Optimization Scheduling of No-crossover Automated Stacking Cranes in Automated Container Terminals

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Abstract

In order to reduce the mutual interference between the non-crossing double stacking cranes and improve the operational efficiency of the No-crossover ASC, a certain shell position in the box area is set as a relay area for temporary storage of containers, and at the same time, the interference between No-crossover ASCs is also transferred to the relay area. With the goal of minimizing the maximum completion time, the shell position of the relay area is regarded as the decision variable of the model, and a mixed integer programming model with the goal of minimizing the completion time is constructed, and a study is designed to verify the correctness of the model. Finally, the design experiment analyzes the sensitivity of the design scheme with relay zone and the design scheme without relay zone to the change of loading and unloading time. Experimental results show that the objective function value under the relay zone design scheme is more sensitive to the variable of loading and unloading time.

Keywords

Automated Dock; Double Stacking Crane; Relay Zone; Sensitivity Analysis.

1. Introduction

As the actual bearer of loading, unloading and stacking operations in the yard, the automatic stacking crane (ASC) has a direct impact on the overall operation efficiency of the terminal [1]. Automated container terminal yards are laid out in a vertical-shore manner, usually with two No-crossover ASCs in a single container area.

Under the No-crossover ASC loading and unloading process, two ASCs share the same track in the box area, and carry out loading and unloading and stacking operations in the same area of the box area, which cannot be crossed by each other. Among them, the seaside ASC is responsible for completing the task of starting and ending shells close to the seaside handover area, and the landside ASC is responsible for completing the task of starting and ending shells close to the landside handover area. Due to the overlap between the starting and ending shells of the missions on both sides of the sea and land, Twin-ASC is prone to mutual interference in order to complete the tasks assigned to them.

In order to ensure the efficient and steady operation of the yard operation, scholars at home and abroad have proposed some practical methods to manage the mutual interference between the incorroverable double cranes in the yard. PARK et al. [3] and CARLO et al. [4] remove interference between twin cranes in a yard by giving priority to the operation of a crane. Jing Zhenwen et al. [5] further studied the combination of priority rules and avoidance rules in the No-crossover ASC scheduling process. HU et al. [6] manage interference between ASCs by analyzing the minimum time interval between two ASCs. Research by Ding et al. [7] has shown that setting a relay zone in the box area can effectively reduce the delay in equipment operation time, and similar studies have been published in the literature [8]. Huang Jiwei et al. [9]

regarded the middle shell of the box area as a relay area for temporary storage of containers, transferring the interference between the No-crossover ASCs to the relay area.

The above studies pointed out that setting up a relay zone in the box area can effectively avoid interference between No-crossover ASCs, but the current research is mostly empirical pre-selected relay zone shells, and there are relatively few quantitative analysis studies on relay shells. Based on this, this paper regards the relay area shell as a decision variable, and constructs a mixed integer programming model for No-crossover ASC scheduling, the optimal job sequence for decision-making No-crossover ASC, and the optimal relay area shell.

2. Problem Description and Model Building

2.1. Problem Description

In order to avoid the interference of interaction between No-crossover ASCs, a certain shell or several shells in the box area is used as a relay area for temporary storage of containers. As shown in Figure 1, the automated container terminal single container area in fixed relay zone mode includes: seaside ASC exclusive area (S-P), landside ASC exclusive area (L-P), fixed relay area (P), and handover area located at both ends of the container area. Among them, the working area of the seaside ASC includes the seaside handover area, the S-P area and the P area; the working area of the landside ASC includes the landside handover area, the L-P area and the P area.

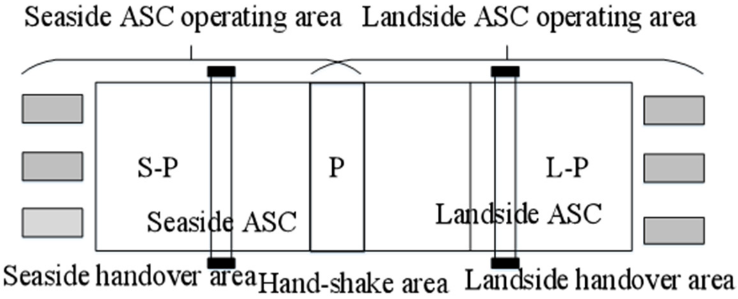

Figure 1. Layout of the single box area

The task box is divided into seaside tasks, landside tasks, and relay tasks according to the starting and ending shell positions. Among them, the seaside task refers to the starting and ending shell positions of the task box are distributed in the seaside handover area, S-P area or P area; the landside task refers to the starting and ending shells of the task box are distributed in the landside handover area, L-P area or P area; the relay task refers to the starting shell position and the target shell position of the task box are distributed on both sides of the P area in the box area, that is, the task box that requires as C on both sides of the sea and land to work together through the P area. For relay tasks, it is further subdivided into seaside relay tasks and landside relay tasks according to the starting and ending shell positions of the task box. Among them, the seaside relay task refers to the starting and ending shells of the relay task including the task box of the seaside handover area, and the landside relay task refers to the starting and ending shells of the relay task including the task box of the landside handover area.

During the task assignment process, the seaside task is assigned to the seaside ASC operation, the landside task is assigned to the landside ASC operation, and the relay task is coordinated by the two ASCs through the P zone. The process of No-crossover ASC collaborative relay tasks is: first, according to the shell position of the relay area, the relay task is split into two sub-task segments; second, according to the starting and ending shells of the two sub-task segments, it is assigned to two ASC operations. Moreover, because the two sub-tasks of the relay task are split from the same task, there is a strict priority relationship between the two sub-tasks. For example, if there are 20 shells in the yard box area, 0 shells in the seaside handover area, 21 shells in the landside handover area, and 10th shell in the relay area, for the relay task with a starting and ending shell position of (0,15), the task box must first be transported from the 0th shell to the 10th bay by the seaside ASC, and then the task box from the 10th shell to the 15th shell by the landside ASC, this process cannot be reversed, otherwise it does not meet the actual operation requirements. Figure 2 shows the specific process of the No-crossover ASC working collaboratively on this relay task.

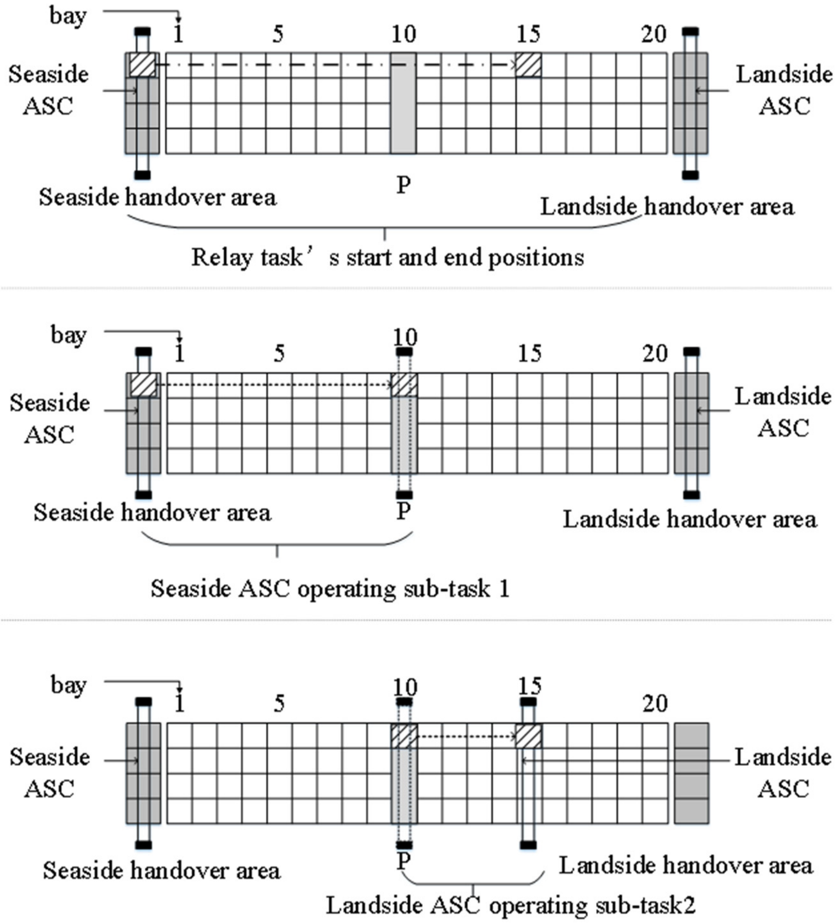

Figure 2. Schematic diagram of the No-crossover ASC co-operation process

In addition, for relay tasks, in order to facilitate the expression of two sub-task segments, this article refers to the sub-task segments of the starting shell or the target shell containing the handover area as the main task segment, and the sub-task segment without the handover area is called the relay task segment.

2.2. Interference Analysis

In the relay zone mode, the No-crossover ASC's working area is artificially restricted, and the sea and land ASC are only allowed to carry out loading and unloading and stacking operations in their respective working areas, and the crossover part of the sea and land side ASC working area only includes the relay zone P of the box area, so the mutual interference between No-crossover ASC is also transferred to the relay zone of the box area, that is, the interference between No-crossover ASC can only occur in the P zone.

When No-crossover ASCs interfere with each other, give priority to one of the ASCs to operate, which can effectively resolve mutual interference. At this point, the operational priority can be either a seaside ASC or a landside ASC. Moreover, S represents the storage task, R represents the boxing task, according to the task type of the priority task and the subsequent operation task when the interference is lifted, the interference between No-crossover ASC can be divided into four modes, namely "SS" mode, "RS" mode, "SR" mode and "RR" mode, as shown in Table 1. For each interference mode, there are two situations: first, the seaside ASC has operational priority, that is, the priority operation task is the seaside task, and the follow-up operation task is the landside task. In case two, the landside ASC has operational priority, that is, the priority operation task is the landside task, and the follow-up operation task is the seaside task. Figure 3 is an interference diagram of the No-crossover ASC in fixed relay zone mode.

Table 1. No-crossover ASCs interference mode

Priority operating task type	The follow-up operating task type	Interference mode
storage task	storage task	“SS”
boxing task	storage task	“RS”
storage task	boxing task	“SR”
boxing task	boxing task	“RR”

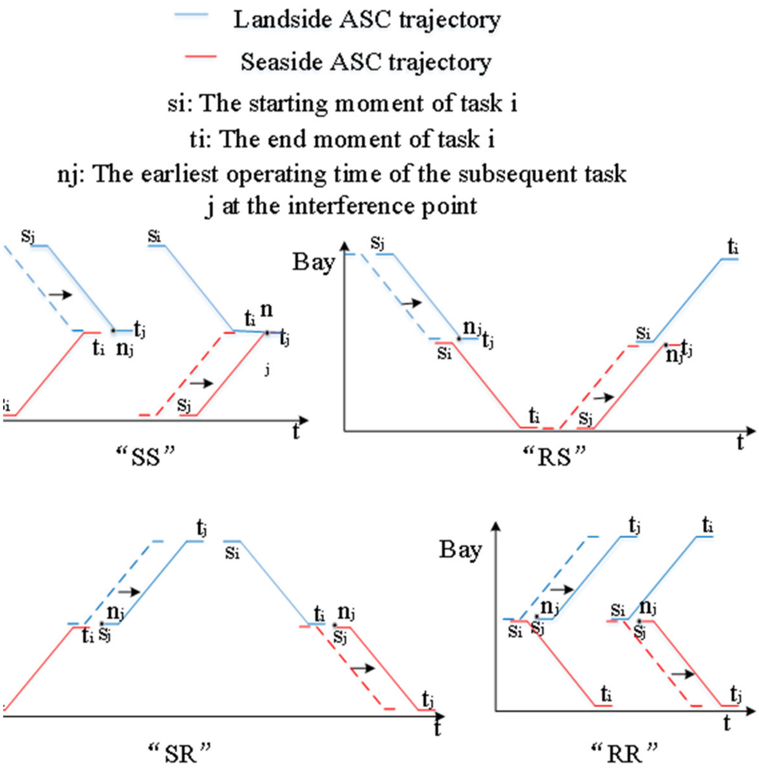

Figure 3. Schematic diagram of the interference between No-crossover ASC

2.3. Model Assumptions

The assumptions made in the model are as follows:

(1) it is assumed that the container position in the yard is determined and known;

(2) Assuming that there are enough storage bins in the yard box area, the capacity limit of the box area is not considered;

(3) It is assumed that the ASC always maintains a uniform speed when moving, ignoring the influence of acceleration and braking on the ASC rate during movement;

(4) In the process of ASC operation, ignore the influence of the number of layers in the container in the yard on the LOADING and unloading time of ASC, that is, assume that the loading and unloading time of ASC is fixed;

(5) Assuming that there are sufficient handover areas at both ends of the yard and sufficient horizontal transport vehicles, ignore the time that ASC waits for the horizontal transport equipment in the handover area.

2.4. Symbol and Variable Descriptions

P : Relay zone shells;

$A(i,j)$: a collection of sub-tasks for relay tasks;

$A1(i,j)$: sub-task pairs split from seaside boxing tasks;

$A2(i,j)$: sub-task pairs split from seaside storage tasks;

$A3(i,j)$: sub-task pairs split from landside boxing tasks;

$A3(i,j)$: sub-task pairs split from landside storage tasks;

K : ASC set, $k \in K, K = \{0,1\}$;

J : task set, $J = J_0 \cup J_1$;

P_i^s : The initial location of the task i ;

P_i^t : The target location of the task i ;

T_{ij} : $T_{ij} = \left|P_i^t - P_j^s\right| / \eta, \forall i, j \in J$, if $i = j$, represents the time it takes for the ASC to run from the initial location of the task i to the target location; if $i \neq j$, represents the transition time required for the ASC to run from the target location of the task i to the initial location of the task j ;

η : The movement speed of the ASC;

τ : Loading and unloading time of the ASC;

σ : Safe distance between two ASCs;

B : The total number of shells in a single box area, $b = 0, \ldots B$;

M : A large enough number;

s_i : The start operating time for the task i ;

t_i : The completion time of the task i ;

nj: The earliest operating time of the subsequent task j at the interference point

u_i : ASC starts with the task i, then $u_i = 1$; otherwise $u_i = 0$;

v_i : ASC end with the task i , then $v_i = 1$, otherwise $v_i = 0$;

$x_i^{(k)}$: $x_i^{(k)} \in \{0,1\}$, if task i was operated by ASCk,then $x_i^{(k)} = 1$, otherwise, $x_i^{(k)} = 0$;

$x_{ij}^{(k)}$: $x_{ij}^{(k)} \in \{0,1\}$, if ASCk complete task i followed by operating task j , then $x_{ij}^{(k)} = 1$, otherwise, $x_{ij}^{(k)} = 0$;

z_{ij} : $z_{ij} \in \{0,1\}, i \in J_k, j \in J_l, k \neq l$,if task i and task j was operated different ASCs, When task i precedes task j for operation, $z_{ij} = 1$;otherwise $z_{ij} = 0$.

2.5. Model Building

With the goal of minimizing the maximum completion time, we build a No-crossover ASC scheduling mixed integer programming model. The objective function of the model is as follows:

$$\min\{Z \geq t_i; \forall i \in J\} \tag{1}$$

Constraints:

$$\sum_{k\in K}\sum_{i\in J} x_{ij}^{(k)} + u_j = 1; \forall j \in J \tag{2}$$

$$\sum_{k\in K}\sum_{j\in J} x_{ij}^{(k)} + v_i = 1; \forall i \in J \tag{3}$$

$$\sum_{i\in J_k} u_i = 1; k \in K \tag{4}$$

$$\sum_{i\in J_k} v_i = 1; k \in K \tag{5}$$

$$t_i \geq s_i + 2\tau + T_{ii}; \forall i \in J \tag{6}$$

$$s_j \geq t_i + T_{ij} - M(1 - x_{ij}^{(k)}); \forall i, j \in J_k, \forall k \in K \tag{7}$$

Equations (2) and (3) mean that each ASC operates only one task at the same time, and each task is only operated once, equations (4) and (5) stipulate that each ASC has only one starting task and one termination task, eliminating the sub-loop of the job sequence, equation (6) means that the difference between the completion time of the task and the job start time of the task must be greater than the operation time required to complete the task, and equation (7) means that there is sufficient transition time between the tightly forward and backward tasks of the asc operation on the same side.

$$s_i \geq t_j + \sigma / \eta; \forall (i, j) \in A1 \tag{8}$$

$$s_j \geq t_i + \sigma / \eta; \forall (i, j) \in A2 \tag{9}$$

$$s_i \geq t_j + \sigma / \eta; \forall (i, j) \in A3 \tag{10}$$

$$s_j \geq t_i + \sigma / \eta; \forall (i, j) \in A4 \tag{11}$$

$$x_i^{(k)} + x_j^{(k)} = 1; \forall (i, j) \in A, \forall k \in K \tag{12}$$

No-crossover ASC operation relays the time of the two sub-tasks of a relay task with a strict front-to-back relationship, and the completion time of the forward sub-task must precede the start time of the immediately followed sub-task. And if the task types of the original relay tasks are different, there is a difference in the tight-forward relationship between the main task segment and the relay task segment after the split. Equations (8) to (11) respectively indicate that when the original relay task is a seaside pick-up task, a sea-side inbound task, a land-side pick-up task, and a land-side inbound task, the operation time constraints that should be met between the main task segment and the relay task segment should be satisfied. Equation (12) indicates that the relay task must be completed by two ASCs in collaboration, and each ASC operates a sub-task of the relay task.

"SS":

$$\begin{cases} n_j \geq t_i + \sigma/v - M(1-z_{ij}) \\ n_j \geq s_j + \tau + \left|P_j^s - P_i^t\right|/v - M(1-z_{ij}); \forall i \in J_k, j \in J_l, k \neq l \\ t_j \geq n_j + \tau - M(1-z_{ij}) \end{cases} \tag{13}$$

"RS":

$$\begin{cases} n_j \geq s_i + \tau + \sigma/v - M(1-z_{ij}) \\ n_j \geq s_j + \tau + \left|P_j^s - P_i^s\right|/v - M(1-z_{ij}); \forall i \in J_k, j \in J_l, k \neq l \\ t_j \geq n_j + \tau - M(1-z_{ij}) \end{cases} \tag{14}$$

"SR":

$$\begin{cases} n_j \geq t_i + \sigma/v - M(1-z_{ij}) \\ s_j \geq n_j - M(1-z_{ij}) \qquad ; \forall i \in J_k, j \in J_l, k \neq l \\ t_j \geq s_j + 2\tau + \left|P_j^s - P_j^t\right|/v - M(1-z_{ij}) \end{cases} \tag{15}$$

"RR":

$$\begin{cases} n_j \geq s_i + \tau + \sigma/v - M(1-z_{ij}) \\ s_j \geq n_j - M(1-z_{ij}) \qquad ; \forall i \in J_k, j \in J_l, k \neq l \\ t_j \geq s_j + 2\tau + \left|P_j^s - P_j^t\right|/v - M(1-z_{ij}) \end{cases} \tag{16}$$

$$z_{ij} + z_{ji} = 1, \forall i \in J_k, j \in J_l, k \neq l \tag{17}$$

In order to ensure the safety of the operation, the No-crossover ASC needs to maintain the necessary safe working distance during operation to prevent collisions. Equations (13) to (16) indicate the safety interval constraints to be met between the operation time of the pre-sequence task i and the post-sequence task i in the "SS" mode, the "RS" mode, the "SR" mode, and the "RR" mode, respectively. (17) Indicates that the tasks i and j belong to the ASC on both sides, and there must be one for the previous task and one for the follow-up task.

Equations (18)~(20) are the range of values for the variables in the model:

$$0 \leq P \leq B \tag{18}$$

$$s_i \geq 0, t_i \geq 0, p_i^s \geq 0, p_i^t \geq 0; \forall i \in J \tag{19}$$

$$u_i, v_i, x_i^{(k)}, x_{ij}^{(k)}, z_{ij} \in \{0,1\}; \forall i, j \in J, k \in K \tag{20}$$

3. Numerical Experiments

3.1. Parameter Settings

Assuming that the box area from the seaside handover zone to the landside handover zone is 0 to 40 bays, the movement speed of the ASC is $\eta = 1$ bay/S, the loading and unloading time of the ASC is $\tau = 3$ S, and the safety distance between the No-crossover ASC is $\sigma = 1$ bay. All of the experiments in this article were run on intel Core i7's processor, a computer with 8GB of memory, and programmed on the pyCharm 2019 platform.

3.2. Experimental Analysis

Given a task group with a study size of 10, given a task group with a start and end of the task, as shown in Table 2.

Table 2. The task group is given

Number	Initial Location	Target Location	The operation ASC	task type
0	0	10	0	1
1	9	0	0	0
2	0	25	0	1
3	25	0	0	0
4	0	12	0	1
5	40	27	1	1
6	40	16	1	1
7	33	40	1	0
8	25	40	1	0
9	40	28	1	1

Table 3. The split task group

Number	Initial Location	Target Location	The operation ASC	task type
0	0	10	0	1
1	9	0	0	0
2	0	20	0	1
3	20	0	0	0
4	0	12	0	1
5	40	27	1	1
6	40	20	1	1
7	33	40	1	0
8	25	40	1	0
9	40	28	1	1
12	20	25	1	3
13	25	20	1	2
16	20	16	0	3

For the task boxes with starting and ending shells distributed on both sides of the relay zone, they are split into two sub-task segments, and the two ASCs work together. Due to the change in the number of tasks after the relay task is split, the original number cannot meet the requirement that the number is unique. Therefore, for relay tasks, the number of its main task segment is the number of the original task before the split, and the number of its relay task segment is expressed by the original task number before the split + N (the total number of tasks for a given task group); for non-relay tasks, its number does not need to change. Similarly, in the case of task type 2, the original task is the relay task segment of the pick-up task; the task type 3 is the relay task segment of the incoming task; the task type of other tasks follows the task type of the corresponding task in the original task group.

For example, if the 20th bay is the shell position of the relay zone, the task of starting and ending shells distributed on both sides of the 20 bays is split into two sub-task segments, and according to the task allocation process, the two sub-task segments are assigned to two ASC operations, and the split task group is shown in Table 3.

Table 4. The study solves the result

Relay zone bays/bay	The objective function value/s	Relay zone bays/bay	The objective function value/s	Relay zone bays/bay	The objective function value/s	Relay zone bays/bay	The objective function value/s
1	226	11	156	21	131	31	173
2	220	12	146	22	133	32	179
3	214	13	144	23	134	33	186
4	208	14	142	24	134	34	194
5	202	15	140	25	136	35	200
6	196	16	138	26	149	36	202
7	190	17	141	27	151	37	208
8	184	18	137	28	155	38	210
9	172	19	135	29	161	39	216
10	160	20	129	30	167	40	223

Use CPLEX to solve the study, and the result of the study solution is shown in Table 4.As can be seen from Table 4, when the relay zone is 20 bays, the No-crossover ASC scheduling reaches the optimal solution. The maximum completion time for the optimal solution is 129s, the optimal seaside ASC operation order is [2, 16, 3, 0, 1, 4], and the optimal landside ASC operation order is [6, 13, 12, 8, 9, 7, 5].Figure 4 is a No-crossover ASC operating path diagram.

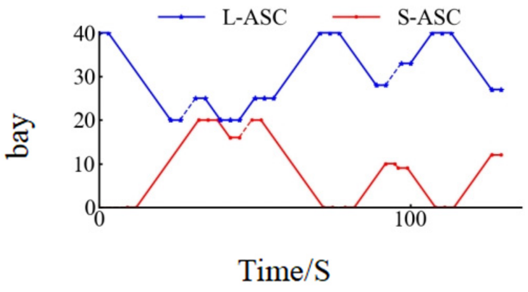

Figure 4. No-crossover ASC operating path diagram

3.3. Sensitivity Analysis

3.3.1. Loading and Unloading Time Impact Analysis

Under the design scheme without relay zone, ASC completes a task process including transfer - pick-up box - horizontal transportation - put box, so the task box only needs to consume one loading and unloading time; under the relay zone design scheme, for the task of starting and ending shells crossing the relay zone, No-crossover ASC completes the relay task Process includes ASC1 transfer - ASC1 pick-up box - ASC1 horizontal transportation - ASC1 boxing - ASC2 transfer - ASC2 pick-up - ASC2 horizontal transportation - ASC2 release, Therefore, under the relay zone design scheme, the transition time of ASC2 and the time of loading and unloading are increased. Based on this, for the above task groups, this paper keeps other variables unchanged, adjusts the loading and unloading time of ASC trolleys 1, 2, 3, 4, 5, and analyzes the sensitivity of relay zones and non-relay zones to changes in loading and unloading times. See Table 5 for experimental results.

Table 5. Loading and unloading time impact analysis

Experiment number	Loading and unloading time	The value of the objective function when there is no relay zone	The value of the objective function when there is a relay zone
1	1	102	100
2	2	112	109
3	3	120	123
4	4	132	137
5	5	139	150

Using the objective function at the loading and unloading time of 1 as a basis, plot the function of the objective function that changes with the loading and unloading time, as shown in Figure 5.

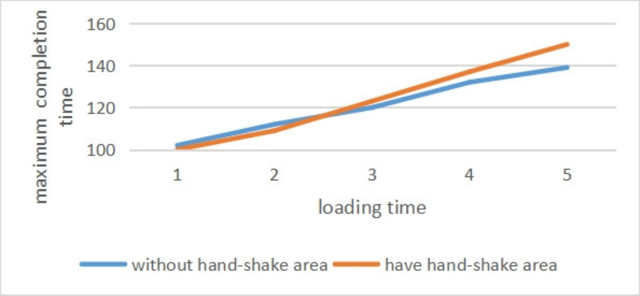

Figure 5. Experimental results

Table 5 experimental results show that as the loading and unloading time increases, the objective function values increase under the relay zone design scheme and the relayless zone design scheme, but the relay zone design scheme is more sensitive to the time change of ASC loading and unloading containers. In the actual scheduling process of the terminal, the impact of the loading and unloading time of the yard operation equipment on the design scheme of the docking force zone can be comprehensively considered.

3.3.2. Task Distribution Impact Analysis

Table 6. Task distribution impact analysis

grade	Optimal relay zone shell position	The objective function value
5-a	19	102
5-b	25	95
7-a	16	130
7-b	26	98

In the automated terminal, in the single box area, there is an imbalance between the amount of tasks assigned to the seaside ASC and the amount of tasks allocated to the landside ASC. Set the task size to 5 and 7, and generate a sub-study set with more seaside task volume and more landside task volume distribution for each set of study sizes. The set of studies with a large distribution of land-side tasks is represented by a, and the set of studies with a large distribution of land-side tasks is represented by b. The case set is solved using CPLEX to return the optimal sequence of operations of the ASC and thebest relay area shells. The experimental results are shown in Table 6.

From Table 6, it can be seen that when the relay zone is used as the decision variable, the distribution of the sea-land side task volume is different, and the optimal relay zone for non-crossover ASC collaborative operation also changes. When the amount of landside tasks is large, the relay area of the non-crossover ASC is close to the landside ASC, which reduces the working intensity of the landside ASC as much as possible. Similarly, when the seaside ASC task is large, the relay area of the non-crossover ASC is close to the seaside ASC. Illustrates that the model built in this article can be applied to a study set in a variety of task distribution scenarios.

4. Conclusion

No-crossover ASC is the main bearer of yard operations, and the operation efficiency of No-crossover ASC directly determines the operational efficiency of the yard, which in turn affects the operational efficiency of the entire dock. Aiming at the optimization problem of No-crossover ASC scheduling, this paper constructs a model of mixed integer programming model of No-crossover ASC scheduling with the goal of minimizing the maximum completion time. In addition, in this paper, the study is designed and the CPLEX is used to solve the study, which verifies the validity of the model. Finally, this paper analyzes the sensitivity of the design scheme with relay zone and the design scheme without relay zone to loading and unloading time.

Future research can add constraints such as time window to the research in this paper to make the problem more realistic.

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