This is the Pre-Published Version.

This is an Accepted Manuscript of an article published by Taylor & Francis in Maritime Policy & Management on 03 Sep 2021 (Published online), available at http://www.tandfonline.com/10.1080/03088839.2021.1972174.

Container Flow Template Planning in Seaport Railway Terminal with On-dock Rails

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Abstract:

With the construction of on-dock rails, the terminal has become an interface between the maritime transport network and the railway transport network. Terminal operators are facing some new challenges like more complicated terminal operations and the scarcity of storage spaces. To address this issue, the managers should improve the operation efficiency of terminals by adjusting the yard templates and equipment deployment plan, which has not been well studied. To fill this gap, we study the transfer flow template planning problem in seaport railway terminals, and a multi-objective model that integrates the decisions on flow volume, yard template, and equipment deployment plan is proposed. Then, a group of numerical experiments is conducted using Ningbo Beilun Container Terminal as an example to analyze the effect of different management objectives, the pattern of yard template, and the influence of handling capacities. The results show that the optimized flow template performs well when using maximizing throughput as the primal objective. It also reports that stacking import containers in the blocks near the seaside could help to reduce the operation cost and time consumption of the terminal. Moreover, the location of on-dock rails shows a significant influence on the yard template.

Keywords: combined container transportation, seaport railway terminal, container flow template planning

Funding:

This work was supported by the Fundamental Research Funds for the Central Universities under Grant [No. 2020JBM027]; China Railway Group Limited Guidance Project under Grant [No. 2020-Guidance-25].

1. Introduction

With the advantage of low carbon emission and mass capacity, sea-rail combined container transportation (SRCCT) has been believed to be a promising way to mitigate air pollution and traffic congestion (Yan et al., 2020). In Europe, the volume of combined SRCCT is expected to increase to 278.4 billion ton-kilometers by 2030 (UIC, 2020). According to the survey conducted by European Union, though the SRCCT has significant advantages, the costly last mile is one of the major factors that hinder its development, especially in China. Due to the absence of the integrated planning of seaports and railway container terminals, they are usually set far apart from each other, and the drayage of containers between them is unavoidable.

To address these issues, one promising method is to connect the seaports and railway container terminal by railway lines and construct on-dock rails inside terminals (Ng and Talley, 2020). The on-dock rail has been widely constructed in seaport container terminals of North America, such as the Port of Long Beach and the Port of Montreal, which has been proved to be an effective way to enhance the connections between shipping terminals and railway stations. A typical example of the seaport rail terminal (SRT) located in the Port of Long Beach is shown in Figure 1. The on-dock rail refers to a set of facilities including the tracks connecting to railway terminals, the storing lines of railway cars, and a cluster of handling operation lines for the loading and unloading operation of trains. We name the area where trains' loading and unloading operations are conducted as the railway handling area (RHA). The RHA is an area with rail tracks for handling operation of trains and some auxiliary facilities, like parking lines for wagons, locating at the end of the SRT, by which the containers can be loaded to trains by rail-mounted gantry cranes (RMG) without leaving the terminal.

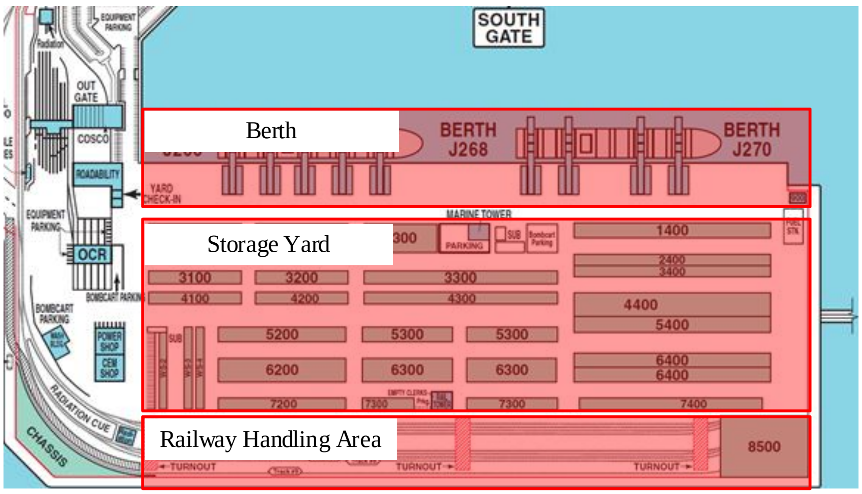


Figure 1. The layout of SRT in the Port of Long Beach

The Chinese government is also committed to tackle the last mile problem by constructing on-dock rails in existing terminals. The National Development and Reform Commission (NDRC) has proposed a plan in 2019 to support the construction of on-dock rail in the major seaports of China. According to the plan, all major seaports in China should be connected to the national railway networks through on-dock rail by 2025 (NDRC, 2019). However, with a given area of the seaport, it is not easy to establish a whole set of on-dock rail facilities in the terminal, and in most cases, only the handling operation lines are constructed.

Although the on-dock rail could help to avoid drayage between terminals, it also imposes more requirements on the management of ports (Bektas and Crainic, 2009). The terminal becomes an interface between maritime transportation and railway transportation. The use of on-dock rail not only induces more container volume but also complicate the terminal operations and increases the workload of handling equipment (Erickson, 2019). The change of the container flow between berth and clients after using on-dock rails is illustrated in Figure 2.

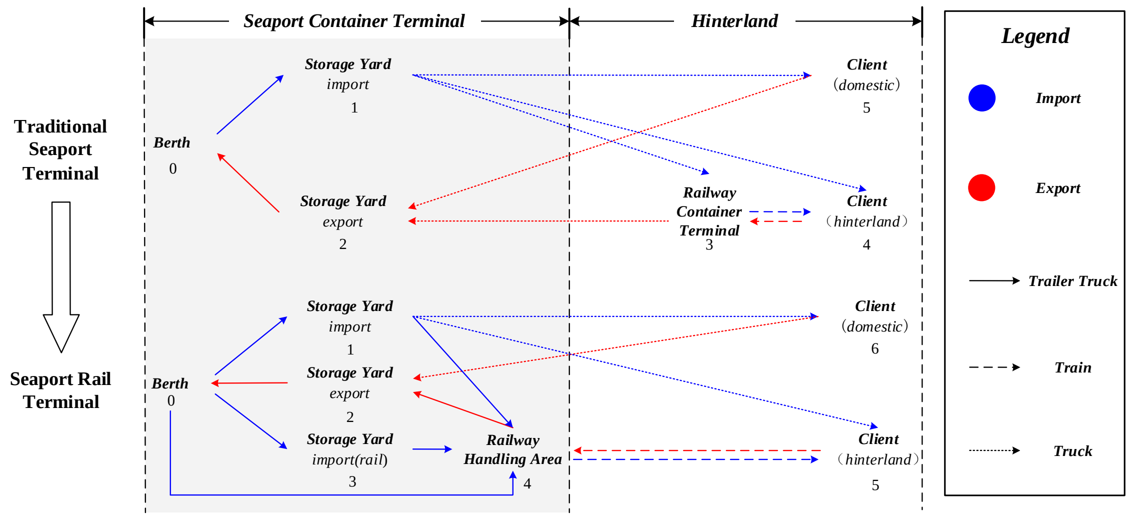


Figure 2. The change of container flow in SRT

As can be observed, in SRT, the sea-rail intermodal containers (SRIC) can be transshipped to trains either directly, i.e., Route 0-4, or indirectly, i.e., Route 0-3-4, which increases the workload of terminal operations, complicates terminal operations, and could induce additional operation cost. Terminal operators have to decide the transfer route of containers. Moreover, the usage of storage yards also becomes more sophisticated since some storage blocks need to be used to store the SRICs. A new problem of storage space shortage could emerge with the increase of transport demand. The shortage of storage spaces is a pressing problem faced by many transshipment terminals (Jiang et al., 2012; Zhen et al., 2011).

Thus, to improve the productivity of the SRT, the container flow inside the terminal should be re-organized based on the layouts of the terminal to meet the demand for SRCCT. Terminal operators need to determine the volume of containers transferred between areas of the terminal, denoted as the transfer flow template. The flow template determines the transfer plan of containers inside the terminal and could be influenced by many factors. To get a well-organized container flow template, the following two decisions should be made.

- *How to use the existing storage resources?* In seaport container terminals, storage spaces are allocated to shipping lines according to their distance to berth with the aim of shortening the route length of trucks. In SRT, the location of on-dock rails could also influence the allocation of storage spaces. Both the distance to the RHA and to the berth should be considered, especially for the terminal with a great demand for sea-rail intermodal transportations.
- *How to deploy equipment?* Reorganizing the transfer flow of containers will lead to the change of workload in each block and the demands for horizontal transportation. Hence terminal operators need to adjust the amount of equipment used in each area to guarantee the supply of operation capacities. Besides, in SRT, the handling capacity of the RHA, determined by the amount of RMG and its unit handling capacity, could also influence the amount of equipment. More yard cranes are needed in the block with more SRICs.

For ease of presentation, we refer to the first problem as the yard template planning problem and the second problem as the equipment deployment problem. The former determines the candidate locations and the storing capacities of yards for different containers, whereas the latter determines the handling capacity of each zone and the transport capacity between different areas. As several storage blocks in the same zone are served by a group of equipment, less equipment could be used by aggregating the blocks with different handling operation demand together to make full use of handling capacities. Therefore, the above two problems should be addressed jointly to improve the operation efficiency and reduce the overall operation cost of SRT, based on which a better transfer flow template can be obtained.

In this paper, we aim to integrate the above two tactical decisions into the planning of the transfer flow template: (1) designing the yard template considering the need for SRCCT, and (2) designing the equipment deployment plan. For the convenience of expression, this joint optimization problem is referred as the transfer flow template planning problem of seaport railway terminals (TFTP-SRT).

Another problem that should be addressed in the TFTP-SRT is the selection of planning objectives since each player, such as terminal operators, port authority, and carriers, has their own interest (Dowd and Leschine, 1990). For example, for port authority, the primal management objective may be to make full use of existing facilities to avoid constructing new facilities, while the terminal operators may care more about how to reduce or stabilize the operation cost per container. For the carriers, the main goal may be shortening the transfer time of containers. With given resource constraints, different management objectives could lead to totally different yard templates and equipment deployment plans. Thus, it is necessary to consider the interests of different entities in this problem and analyze their influence on the final plan.

The structure of the problem is illustrated in Figure 3. We intend to improve the productivity of the SRT by optimizing the yard template and equipment deployment plan that enable the most effective flow inside the terminals. Moreover, we will consider multiple objectives in a hierarchical manner, including maximizing throughput, minimizing operation and transportation cost, minimizing total time consumption, and minimizing the deployment cost of equipment. Based on this problem, we will further gain valuable managerial insights into some key factors that could influence the performance of the SRT.

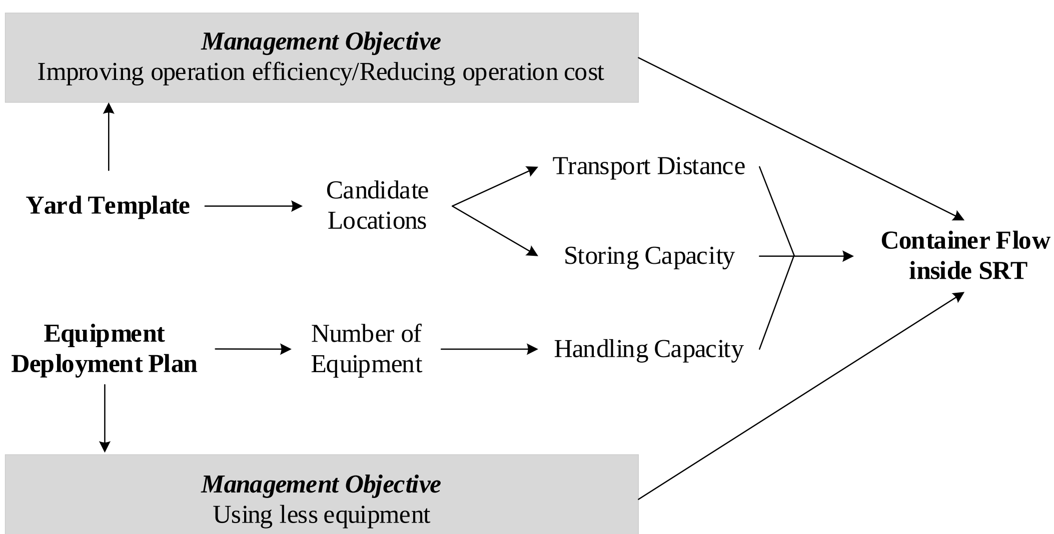


Figure 3. An illustration of the structure of TFTP-SRT

The paper is organized as follows. Section 2 reviews the relevant studies with a particular focus on evaluating the layout of container terminals. Section 3 elaborates the research problem. Section 4 formulates the model with multiple objective functions. Section 4 conducts a realistic case study and analyzes the influence of some key factors. Section 5 concludes this study and highlights possible future research directions. Moreover, a summary table of abbreviations used throughout the paper is given in the Appendix. Readers may refer to it for easy referencing.

2. Literature review

The multimodal freight transportation network has been well studied by many scholars from different perspectives. SteadieSeifi et al. (2013) have presented a schematic overview of the research regarding multimodal transportation, in which all the literature is divided into three groups, namely the strategic, tactical, and operational planning problems. The tactical planning problems mainly deal with optimally utilizing the given facilities by the selection of transportation modes and services as well as the allocation of capacities. There are two groups of models involved in this problem, namely the network flow planning (NFP) and the service network designing (SND). The main difference between the two models is that the latter makes a more comprehensive decision, including the selection of transport mode and the allocation of various capacities. Readers can refer to Cranic (2009) for a more detailed introduction of the SND problem. Thus, the TFTP-SRT problem can be seen as an SND problem.

The SND problem has been well studied by many researchers, most of which mainly focus on the design of the transport network connecting the ports, stations, and clients. Andersen et al. (2009) studied the SND problem with assessment management constraints, in which the constraint of fleet size is considered. The objective of the problem is to minimize the sum of fixed cost and flow cost incurred in the network. Wang and Meng (2011) studied the intermodal hub-and-spoke network planning problem from the perspective of user equilibrium. The transportation network is divided into a physical network, a collection of network elements, and a service network reflecting the transfer flow of container flows. The transport route is chosen following the Wardropian User Equilibrium principle. Then, Wang and Meng (2017) proposed a mixed-integer nonlinear programming model to minimize the network construction cost and operational cost, in which the economies of scale and congestion effects are considered. Cranic et al. (2018) proposed a planning model that contains both strategic decisions of resource acquisition and tactical decisions of service network design to minimize the total cost of resource acquisition. Zhang et al. (2020) studied the SND problem of a sea-rail-road intermodal transportation system with multiple objective functions, which include reducing the total cost and time consumption and improving the reliability of the system. To solve the problem effectively, the authors reformulated the model by introducing ε-constraint and reformulate it as a single objective optimizing problem.

Though the SND problem has been well studied, most of them mainly focus on the transportation network. The planning of container flows inside the container terminal has not been well studied from the perspective of optimization. Simulation methods are more often used to analyze the container flow inside the terminals. Angeloudis and Bell (2011) made an overview of the widely used container terminal simulation models. The authors proposed that a model with lesser detail is required when the tactical decision like berth assignment and quay crane allocation is optimized. Petering (2009) evaluated the influence of storage block width on the performance of container terminals using a discrete event simulation model. Meng et al. (2017) developed a queuing network model to depict all key operational processes in the container terminal and used it to analyze the influence of mega vessels on terminal operations. Yu et al. (2018) analyzed the relationship between the degree of container dispersion and Gross Crane Rate stability in transshipment container terminals using a simulation model, in which Gross Crane Rate is an indicator to measure the productivity of quay cranes. According to the results, storing containers in yards at a low dispersion level is more preferred in the terminal with insufficient handling capacity. Chen et al. (2018) developed a simulation platform to simulate train movements as well as the operations in railway container terminals.

Although more details could be considered using the simulation method, the interaction among container flow template, yard template, and equipment deployment plan cannot be fully considered using the simulation method. Moreover, it is not suitable to evaluate the performance of the terminal from a long-term view using the simulation method because it could be greatly influenced by the pre-determined operation rules. Thus, it would be better if we obtain the performance of the terminal could achieve by optimizing the container flow template. For our best knowledge, the most relevant work to our study is provided by Abu et al. (2020), in which they evaluated the performance of a newly proposed layout of the sea-rail intermodal container terminal by optimizing the container flow. However, the authors failed to consider the influence of the yard template, in which the yard template, as well as the handling capacity, is pre-determined.

The other stream of research related to this research is about yard template planning and equipment deployment plan. With the increasing volume of transshipment container handling, the scarcity of storage space urges new studies to improve the land utilization under the complex requirements of transshipment ports (Jiang et al., 2012). Jiang and Jin (2017) divided the yard management problem into three decision levels. (1) At the tactical decision level, the yard template is determined considering the transport distance and storage spaces demand. (2) In the short-term, once more information of the arrival container is known, terminal operators can determine the container allocation plan by assigning the pre-reserved spaces to the incoming containers flexibly. (3) At the operational decision level, the decisions such as the container handling sequence and equipment schedule plan are determined. Zhen et al. (2011) proposed an integrated model for berth allocation and yard template planning in transshipment terminals to minimize the service cost incurred by the delay of vessels and the transport cost related to the length of transfer routes. Jiang et al. (2012) proposed a spaces-sharing strategy to addressing the scarcity of storing spaces in transshipment terminals. He et al. (2010) studied the yard crane deployment plan optimization problem and proposed a model with the objective of minimizing the frequency of inter-block movement. Furthermore, as the yard template and yard crane deployment plan interrelate, Jin et al. (2014) and Tan et al. (2017) combined the two problems together and proposed an integrated optimization model to decide them simultaneously.

Although plenty of efforts have been made in the related fields, there is still some research gap waiting to be filled. First, with the construction of on-dock rails, the facilities in SRT can also be treated as a microscopic service network. Terminal operators need to allocate storing and handling capacities to meet various demands and determine the container flow inside the terminal, which are optimized separately in existing studies. Second, the multi-objective models are usually changed into a single objective model by adding them together or using ε-constraint. The influence of objectives has not been well discussed. However, in practice, there will be various objectives with different priorities. The decisions should be made according to the hierarchy of objectives. The container flow could change greatly when the hierarchy of objectives changes.

To fill this gap, inspired by the idea of the SND problem, we propose a TFTP-SRT problem to optimize the service network inside terminals, in which the decisions on the flow volume between areas, yard templates, and equipment deployment plan are integrated. Moreover, the hierarchy of objectives is considered when solving the models, and the influence of management objectives and some other key factors are analyzed.

3. Problem description

The TFTP-SRT problem in question is to optimize the transfer flow of containers inside the SRT by a joint adjustment of yard template and equipment deployment plan. We will elaborate on the problem in detail by analyzing the relationship among multiple objectives and constructing the service network of container terminals.

3.1 The layout of the SRT

Figure 4 shows the layout of an example of SRT studied in this paper. The storage blocks, the RHA, the gate, and the berth are labeled for easy identification. The storage yard is divided into several blocks, and the sequenced blocks with the same color form a zone. A zone is a sequence of blocks that together form a single lane for the movement of yard cranes (Petering, 2009).

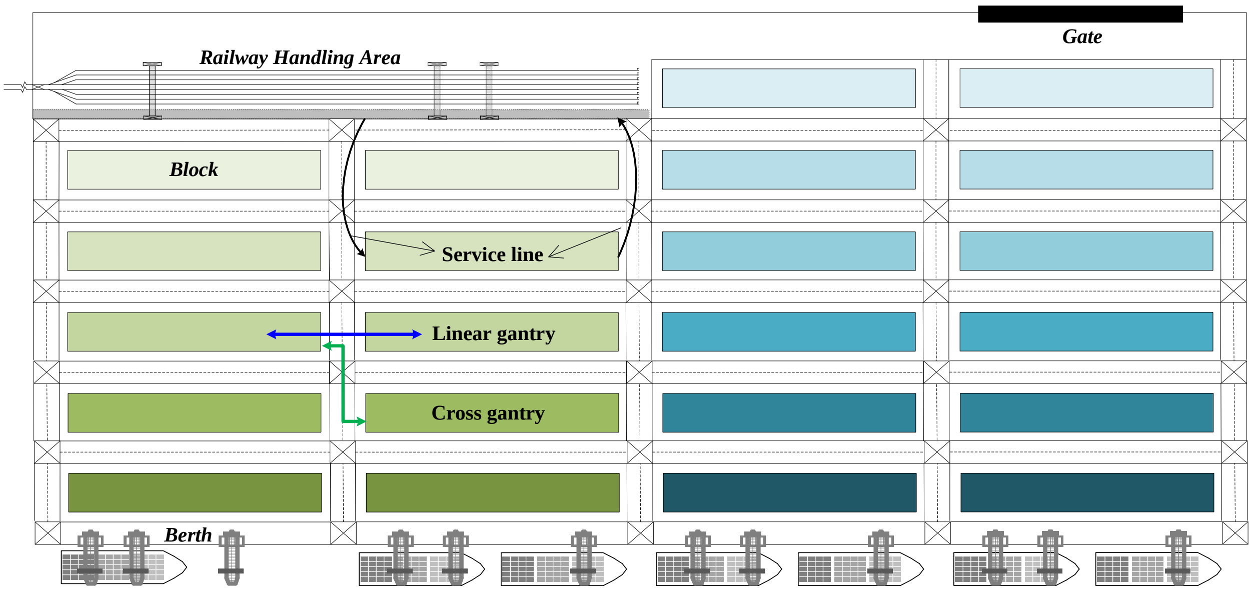


Figure 4. The general layout of SRT

Four types of equipment are used in the SRT to transfer containers. The quay cranes (QC) are used near the berth to load and discharge vessels. The operations in the yard and RHA are conducted by rubber-tired gantry cranes (RTGC) and RMGs separately. Internal trucks (IT) are used for horizontal transportation between areas. In addition to the aforementioned equipment, there are also external trucks (XT) in the SRT, which are used to deliver containers to clients or collecting containers from them.

The blocks in the same zone are handled by a group of RTGCs. The RTGCs can move easily in each block and from block to block in the same zone, i.e., linear-gantry movement. But the cross-gantry movement is not recommended because of extra energy and running time consumption (Yu et al., 2019). The RTGCs will take at least 15 min to make vertical turns (Petering, 2009). Thus, we assume that the RTGCs cannot be shared between zones. The other reason that we make this assumption lies in that sharing the RTGCs between zones in this problem could lead to a shortage of handling capacities in operational-level planning. The running time of RTGCs between blocks cannot be effectively considered in this problem, as well as the conflictions in the movement. For horizontal transportation, we refer to the transfer operations between two specific areas as a couple of service lines. All service lines are divided into several clusters and each of them is assigned to a separate fleet consisting of several ITs. Similarly, we assume that the fleet cannot be shared between clusters (Yu et al., 2018). Denote the group of RTGCs deployed in one zone and the fleet of ITs employed in a cluster of service lines as a group of equipment.

3.2 The objectives of planning

The management objectives reflect the preference of management and could influence the final plan significantly. Different players have different indicators to evaluate the performance because of their self-interest. According to Dowd and Leschine (1990), the productivity of container terminals is usually measured by the following three indicators.

- *Throughput*: representing the number of containers that are delivered to clients or loaded on vessels during a given time period. This indicator is mainly concerned by the port authority as it measures the capacity usage level of the terminal.
- *Operation and transport cost*: including the operation cost of SRT and the transport cost between clients and the terminal, which is mainly concerned by terminal managers. The operation cost can be further divided into the handling cost for loading/unloading and receiving/retrieving operations and the storing cost of containers.
- *Time consumption*: including the transfer, operation, and storing time consumption inside the terminal and the transport time consumption between the SRT and clients. The time consumption can be used to measure the transfer efficiency of the whole SRCCT system, which is usually concerned by shippers.

Note that compared to the indicators mentioned in Dowd and Leschine (1990), we also take the transport cost between the SRT and clients into consideration. The reason lies in two aspects. On the one hand, optimizing the productivity of terminals only might shift the bottleneck to other processes of the SRCCT. Thus, it is necessary to consider the entire process to increase the efficiency of the whole system. On the other hand, the transfer flow between the SRT and clients could influence the yard template greatly since the block can only be used to stack containers to the same destination. The change of transfer flow template could lead to the change of storage demand for containers to different destinations. Hence, considering the transport cost could help to determine the yard template effectively.

Besides, an indicator is also needed to evaluate the performance of the equipment deployment plan. As the goal of the plan is to meet the operation demand with as less equipment as possible, we use the total deployment cost of equipment to evaluate the performance of the deployment plan, in which the unit deployment cost represents the availability of the equipment. In other words, the equipment with limited handling capacities, such as QC and RTGC, is associated with a high deployment cost.

Hence, four objectives are involved in the TFTP-SRT problem, i.e., (1) maximizing the throughput, (2) minimizing the operation and transportation cost, (3) minimizing the time consumption, and (4) minimizing the total deployment cost. The three indicators represent the interests of different entities. Specifically, the port authority cares more about the throughput in order to avoid the construction of new terminals and related facilities. The terminal operators would try to obtain a higher revenue by controlling operation cost and making full use of existing equipment. The carriers and shippers would prefer a more efficient plan with less dwell time in the terminals.

Though the four goals are all important for terminal operation, it is difficult to find a feasible solution that optimizes all objective functions simultaneously in practice. For example, a higher throughput usually needs more equipment and leads to higher deployment costs. Meanwhile, as railway transportation has lower transport costs but may need longer transport time, especially for long-distance transportation, it is hard to minimize the cost and time consumption simultaneously when the transport process between SRT and clients is considered. As the selection of objectives could influence the performance of the transfer flow template greatly, how to handle the conflicts among the objectives and analyze the performance of the template under different objectives is a crucial problem remains to be addressed.

Generally, there are two ways to handle multiple objectives, namely combining the objectives together with different weights and solving the problem hierarchically to get a group of Pareto-optimal solutions, in which the former is more suitable for the problem with equally important objectives, whereas the latter is usually applied in the problem with objectives differentiating in their priorities. For the TFTP-SRT problem, it is evident that the objectives have different priorities in practice. For example, for port authority, reducing the cost and time consumption makes sense only when the throughput has been optimized. Similarly, it is unreasonable to reduce the deployment cost of equipment by handling fewer containers.

Therefore, instead of using a weighted combination of objectives, we set a hierarchy for the multiple objectives, in which a dominance sequence exists between different objectives. The problem will be optimized using the objective with a higher priority first. When the objective function with a lower priority is considered, only the solutions that would not degrade the objective values of higher-priority objectives will be considered, by which we can get a Pareto-optimal solution in this way because any of the objective value cannot be further improved without degrading at least one of the other objectives. The detailed dominance sequence of the objectives will be tested and analyzed in Section 5.

3.3 The transport network of SRCCT

As the transport cost and time consumption between SRT and clients have a significant effect on the container flow in the SRT, we consider the whole process of transferring containers between vessels and clients in this paper. The problem can be formulated as a multi-commodity network flow problem with problem-specific constraints, in which a group of containers needs to be transferred between berths and clients through the network. To make an effective evaluation of the performance of SRT, in this paper, we assume that all containers need to be stored in storage yards. An illustration of the network is shown in Figure 2 is illustrated in Figure 5(a), in which three storage yards and two types of clients are involved.

Transport demand is a group of containers characterized by their origin and movement direction. We consider two types of containers in this study, namely the import and export containers, which can be further divided into different groups according to their movement directions. The volume of demand represents the number of containers it includes. The main target of the TFTP-SRT problem is to find a group of routes connecting the origins and destinations of each demand and distribute the demand to the routes considering various constraints.

The nodes in the graph represent the areas involved in SRCCT, including the berth, the blocks, the RHAs, and the clients. Note that for the convenience of illustration, the yard template has been given in Figure 5(a). Only the arcs to the corresponding direction are shown in the graph. Using Node 1 as an example, all arcs connecting to it are shown in Figure 5(b). Moreover, the RHA (Node 4 in Figure 2) is separated into two nodes, i.e., Node 4 and 4’, for export and import containers separately. The two nodes share the same storage spaces. In this paper, we assume that containers can only be stored in storage yards and clients. The clients are divided into two groups, namely the domestic clients and the hinterland clients, distinguished by whether the containers can be transported by rail or not. To be specific, the hinterland clients can choose either railway or highway, and the domestic clients can only be reached by highways.

The arcs represent the transfer operations and storing operations distinguished by their origins, destinations, and types. Three types of arcs are involved, namely the railway transportation arc, road transportation arc, and the storing arc, indexed by *r*, *t*, and *s*, respectively. The road transportation arcs include both the service lines connecting nodes inside the terminal and the transportation process between the terminal and clients. The transshipment flow of export containers can be easily observed from the graph. For import containers of hinterland clients, after being discharged from vessels, they can be transported by either railways or highways. Furthermore, two types of transfer routes can be selected by import intermodal containers, namely the directly-transshipped route (0→4→5) and the indirectly-transshipped route (0→1→4→5).

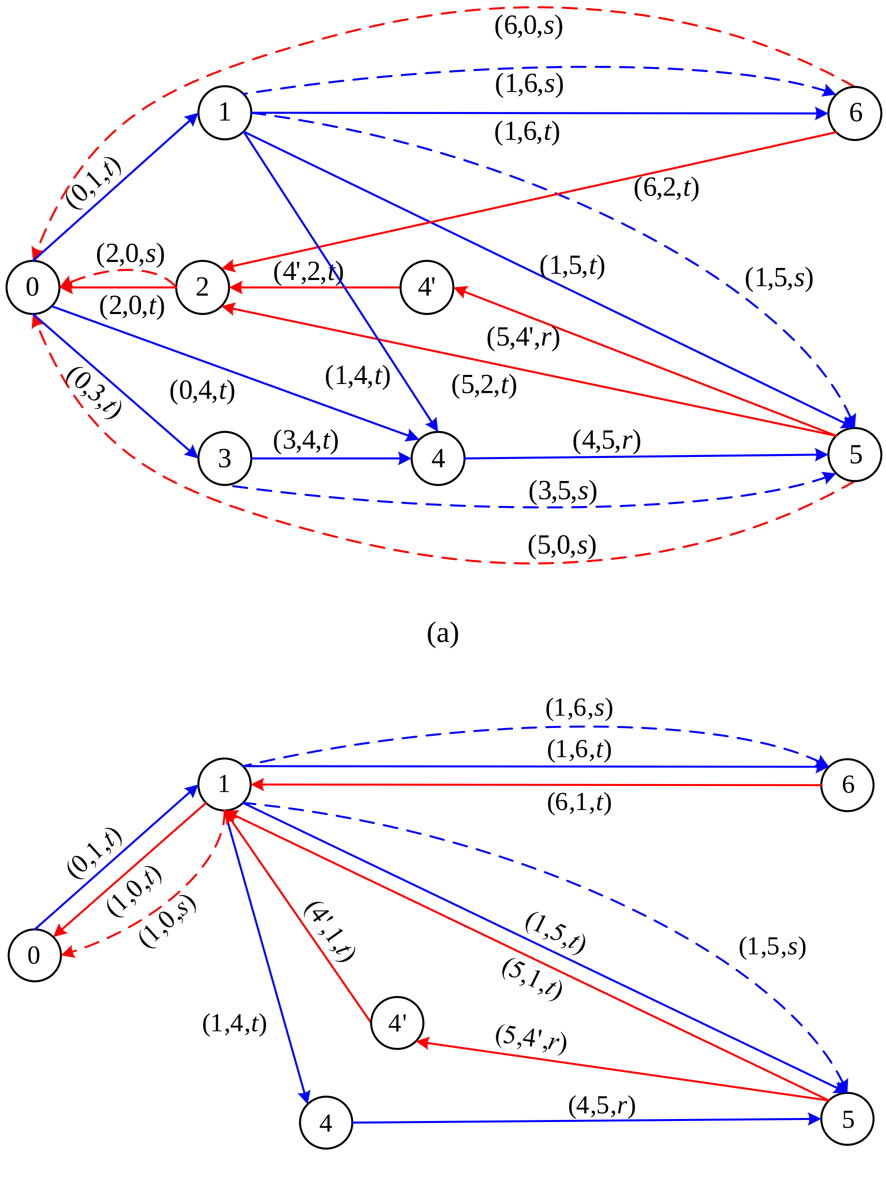


Figure 5. The service network for SRCCT

3.4 Some capacity constraints

As containers to different directions are usually stored separately, i.e., the consignment strategy, terminal operators need to assign each block a direction. (Jiang and Jin, 2017). In seaport container terminals, the yard template is usually determined to minimize the transport distance of containers between blocks and berth. However, in SRT, as the SRICs need to be transferred between blocks and RHA, considering the distance between berth and blocks only cannot guarantee a lower operation cost, and the location of RHA should also be considered.

The equipment deployment plan delineates the amount of equipment that is employed for each zone or cluster of service lines. Obviously, the equipment deployment plan has a significant influence on the handling capacity. More handling capacity could be obtained by deploying more equipment. However, given a limited handling area, the amount of equipment in each area should not exceed an upper bound to avoid conflicts between equipment when conducting operations.

In addition to the handling capacity determined by the equipment deployment plan, the following two capacity constraints are also considered.

- *The through capacity of the gate*: we define the maximum number of containers that can travel through the gate as the through capacity of the gate, which is determined by the number of trucks that can pass through the gate. Moreover, because containers of different sizes are handled in container terminals, a coefficient should be introduced to modify the capacity. Let cg denote the through capacity of the gate, and cgv represents the maximum number of trucks that can pass. Then, we can get $cg = cgv \cdot \eta$, where η is a coefficient that represents the average number of containers that are loaded on trucks.
- *The storing capacity of yards*: we define the number of containers that can be stored in each block during the decision horizon as the storing capacity. Let sp_i denote the storing capacity of block i. Then, we have $sp_i = \alpha \cdot n_i \cdot T$, in which n_i is the number of slots in the block, T is the length of the planning horizon, and α is the usage efficiency of the yard.

4. Model formulation

The following notations are used in model formulation.

Table 1 The list of key parameters and variables

Notations	Description
Sets	
K	The set of transfer demand
A	The set of arcs
I	The set of nodes, representing storage blocks, railway handling area, etc.
B	The set of railway storage blocks
F	The set of the equipment types
D_{ex}	The set of export container flow directions
D_{im}	The set of import container flow directions
Indices	
i	The index of nodes, $i \in I$
b	The index of railway storage blocks, $b \in B$
k	The index of transfer demand, $k \in K$
e	The index of equipment groups, $e \in E$
f	The index of equipment types, $f \in F$
d	The index of destination, $f \in D_{ex} \cup D_{im}$

(i, i', v)	The index of arc from node i to node i' with mode v, in which $v \in \{t, r, s\}$ representing transferring by truck, transferring by rail and storing respectively

Subsets

K_{ex}	The subset of export demand
K_{im}	The subset of import demand
I_h	The subset of nodes representing storage blocks for both railway and road, namely $I_h \subseteq I$
I_r	The subset of nodes representing storage blocks for railway only and $I_h \cap I_r = \emptyset$
I_e	The subset of storing nodes served by handling equipment group e
I_b	The subset of storing nodes included in railway storage block b and $I_h \cap I_b = \emptyset$
A_i^+	The subset of arcs ending at node i
A_i^-	The subset of arcs starting from node i
A_e	The subset of transfer arcs sharing handling equipment e
AS_i^{im}	The subset of storage arcs for import containers using storing node i
AS_i^{ex}	The subset of storage arcs for export containers using storing node i
A_i^{ex}	The subset of export arcs starting from or ending at node i
A_i^{im}	The subset of import arcs starting from or ending at node i
A_{out}	The subset of outbound arcs of container terminal
A_G^{in}	The subset of inbound transport arc going through the gate of container terminal
A_G^{out}	The subset of outbound transport arc going through the gate of container terminal
G_e	The subset of storage blocks served by equipment group e
E_a	The subset of transfer equipment groups
E_v	The subset of handling equipment groups
E_f	The subset of equipment groups using equipment of type f
K_d	The subset of demands coming from/ going to direction d

Parameter

$O(k)$	The origin of transfer demand k
$D(k)$	The destination of transfer demand k
$d(k)$	The volume of transfer demand k
sp_i	The storing capacity of storing node i, $i \in I_h$
spr_b	The storing capacity of railway storage block b, $b \in I_h$
cap_e	The operation capacity of the equipment in group e
cn_{iv}^-	The average operating time for outbound containers of node i using mode v
cn_{iv}^+	The average operating time for inbound containers of node i using mode v
$ca_{(i,i',v)}^k$	The transport capacity consumption for containers included in demand k on arc (i, i', v)
$cs_{(i,i',v)}^k$	The storage capacity consumption for containers included in demand k on arc (i, i', v)
cg	The through capacity of the gate
$c_{(i',i,v)}^k$	The transport/transfer/storing cost of arc (i, i', v) for demand k
$t_{(i',i,v)}^k$	The transport/transfer/storing time of arc (i, i', v) for demand k

Decision Variables

$x_{(i,i',v)}^k$	The volume of demand k traveling through arc (i, i', k)
y_{id}^{ex}	$y_{id}^{ex} = 1$ if node i is assigned to export containers to direction d, otherwise $y_{id}^{ex} = 0$, $i \in I_h$, $d \in D_{ex}$
y_{id}^{im}	$y_{id}^{im} = 1$ if node i is assigned to import containers to direction d, otherwise $y_{id}^{im} = 0$, $i \in I_h$, $d \in D_{im}$

n_e	The amount of equipment used in group e

As discussed before, four types of objectives are considered in this problem, namely minimizing the total operation cost (obj_1), minimizing the total time consumption (obj_2), maximizing the throughput of the terminal (obj_3), and minimizing the deployment cost of equipment (obj_4).

$$obj_1: min \sum_{k\in K} \sum_{(i',i,v)\in A} c^k_{(i',i,v)} x^k_{(i',i,v)} \tag{1}$$

$$obj_2: min \sum_{k\in K} \sum_{(i',i,v)\in A} t^k_{(i',i,v)} x^k_{(i',i,v)} \tag{2}$$

$$obj_3: max \sum_{k\in K} \sum_{(i',i,v)\in A_{out}} x^k_{(i',i,v)} \tag{3}$$

$$obj_4: min \sum_{f\in F} \sum_{e\in E_f} c_f n_e \tag{4}$$

The formulation of the objectives is shown as Eqs. (1) - (4). In this paper, we treat the four objectives hierarchically, in which obj_4 is given a lower priority. The priority of $obj_1 - obj_3$ represents the preference of terminal management. Different transfer flow template could be obtained by changing the priorities. Hence, the dominance sequence of them remains to be determined by numerical experiments, in which the influence of them on the flow template will be analyzed.

$$\sum_{(i,i',v)\in A_i^- \cap A_i^{im}} x^k_{(i,i',v)} - \sum_{(i',i,v)\in A_i^+ \cap A_i^{im}} x^k_{(i',i,v)} = \begin{cases} d_k, if\ i = O(k) \\ -d_k,\ if\ i = D(k) \\ 0,\ otherwise \end{cases}, \forall k \in K_{im}, i \in I \tag{5}$$

$$\sum_{(i,i',v)\in A_i^- \cap A_i^{ex}} x^k_{(i,i',v)} + \sum_{(i',i,v)\in A_i^+ \cap A_i^{ex}} x^k_{(i',i,v)} = 0, \forall k \in K_{im}, i \in I \tag{6}$$

$$\sum_{(i,i',v)\in A_i^- \cap A_i^{ex}} x^k_{(i,i',v)} - \sum_{(i',i,v)\in A_i^+ \cap A_i^{ex}} x^k_{(i',i,v)} = \begin{cases} -d_k, if\ i = O(k) \\ d_k,\ if\ i = D(k) \\ 0,\ otherwise \end{cases}, \forall k \in K_{ex}, i \in I \tag{7}$$

$$\sum_{(i,i',v)\in A_i^- \cap A_i^{im}} x^k_{(i,i',v)} + \sum_{(i',i,v)\in A_i^+ \cap A_i^{im}} x^k_{(i',i,v)} = 0, \forall k \in K_{ex}, i \in I \tag{8}$$

Constraints (5) - (8) are the flow balance constraints. In particular, Constraints (5) guarantee the flow balance of each node for import transport demand separately. Constraints (6) make sure that the import containers cannot be transferred through the arcs representing export direction. Similarly, Constraints (7) and (8) determine the flow of export containers.

$$\sum_{d\in D} \left(y^{ex}_{id} + y^{im}_{id}\right) \le 1, \forall i \in I_h \tag{9}$$

$$\sum_{k\in K_d} \sum_{(i,i',v)\in A_i^{ex} \cap A_i^-} cs^k_{(i,i',v)} x^k_{(i,i',v)} \le sp_i \cdot y^{ex}_{id}, \forall d \in D, i \in I_h \tag{10}$$

$$\sum_{k\in K_d} \sum_{(i,i',v)\in A_i^{im} \cap A_i^-} cs^k_{(i,i',v)} x^k_{(i,i',v)} \le sp_i \cdot y^{im}_{id}, \forall d \in D, i \in I_h \tag{11}$$

$$\sum_{i\in I_b}\sum_{k\in K}\sum_{(i,i',v)\in(A_i^{im}\cap A_i^-)\cup(A_i^{ex}\cap A_i^-)} cs_{(i,i',v)}^k x_{(i,i',v)}^k \leq spr_b, \forall b \in B \quad (12)$$

The yard template is determined by Constraints (9), in which the import and export containers to different directions cannot be stored in the same storage yard. Constraints (10)-(12) control the maximum number of containers that can be transferred through the storage yard. To be specific, Constraints (10) and (11) imply that the general storage block can only be used to store the containers for the designated direction. Constraints (12) indicate that both import and export containers can be stored in the railway storage yards. Moreover, in this research, we assume that the containers transferred through the storage yard, i.e., $v = t$, and the containers stored in storage yard i.e., $v = s$, have different storage resources consumption, and the latter consumes more resources, namely $cs_{(i,i',s)}^k \geq cs_{(i,i',t)}^k$.

$$\sum_{i\in I_e}\sum_{k\in K}\left(\sum_{(i,i',v)\in A_i^-} cn_{iv}^- x_{(i,i',v)}^k + \sum_{(i',i,v)\in A_i^+} cn_{iv}^+ x_{(i',i,v)}^k\right) \leq cap_e n_e, \forall e \in E_v \quad (13)$$

$$\sum_{(i,i',v)\in A_e}\sum_{k\in K} ca_{(i,i',v)}^k x_{(i,i',v)}^k \leq cap_e n_e, \forall e \in E_a \quad (14)$$

$$\sum_{e\in E_f} n_e \leq N_f, \forall f \in F \quad (15)$$

$$\sum_{(i,i',v)\in A_G^{in}}\sum_{k\in K} x_{(i,i',v)}^k + \sum_{(i,i',v)\in A_G^{out}}\sum_{k\in K} x_{(i,i',v)}^k \leq cg \quad (16)$$

Constraints (13) indicate that the containers passing through the storage zone should not exceed the usable handling capacity determined by the number of handling equipment deployed in the zone. Similarly, the constraint of transport and transfer capacity determined by the number of vehicles is formulated as Constraints (14). The quantity of equipment that can be used to handle or transfer containers is restricted by Constraints (15). Constraints (16) imply that the inbound and outbound vehicles going through the gate should not exceed the traffic capacity of the gate. The decision variables are defined in Constraints (17)-(20) as follows.

$$x_{(i,i',v)}^k \in \mathbb{Z}_+, \forall (i,i',v) \in A, k \in K \quad (17)$$

$$y_{id}^{ex} \in \{0,1\}, \forall i \in I_h,\ d \in D_{ex} \quad (18)$$

$$y_{id}^{im} \in \{0,1\}, \forall i \in I_h,\ d \in D_{im} \quad (19)$$

$$n_e \in \mathbb{Z}_+, \forall e \in E \quad (20)$$

5. Numerical experiments

In this section, we use the Ningbo Beilun Container Terminal (NBCT) as an example to test the proposed model and analyze the influence of some key factors. NBCT is one of the main SRT in China. The volume of SRICs transferred through NBCT has increased from 1690 TEU/year to over 1 million TEU/year from 2009 to 2020. In 2020, the volume of SRICs accounts for nearly 20% of the total throughput of the terminal. However, the increasing transport demand has also put great pressure on terminal operations leading to the storing spaces shortage problem. Terminal operators need to adjust the yard template and equipment deployment plan to address the emerging problems. Thus, we select NBCT as an example to analyze the yard template pattern of NBCT. Besides, the influence of the usable handling capacity of the RHA on the deployment plan of other equipment is elaborated. The detailed information of the hinterland transport network of NBCT is tabulated in Table 2, where the percentage in the last column of the table is calculated based on the number of trains running between NBCT and the cities. The data in the table is collected from China Railway Container Transport Corp. Ltd, the biggest railway container transportation company in China. All cases in this section are solved using Gurobi 9.0.3 with a MIPGap = 0.5%.

Table 2 The detailed information of the service network of NBCT

City	Distance (km)	Time (hours)		Cost (RMB)		Pct.
		Railway	Highway	Railway	Highway	
Shangrao	778	158	48	2664	4850	18.9%
Jinhua	330	83	19	1876	1700	43.2%
Hefei	572	93	13	4352	7600	18.9%
Hangzhou	146	24	6	2098	2000	9%
Domestic	--	--	6	--	1500	10%

5.1 Scenario setting

Figure 6 shows the layout of NBCT, in which different areas are distinguished by colors. A total of 17 QCs are deployed in the berth. Y01-Y35 are general storage yards. YR1 and YR 2 are storage blocks for the intermodal containers only. The import SRICs can be stored in these two blocks before being loaded on trains. The number of slots in each block has been noted in the graph. In this paper, we assume that 75% of the storage spaces could be used to store containers. The blocks in the same row are divided into 3 zones, and a total of 18 zones are involved. YR1 and YR2 are also served by two groups of RTGCs separately. Two RHAs are used in the terminal, namely RHA1 and RHA2, with 4 RMGs deployed in each of them. We assume that at most 50 RTGCs and 110 trailer trucks can be used in the terminal.

The transfer operations between areas are conducted by ITs. The service lines are divided into 10 clusters, and each of them is served by a fleet. The grouping plan is illustrated in Table 3. The distance between areas is obtained using Google Map, and the speed of the truck is set to be 20km/h. The gate of NBCT has 8 lanes, and 25 vehicles can pass through the lane per hour, each of which carries 1.45 TEUs on average. The handling capacity of QC and RTGC is 30 and 25 lifts per hour, respectively.

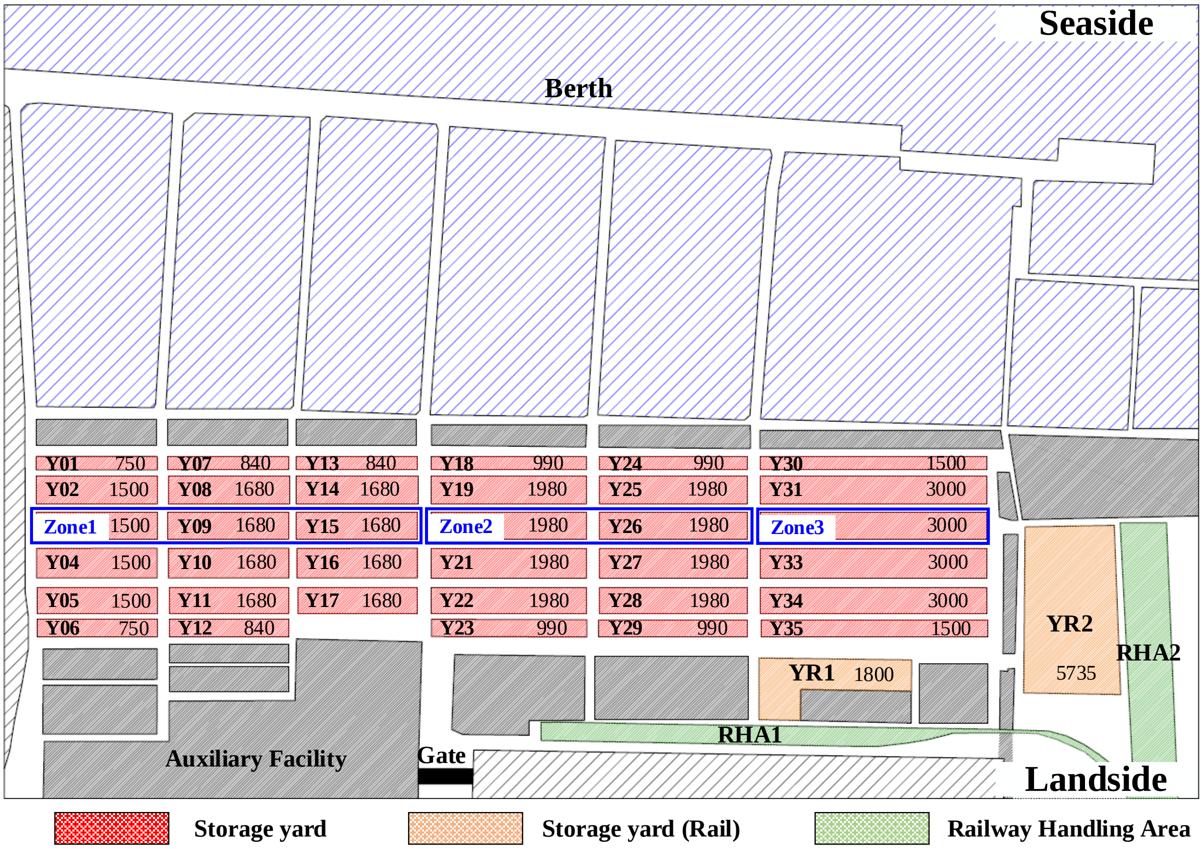


Figure 6. The basic layout of Ningbo Beilun Terminal

Table 3 The grouping plan of trucks

Description of the service lines	Number of clusters	Detailed information
The transfer operations between berth and general storage blocks	6	(Y01~Y06)-Berth/Berth-(Y01~Y06) …… (Y30~Y35)-Berth/Berth-(Y30~Y35)
The transshipment operations between the berth, RHA, and railway storage yards	2	Berth-RHA1/ Berth-YR1 Berth-RHA2/ Berth-YR2
The transfer operations between storage yards and RHA	2	(YR1, Y1~Y35)-RHA1/RHA1-(Y1~Y35) (YR2, Y1~Y35)-RHA2/RHA2-(Y1~Y35)

5.2 The performance of the model with different primal objectives

First, we conduct a set of experiments to analyze the performance of the terminal under different primal management objectives. Specifically, we use $obj_1 \sim obj_3$ as the primal objective in turns and set obj_4 as the second objective. The three productivity indicators, namely operation and transportation cost, time consumption, and throughput, are used to evaluate the transfer template.

The detailed method of handling the multi-objective is elaborated as follows. Suppose we have two objective functions, i.e., $\min(f(x), g(x))$, and $f(x)$ is given a higher priority; the model will be solved twice. In the first time, only $f(x)$ is considered to get the optimal solution $\tilde{x}$ and the optimal value $a = f(\tilde{x})$. Then, the model with a new constraint for the bound of $f(x)$, i.e., $f(x) \leq a$, will be solved again using $g(x)$ as the objective function. Let $\bar{x}$ denote the final optimal solution. Obviously, we can have $f(\bar{x}) = f(\tilde{x}) = a$ and $g(\bar{x}) \leq g(\tilde{x})$ in this way, which means that the solution $\bar{x}$ is a Pareto-optimal solution for the problem.

Moreover, we also change the total volume of demand from 1 million TEUs/year to 3 million TEUs/year. We assume that a total of 10 RMGs are available in each instance and the operation capacity of them is 30 lift/hour. The variations of three key indicators in different scenarios are shown in Figure 7(a), (b), and (c), respectively. As can be observed, a more desirable transfer flow template with less time consumption as well as operation cost could be obtained when maximizing the throughput is used as the primal objective. On the other hand, the transfer flow template performs poorly when minimizing the total cost is given the highest priority. A great proportion of containers are stored in the terminal and wait to be transferred by railways. Moreover, a trade-off between time consumption and cost can be observed when the transportation cost is considered. To be specific, as railway transportation has a lower transport cost, the containers prefer to be transferred by trains when the total cost is minimized, which, however, performs poorly in time efficiency. Note that the units of container volume, time consumption, and costs are same in the following analysis.

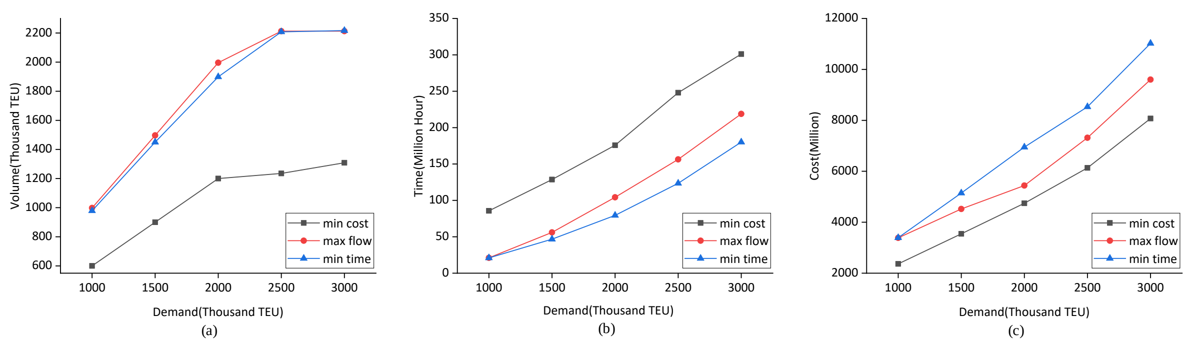


Figure 7. The change of key performance indicators of NBCT in different scenarios

5.2 The performance of the model with different combinations of objectives

The selection of objectives represents the preference of management. There are two types of preference in practice, namely efficiency priority and cost priority. The former mainly focuses on reducing time consumption, and the latter aims to reduce the average cost of operations. In this subsection, groups of instances are used to illustrate the performance of the flow template under different preferences. Moreover, although both efficiency and cost are important for terminal operation, they only make sense when the maximum throughout has been reached. It is no doubt that reducing the operation cost by handling fewer containers is an unacceptable method in practice.

Next, using the same instances in the previous subsection, we proceed to use obj_3 as the primal objective and analyze the performance of the container transfer flow under the preference of efficiency priority, i.e.,

$obj_3 - obj_2$, and cost priority, i.e., $obj_3 - obj_1$. To gain an insight into its influence on the flow template, four auxiliary indicators are introduced. The key indicators of the container flow template in different cases are listed in Table 3, in which the string in the first column represents the dominance sequence of objectives. For example, "f-c-e" means the priority of the three objectives are $obj_3 \geq obj_1 \geq obj_4$. The data in the last three columns represent the number of needed equipment.

First, from the perspective of sea-rail intermodal transportations, the results show that the cost and time consumption could be further reduced by adjusting the proportion of SRICs. To be specific, the total cost could be further reduced by transferring more containers using railways. For example, in the instance with Demand = 1500, the cost decreases from 4306.3 to 3545.9 by 21.4% when the proportion of SRICs increases from 20.63% to 41.52%. However, the increase of SRICs could put more pressure on terminal operations in order to transfer containers among berths, yards, and railway handling areas since more ITs are deployed when the volume of SRICs increases.

Second, the results show that, for a given throughput level, further optimization of cost and time consumption shows different effects on the deployment plan of equipment. Compared with the instances of f-e, more trucks are used when the cost is minimized, i.e., f-c-e, and more cranes are deployed when the time consumption is further reduced, i.e., f-t-e. The reason for this should be attributed to the change in the proportion of SRICs. More containers need to be transferred to hinterland cities by highways to reduce time consumption further. Thus, the workload of storage yards increases greatly and accordingly more RTGCs are needed. On the contrary, the increase of SRICs gives rise to more transfer operations between the RHA and storage yards and thus more ITs are needed to meet the increasing demand.

Table 3 The variations of key indicators for the instances using obj_3 as the primal objective

Obj.	Demand	Vol.$^{(1)}$	Cost	Time	SRIC		RTGC	IT
					Vol.$^{(2)}$	pct.$^{(3)}$		
f-e	1000	998.0	3382.5	20.9	0.0	0.00%	8	31
f-e	1500	1497.0	4306.3	61.8	377.5	25.22%	7	57
f-e	2000	1996.0	5305.7	103.5	809.6	40.56%	9	85
f-e	2500	2464.8	6860.2	142.8	1256.5	50.98%	11	113
f-e	3000	2464.8	9221.2	207.6	1261.4	51.18%	9	111
f-c-e	1000	998.0	2363.7	56.8	376.7	37.75%	5	43
f-c-e	1500	1497.0	3545.9	86.1	610.5	40.78%	7	65
f-c-e	2000	1996.0	4743.1	120.0	920.2	46.10%	9	89
f-c-e	2500	2464.8	5973.4	157.3	1261.4	51.18%	11	114
f-c-e	3000	2464.8	7520.5	223.1	1260.1	51.13%	13	126
f-t-e	1000	998.0	3383.3	20.9	0.0	0.00%	8	31
f-t-e	1500	1497.0	5120.0	46.7	296.9	19.84%	10	55
f-t-e	2000	1996.0	6900.9	84.2	790.3	39.59%	12	85
f-t-e	2500	2464.8	8268.8	124.5	1256.6	50.98%	13	113
f-t-e	3000	2464.8	10045.2	170.5	1259.2	51.09%	9	111

* f-e: obj_3-obj_4, f-c-e: obj_3-obj_1-obj_4, f-t-e: obj_3-obj_2-obj_4
* $(3) = (2)/(1) * 100\%$,

In addition to productivity indicators, we find that the choice of objectives also shows a great influence on the selection of transfer plans. For example, for the instances with Demand = 2500 and Demand = 3000, the volumes of SRICs for hinterland cities under different objective combinations are shown in Table 3. As can be observed, with a certain amount of SRICs, changing the transfer plan of different cities could help to improve the overall performance of the transfer template further. Using railways to transfer containers between the terminal and hinterland cities, especially the cities with long transport distance, could help to reduce the total cost, which will, however, lead to more transportation time.

Table 4 The volumes of SRIC for different cities

Obj.	Destination	Demand = 2500			Demand = 3000		
		SRICs(1)	Vol. (2)	pct. (3)	SRICs(4)	Vol. (5)	pct. (6)
j-e	Jinhua	1256.5	205.0	33.60%	1261.4	189.7	30.73%
	Hangzhou		225.0	16.32%		162.0	15.04%
	Hefei		135.0	26.05%		126.0	27.26%
	Shangrao		422.2	24.04%		387.6	26.97%
j-t-e	Jinhua	1256.6	907.8	14.61%	1259.1	838.2	0.01%
	Hangzhou		184.3	10.70%		0.1	10.00%
	Hefei		327.3	37.46%		343.9	45.00%
	Shangrao		123.8	37.23%		258.9	45.00%
j-c-e	Jinhua	1261.4	472.5	72.24%	1260.1	567.0	66.57%
	Hangzhou		302.0	17.91%		340.2	12.87%
	Hefei		0.0	9.85%		0.0	20.56%
	Shangrao		469.6	0.00%		567.0	0.00%

* Vol.: the volume of SRICs transported to or from the corresponding city
* $(3) = (2)/(1) * 100\%,\ (6) = (5)/(4) * 100\%$

Then, we also conduct a group of experiments to illustrate the necessity of considering the equipment deployment plan. The same instances involved in Table 3 are used, in which obj_4 is not considered. The results are shown in Table 5. It is obvious that the numbers of RTGCs and RMGs decrease significantly. The decrease of RTGCs is mainly resulted from the aggregation of storage yards, and, thus, the equipment can be shared by different yards. The reason for the decrease of RMGs is similar. The results show that RHA1 is more intensively used when the equipment deployment plan is optimized.

Table 4 The comparison between instances with and without obj_4

Obj.	Demand	SRICs		RTGC		IT		RMG	
		original	optimal	original	optimal	original	optimal	original	optimal
f	100	842.2	0.0	50	8	79	31	10	0
	150	1146.3	377.5	50	7	117	57	10	3
	200	1217.1	809.6	50	9	140	85	10	7
	250	1261.4	1256.5	50	11	161	113	10	10
	300	1261.4	1261.4	50	9	182	111	10	10

	100	378.0	376.7	50	5	45	43	10	3
	150	567.0	610.5	50	7	66	65	10	5
f-c	200	898.3	920.2	50	9	90	89	10	8
	250	1261.4	1261.4	50	11	116	114	10	10
	300	1261.4	1260.1	50	13	129	126	10	10
	100	0.0	0.0	50	8	34	31	10	0
	150	295.9	296.9	50	10	57	55	10	3
f-t	200	791.5	790.3	50	12	88	85	10	7
	250	1261.2	1256.6	50	13	118	113	10	10
	300	1261.4	1259.2	50	9	111	111	10	10

* original - obj_4 is not considered, optimal –obj_4 is included

5.3 The performance of yard template

In this Subsection, two groups of instances are used to analyze the influence of on-dock rails on the yard template, where obj_3-obj_1-obj_4 and obj_3-obj_2-obj_4 are used as the objective, respectively. Moreover, to ease the influence of demand scale and handling capacity on the result, we also vary the scale of demand from 1 million TEUs to 3 million TEUs by a step of 0.5 million TEUs and increase the number of RMGs from 8 to 15. A total of 80 instances are used in this section. Moreover, for the convenience illustration, the storage block is identified using its row index and column index. The coordinate of the blocks is illustrated in Figure 8.

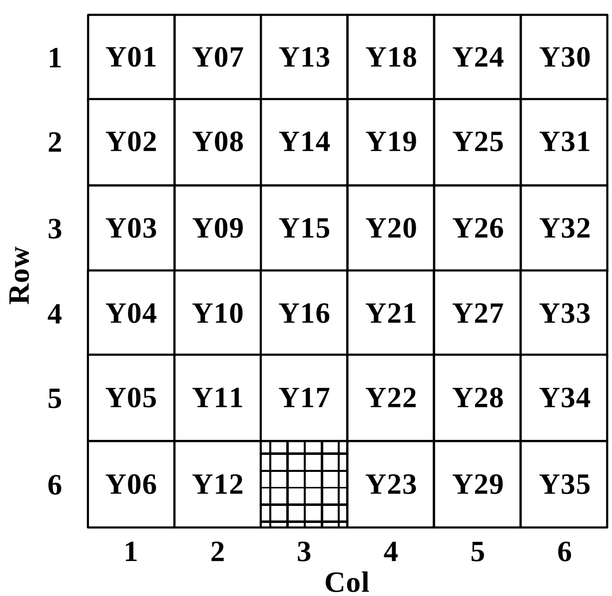
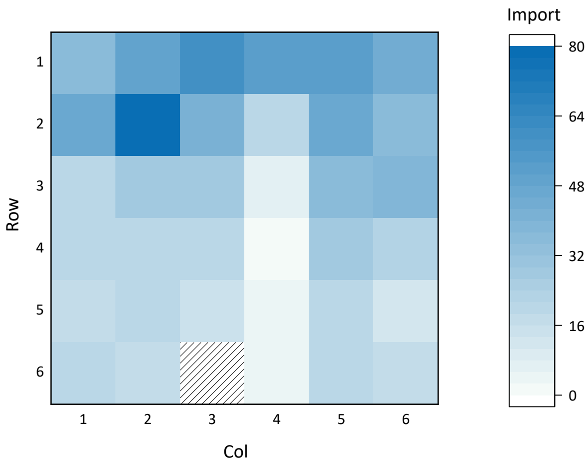
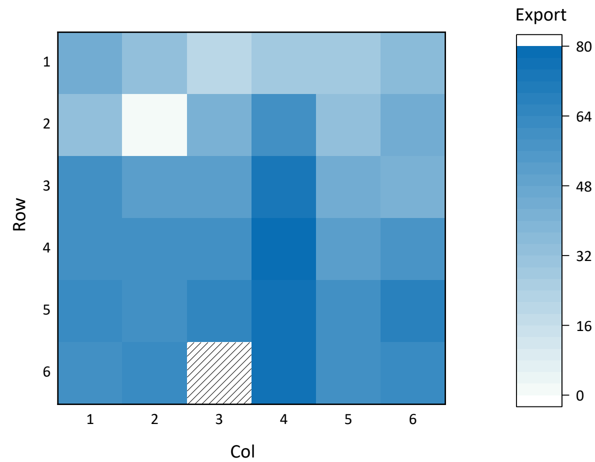


Figure 8. The coordinates of blocks

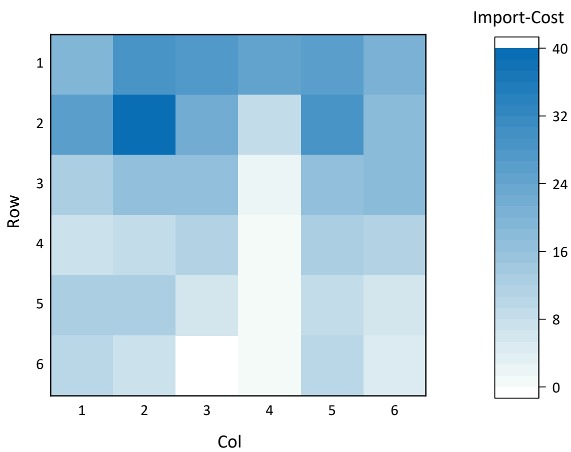
Figure 9 is a heat map that shows the selection preference of import and export containers among all general storage blocks, in which (a) and (b) is a sum of all instances, (c) and (d) corresponds to instances with the objective of obj_3-obj_1-obj_4, and (e) and (f) corresponds to instances with the objective of obj_3-obj_2-obj_4. The color of each area is determined by the number of times that the block is selected to storing import or export containers. The darker the color, the higher probability the block appears in the optimal solutions of all instances. According to the results, we can find that blocks near the seaside are more often used to stack import containers, while the export containers prefer to be stored in blocks near to the landside. A similar pattern can be found in both groups. The reason for this lies in that storing import containers in blocks near the seaside could help to reduce the transport distance of ITs inside the terminals. Moreover, we can also see that, for import containers, the blocks in the first row are mostly selected, while for the export containers, the blocks in the fourth column are more preferred. These two groups of blocks are the group of blocks that is closest to RHA2 and RHA1, respectively, which implies that, in the SRT, the blocks that close to the RHA are more likely to be selected.



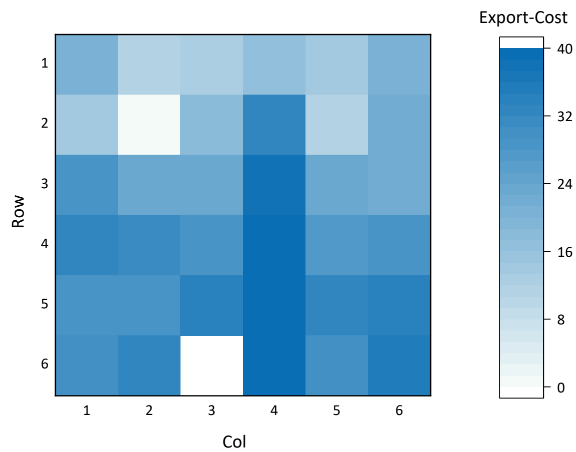
(a)



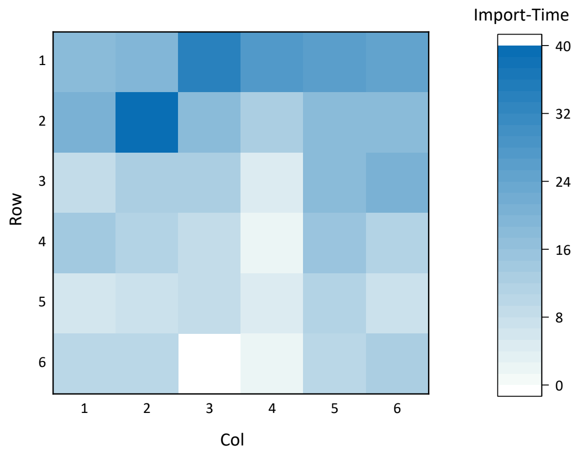
(b)



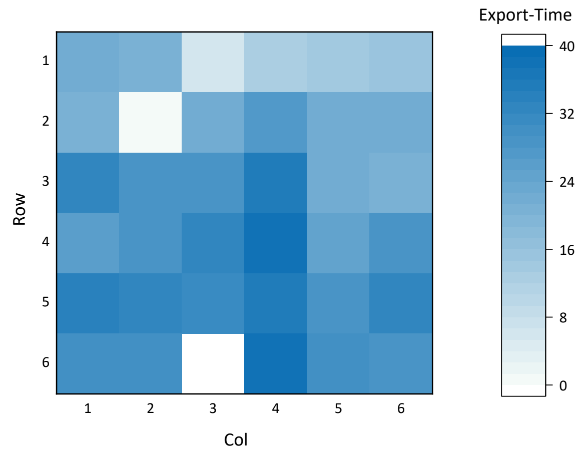
(c)



(d)



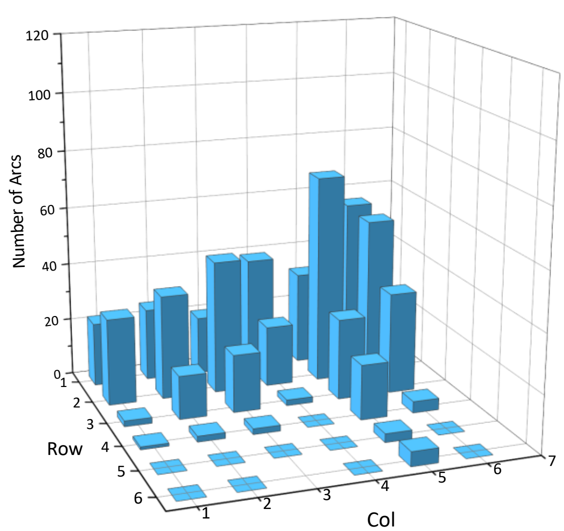
(e)



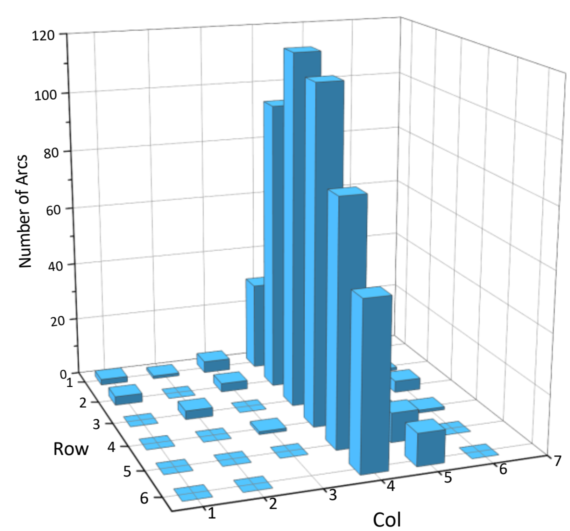
(f)

Figure 9. The selection preference of import and export containers among general storage blocks

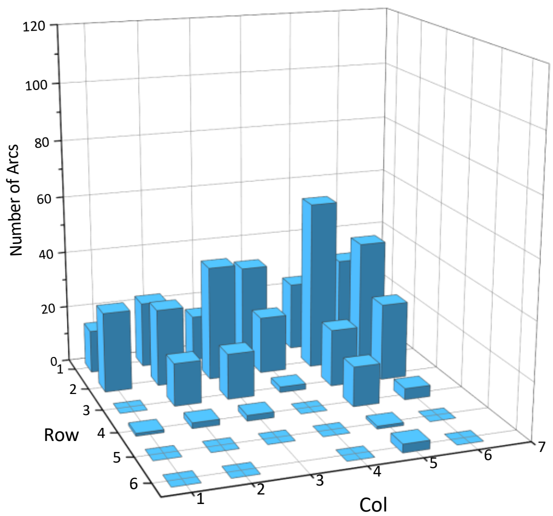
To explore the influence of on-dock rails on the yard template, or each block, we count the number of arcs that connecting the block to railway handling areas in the optimized plan for all instances. The results are shown in Figure 10, in which Figure 10(a), (c), and (e) illustrate the number of import arcs starting from the block, and Figure 9(b), (d), and (f) illustrate the number of export arcs ending at the block. As can be observed, the location of on-dock rails shows a significant influence on the yard template, especially for the export SRICs. Though the blocks in the rows near the landside are more likely to be selected by the export containers, for the export SRICs, the blocks in the fourth row are selected in most of the instances. It is because that the blocks in this column have a closer distance to RHA1. The other reason that leads to this pattern is that the blocks in the same column are served by a fleet of ITs. Therefore, it would need more ITs to select the blocks in row 6. Moreover, we can see that RHA1 is busier than RHA2, and RHA2 is only used to transfer import containers. The reason lies in that RHA2, on the one hand, RHA2 is actually a newly-built railway handling area with a farther distance. Transferring SRICs using it could give rise to additional time consumption as well as more operation cost. On the other hand, RHA2 is close to the preferred storage area for import containers. Hence, it is more likely to be used to transfer import containers.



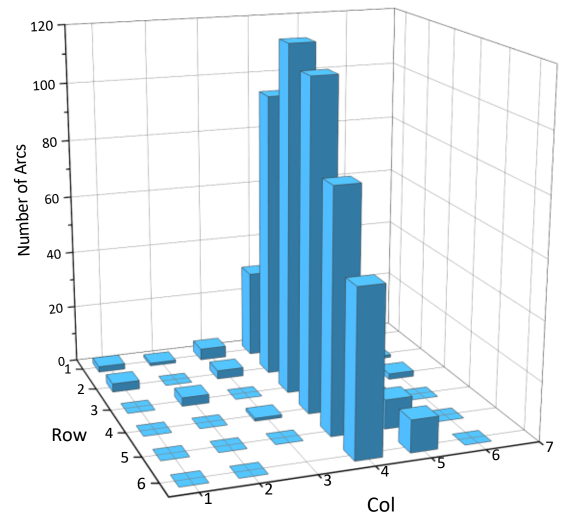
(a) Import_SUM



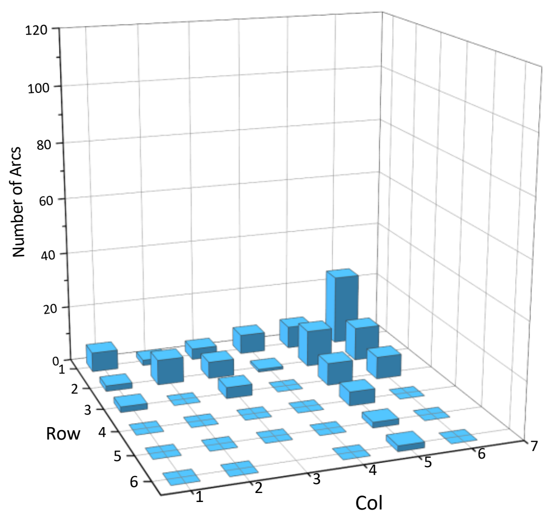
(b) Export_SUM



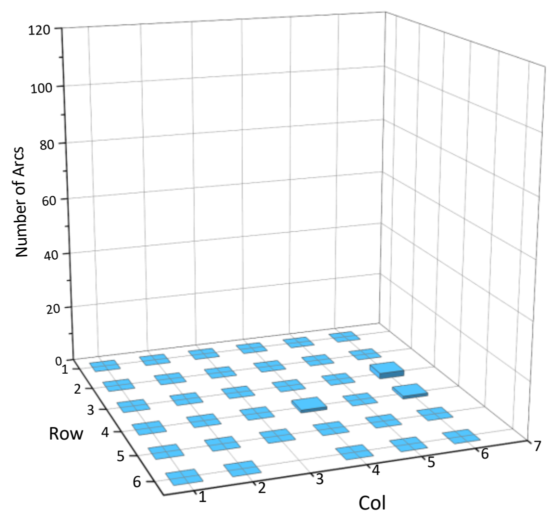
(c) Import_RHA1



(d) Export_RHA1



(e) Import_RHA2



(f) Export_RHA2

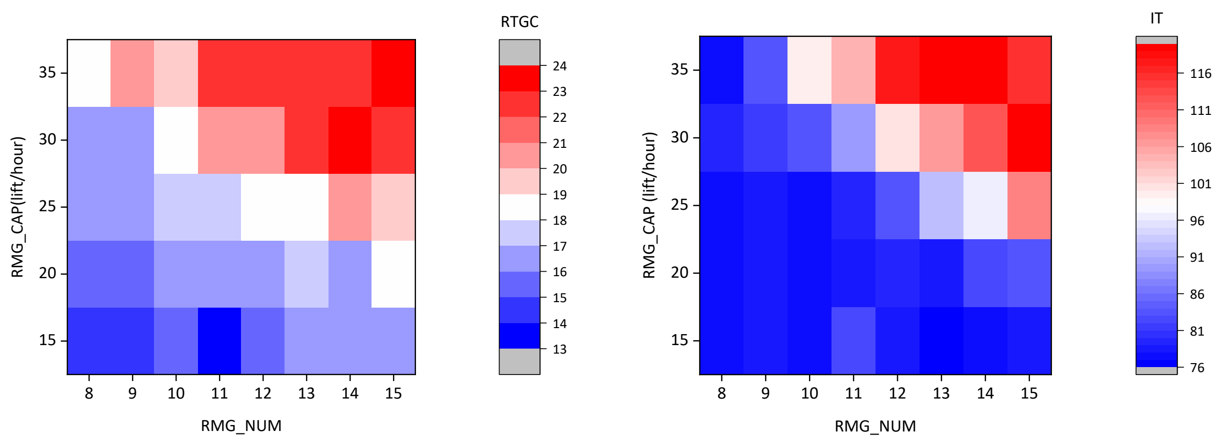
Figure 10. The selection preference of intermodal containers among general storage blocks

5.4 The performance of equipment deployment plan

In this Subsection, the influence of the handling capacity of RHAs on the equipment deployment is analyzed. We adjusted the handling capacity of RHA by changing the maximum number of RMGs that can be deployed from 8 to 15 (the x-axis) and increasing the handling capacity of them from 15 lift/hour to 35 lift/hour (the y-axis). The maximum number constraints on RTGCs and trailer trucks are relaxed in this set of instances. The volume of transport demand is 3 million TEUs, and the dominance sequence of the objectives is obj_3-obj_4.

The change of the number of RTGC and IT in different scenarios are shown in Figure 11. The color represents the number of equipment that is employed to transfer containers to get the maximum throughput.

We can see that, generally, more equipment is needed when the handling capacity of RHA increases. The deployment plan of RTGC and IT are more sensitive to the change of the number of RMGs when the unit handling capacity is large enough. For the instances with low handling capacity ($\leq 20\ lift/hour$), the deployment of other equipment shows no significant changes. Compared to the deployment plan of RTGCs, the deployment plan of trucks seems to be less sensitive to the change of RMG. Considering the current situation of NBCT, i.e., with 8 RMGs, the number of equipment and thus it is more recommended to improve the productivity of the terminal by optimizing the scheduling plan of the equipment. On the other hand, according to Figure 10(b), in order to make full use of the on-dock rails, at least 76 ITs are needed, i.e., when the handling capacity is 20 $lift/hour$. Hence, the terminal operators should pay more attention to the schedule of ITs inside the terminal to ease the congestion of truck lanes.



(a) (b)

Figure 11. The change of equipment deployment plan

6. Conclusion and future research directions

The establish and use of on-dock rail in existing seaport terminals put great pressure on terminal operations. Terminal operators are faced with some new problems like the shortage of storing spaces and insufficient handling capacities with limited resources. Comparing with squeezing out some marginal handling capacity by optimizing the schedule plan of equipment at the operational decision level, it could be more helpful to guarantee a sufficient supply of capacity over the long term by adjusting the usage pattern of the terminal as well as the container flow inside the terminal according to the transport demand. Inspired by the idea of service network planning, this paper studies the transfer flow template planning problem arising in seaport railway terminals with on-dock rails, in which the interactions among container flow, the yard template, and equipment deployment plan are considered. A multi-objective model considering the constraints of handling capacity and storing capacity is proposed. Then, a case study is carried out on Ningbo Beilun Container Terminal, in which the dominance sequence of different objectives is considered when solving the instances. The results report the following observations.

- For the instance of NBCT, a more promising transfer flow template can be achieved when maximizing the throughput is used as the primal objective, by which the operation and transportation cost, as well as the time consumption, are not significantly influenced. Meanwhile, the objective of minimizing the operation and transportation cost is not recommended to be used as the primal objective due to a significant decrease of throughput and longer time consumption.
- It is possible to shorten the time consumption or reduce the cost further when the maximum throughput has been reached. Specifically, if the secondary objective is to reduce the cost, it is

recommended to transfer containers by rails, especially for the hinterland cities with long transport distances.

- The change of management preference could also influence the equipment deployment plan of the terminal. The preference of cost priority will lead to more transfer operations inside the terminal and, thus, more ITs are needed. Meanwhile, the preference of time priority will increase the workload in storage yards, and more RTGCs are needed to complete the tasks.
- The location of on-dock rails shows the evident influence on the yard template. The block with a closer distance is more likely to be selected. Moreover, the cluster of service lines and the group of blocks also show significant influence. The blocks in the same group are likely to be selected together.
- When the unit handling capacity of RMG is at a low level, the deployment plan of other equipment shows is insensitive to the change of the number of RMG. For the NBCT, terminal operators can try to make full use of the on-dock rails by deploying more ITs.

The main limitation of this research is that the TFTP-SRT problem is a static problem and has not taken the arrival time of vessels and the service frequency and operation capacity of trains. Besides, the effect of the economies of scale is not considered. We can further make some interesting extensions based on the current work. First, we will try to study the problem from the dynamic view and propose a model based on the two dimensions time-space network. Second, introducing the temporal dimension into the problem will make the problem difficult to be solved. We can do some research on the algorithm to solving dynamic transfer flow template planning problems effectively. Moreover, as several entities are involved in SRCCT, the interests of them should be further analyzed in future research.

Acknowledgement

The authors would like to thank the anonymous referees for their constructive comments that helped improve the quality of this paper.

References

Abu Aisha, T., Ouhimmou, M., & Paquet, M. 2020. "Optimization of Container Terminal Layouts in the Seaport—Case of Port of Montreal." *Sustainability,* 12(3), 1165. https://doi.org/10.3390/su12031165.

Andersen, J., Christiansen, M., Crainic, T. G., & Grønhaug, R. 2011. "Branch and price for service network design with asset management constraints." *Transportation Science*, 45(1), 33-49. https://doi.org/10.1287/trsc.1100.0333.

Angeloudis, P., & Bell, M. G. 2011. "A review of container terminal simulation models". *Maritime Policy & Management,* 38(5), 523-540. https://doi.org/10.1080/03088839.2011.597448.

Bektas, T., & Crainic, T. G. 2007. "A brief overview of intermodal transportation." In *Engineering Handbook*, edited by Teodor Crainic, 1-23. Taylor and Francis Group

Chen, X., He, S., Li, T., & Li, Y. 2018. "A simulation platform for combined rail/road transport in multi-yards intermodal terminals." *Journal of Advanced Transportation*, 2018. https://doi.org/10.1155/2018/5812939.

Crainic, T. G. 2009. "Service design models for rail intermodel transportation. In Innovations in distribution logistics." In *Innovations in Distribution Logistics. Lecture Notes in Economics and Mathematical Systems*, edited by Nunen J., Speranza M., Bertazzi L., 53-67. Berlin: Springer. https://doi.org/10.1007/978-3-540-92944-4_4.

Crainic, T. G., Hewitt, M., Toulouse, M., & Vu, D. M. 2018. “Scheduled service network design with resource acquisition and management.” *EURO Journal on Transportation and Logistics*, 7(3), 277-309. https://doi.org/10.1007/s13676-017-0103-x.

Dowd, T. J., & Leschine, T. M. 1990. “Container terminal productivity: a perspective.” *Maritime Policy & Management*, 17(2), 107-112. https://doi.org/10.1080/03088839000000060.

Erickson, M. A. 2019. “The Long Beach On-Dock Rail Support Facility: An Innovative Local Plan in a Complex Environment.” In *Ports 2019: Port Planning and Development*, edited by American Society of Civil Engineers., 152-161. https://doi.org/10.1061/9780784482629.015.

He, J., Chang, D., Mi, W., & Yan, W. 2010. “A hybrid parallel genetic algorithm for yard crane scheduling.” *Transportation Research Part E: Logistics and Transportation Review*, 46(1), 136-155. https://doi.org/10.1016/j.trb.2019.08.008.

Jiang, X., Lee, L. H., Chew, E. P., Han, Y., & Tan, K. C. 2012. “A container yard storage strategy for improving land utilization and operation efficiency in a transshipment hub port.” *European Journal of Operational Research*, 221(1), 64-73. https://doi.org/10.1016/j.ejor.2012.03.011.

Jiang, X. J., & Jin, J. G. 2017. “A branch-and-price method for integrated yard crane deployment and container allocation in transshipment yards.” *Transportation Research Part B: Methodologi*cal, 98, 62-75. https://doi.org/10.1016/j.trb.2016.12.014.

Jin, J. G., Lee, D. H., & Cao, J. X. 2016. “Storage yard management in maritime container terminals.” *Transportation Science*, 50(4), 1300-1313. https://doi.org/10.1287/trsc.2014.0527.

Meng, Q., & Wang, X. 2011. “Intermodal hub-and-spoke network design: incorporating multiple stakeholders and multi-type containers.” *Transportation Research Part B: Methodological*, 45(4), 724-742. https://doi.org/10.1016/j.trb.2010.11.002.

Meng, Q., Weng, J., & Suyi, L. 2017. “Impact analysis of mega vessels on container terminal operations.” *Transportation Research Procedia*, 25, 187-204. https://doi.org/10.1016/j.trpro.2017.05.389.

NDRC. 2019. “Guiding Opinions on Accelerating the Construction of Special Railway Lines.” Accessed September 18, 2019. https://www.ndrc.gov.cn/fggz/zcssfz/zcgh/201909/t20190918_1195138.html

Ng, M., & Talley, W. K. 2020. “Rail intermodal management at marine container terminals: Loading double stack trains.” *Transportation Research Part C: Emerging Technologies*, 112, 252-259. https://doi.org/10.1016/j.trc.2020.01.025.

Petering, M. E. 2009. “Effect of block width and storage yard layout on marine container terminal performance.” *Transportation Research Part E: Logistics and Transportation Review*, 45(4), 591-610. https://doi.org/10.1016/j.tre.2008.11.004.

SteadieSeifi, M., Dellaert, N. P., Nuijten, W., Van Woensel, T., & Raoufi, R. 2014. “Multimodal freight transportation planning: A literature review.” *European Journal of Operational Research*, 233(1), 1-15. https://doi.org/10.1016/j.ejor.2013.06.055.

Tan, C., He, J., & Wang, Y. 2017. “Storage yard management based on flexible yard template in container terminal.” *Advanced Engineering Informatics*, 34, 101-113. https://doi.org/10.1016/j.aei.2017.10.003.

UIC. 2020. “2020 report on combined transport Program.” Accessed October 28, 2020. https://uic.org/IMG/pdf/2020_combined _transport_report_press_conference_202010230.pdf

Wang, X., & Meng, Q. 2017. “Discrete intermodal freight transportation network design with route choice behavior of intermodal operators.” *Transportation Research Part B: Methodological*, 95, 76-104. https://doi.org/10.1016/j.trb.2016.11.001.

Yan, B., Zhu, X., Lee, D. H., Jin, J. G., & Wang, L. 2020. “Transshipment operations optimization of sea-rail intermodal container in seaport rail terminals.” *Computers & Industrial Engineering*, 141, 106296. https://doi.org/10.1016/j.cie.2020.106296.

Yu, D., Li, D., Sha, M., & Zhang, D. 2019. “Carbon-efficient deployment of electric rubber-tyred gantry cranes in container terminals with workload uncertainty.” *European Journal of Operational Research*, 275(2), 552-569. https://doi.org/10.1016/j.ejor.2018.12.003.

Yu, H., Ge, Y. E., Chen, J., Luo, L., Liu, D., & Tan, C. 2018. “Incorporating container location dispersion into evaluating GCR performance at a transhipment terminal.” *Maritime Policy & Management*, 45(6), 770-786. https://doi.org/10.1080/03088839.2017.1410243.

Zhang, W., Wang, X., & Yang, K. 2020. “Uncertain multi-objective optimization for the water–rail–road intermodal transport system with consideration of hub operation process using a memetic algorithm” *Soft Computing*, 24(5), 3695-3709. https://doi.org/10.1007/s00500-019-04137-6.

Zhen, L., Chew, E. P., & Lee, L. H. 2011. “An integrated model for berth template and yard template planning in transshipment hubs.” *Transportation Science*, 45(4), 483-504. https://doi.org/10.1287/trsc.1100.0364.

Appendix

Table A.1 The table of key terms and abbreviations

Term	Abbreviation
External Truck	XT
Internal Truck	IT
Network Flow Planning	NFP
Quay Crane	QC
Rail-mounted Gantry Crane	RMG
Rubber-tired Gantry Crane	RTGC
Seaport Rail Terminal	SRT
Sea-rail Combined Container Transportation	SRCCT
Service Network Design	SND
Transfer Flow Template Planning Problem of Seaport Railway Terminals	TFTP-SRT