IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 20, 2019, accepted April 11, 2019, date of publication April 24, 2019, date of current version May 6, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2913019

Modeling and Solution of Joint Storage Space Allocation and Handling Operation for Outbound Containers in Rail-Water Intermodal Container Terminals

YIMEI CHANG[1], XIAONING ZHU[1], AND ALI HAGHANI[2]
[1]School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
[2]Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA

Corresponding author: Xiaoning Zhu (xnzhu@bjtu.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFB1201403, in part by Civil Aviation Administration of China Major projects under Grant 201501, and in part by the Major Research Plan of the National Natural Science Foundation of China under Grant 71390332.

ABSTRACT Storage space allocation and handling operation problems are two main crucial problems in container terminals. Early research efforts, however, are seldom devoted to studying them together. Therefore, this paper considers these two problems simultaneously for outbound containers in rail-water intermodal container terminals (RWICTs), where rail-mounted gantry cranes, inner trucks, and quay cranes are involved. A two-stage problem is proposed: Stage 1 is to determine locations of the containers and reduce the overlapping amount, considering container weight, departure time, destination ports, and containers left from earlier planning periods in railway container yards, according to the locations of containers from Stage 1; and Stage 2 aims at obtaining optimal job sequences of different types of equipment and minimizing makespans of handling operations, considering some operational constraints, particularly rehandling time and inner truck congestion. To solve the problem, a two-stage heuristic algorithm is proposed, where the rolling planning horizon and a new update strategy are introduced. A heuristic algorithm is introduced in Stage 1 and a novel two-layer genetic algorithm is proposed in Stage 2, which introduces proximity principles and the reselection operation. Afterward, the results from Stage 2 are used to resolve the first stage problem, while the problem in Stage 2 is also resolved using the new results from Stage 1. This iterative process continues until there are no more improvements in Stage 1. Finally, the results of the computational experiments indicate that the proposed model and solution approaches are effective and efficient in solving the two-stage problem for outbound containers in RWICTs.

INDEX TERMS Rail-water intermodal transportation, storage space allocation, handling operation, two-stage algorithm, container terminal.

I. INTRODUCTION

One Belt One Road was proposed as an important development initiate in China in 2015, and international trades between China and other countries have been rapidly developed. Although the proportion of containers transported by railway is very low in China, the development trend is very fast. Fig. 1 shows the throughput and rail-water intermodal transportation ratio of major ports in 2017. Meanwhile, Table 1 presents the throughput of rail-water intermodal transportation in major ports in China from 2011 to 2016. Additionally, based on the development initiate, the railway will cover about 80% of the main container terminals in China by the end of 2018.

Additionally, the intercontinental trades among countries do not just rely on the single transportation mode or only marine transportation, but a mixed transportation mode, especially rail-water intermodal transportation. Additionally, railway transportation is an environmentally-friendly, safe and fast transportation mode, which plays a dominant role in long

The associate editor coordinating the review of this manuscript and approving it for publication was Roberto Sacile.

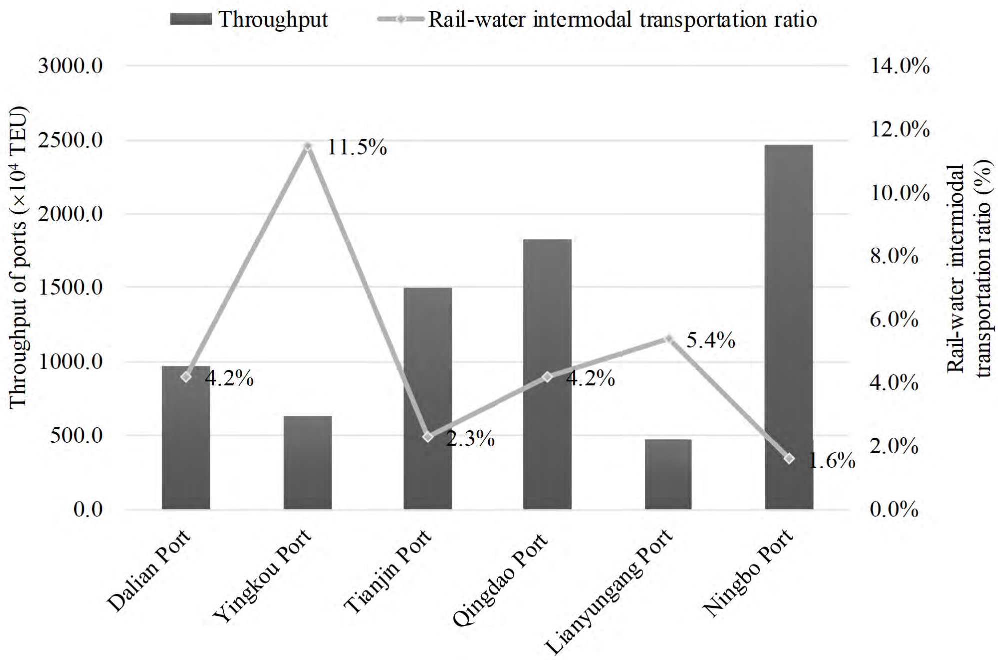

FIGURE 1. The throughput and rail-water intermodal transportation ratio of major ports in 2017.

TABLE 1. The throughput of rail-water intermodal transportation in major ports from 2011 to 2016 (× 10^4 TEU).

Port	2011	2012	2013	2014	2015	2016
Dalian Port	31.3	38.0	29.0	32.2	34.9	40.6
Yingkou Port	29.2	30.2	32.4	41.5	43.1	52.6
Tianjin Port	26.4	34.6	26.9	26.0	31.0	32.0
Qingdao Port	19.1	23.1	8.4	22.0	30.0	48.3
Lianyungang Port	27.5	30.3	25.7	22.0	30.0	20.6
Ningbo Port	4.7	5.9	10.5	13.5	17.0	25.0

distance transportation, compared with road transportation. As a result, an increasing amount of cargo is transported by both rail and water. In inland regions, railway transports cargo from their gathering places to the destination ports or from ports to their inland destination regions. In 2011, the first Sino-Europe block train (officially named as "China Railway Express" (CR express)) started its first trip at Chonqing. After that, more CR express begins to operate in China.

Thus, railways are introduced to the ports and an increasing number of rail-water intermodal container terminals (RWICTs) are built, such as Dalian RWICT and Chongqing RWICT. RWICTs are an interface between water transportation and land transportation, especially railway transportation. Generally, there are 5 parts in RWICTs: quayside area, container yards, traveling paths, railway operation area and the gate. In this paper, we mainly concentrate on the operations of containers transported by railway, therefore, only quayside area, railway operation area and IT traveling paths are considered.

Although there are types of equipment used in these three areas, such as quay cranes (QCs), inner trucks (ITs), rail mounted gantry cranes (RMGCs), reach stackers (RS) and automated guided vehicles (AGVs), we only consider QCs, RMGCs and ITs. Since we do not consider the automated container terminals, AGVs are not used in this paper. Additionally, RSs are usually used in the auxiliary container yards; although they can be used to handle containers from the train, there may be some congestion between RSs and ITs. This will make the problem more complicated.

According to the direction of containers, there are two types of containers: inbound and outbound containers. Inbound containers are containers from vessels, while outbound containers are containers from trains or outer trucks. Fig. 2 shows the simple process of inbound and outbound containers. Take the process of outbound containers as an example: when a train arrives at the RWICT, RMGCs begin to load containers from the train to slots in railway container yards; as the vessels belonging to the containers arrive, RMGCs not only load containers from the train to railway container yards, but load containers to ITs; then ITs deliver containers to quayside area; if there is no available QC, ITs have to wait at the working point of QCs until QCs are idle; once QCs are available, they pick up containers from ITs and put them onto the vessels. The process of inbound containers is similar. In this paper, only outbound containers from trains are considered.

Storage space allocation problem (SSAP) is a critical problem defined as temporary allocation of inbound or outbound containers to container yards with the aim of balancing the

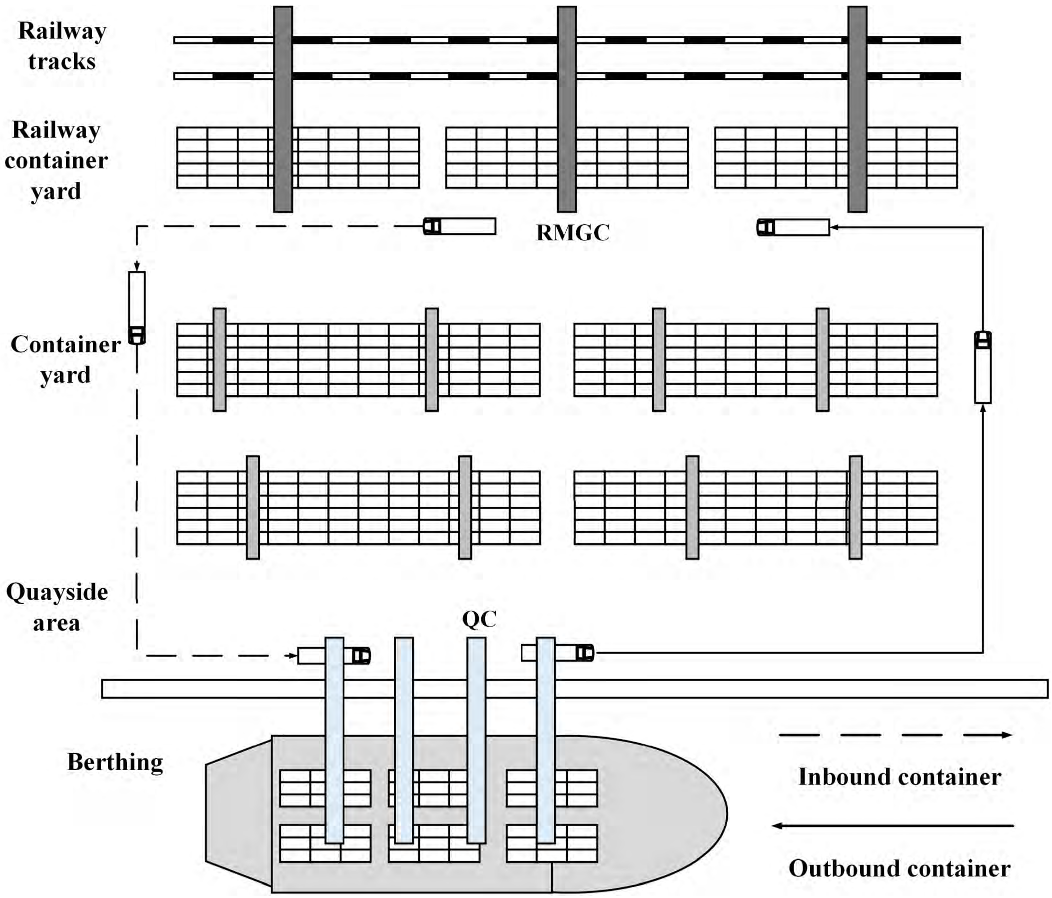

FIGURE 2. The process of inbound and outbound containers.

workload between blocks and minimizing rehandling operations. In general, SSAP can be divided into two parts: block allocation problem and slot allocation problem. The former one is to allocate containers into various blocks so that the workload between them can be balanced, while the later one aims at minimizing the rehandling operations by assigning containers into specific slots. Most studies focused on only the former one, such as [1]–[6], [8], [28], while compared to the former, studies on the latter are less than the former, such as [7], [9], [10].

Additionally, handling operation problem (HOP) has also been one of the hot issues in container terminals, which is to integrate different types of equipment together to minimize the makespans of handling operations.

Therefore, both SSAP and HOP are of vital importance in improving the productivity and efficiency of container terminals. Existing literatures have been devoted to these two problems separately, while these two problems are highly interrelated in actual situations: (1) since the functions of RMGCs in RWICTs are different from yard cranes (YCs) in traditional container terminals: YCs only handle or store containers from trucks, while RMGCs handle or store containers not only from trucks, but from trains at the same time; (2) SSAP can reduce the reallocation amount of containers, which will directly reduce the RMGC operation time; in turn, job sequences of each RMGC will also affect the locations of the new arrival containers. Thus, it is essential to consider these two problems simultaneously.

Consequently, the main contributions of this paper are: (1) we concentrate on the integration of SSAP and HOP, considering both storage allocation constraints, such as weight, departure time, destination ports and stack height difference, and handling operation constraints, such as rehandling time and IT congestion; (2) a two-stage algorithm based on the rolling planning horizon is introduced, which also proposes a new update strategy.

The paper is organized as follows: In section 2, a brief review of related literatures is presented. Section 3 describes the problem and the two-stage optimization model. In Section 4, a two-stage heuristic algorithm is proposed to solve the problem. Section 5 provides computational experiments to validate the feasibility and effectiveness of the proposed algorithm. Section 6 concludes this paper and proposes the future works.

II. LITERATURE REVIEW

Because of the increasing importance of container transportation and intermodal transportation, numerous studies have focused on container operations of container terminals, particularly SSAPs and HOPs.

Kim and Park [1] discussed SSAP of outbound containers in maritime container terminals and introduced two heuristic algorithms. However, they only allocated containers to blocks of container yards. McKendall and Jaramillo [2] as well as McKendall [3] considered the dynamic SSAP to minimize the reallocation cost. Bazzazi et al. [4] introduced an efficient genetic algorithm (GA) to solve the extended SSAP in a maritime container terminal, considering containers' types. Three optimization models under different strategies of storing containers were considered to solve SSAP [5]. However, only block allocation problem was considered, and the specific slots of containers cannot be determined. A novel approach was introduced for allocating containers to storage blocks in a marine container terminal to balance the operational quantities among different blocks [6]. Li et al. [7] studied SSAP under the inbound and outbound container mixed storage mode in railway container terminals and developed a two-stage optimization model and a heuristic algorithm. However, they only considered departure time in the study and assumed that there were only 2 layers in the railway container yard. Yang et al. [8] studied SSAP in maritime container terminals of inbound containers, considering the real-time strategic planning and intense loading and unloading synchronously. A new SSAP was introduced in RWICTs, considering the stowage plan [9], but they neglected the stacking height difference constraint between two adjacent stacks and handling operations. Wang et al. [10] studied the container assignment problem in rail-road transshipment terminals; however only departure time constraint was considered.

Most studies on SSAP only considered allocating containers to blocks, not to the specific locations. Meanwhile, although some literatures on SSAP paid attention to railway container terminals or RWICTs, they only considered parts of constraints on storing containers and neglected some important constraints, which may also affect the storage. Meanwhile, all the studies above just concentrated on SSAP, and ignored the relationship between SSAP and HOP.

Nowadays, an increasing number of researchers focused on the scheduling problem of equipment in container terminals, such as [30], [31] and [32]. Although these studies concentrated on the single equipment scheduling, they laid a good foundation for integrated scheduling problems of different types of equipment and provide solution ideas and methods for integrated scheduling problems of different types of equipment. Meersmans and Wagelmans [11] made the first attempt at establishing an integrated scheduling model for QCs, AGVs and automated stacker cranes in automated container terminals. They presented a branch and bound algorithm and a heuristic beam search algorithm to minimize the completion time. Vairaktarakis [12] optimized container handling operations and proposed an optimal algorithm and some heuristic algorithms to solve the problem; however, they only considered a single QC. Chen et al. [13] presented an integrated model to schedule the container handling system. The problem was formulated as a hybrid flow shop scheduling problem with precedence and blocking constraints (HFSS-B). Lau et al. [14], [15] studied the integrated scheduling problem of QCs, AGVs and YCs in automated container terminals; however, they all neglected QC and YC interference as well as rehandling operations. Kaveshgar et al. [16], [17] addressed an integrated optimization problem on QC and IT scheduling in container terminals: the former considered many real-world operational constraints and developed a GA combined with a greedy algorithm to solve the problem, while the latter used a particle swarm optimization-based solution method to solve the problem. However, none of them considered rehandling operations and container locations. Chang et al. [18] studied the integrated scheduling problem of RMGCs, ITs, and YCs, considering many real-world operational constraints; however, container locations were known in advance.

The studies above all focused on integrated scheduling problems of different types of equipment, but most of them only considered operations in marine container terminals. Only in [18], the influence of the railway operation area was considered; however, they did not combine HOP with SSAP, either.

Moreover, studies on the coordination between SSAPs and other scheduling problems existed. Bish [19] studied container handling and SSAP in maritime container terminals to determine locations of each unloaded container and schedule vehicles and cranes of each container. However, the dispatching plan of YCs was not determined. Lee et al. [20] introduced a novel approach that integrated IT scheduling and SSAPs. However, they assumed that each IT could only serve just one QC. Luo et al. [21], [22] proposed a novel way to determine dispatching rules of AGVs and container allocation, considering discharging and loading simultaneously. A mixed integer programming (MIP) was proposed to minimize the ship's berthing time, and a GA was designed to solve the problem. However, when determining container locations, they ignored specific storage constraints. Tang et al. [23] proposed a new MIP model to integrate SSAP and ship scheduling to achieve high space utilization, low material loss, and low transportation costs. Zeng et al. [24] studied the coordination of SSAP and RMGC scheduling problem in railway container terminals, considering some operational constraints and storage modes. However, the specific locations of containers cannot be determined. Jiang et al. [25] studied YC deployment and container allocation together and formulated a MIP to minimize YC deployment costs and guarantee the container allocation requirements and operational efficiency. However, they only focused on container yards and neglected the handling operations in quayside area.

Although the literatures above concentrated on combining SSAP with some other scheduling problems, they neglected the whole process of handling operations; for example, Zeng et al. [24] did not consider the specific storage

FIGURE 3. An example of the railway container yard in Dalian Rail-water Intermodal Container Terminal.

constraints and the interrelation between the quayside area and railway operation area.

From all the literatures above, they seldom considered SSAP and HOP together in rail-water intermodal container transportation. The reason is that although intermodal transportation develops dramatically, the studies on intermodal transportation fail to form an integral system. Meanwhile, most researchers wrongly assumed that the operations in RWICTs are the same as those in traditional container terminals. Thus, the number of studies on RWICTs is too few.

Therefore, the joint problem of SSAP and HOP for outbound containers is proposed in this paper, considering not only the specific storage constraints, such as weight, departure time and destination port constraints, but handling constraints, such as RMGCs' rehandling time, IT congestion, and RMGCs' traveling time.

III. PROBLEM DESCRIPTION AND FORMULATION

A. PROBLEM DESCRIPTION

We consider a RWICT, whose layout is like Dalian RWICT, including berthing area at the quayside area, several IT traveling paths, container yards and railway operation area (see Fig. 2). Container yards are the places storing maritime containers, while railway container yards in the railway operation area are the places storing railway containers. Meanwhile, the railway container yard is next to the railway handling tracks (shown in Fig. 3), which is composed of several bays. Each bay consists of several slots. Each slot is identified using three indices: bay-stack-layer.

Since SSAP and HOP are considered simultaneously in the paper, the problem can be decomposed into two stages:

Stage 1: According to the storage constraints, assign outbound containers to the optimal slots in railway container yards with the aim of reducing the number of rehandling operations;

Stage 2: According to container locations from Stage 1 and container departure time, integrate the scheduling of RMGCs, ITs and QCs to minimize makespans of handling operations.

Therefore, Stage 1 mainly focuses on the slot allocation problem, considering unloading containers form trains to railway container yards after a train arrives, while Stage 2 pays attention to the handling operation problem, considering handling operations and retrieval operations after the vessel arrives.

1) STORAGE SPACE ALLOCATION PROBLEM

In traditional container yards, containers with the same ship name and voyage number are stored in the same bay, while in railway container yards containers with different vessels can be stored in the same bay. So, both container weight and departure time should be considered. To reduce the rehandling operations and ensure the safety of railway container yards, some storage principles are introduced:

1) To guarantee the stability of the containership, heavier containers should be stored on lighter containers in the railway container yard;
2) To ensure the loading order of the containership, containers with earlier departure time should be stored on containers with later departure time;
3) To guarantee the unloading order during the voyage, containers with further destinations should be stored below containers with nearer destinations on containerships; thus, in the railway container yard, to guarantee containers with further destinations can be loaded onto containerships at first, containers with further destinations should be stored on containers with nearer destinations;
4) To guarantee storage safety in the railway container yard, the height difference between two adjacent stacks in the same bay should not exceed 3 layers.

So, if two containers in the same stack do not satisfy the first three storage principles, rehandling operations generate, which means that some container needs to be removed from its initial position to another position in the same bay. However, the specific rehandling process is not considered in this stage, so it is difficult to quantify the number of rehandling operations. To solve this problem, in our paper the overlapping amount is used to represent the number of rehandling operation indirectly. Consequently, the objective of Stage 1 is converted into minimize the overlapping amount.

Additionally, the weight and departure time priority are used to describe the actual weight and departure time of containers, respectively: the heavier the container is, the larger the container weight priority is; the later the departure time is, the larger the container departure time priority is. Since departure time of containers is different, to compare the destination ports among containers, it is assumed that containers with the same departure time belong to the same vessel. So, the further the destinations are, the larger the number is.

Since containers are loaded to the vessel at different planning periods, there must be some containers left from earlier planning periods, which may also cause rehandling operations. Hence, containers left from earlier planning periods are also considered in the paper.

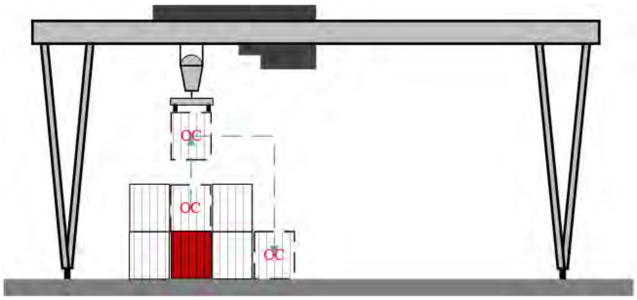

FIGURE 4. An example of rehandling operations of a RMGC.

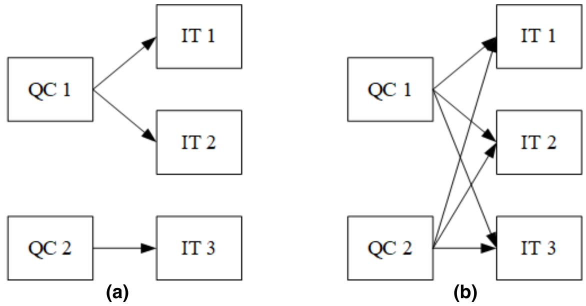

FIGURE 5. An example of IT working mode: (a) operation-line mode (b) operation-flat mode.

2) HANDLING OPERATION PROBLEM

RMGCs are responsible for handling containers from railway container yards to ITs when vessels arrive. During the handling process, when a RMGC picks up a container to an IT, there may be some container (named as obstruction container) on it to prevent it from being loaded to the IT immediately (see Fig. 4). In Fig. 4, the container with dotted lines and the name 'OC' is the container that needs to be moved firstly so that the red container can be loaded onto an IT. Therefore, the RMGC should move 'OC' to another empty slot in the same bay firstly and then return to load the red container onto the waiting IT. Consequently, the process that the RMGC moves 'OC' and returns to the red container is called rehandling operation, and the time that the RMGC moves 'OC' and returns to the red container is called rehandling time, which should be added to the operation time of RMGCs as well.

Because of all the RMGCs or QCs traveling on the same tracks in the railway container yard or the quayside area, respectively, they are not allowed to cross over each other. Therefore, interference and safety distance between each RMGC and QC should be considered. Meanwhile, since traveling time of RMGCs and QCs may also influence the completion time of each RMGC and QC, separately, RMGCs' and QCs' traveling time are considered as well.

In previous studies, when more than two ITs working for a vessel, either operation-line or operation-flat mode was adopted (shown in Fig. 5a and 5b). Fig. 5a shows the operation-line mode, which means that an IT can only serve just one QC. This mode is easy for terminal managers to coordinate and control ITs; however, ITs cannot be used fully. Fig. 5b is the operation-flat mode, which means that each IT can serve any QCs. This mode has been widely adopted in both marine and railway container terminals, thus this mode is also adopted in this paper.

B. BASSUMPTION

The following assumptions are made to formulate the problem:

1) It is assumed that all the containers are the same size and all the containers are from railway;
2) Initial assigning number of containers is assumed to be known beforehand, and the number of containers left from earlier planning periods in the railway container yard is assumed to be known in advance as well;
3) Containers' information, such as arrival time, departure time, weight and destination ports, is known beforehand;
4) RMGCs are assumed to operate only one container at a time: RMGCs can only move containers from either the railway container yard to ITs or from one slot to another slot in the same bay of the railway container yard;
5) The initial position of each IT is assumed to be located near different bays of the railway container yard;
6) The container locations in the vessel are assumed to be known beforehand.

C. CPROBLEM FORMULATION

The notations and variables used in the following model are shown in Table 2.

1) FIRST STAGE OPTIMIZATION MODEL

In Stage 1, containers are allocated to optimal slots to reduce the overlapping amount. Hence, the mathematical model can be formulated as follows:

$$F_1 = Min \sum_{i=0}^{N}\sum_{j=1}^{N} Y^{ij}_{(b,s,c_1),(b,s,c_2)} \quad (1)$$

$$\sum_{i=1}^{N} \varsigma^{i}_{(b,s,c)} \le 1 - X_{(b,s,c)}, \quad \forall b \in B,\ \forall s \in S_b,\ \forall c \in C_{b,s} \quad (2)$$

$$\sum_{(b,s,c)\in P} \varsigma^{i}_{(b,s,c)} \le 1, \quad i = 1, 2, \ldots, N \quad (3)$$

$$\sum_{i,b,s,c} \varsigma^{i}_{(b,s,c)} = N, \quad i = 1, 2, \ldots, N \quad \forall b \in B,\ \forall s \in S_b,\ \forall c \in C_{b,s} \quad (4)$$

$$\sum_{i} \varsigma^{i}_{(b,s,c)} + X_{(b,s,c)} \ge \sum_{i} \varsigma^{i}_{(b,s,(c+1))}, \quad \forall b \in B,\ \forall s \in S_b,\ \forall c \in C_{b,s} \quad (5)$$

$$\varsigma^{i}_{(b,s,c)} + X_{(b,s,c)} \le 1, \quad i = 1, 2, \ldots, N,\ \forall b \in B,\ \forall s \in S_b,\ \forall c \in C_{b,s} \quad (6)$$

$$\sum_{i,c} \varsigma^{i}_{(b,s,c)} \le H_{b,s}, \quad \forall b \in B,\ \forall s \in S_b \quad (7)$$

$$\left|h_{b,s_1}-h_{b,s_2}\right|-M(1-\vartheta_{b,s_1,s_2})\leq 3,\quad \forall b\in B,\quad \forall s_1,s_2\in S_b \tag{8}$$

$$\xi^{ij}_{(b,s,c_1),(b,s,c_2)}\leq \varsigma^{i}_{(b,s,c_1)}+\varsigma^{j}_{(b,s,c_2)},\quad i,j=1,2,\ldots,N,\ \forall b\in B,\ \forall s\in S_b,\ \forall c_1,c_2\in C_{b,s} \tag{9}$$

$$W^*_i\varsigma^{i}_{(b,s,c_1)}-W^*_j\varsigma^{j}_{(b,s,c_2)}+L^*(1-\xi^{ij}_{(b,s,c_1),(b,s,c_2)})\geq 0,\quad i,j=1,2,\ldots,N,\quad \forall b\in B,\ \forall s\in S_b,\ \forall c_1\neq c_2\in C,\quad c_1>c_2 \tag{10}$$

$$D^*_i\varsigma^{i}_{(b,s,c_1)}-D^*_j\varsigma^{j}_{(b,s,c_2)}+L^*(1-\xi^{ij}_{(b,s,c_1),(b,s,c_2)})\geq 0,\quad i,j=1,2,\ldots,N,\quad \forall b\in B,\ \forall s\in S_b,\quad \forall c_1\neq c_2\in C,\ c_1>c_2 \tag{11}$$

$$U^*_i\varsigma^{i}_{(b,s,c_1)}-U^*_j\varsigma^{j}_{(b,s,c_2)}+L^*(1-Y^{ij}_{D_iD_j})+L^*(1-\xi^{ij}_{(b,s,c_1),(b,s,c_2)})\geq 0,\quad i,j=1,2,\ldots,N,\ \forall b\in B,\quad \forall s\in S_b,\ \forall c_1\neq c_2\in C,\ c_1>c_2 \tag{12}$$

Equation (1) is the objective function of Stage 1, which is to minimize the overlapping amount. (2) guarantees that a slot can be occupied by at most one container. (3) ensures that one container can occupy only one slot. (4) indicates that the number of containers that need to be stored in the railway container yard equals to the number of new arrival containers. (5) implies that containers cannot be located on empty slots. (6) ensures that the slot must be empty before the container i is allocated into it. (7) guarantees that the stacking height of the stack s should not exceed its limited height. (8) ensures the height different between two adjacent stacks in the same bay should not exceed 3 layers. (9) indicates the relationship between the decision variables $\varsigma^{i}_{(b,s,c)}$ and $\xi^{ij}_{(b,s,c_1),(b,s,c_2)}$. (10) prevents lighter containers being located on heavier containers. (11) guarantees containers with later departure time must be located under containers with earlier departure time. (12) implies that containers with further destination ports must be placed on the containers with nearer destination ports.

2) SECOND STAGE OPTIMIZATION MODEL

In Stage 2, based on the container locations from Stage 1 and departure time of each container, the job sequences of RMGCs, ITs and QCs can be optimized to minimize the makespans of handling operations. A MIP model can be formulated as follows:

$$F_2=Min(\max_q(u_{qN_q}+th_{qN_q}+(dr_{qm}+dr_{mm'})/v_q)) \tag{13}$$

$$\sum_{E_{gi}\in O_s}\alpha^{gj}_{gi}=1,\quad i,j=1,2,\ldots,N_g,\ \forall E_{gj}\in O_f,\ \forall g\in G \tag{14}$$

$$\sum_{E_{gj}\in O_f}\alpha^{gj}_{gi}=1,\quad i,j=1,2,\ldots,N_g,\ \forall E_{gi}\in O_s,\ \forall g\in G \tag{15}$$

TABLE 2. Properties notations and variables.

Indexes	Instructions
i,j,τ	container index, where τ represents the obstruction container
q,l	QC index
g,k	RMGC index
b,b'	bay index of the railway container yard
s	stack index in the bay b
c	layer index in the stack s of the bay b
m	bay index in the vessel
Sets	**Instructions**
Q	the set of QCs
G	the set of RMGCs
V	the set of ITs
B	the set of bays in the railway container yard
S_b	the set of stacks in the bay b in the railway container yard
$C_{b,s}$	the set of layers in the stack s of the bay b in the railway container yard
P	the set of tasks' positions in the railway container yard
M	the set of bays in the vessel
O_s	the set of tasks RMGCs need to operate, including all the tasks and the dummy beginning task
O_f	the set of tasks RMGCs need to operate, including all the tasks and the dummy end task
O	the set of tasks RMGCs need to operate, including all the tasks, the dummy beginning task and the dummy end task
Notations	**Instructions**
E_{gi}	the task of the RMGC g loading the container i onto the IT from the railway container yard
$E_{g\tau}$	the task of the RMGC g rehandling the obstruction container τ in the railway container yard
e_{qi}	the task of the QC q loading the task E_{gi} onto the vessels
(b,s,c)	the position of the task E_{gi} in the railway container yard
Parameters	**Instructions**
N	the total number of containers need to be stored
N_g	the number of tasks that the RMGC g needs to operate
N_q	the number of tasks that the QC q needs to operate
$N_{b,s}$	the number of tasks in the stack s of the bay b
N_b	the number of tasks in the bay b
$H_{b,s}$	the limited height of the stack s in the bay b
$h_{b,s}$	the actual height of the stack s in the bay b
W_i	the weight of the container i
D_i	the departure time of the container i
U_i	the destination port of the container i
$X_{(b,s,c)}$	if the layer c of the stack s in the bay b is occupied, $X_{(b,s,c)}$=1 , otherwise; $X_{(b,s,c)}$=0
$Y^{ij}_{D_iD_j}$	if the departure time of the container i and j is the same, $Y^{ij}_{D_iD_j}$=1 ; otherwise, $Y^{ij}_{D_iD_j}$=0
$w_{g\tau}$	beginning time of the task $E_{g\tau}$
th_{qi}	operation time of the task e_{qi} , including QC hoisting/lowing time
a_{gi}	operation time of the task E_{gi} including RMGC hoisting/lowing time
$r_{g\tau}$	rehandling time of the RMGC g , including RMGC hoisting/lowing time
tr_{qb}	traveling time of ITs between transfer point of the bay b and the working point for the QC q
d^{gj}_{gi}	traveling distance of the RMGC g between the end position of the task E_{gi} and the beginning position of the task E_{gj}

TABLE 2. ***(Continued.)*** **Properties notations and variables.**

$d_{bb'}$	traveling distance of the RMGC g between the transfer point of the bay b to the transfer point of the bay b'
$d_b^{(b,s,c)}$	traveling distance of the RMGC g between the transfer point of the bay b and the position of the task E_{gi} at the bay b
$d_{(b,s,c)}^{(b',s',c')}$	traveling distance of the RMGC g between the position before rehandling and the position after rehandling
dr_{qm}	traveling distance of the QC q between the working point of the QC q and the container's bay m in vessels
$dr_{mm'}$	traveling distance of the QC q between container's bay m in vessels and the container's bay m' in vessels
v_g	the average traveling speed of the RMGC g
v_q	the average traveling speed of the QC q
$\eta_{gi}^{g\tau}$	if the RMGC g performs the task $E_{g\tau}$ before the task E_{gi}, $\eta_{gi}^{g\tau}=1$; otherwise, $\eta_{gi}^{g\tau}=0$
χ_b^{gigj}	if the task E_{gi} and E_{gj} are located in the same bay b, $\chi_b^{gigj}=1$; otherwise, $\chi_b^{gigj}=0$
ϕ_b^{gi}	if the task E_{gi} is in the bay b, $\phi_b^{gi}=1$; otherwise, $\phi_b^{gi}=0$
θ_{qi}^m	if the task e_{qi} is in the bay m in vessels, $\theta_{qi}^m=1$; otherwise, $\theta_{qi}^m=0$
L	a sufficiently positive integer
Variables	**Instructions**
$Y_{(b,s,c_1),(b,s,c_2)}^{ij}$	decision variable, overlapping amount, if the container i and j are stored in the layer c_1 and c_2 of the stack s in the bay b respectively, and they do not satisfy weight, departure time and destination port constraint, $Y_{(b,s,c_1),(b,s,c_2)}^{ij}=1$; otherwise, $Y_{(b,s,c_1),(b,s,c_2)}^{ij}=0$
u_{qi}	decision variable, the beginning time of the task e_{qi}
w_{gi}	decision variable, the beginning time of the task E_{gi}
ϑ_{b,s_1,s_2}	decision variable, if the stack s_1 and s_2 are two adjacent stacks of the bay b, $\vartheta_{b,s_1,s_2}=1$; otherwise, $\vartheta_{b,s_1,s_2}=0$
$\varsigma_{(b,s,c)}^i$	decision variable, if the container i is stored in the layer c of the stack s in the bay b, $\varsigma_{(b,s,c)}^i=1$; otherwise, $\varsigma_{(b,s,c)}^i=0$
$\xi_{(b,s,c_1),(b,s,c_2)}^{ij}$	decision variable, if the container i and j are stored in the layer c_1 and c_2 of the stack s in the bay b, respectively, $\xi_{(b,s,c_1),(b,s,c_2)}^{ij}=1$; otherwise, $\xi_{(b,s,c_1),(b,s,c_2)}^{ij}=0$,
α_{gi}^{gj}	decision variable, if the RMGC g operates the task E_{gj} immediately after the task E_{gi}, $\alpha_{gi}^{gj}=1$; otherwise, $\alpha_{gi}^{gj}=0$
β_{gi}^{kj}	decision variable, if the IT transports the task E_{kj} just after the task E_{gi}, $\beta_{gi}^{kj}=1$; otherwise, $\beta_{gi}^{kj}=0$
γ_{qi}^{qj}	decision variable, if the QC q operates the task e_{qj} immediately after the task e_{qi}, $\gamma_{qi}^{qj}=1$; otherwise, $\gamma_{qi}^{qj}=0$

$$\sum_{k\in G}\sum_{i=1}^{N_g}\beta_{gi}^{kj}=1,\quad j=1,2,\ldots,N_k,\ \forall g,k\in G \tag{16}$$

$$\sum_{k\in G}\sum_{j=1}^{N_k}\beta_{gi}^{kj}=1,\quad i=1,2,\ldots,N_g,\ \forall g,k\in G \tag{17}$$

$$\sum_{q\in Q}\sum_{i=1}^{N_q}\gamma_{qi}^{qj}=1,\quad j=1,2,\ldots,N_q \tag{18}$$

$$\sum_{q\in Q}\sum_{j=1}^{N_q}\gamma_{qi}^{qj}=1,\quad i=1,2,\ldots,N_q \tag{19}$$

$$\begin{aligned}&\phi_{b_1}^{gi*}\phi_{b_2}^{gj*}\alpha_{gi}^{gj}+1-\phi_{b_3}^{(g+1)i'*}\phi_{b_4}^{(g+1)j'*}\alpha_{(g+1)i'}^{(g+1)j'}\\&\quad\le(b_3-b_2)(b_3-b_1)(b_4-b_2)(b_4-b_1),\\&\quad i,j=1,2,\ldots,N_g,\quad i',j'=1,2,\ldots,N_k,\\&\quad\forall g\in G,\quad\forall b_1,b_2,b_3,b_4\in B\end{aligned} \tag{20}$$

$$\begin{aligned}&\gamma_{qi}^{qj}+1-\gamma_{(q+1)i'}^{(q+1)j'}\le(m_3-m_2)(m_3-m_1)\\&\quad{}^*(m_4-m_2)(m_4-m_1),\\&\quad i,j=1,2,\ldots,N_q,\ i',j'=1,2,\ldots,N_l,\\&\quad\forall q\in Q,\ \forall m_1,m_2,m_3,m_4\in M\end{aligned} \tag{21}$$

$$\begin{aligned}&d_{gi}^{gj}=d_b^{(b,s',c')*}\chi_b^{gigj*}\alpha_{gi}^{gj*}\varsigma_{(b,s,c)}^{i*}\varsigma_{(b',s',c')}^{j}\\&\quad+(d_{bb'}+d_{b'}^{(b',s',c')*}(1-\chi_b^{gigj})^*\alpha_{gi}^{gj*}\varsigma_{(b,s,c)}^{i}{}^*\varsigma_{(b',s',c')}^{j},\\&\quad i,j=1,2,\ldots,N_g,\quad\forall E_{gi},E_{gj}\in O,\\&\quad\forall g\in G,\ \forall(b,s,c),(b',s',c')\in P\end{aligned} \tag{22}$$

$$\begin{aligned}&u_{lj}-u_{qi}\ge th_{qi}+(dr_{qm}+dr_{mm'})/v_q^*\theta_{qi}^m-L(1-\gamma_{qi}^{lj}),\\&\quad i=1,2,\ldots,N_q,\quad j=1,2,\ldots,N_l,\\&\quad\forall q,l\in Q,\quad\forall m,m'\in M\end{aligned} \tag{23}$$

$$\begin{aligned}&w_{gj}-w_{gi}\ge a_{gi}+(d_b^{(b,s,c)}+d_{gi}^{gj})/v_g\\&\quad+(r_{g\tau}+2^*d_{(b,s,c)}^{(b',s',c')}/v_g)^*\eta_{gi}^{g\tau}-L(1-\alpha_{gi}^{gj}),\\&\quad i,j=1,2,\ldots,N_g,\quad\forall E_{gi}\in O_s,\ \forall E_{gj},E_{g\tau}\in O_f,\\&\quad\forall g\in G,\quad\forall(b,s,c),(b',s',c')\in P\end{aligned} \tag{24}$$

$$\begin{aligned}&w_{gi}-w_{g\tau}\ge r_{g\tau}+2^*d_{(b,s,c)}^{(b',s',c')}/v_g-L(1-\eta_{gi}^{g\tau}),\\&\quad i=1,2,\ldots,N_g,\quad\forall E_{gi}\in O_s,\ \forall E_{g\tau}\in O_f,\\&\quad\forall g\in G,\quad\forall(b,s,c),(b',s',c')\in P\end{aligned} \tag{25}$$

$$\begin{aligned}&w_{kj}+a_{kj}+d_b^{(b,s,c)}/v_k+(r_{k\tau}+2^*d_{(b,s,c)}^{(b',s',c')}/v_k)^*\eta_{kj}^{k\tau}\\&\quad-(u_{qi}+th_{qi})\ge\sum_{b\in B}tr_{qb}^*\phi_b^{gi}-L(1-\beta_{gi}^{kj}),\\&\quad i=1,2,\ldots,N_q,\quad j=1,2,\ldots,N_k,\\&\quad\forall E_{gi}\in O_s,\quad\forall E_{kj},E_{k\tau}\in O_f,\ \forall g,k\in G,\ \forall q\in Q,\\&\quad\forall(b,s,c),(b',s',c')\in P\end{aligned} \tag{26}$$

$$\begin{aligned}&w_{gj}+L(1-\alpha_{gi}^{gj})\ge u_{qi}+th_{qi}+\sum_{b\in B}tr_{qb}{}^*\phi_b^{gi},\\&\quad i=1,2,\ldots,N_q,\quad j=1,2,\ldots,N_g,\ \forall E_{gi},E_{gj}\in O,\\&\quad\forall g\in G,\quad\forall q\in Q\end{aligned} \tag{27}$$

$$\begin{aligned}&w_{gi}+a_{gi}+d_b^{(b,s,c)}/v_g+\eta_{gi}^{g\tau*}(r_{g\tau}+2^*d_{(b,s,c)}^{(b',s',c')}/v_g)\\&\quad+\sum_{b\in B}tr_{qb}{}^*\phi_b^{gi}\le u_{qi},\quad i=1,2,\ldots,N_q,\ \forall E_{gi}\in O_s,\\&\quad\forall E_{g\tau}\in O_f,\quad\forall g\in G,\ \forall q\in Q,\ \forall(b,s,c),(b',s',c')\in P\end{aligned} \tag{28}$$

$$\begin{aligned}&u_{qi},w_{gi},w_{g\tau}\ge 0,\quad i=1,2,\ldots,N_g\ or\ N_q,\\&\quad\forall E_{gi}\in O_s,\quad\forall E_{g\tau}\in O_f,\ \forall g\in G,\ \forall q\in Q\end{aligned} \tag{29}$$

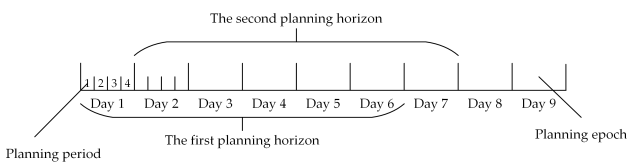

FIGURE 6. An example of the rolling planning horizon.

Since the last operation process is that a QC hoists a container from an IT and puts it onto the assigned slot in the vessel, the makespans of the whole loading process refer to the completion time of the last container operation by QC. The objective of Stage 2 shown in (13) is to minimize the makespan of handling operations, which is calculated by the beginning time of the last task plus the operation time and traveling time of the QC. (14)-(19) imply that each RMGC, IT and QC has only one successive or previous task. (20)-(21) ensure that tasks between two adjacent RMGCs or QCs must not interfere. (22) calculates the traveling distance of the RMGC g between two continuous tasks. (23) implies that the QC q cannot begin to handle the next task until it completes the former task. (24)-(25) indicate that the RMGC g cannot begin to handle the next task until it completes the former task. (24) means that the two continuous tasks are both loading tasks, while (25) implies that the two continuous tasks are loading task and rehandling task. (26) presents that an IT can only begin to deliver the next task from the transfer point of the bay b after the IT delivers the task to the working point of the QC and returns to the transfer point of the bay b. (27) implies a RMGC cannot load the next task onto the IT until the IT returns to the transfer point of the bay from the working point of the QC. (28) indicates that a QC can only start to load the task into the vessel after the IT delivers the task to the working point of the QC. (29) shows non-negative restrictions.

IV. SOLUTION APPROACHES

To solve the proposed models, a two-stage heuristic algorithm is developed, where the rolling planning horizon and update strategy are adopted. According to [29], a fixed horizon in the immediate future is introduced at each planning epoch and the plan is executed accordingly up to the next planning epoch; then a new plan is formulated based on the latest information and this pattern continues. Fig. 6 shows an example of the rolling planning horizon.

The procedure of the two-stage heuristic algorithm is based on the rolling planning horizon (shown in Fig. 7).

A. HEURISTIC ALGORITHM FOR STAGE 1

Considering the characteristics of Stage 1, a heuristic algorithm is developed. The heuristic algorithm is like an enumeration approach:

Select the heaviest or latest departure time container and choose the feasible slots from empty slots of the bay;

Then calculate the overlapping amount of the feasible slots and choose the slot with the minimum overlapping amount or the minimum increase in the overlapping amount;

Iteratively, choose the second heaviest or latest departure time container under the result of the heaviest or latest departure time container, and calculate the overlapping amount;

Finally, choose the optimal allocation plan with the minimum overlapping amount.

Fig. 8 shows an example of the heuristic algorithm, which firstly chooses the heaviest container. The notations used in the description of the procedure and the detailed descriptions of the procedure are as follows:

I_w: the set of weight priority in an ascending order, $I_w = \{i_{w\min}, \ldots, i_w, \ldots, i_{w\max}\}$, i_w means the container with the specified weight priority;

E: the set of departure time priority with the same weight priority in an ascending order, $E = \{i_{w,\min}, \ldots, i_{w,e}, \ldots, i_{w,e\max}\}$, $i_{w,e}$ means the container with the specified departure time priority;

P : the set of destination ports with the same departure time priority in an ascending order, $P = \{i_{w,e,p\min}, \ldots, i_{w,e,p}, \ldots, i_{w,e,p\max}\}$, $i_{w,e,p}$ means the container with the specified destination port;

$C_{b,s}$: the set of tiers in stack s of bay b, $C_{b,s} = \{c_{\min}, \ldots, c, \ldots, c_{\max}\}$, $c_{\max} = H_{b,s}$;

A_0: the initial storage matrix;

n: the number of the container;

A_n: the storage matrix after allocating the container;

N_r: the overlapping amount after allocating a container;

$N_{r'}$: the overlapping amount before allocating a container.

Step 1: Input the initial storage matrix A_0 and set $n = 0$, $N_r = 0$ and $N_{r'} = 0$;

Step 2: According to the first principle, traverse the weight priority of all the containers left from earlier planning horizons and the new arrival containers and sort them: I_w;

Step 3: Choose the lightest container i_w. If there is only one container i_w and it has already been in the bay, then go to Step 12;

Step 4: If there is more than one container i_w, then go to Step 10; otherwise, assign the container into the bay;

Step 5: Sort the layers in the bay: $C_{b,s}$, select the layer c from the bottom;

Step 6: Check whether there is an empty slot in layer c, if there is no empty slot, then go to Step 9;

Step 7: If there is only one empty slot, then allocate the container to this slot, update the storage matrix A_n and go to Step 13; otherwise, there is over one slot;

Step 8: Select the best slot from these empty slots. Set $N_{r'} = N_r$. Compare the overlapping amount between before and after allocating the container into the slots, if $N_{r'} \geq N_r$ then allocate the container into the slot; otherwise, allocate the container into the slot whose value of $N_r - N_{r'}$ is the minimum. Update the storage matrix A_n and go to Step 12;

Step 9: Update the layer $c = c + 1$, if $c <= H_{b,s}$, then go to Step 6; otherwise, select another bay to store the container and go to Step 5;

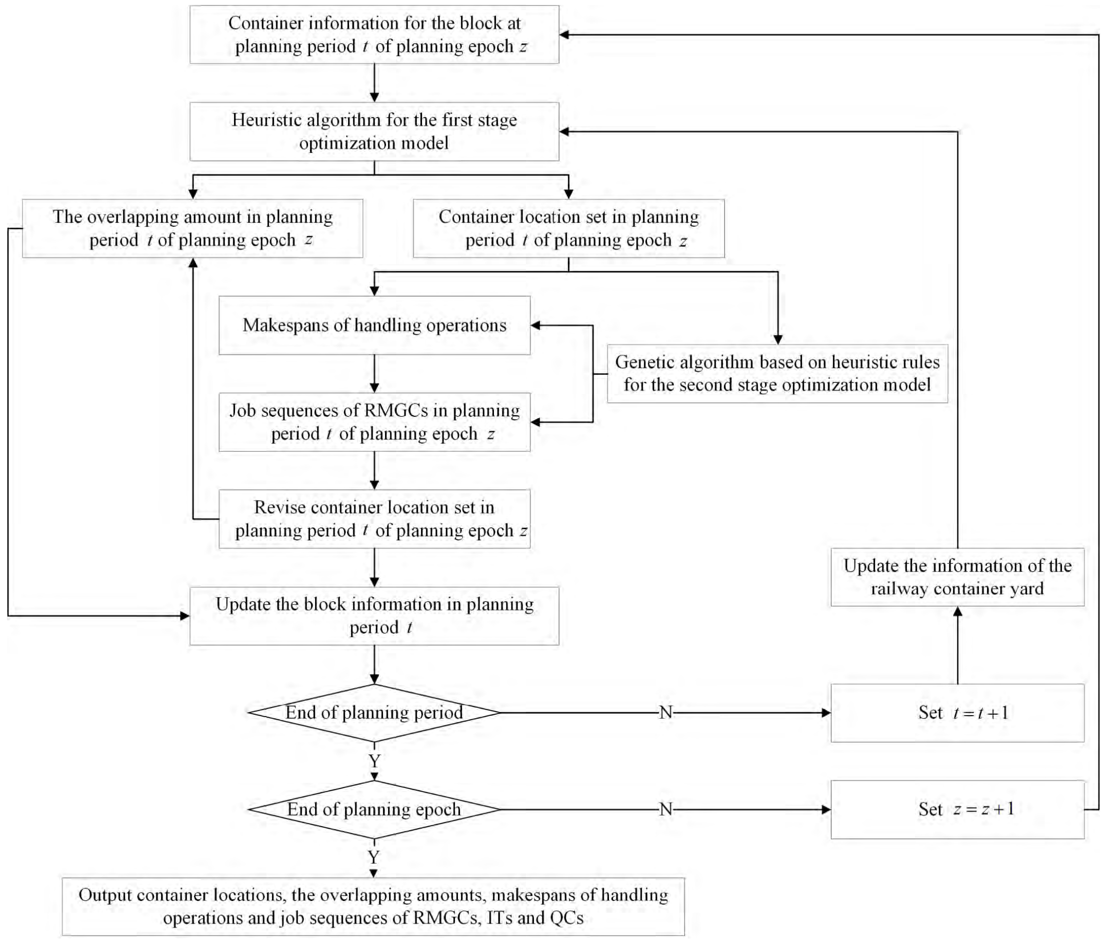

FIGURE 7. **The procedure of the two-stage heuristic algorithm.**

Step 10: Traverse the departure time priority with the same weight priority and sort them: E; then choose the container $i_{w,e}$, if there is only one container $i_{w,e}$, then go to Step 5;

Step 11: Traverse the arrival port order with the same departure time priority and sort them: P; then allocate them in ascending order and go to Step 5;

Step 12: Set $n = n + 1$, if $n \leq N + \sum_{b,s,c} X_{(b,s,c)}$, then go to Step 3; otherwise, go to Step 14;

Step 13: If the new container and its lower layer container satisfy the storage principles, then go to Step 12; otherwise, update N_r and go to Step 12;

Step 14: Storage task ends. Output the final value of N_r.

B. TWO-LAYER GENETIC ALGORITHM FOR STAGE 2

Because of container locations in the vessel known beforehand, the corresponding QC is known at the beginning time as well. Meanwhile, since each task E_{gi} corresponds to a fixed QC, job sequences of each QC will also be determined according to job sequences of the task E_{gi}. Additionally, job sequences of each IT should remain consistent with job sequences of RMGCs and QCs, if not, an infeasible solution will exist. Consequently, the optimal sequences of ITs must keep consistent with the optimal sequences of the task E_{gi}.

So, HOP can be diverted into two parts: the first part is to determine the optimal sequences of RMGCs and QCs; the second part is to allocate the task E_{gi} to ITs and find out the optimal sequences of ITs for each task.

Since the problem in Stage 2 is like a flow shop scheduling problem, which has been proved to be a NP-hard problem, many heuristic and meta-heuristic algorithms can be used to solve this problem, such as GA and tabu search algorithm. Meanwhile, as GAs have been already successfully applied to solve the integrated scheduling problem in maritime and railway container terminals with different situations such as [14], [18], [22], [26] and [27], a novel two-stage GA is designed to solve the problem, which introduces some heuristic rules.

Consequently, in the outer layer, a GA is developed to determine the optimal schedules of the task E_{gi}, while in the inner-layer, heuristic rules are proposed to find optimal job sequences of the task E_{gi} for ITs. The procedure of the two-stage GA is illustrated in Fig. 9.

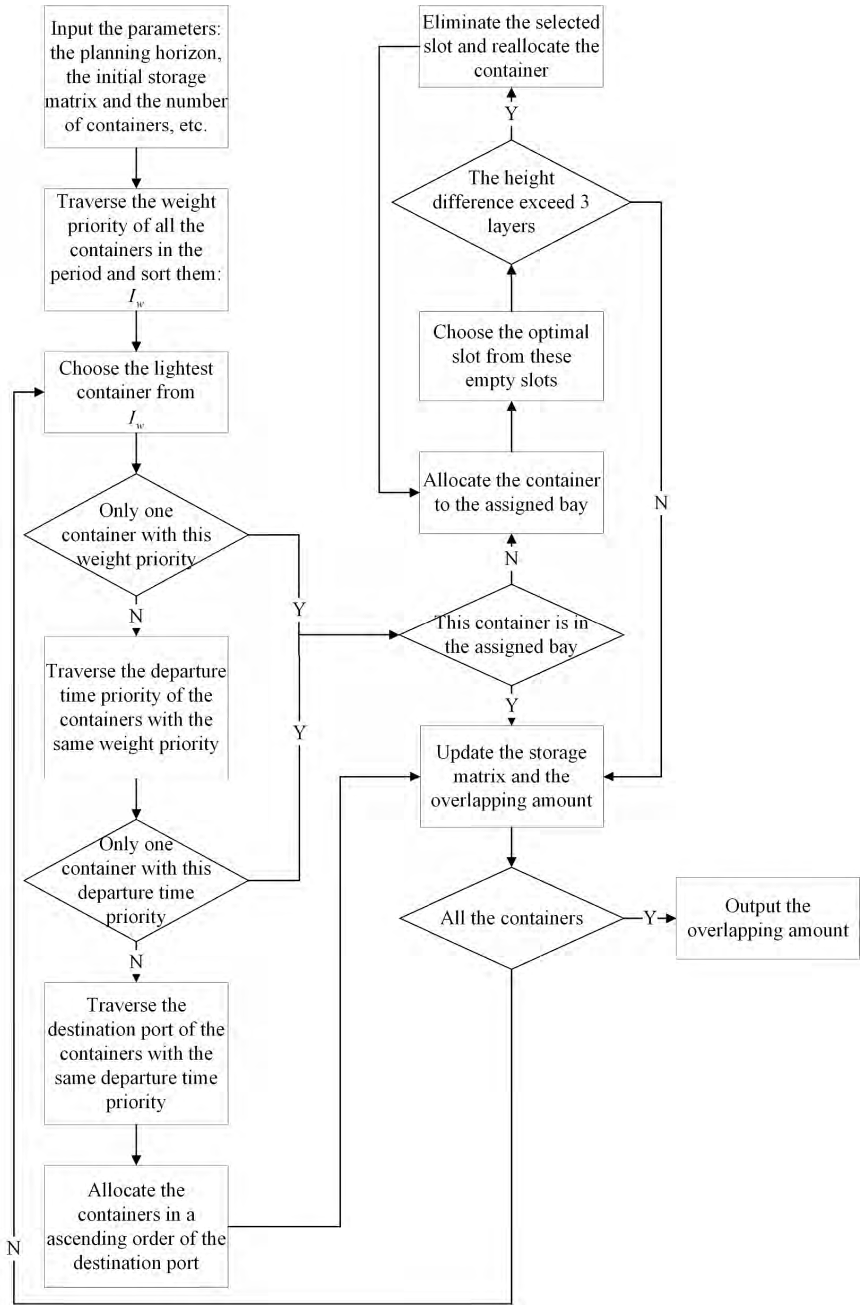

FIGURE 8. **The procedure of the heuristic algorithm for Stage 1.**

As a result, the main steps are shown as follows:

Step 1: Initialize and set up basic conditions. Input the population size, maximum iterations, selection, crossover and mutation rate;

Step 2: Generate individuals of the outer layer randomly so that the initial job sequences of RMGCs and QCs can be obtained;

Step 3: According to proximity rules and the individuals in the outer layer, generate inner layer individuals for each outer layer individual;

Step 4: Generate the job sequences of each IT;

Step 5: Calculate the current makespan and fitness value of every individual;

Step 6: Examine whether the inner layer iterations satisfy stopping criterion, if not, go to Step 7; otherwise, keep the best inner layer individual and fitness value and go to Step 9;

Step 7: Conduct selection operation on the inner layer individuals;

Step 8: Conduct balanced operation on the selected individuals to generate new inner layer individuals, and go to Step 4;

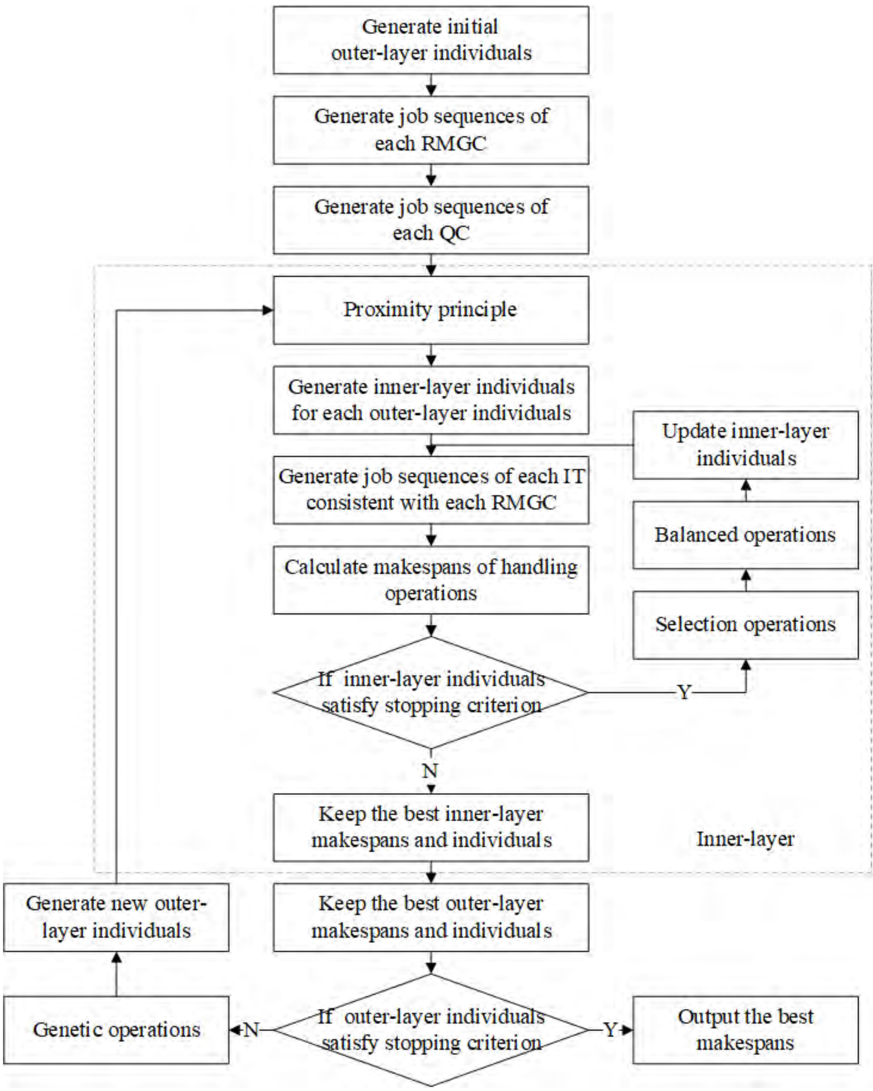

FIGURE 9. The procedure of the two-stage GA for Stage 2.

Step 9: Examine whether the outer layer iterations satisfy stopping criterion, if not, go to Step 10; otherwise, go to Step 14;

Step 10: Select the outer layer individuals according to their fitness values and copy them into the next iteration;

Step 11: Conduct crossover operation on the selected individuals to generate new individuals;

Step 12: Conduct mutation operation on the new individuals;

Step 13: Insert new individuals into the original population in the outer layer and go to Step 3;

Step 14: Output the minimum makespan and the corresponding optimal schedule of RMGCs, ITs and QCs.

1) REPRESENTATION

Considering the decision variables α_{gi}^{gj} and γ_{gi}^{kj}, in the outer layer, we take each job sequence as a chromosome. Fig. 10 shows a detailed example of the chromosome in the out layer. We use 'N' to express that containers can be loaded onto an IT directly and 'Y' to show that containers cannot be loaded onto ITs immediately. additionally, the initial chromosomes and initial positions of each RMGC are produced randomly in the outer layer.

Since the initial positions of ITs are generated randomly, to determine the initial task for each IT, the proximity principle is introduced, which means that an IT will choose the nearest task to perform. Each IT will choose the task whose traveling distance between the task and the initial position of the IT is the shortest.

However, although the initial task of each is determined by the proximity principle, job sequences of ITs should keep consistent with job sequences of the task E_{gi}. Take 2 ITs and the chromosome in Fig. 10 as an example, the initial positions of 2 ITs are Bay 11 and Bay 2. According to proximity principle, the initial task of IT 1 is task 3, while the initial task of IT 2 is task 7 or task 8. Then based on the job sequences of

Chromosome	7	3	5	1	2	4	6	8
RMGC	2	1	2	1	1	1	2	2
QC	1	3	2	1	2	3	2	1
Bay in the vessel	9	30	16	3	20	35	18	12
Stack in the vessel	3	5	2	7	6	4	1	3
Layer in the vessel	2	4	1	4	3	1	2	3
Bay in the railway container yard	1	12	15	13	17	8	5	3
Stack in the railway container yard	2	3	1	4	4	2	3	1
Layer in the railway container yard	4	3	2	1	3	3	2	4
Obstruction Container	N	N	Y	Y	N	Y	Y	N

	RMGC 1				RMGC 2			
Sequences	3	1	2	4	7	5	6	8
Bay in the railway container yard	12	13	17	8	1	15	5	3
Stack in the railway container yard	3	4	4	2	2	1	3	1
Layer in the railway container yard	3	1	3	3	4	2	2	4
Obstruction Container	N	Y	N	Y	N	Y	Y	N

	QC 1			QC 2			QC 3	
Sequences	7	1	8	5	2	6	3	4
Bay in the vessel	9	12	3	18	16	20	35	30
Stack in the vessel	3	3	7	1	2	6	4	5
Layer in the vessel	2	3	4	2	1	3	1	4

FIGURE 10. An example of chromosome representation in the outer layer.

the task, task 7 must precede task 8, so the initial task of IT 2 is task 7. Then according to these principles, the job sequences of IT 1 is 3-1-5-2, while the job sequences of IT 2 is 7-6-4-8. So, when the job sequences of tasks of the IT chosen by the proximity principle violates the job sequences of the task E_{gi}, the job sequences of each IT should be satisfied the job sequences of the task E_{gi} firstly.

Thus, according to chromosome encoding in the outer layer and the proximity principle, the individuals for each outer layer individual can be generated randomly.

2) FITNESS FUNCTION AND SELECTION

The choice of the fitness function has a significant impact on the convergence rate of GAs and whether the optimal solutions can be found. Since the proposed problem is a minimization problem, the smaller the objective value is, the higher the fitness value should be. So, the reciprocal of the objective function should be taken as the fitness function.

$$f = 1/F_2 \tag{30}$$

The roulette wheel method with the elitist strategy is used to select the better parent individuals in the outer layer. Firstly, some parent individuals with better fitness value will be reserved and do not participate in genetic operations in the current generation; then the rest will be retained based on the roulette wheel method.

In the inner layer, a novel selection operation is introduced, named quadratic selection, whose objective is to reserve good individuals. Firstly, the roulette wheel method is used, which is similar in the outer layer. To prevent the algorithm from being trapped in the local optima, after the roulette wheel method, a reselection operation will be carried out. A reselection probability p is introduced, and the notations and calculation of this selection probability are given below.

f_1: the fitness value of the task i in the unselected individual group;

f_{best}: the best fitness value of the selected individuals;

$S_{fitness}$: the sum of fitness values of selected and unselected individuals;

p: reselection probability.

$$p = \exp[-(f_1 - f_{best})/S_{fitness}] \tag{31}$$

Compare this reselection probability with a 0-1 random number, if the reselection probability exceeds the random number, the unselected individuals will be removed into the reserved individuals and participate in next genetic operations; otherwise, they will be eliminated.

3) CROSSOVER

Crossover operations are a vital operation in GAs, which will affect the convergence rate of GAs. There are numerous methods of crossover operations, while in the paper partially mapped crossover is applied (see Fig. 11). Firstly, give two parent individuals and randomly select two crossover points. Then propagate the overall assignment structure and the sub-sequences from one of the parent individuals into the child individual and complete it with the remaining genes from the other parent individual. Consequently, a new child individual is generated.

4) MUTATION

To improve the diversity of the individuals and generate new chromosomes, swap mutation is adopted in the outer layer, which means that two gene positions are selected randomly, and then their positions are exchanged.

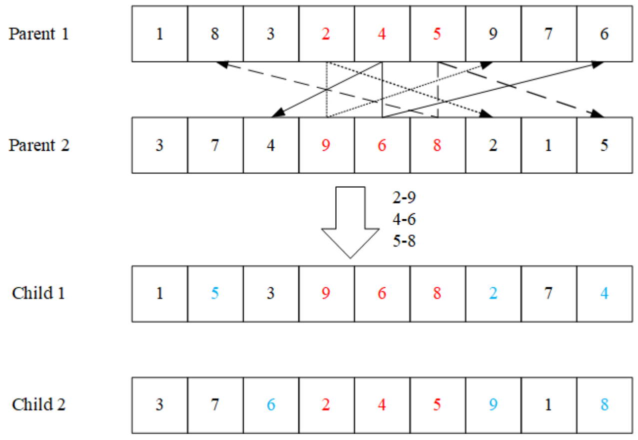

FIGURE 11. An example of partially mapped crossover in the outer layer.

5) BALANCED OPERATION

In the pre-experiment, tasks are not uniformly assigned among ITs: some ITs perform almost all the tasks, while others only operate a few. This will cause the makespans of the whole handling operation much longer. Additionally, this will lead to some ITs waiting for a long time to begin their next task, while others are always busy all the time. Therefore, it will affect the use of handling equipment and the efficiency of the RWICTs.

To solve this situation, according to [18], a balanced operation is introduced in the inner layer to make tasks evenly distributed among ITs. The balanced operation will be performed after selection operations are finished in the inner layer.

The balanced operation begins to select the ITs to which the maximum and minimum number of tasks are assigned and reallocate their tasks to balance the number of tasks among ITs. Then the new chromosomes in the inner layer are generated, and the new fitness value is calculated. Finally, the new fitness value is compared with the original fitness value, and if the new one is better, then the new one is substituted for the old one; otherwise, the old allocation scheme is reserved.

6) FLOATING OPERRATION

Since there is more than one IT traveling on traveling paths, IT congestion may happen, which cannot be neglected. However, it is difficult to model IT interferences without obtaining the detailed schedule and control of ITs. Thus, a novel approach is introduced to solve this problem by generating floating proportion of IT traveling time randomly, varying from 0 to 0.6, when calculating traveling time of ITs.

Firstly, we use traveling distance and speed of ITs to calculate IT initial traveling time; then randomly generate a floating proportion and multiply by the IT initial traveling time to get a value; finally, add the value to the IT initial traveling time to obtain the final traveling time of ITs.

7) OPERRATION STOPPING CRITERION

Two common stopping criteria are adopted in both outer and inner layer to balance the computation time and convergence to the approximate optimal solution:

1) The maximum generations are proposed;
2) The standard deviation of the fitness values (f) in the current generation should be below a small value.

C. SITUATIONS OF MULTIPLE SOLUTIONS

In Stage 1, although the number of rehandling operations is unique, there are multiple solutions (container locations) in the railway container yard. Thus, all the groups of containers' positions will be input into Stage 2 and then the group of containers' positions with the minimized makespans will be reserved as the optimal solutions in Stage 1.

D. UPDATE STRATEGY

After Stage 2 finishes, the job sequences of each RMGC can be determined, so the picking sequences of containers can be determined. According to the new picking sequence of containers and other basic information of containers and the railway container yard, update container locations and the number of rehandling operations in Stage 1. Continuously, input the new container locations into Stage 2, and update the makespans of handling and the job sequences of RMGCs, ITs and QCs. Then the iterative process continues until there are no improvements in the number of rehandling operations in Stage 1.

V. COMPUTATIONAL EXPERIMENTS

In this section, some computational experiments are carried out to validate the effectiveness and feasibility of the proposed model and algorithm. Firstly, some initial settings are introduced. Secondly, to evaluate the performance of our algorithm (OA), some comparison experiments are conducted with random search algorithm (RSA), which is widely adopted in railway container terminals.

A. INITIAL SETTINGS

Some experimental and parameter settings are considered to conduct the experiments as follows.

1) All experiments are based on the layout shown in Fig. 2.
2) In all experiments, we set 3 days as a planning horizon, 1 day as a planning epoch and 6 hours as a planning period.
3) The data we used in all experiments are from the survey data we collected from Dalian RWICT and Chengdu Container Terminal.
4) Each block has 5 bays, which has 5 stacks and 4 layers. Because of reallocation operations, when the layer in one bay is 4, it is necessary to leave 3 empty slots in a bay. Thus, one bay can store 17 containers at most.
5) The type of RMGCs and QCs used in all experiments is SRMG5507 and SRTG5203 respectively, which are used extensively in most railway container terminals

TABLE 3. Parameters of RMGCs.

Parameters of RMGCs	Quantity
Hoisting speed (full-load)	0.25 (m/s)
Hoisting speed (empty-load)	0.4 (m/s)
Trolley speed	1.42 (m/s)
Cart speed	1.33 (m/s)
Hoisting height	10 (m)

TABLE 4. Parameters of QCs.

Parameters of QCs	Quantity
Hoisting speed (full-load)	0.5 (m/s)
Hoisting speed (empty-load)	1.25 (m/s)
Trolley speed (full-load)	1 (m/s)
Trolley speed (empty-load)	2 (m/s)
Cart speed	30 (m)
Hoisting height	35 (m)

TABLE 5. Other parameters used in the experiments.

Parameters	Quantity
Distance between railway container yard and quayside area	1500 (m)
Distance between each bay in railway container yard	6.1 (m)
Distance between each bay in vessel	6.1 (m)
Speed of IT (full-load)	5 (m/s)
Speed of IT (empty-load)	10 (m/s)
Rehandling time	60.1 (s)
Container length	6.1 (m)
Container width	2.5 (m)
Container height	2.5 (m)

in China. Table 3 and 4 shows the parameters of RMGCs and QCs.

6) Some other parameters used in the experiments, such as the length, width, and height of a container, are shown in Table 5.
7) According to the pilot experiments, the population size in the outer layer, population size in the inner layer, maximum iteration in the outer layer, maximum iteration in the inner layer, probability of selection, probability of crossover and probability of mutation are set to be 100, 60, 80, 50, 0.9, 0.9 and 0.1, respectively.
8) Each experiment is operated 30 times to eliminate potential error rooted in the randomness of every single experiment, and the results are the average value of the results of 30 experiments.
9) The locations of containers used in all the experiments in Stage 2 are obtained from the experiments in Stage 1.
10) The proposed algorithm in our paper is carried out using MATLAB R2016b. All the experiments are conducted based on a personal computer with Intel Core i5-2520M @ 2.50GHz processors and 4 GB RAM under the Windows 10 operating system.

TABLE 6. The results between OA and RSA in stage 1 for one planning epoch.

Planning period	F_{1OA}	F_{1RSA}	The number of new arrival containers	GAP_1
1	9	19	20	52.6%
2	9	22	20	59.0%
3	9	23	18	60.9%
4	22	45	22	51.1%

TABLE 7. The results between OA and RSA in stage 2 for one planning epoch.

Planning period	F_{2OA}	F_{2RSA}	GAP_2
1	2280.7 (s)	2360.9 (s)	3.4%
2	2295.4 (s)	2403.7 (s)	4.5%
3	2203.5 (s)	2290.5 (s)	3.8%
4	2381.5 (s)	2460.2 (s)	3.2%

B. PERFORMANCE OF THE PROPOSED ALGORITHM

Firstly, we choose one planning epoch to verify the feasibility of the proposed algorithm. In the experiments, the number of RMGCs, ITs and QCs is 3, 3 and 3, respectively. To show the performance of our algorithm (OA), we compare OA with random search algorithm (RSA). GAP_1 and GAP_2 are introduced to evaluate the difference between these two methods. The calculation of GAP_1 and GAP_2 is shown as follows.

F_{1OA} : the overlapping amount in OA;
F_{1RSA} : the overlapping amount in RSA;
F_{2OA} : the makespans of OA;
F_{2RSA} : the makespans of RSA;
GAP_1 : the difference between F_{1OA} and F_{1RSA};
GAP_2 : the difference between F_{2OA} and F_{2RSA}.

$$GAP_1 = (F_{1RSA} - F_{1OA})/F_{1RSA}{}^{*}100\% \tag{32}$$
$$GAP_2 = (F_{2RSA} - F_{2OA})/F_{2RSA}{}^{*}100\% \tag{33}$$

Table 6 and 7 show the results of Stage 1 and Stage 2, separately.

As is observed from Table 5 and 6, the overlapping amount and makespans of OA are both better than them in RSA. Meanwhile, the average computation time of each planning period is 5.6 min in OA, while the average computation time of each planning period is 12.3 min in RSA.

To evaluate the performance of OA in large-sized experiments, computational experiments on 30 days are implemented. The results are shown in Fig. 12 and 13.

From Fig. 10 and 11, it can be seen obviously that OA performs better than RSA. The average of GAP_1 and GAP_2 is 35.5% and 4.1%. As the overlapping amount and makespans of handling operations decrease, the efficiency of RWICTs will be improved.

Based on different sizes of the computational experiments, the proposed algorithm is effective and efficient in solving the integration problem of SSAP and HOP.

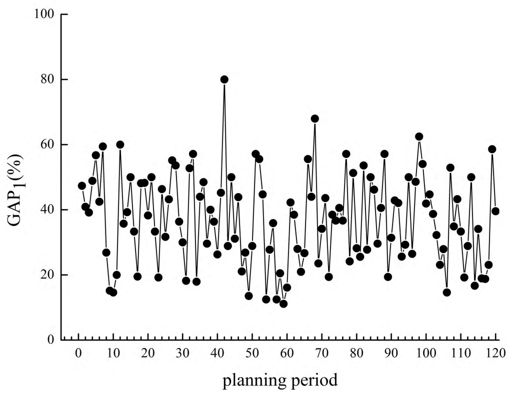

FIGURE 12. GAP_1 **of 30 days.**

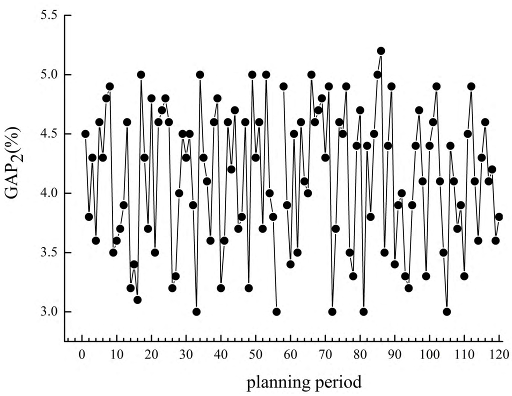

FIGURE 13. GAP_2 **of 30 days.**

VI. CONCLUSION

A novel idea for enhancing the efficiency of RWICTs by considering SSAP and HOP together is introduced for outbound containers. The objective is to decrease the overlapping amount and makespans of handling operations. Therefore, according to characteristics of these two problems, a two-stage optimization model is formulated to increase the productivity of RWICTs.

In Stage 1, container weight, departure time, destination ports, containers left from earlier planning periods and stacking height difference are considered and a heuristic algorithm is introduced to solve the problem. In Stage 2, based on container locations from Stage 1, the integrated scheduling of RMGCs, ITs, and QCs is developed and some realistic operational constraints, like RMGC and QC interference, rehandling time and IT congestion, are considered. A novel two-stage GA is introduced to solve the problem, which introduces some heuristic rules, such as proximity principles and reselection operation. After the problem in Stage 2 is solved, container locations in Stage 1 are updated based on the results from Stage 2; then the results in Stage 2 are also updated. The iterative process does not end until there are no improvements in Stage 1. Finally, some computational experiments are conducted to validate that the proposed algorithm is effective and efficient in solving the joint problem of SSAP and HOP.

In this paper, containers are the same, while in actual situations, there are various sizes of containers. Hence, in future, all the types of containers will be considered in this problem. Meanwhile, we only consider outbound containers in this paper, and therefore outbound and inbound containers can be simultaneously in future research. Meanwhile, in our paper, only railway containers are considered, so in future railway containers and road containers should be considered at the same time. Additionally, stochastic and uncertain factors can be drawn into the model as well.

ACKNOWLEDGMENT

The authors wish to acknowledge Dr. Baicheng Yan for his kind help in design of the algorithm.

REFERENCES

[1] K. H. Kim and K. T. Park, "A note on a dynamic space-allocation method for outbound containers," *Eur. J. Oper. Res.*, vol. 148, no. 1, pp. 92–101, Jul. 2003. doi: 10.1016/S0377-2217(02)00333-8.

[2] A. R. McKendall, Jr., and J. R. Jaramillo, "A tabu search heuristic for the dynamic space allocation problem," *Comput. Oper. Res.*, vol. 33, no. 3, pp. 768–789, Mar. 2006. doi: 10.1016/j.cor.2004.08.007.

[3] A. R. McKendall, Jr., "Improved Tabu search heuristics for the dynamic space allocation problem," *Comput. Oper. Res.*, vol. 35, no. 10, pp. 3347–3359, Oct. 2008. doi: 10.1016/j.cor.2007.03.002.

[4] M. Bazzazi, N. Safaei, and N. Javadian, "A genetic algorithm to solve the storage space allocation problem in a container terminal," *Comput. Ind. Eng.*, vol. 56, no. 1, pp. 44–52, Feb. 2009. doi: 10.1016/j.cie.2008.03.012.

[5] M. Yu and X. Qi, "Storage space allocation models for inbound containers in an automatic container terminal," *Eur. J. Oper. Res.*, vol. 226, no. 1, pp. 32–45, Apr. 2013. doi: 10.1016/j.ejor.2012.10.045.

[6] O. Sharif and N. Huynh, "Storage space allocation at marine container terminals using ant-based control," *Expert Syst. Appl.*, vol. 40, no. 6, pp. 2323–2330, May 2013. doi: 10.1016/j.eswa.2012.10.032.

[7] W. Li, X. Zhu, and Z. Xie, "Storage space allocation of inbound container in railway container terminal," *Math. Problems Eng.*, vol. 2014, Jul. 2014, Art. no. 956536. doi: 10.1155/2014/956536.

[8] X. Yang, N. Zhao, Z. Bian, J. Chai, and C. Mi, "An intelligent storage determining method for inbound containers in container terminals," *J. Coastal Res.*, vol. 73, no. 1, pp. 197–204, Mar. 2015. doi: 10.2112/SI73-035.1.

[9] Y. Li, X. Zhu, L. Wang, and X. Chen, "Stowage plan based slot optimal allocation in rail-water container terminal," *J. Control Sci. Eng.*, vol. 2017, Feb. 2017, Art. no. 5489597. doi: 10.1155/2017/5489597.

[10] L. Wang, X. Zhu, and Z. Xie, "Container assignment optimization considering overlapping amount and operation distance in rail-road transshipment terminal," *Adv. Prod. Eng. Manage.*, vol. 12, no. 4, pp. 363–374, Dec. 2017. doi: 10.14743/apem2017.4.264.

[11] P. J. M. Meersmans and A. P. M. Wagelmans, "Effective algorithms for integrated scheduling of handling equipment at automated container terminals," Social Sci. Electron., Rochester, NY, USA, Tech. Rep. ERS-2001-36-LIS, Feb. 2001.

[12] C. L. Li and G. L. Vairaktarakis, "Loading and unloading operations in container terminals," *IIE Trans.*, vol. 36, no. 4, pp. 287–297, Aug. 2004. doi: 10.1080/07408170490247340.

[13] C. Lu, N. Bostel, P. Dejax, J. Cai, and L. Xi, "A tabu search algorithm for the integrated scheduling problem of container handling systems in a maritime terminal," *Eur. J. Oper. Res.*, vol. 181, no. 1, pp. 40–58, Aug. 2007. doi: 10.1016/j.ejor.2006.06.033.

[14] H. Y. K. Lau and Y. Zhao, "Integrated scheduling of handling equipment at automated container terminals," *Ann. Oper. Res.*, vol. 112, no. 2, pp. 665–682, Apr. 2008. doi: 10.1016/j.ijpe.2007.05.015.

[15] XJ. B. Xin, R. R. Negenborn, and G. Lodewijks, "Energy-aware control for automated container terminals using integrated flow shop scheduling and optimal control," *Transp. Res. C-Emer.*, vol. 44, pp. 214–230, Jul. 2014, doi: 10.1016/j.trc.2014.03.014.

[16] N. Kaveshgar and N. Huynh, "Integrated quay crane and yard truck scheduling for unloading inbound containers," *Int. J. Prod. Econ.*, vol. 159, no. 3, pp. 168–177, Jan. 2015. doi: 10.1016/j.ijpe.2014.09.028.

[17] L. Zhen, S. Yu, S. Wang, and Z. Sun, "Scheduling quay cranes and yard trucks for unloading operations in container ports," *Ann. Oper. Res.*, vol. 273, nos. 1–2, pp. 455–478, Oct. 2016. doi: 10.1007/s10479-016-2335-9.

[18] Y. Chang, X. Zhu, B. Yan, and L. Wang, "Integrated scheduling of handling operations in railway container terminals," *Transp. Lett.*, vol. 1, pp. 1–11, Sep. 2017. doi: 10.1080/19427867.2017.1374500.

[19] E. K. Bish, "A multiple-crane-constrained scheduling problem in a container terminal," *Eur. J. Oper. Res.*, vol. 144, no. 1, pp. 83–107, Jan. 2003. doi: 10.1016/S0377-2217(01)00382-4.

[20] D. H. Lee, J. X. Cao, Q. Shi, and J. H. Chen, "A heuristic algorithm for yard truck scheduling and storage allocation problems," *Transp. Res. E, Logistics Transp. Rev.*, vol. 45, no. 5, pp. 810–820, Sep. 2009. doi: 10.1016/j.tre.2009.04.008.

[21] J. Luo and W. Yue, "Modelling of dual-cycle strategy for container storage and vehicle scheduling problems at automated container terminals," *Transp. Res. E, Logistics Transp. Rev.*, vol. 79, pp. 49–64, Jul. 2015. doi: 10.1016/j.tre.2015.03.006.

[22] J. Luo, Y. Wu, and A. B. Mendes, "Modelling of integrated vehicle scheduling and container storage problems in unloading process at an automated container terminal," *Comput. Ind. Eng.*, vol. 94, pp. 32–44, Apr. 2016. doi: 10.1016/j.cie.2016.01.010.

[23] L. Tang, D. Sun, and J. Liu, "Integrated storage space allocation and ship scheduling problem in bulk cargo terminals," *IIE Trans.*, vol. 48, no. 5, pp. 428–439, Nov. 2016. doi: 10.1080/0740817X.2015.1063791.

[24] M. Zeng, W. Cheng, and P. Guo, "Modelling and metaheuristic for gantry crane scheduling and storage space allocation problem in railway container terminals," *Discrete Dyn. Nature Soc.*, vol. 2017, Nov. 2017, Art. no. 9025482. doi: 10.1155/2017/9025482.

[25] X. J. Jiang and J. G. Jin, "A branch-and-price method for integrated yard crane deployment and container allocation in transshipment yards," *Transp. Res. B, Methodol.*, vol. 98, pp. 62–75, Apr. 2017. doi: 10.1016/j.trb.2016.12.014.

[26] E. Nishimura, A. Imai, and S. Papadimitriou, "Berth allocation planning in the public berth system by genetic algorithms," *Eur. J. Oper. Res.*, vol. 131, no. 2, pp. 282–292, Jun. 2001. doi: 10.1016/S0377-2217(00)00128-4.

[27] E. Nishimura, A. Imai, and S. Papadimitriou, "Yard trailer routing at a maritime container terminal," *Transp. Res. E, Logistics Transp. Rev.*, vol. 41, no. 1, pp. 53–76, Jan. 2005. doi: 10.1016/j.tre.2003.12.002.

[28] R. Choe, T. Park, M. S. Oh, J. Kang, and K. R. Ryu, "Generating a rehandling-free intra-block remarshaling plan for an automated container yard," *J. Intell. Manuf.*, vol. 22, no. 2, pp. 201–217, Apr. 2011. doi: 10.1007/s10845-009-0273-y.

[29] C. Zhang, J. Liu, Y.-W. Wan, K. G. Murty, and R. J. Linn, "Storage space allocation in container terminals," *Transp. Res. B, Methodol.*, vol. 37, no. 10, pp. 883–903, 2003. doi: 10.1016/S0191-2615(02)00089-9.

[30] W. Li, Y. Wu, M. E. H. Petering, M. Goh, and R. Souza, "Discrete time model and algorithms for container yard crane scheduling," *Eur. J. Oper. Res.*, vol. 198, no. 1, pp. 165–172, Oct. 2009. doi: 10.1016/j.ejor.2008.08.019.

[31] W. Li, M. Goh, Y. Wu, M. E. H. Petering, R. de Souza, and Y. C. Wug, "A continuous time model for multiple yard crane scheduling with last minute job arrivals," *Int. J. Prod. Econ.*, vol. 136, no. 2, pp. 332–343, Apr. 2012. doi: 10.1016/j.ijpe.2011.12.020.

[32] J. H. Chen, D.-H. Lee, and M. Goh, "An effective mathematical formulation for the unidirectional cluster-based quay crane scheduling problem," *Eur. J. Oper. Res.*, vol. 232, no. 1, pp. 198–208, Jan. 2014. doi: 10.1016/j.ejor.2013.06.051.

YIMEI CHANG was born in Shenyang, Liaoning, China, in 1991. She received the B.S. degree in traffic and transportation from Beijing Jiaotong University, Beijing, China, in 2014, where she is currently pursuing the Ph.D. degree in transportation planning and management.

Her research interests include container transportation and rail-water intermodal transportation.

XIAONING ZHU was born in Tieling, Liaoning, China, in 1965. He received the B.S. degree in material engineering, the M.S. degree in industrial management engineering, and the Ph.D. degree in transportation engineering from Beijing Jiaotong University, Beijing, China, in 1988, 1991, and 2000, respectively.

He was a Research and Teaching Assistant (1991–1993), an Assistant Professor (1993–1998), and an Associate Professor (1998–1999) with Northern Jiaotong University. From 1999 to 2000, he was a Research Assistant with The Hong Kong Polytechnic University. From 2000 to 2003, he was a Postdoctoral Fellow of Tongji University. Since 2003, he has been a Professor with Beijing Jiaotong University. He is the author of two books and over 150 articles. His research interests include transportation planning and management, logistics engineering, transportation organization, urban traffic engineering, and integrated transportation.

Prof. Zhu was a recipient of many awards and honors, including the First Prize of the Science and Technology Award of the China Railway Society, the Third Prize of the Science and Technology Award of the China Science and Technology Award Committee, and the Third Prize of the Ministry of Railway's Science and Technology Progress Award.

ALI HAGHANI received the B.S. degree in civil engineering from Pahlavi University, Shiraz, Iran, in 1976, and the M.S. and Ph.D. degrees in civil engineering from Northwestern University, Evanston, IL, USA, in 1982 and 1986, respectively.

From 1976 to 1981, he held several design band consulting positions in various public and private agencies in Tehran, Iran. From 1981 to 1985, he was a Research and Teaching Assistant with Northwestern University, where he was a Postdoctoral Fellow and Research Scientist, from 1986 to 1987. From 1987 to 1990, he was an Assistant Professor of civil engineering and transportation with the University of Pittsburg. From 1990 to 1996, he was an Assistant Professor of civil engineering and transportation with the University of Maryland. From 1996 to 2002, he was an Associate Professor of civil engineering and transportation with the University of Maryland, where he has been a Professor of civil engineering and transportation, since 2002. He has authored/coauthored over 100 articles in refereed journals, over 120 articles in refereed conference proceedings, over 75 professional publications, and over 120 conferences, workshops and talks (presentation). His research interests include analysis of freight transportation and logistics, container transportation, mass transit operations, transportation network modeling, emergency response, and dynamic fleet management.

Prof. Haghani is a member of the Transportation Research Board, the Institute of Transportation Engineers, and INFORMS. His awards and honors include the V.1. Research Fellowships, Prizes, and Awards; the WCTR 2016, Shanghai, China; the Grand Prize for Best Paper and TRB 2017; and the Network Modeling Committee Stella Dafermos Best Paper Award.