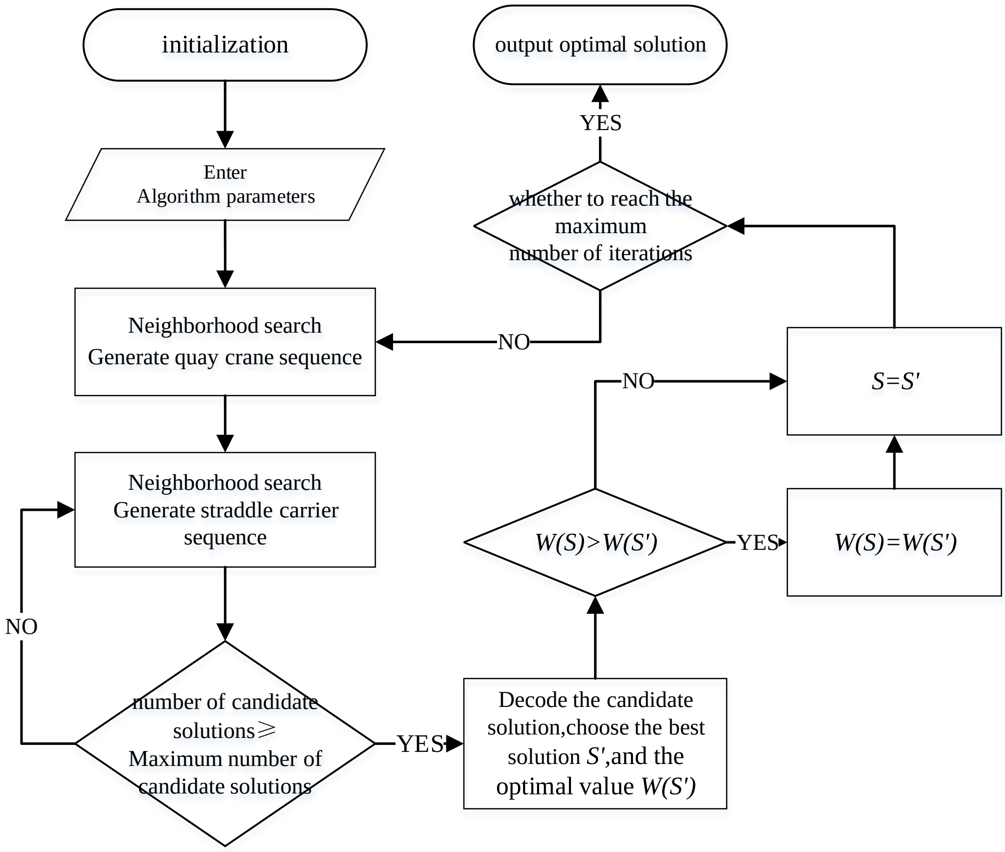

Figure 4. Algorithm flow chart

4.3 Encoding Method

The coding method is shown in Table 6. The first row in Table 6 represents all tasks, for example, 11 represents the first task of the first quay crane. The second line represents each task number, for example task 11 is coded as 1.The coding rules are: the first quay crane task sequence is coded as 0-1-2-3-4-5-0, and the second quay crane task sequence is coded as 0-6-7-8-9-10-0. The straddle carrier (SC) operation sequence is, 0-1-2-3-0-4-5-6-0-7-8-9-10-0, which means SC1: 0-1-2-3-0 , SC2: 0-4-5-6-0, SC3: 0-7-8-9-10-0.

Table 6. Coding table

Task	VC	VS	VE	11	12	13	14	15	21	22	23	24	25
Coding	0	0	0	1	2	3	4	5	6	7	8	9	10

4.4 Neighborhood Structure Design

Tabu search algorithm neighborhood settings. Tabu search searches based on neighborhood transformation, and it is crucial to determine the neighborhood operation.This paper selects three neighborhood structures applied to the vehicle routing problem, and randomly selects one of them during operation.For example, the straddle carrier task priority sequence is $\varphi = \{1,2,3,4,5,6\}$,Shaded are two randomly selected tasks i and j.The article neighborhood search is to transform the task

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sequence of the unloading task first, then transform the task sequence of the loading task, and finally merge the task sequence to obtain the job sequence of "unloading then loading".

Exchange: Choose the positions of tasks i and j to be swapped, and get:1-4-3-2-5-6.

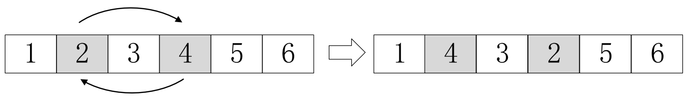

Figure 5. Algorithm flow chart

2-0pt: Then choose the task inverse order between tasks i and j, and get:1-5-4-3-2-6.

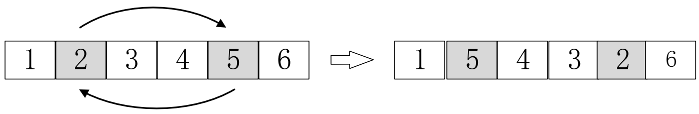

Figure 6. 2-0pt

4.5 Tabu Objects and Tabu Length

Tabu objects are task sequences.Three different tabu tables are set up for three different neighborhood search methods.The tabu length is the storage time of each tabu object in the tabu list. When the tabu list is full, the first task stored in the tabu list will be released.If the tabu length is too short, it may enter the loop and cannot jump out; if the tabu length is too long, the search space may be small and the search may be insufficient.

5. Numerical Example Analysis

5.1 Example Design and Solution Results

Reference [14, 12, 10, 11] design examples and example parameters,sets up 2 quay cranes and 5 straddle carriers, and each quay crane has 7 containers to be loaded and unloaded, with a total of 14 tasks. Table 7 is the parameter, and Table 8 is the task and the coding of the task.

Table 7. parameter

Quay Crane parameters	Numerical value	Straddle carrier parameters	Numerical value
t_l	30S	t_v	20S
b_q	3	*Speed*	10km/h
t_b	5S		

Table 8. task collection

Type	task							
Loading container	11	14	15	21	22	24	25	
Coding	1	4	5	8	9	11	12	
Unloading container	12	13	16	17	23	26	27	
Coding	2	3	6	7	10	13	14	

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Using the improved tabu search algorithm to solve this example, the final objective function value is 2880s, and the task sequence is shown in Table 9. In this example, the joint operation sequence of the quay crane and the straddle carrier is: quay crane 1: 7-6-2-3-5-4-1, quay crane 2: 14-10-13-8-11- 12-9; straddle carrier 1: 6-11-9, straddle carrier 2: 7-8-1, straddle carrier 3: 10-3-12; straddle carrier 4: 13-5, straddle carrier 5 : 14-2-4. The specific schedule is shown in Table 11.

Table 9. task sequence

equipment	task sequence
Quay crane1	0-6-7-3-2-1-5-4-0
Quay crane2	0-14-13-10-12-8-11-9-0
SC	0-6-1-0-7-12-9-0-10-8-11-0-13-2-4-0-14-3-5

5.2 Performance Analysis

In order to verify the effectiveness of the algorithm in the article, reference [12] designs examples, and analyzes and compares the solution results of the article algorithm and CPLEX and traditional tabu search algorithm. The results are shown in Table 10.

From Table 6, it can be seen that when the amount of tasks is small, the calculation speed of CPLEX is faster, and the calculation target values of the two are equal. When the number of tasks reaches 14, the calculation speed of CPLEX is greater than 450 seconds, while the calculation speed of the article algorithm is 123 seconds, and the calculation results are not biased. However, when the number of tasks reaches 30, CPLEX cannot get the solution within the feasible time, and the calculation time of the improved tabu search algorithm is 257 seconds. Therefore, the improved tabu search algorithm can well solve the scheduling problem of straddle carriers and quay cranes.

Table 10. task sequence

Experiment number	Basic data	CPLEX		Improved tabu search algorithm	
		Completion time/second	Solving time/second	Completion time/second	Solving time/second
1	4/2/2/2	1680	0.09	1680	0.4
2	6/2/2/2	2640	0.15	2640	0.4
3	6/2/3/2	1860	0.19	1860	0.5
4	6/3/3/2	1620	0.19	1620	0.4
5	14/2/3/4	4440	528	4440	127
6	14/2/4/4	3420	905	3420	123
7	14/2/5/4	2880	458	2880	124
8	20/2/5/4	3510	1453	3426	123
9	15/3/5/4	-	-	1872	123
10	30/3/5/4	-	-	4230	257
Note: The basic data is "task volume/quay crane number/straddle carrier number/buffer area capacity"					

6. Conclusion

This paper introduces the "Operation surface" mode of the straddle carrier, and studies the joint operation problem of the quay crane and the straddle carrier. Taking the quay crane and straddle carrier as the research object, considering the capacity limitation of the quay crane buffer area, the operation of "first unloading and then loading" of the quay crane, and the "working face" transportation strategy of the straddle carrier, a mathematical programming model aiming at minimizing the total completion time is established. Aiming at the limitation of the tabu search algorithm, an improved tabu search algorithm is designed to solve the problem, and an example is designed to verify the effectiveness of the model and the algorithm. Finally, an experiment is designed to compare the performance of CPLEX and the improved tabu search algorithm. Finally, the validity of the algorithm and model of the article is verified.

When studying the joint operation problem of quay cranes and straddle carriers, the article does not consider the problem of straddle carriers overturning. When the straddle carriers are loaded and unloaded in the yard and the buffer area, the situation that needs to be turned over may inevitably occur. , so the problem of box turnover can be further studied in the future. When dealing with large-scale problems, the algorithm of the article will have difficulty in finding optimization, and further research and improvement are required. In addition, the operation of dual-cycle quay cranes can bring higher value to the port. Deadlock will occur when the dual-cycle quay cranes and straddle carriers are jointly dispatched, so this problem can be studied in the future.

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