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Research Article

A Mathematical Application Method for Configuring Rail-Water Intermodal Transportation Equipment in Container Terminals

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Abstract: The quantity configuration of loading, unloading, and transfer equipment at intermodal hubs for container rail-water transportation significantly impacts terminal operational efficiency. This paper takes the container rail-water intermodal hub as the research carrier and focuses on various types of lifting equipment and horizontal transportation equipment within the hub. From the perspective of the interests involved in the intermodal hub, the research objectives are established as minimizing the loading and unloading durations of ships and trains, the equipment handling costs, and the carbon tax cost from container truck movements. Constraints are set considering the impacts of equipment allocation and scheduling, as well as container transfer plans. A multi-objective loading and unloading equipment configuration model based on time periods and with incoming ships and trains as allocation units is constructed. Based on this, a Genetic Algorithm with specific search rules is designed to solve the model. Through case study analysis, an optimal allocation scheme for loading and unloading equipment is achieved, and the validity of the model and algorithm is verified. This research provides support for the efficient operation of container multimodal transport terminals.

***Keywords*:** rail-water intermodal transportation, multi-objective optimization, specific search rule Genetic Algorithm, loading and unloading infrastructure, equipment management

MSC: 90B06, 90C11, 90C29

1. Introduction

Container multimodal transportation, as a representative modern and high-quality mode of transportation characterized by high efficiency and low emissions, has played a pivotal role in advancing cargo transportation reforms worldwide. Among its components, container rail-water intermodal transportation stands out by fully leveraging the advantages of low cost, high capacity, and environmental friendliness of railways and waterways. It is currently one of the key transportation modes promoted by China. The "14th Five-Year Plan for the Development of a Modern Integrated Transportation System" explicitly outlines the need to enhance the connectivity and integration of transportation networks, with targets such as increasing the railway access rate to major coastal port areas to over 70% by 2025 and achieving an average annual growth rate of 15% in container rail-water intermodal volume. Furthermore, container rail-water intermodal transportation aligns

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with the call for "shifting from road to water" and "shifting from road to rail" in green transportation, contributing to the goal of reducing carbon dioxide emission intensity in transportation by 5% in 2025 [1].

However, the current hub equipment configuration has problems such as 'emphasizing the efficiency of a single device and neglecting the coordination of multiple devices' and 'ignoring carbon emission costs', resulting in a delay rate of 12%–15% for ship loading and unloading, and high operating costs. It is urgent to optimize the equipment configuration plan. Therefore, this study will construct a time segmented and multi-objective equipment configuration model for container intermodal transportation hubs under specific transportation conditions, to achieve efficient collaboration of equipment. Through algorithm optimization, the number and scheduling of loading and unloading equipment will be studied to minimize ship loading and unloading time, equipment operating costs, and Internal Trucks (IT) carbon emissions. The goal is to improve the overall operational efficiency and driving safety of the terminal, ensure the continuous and smooth operation of various transportation links, and play an important role in improving the operational efficiency, traffic flow, and cargo flow efficiency of multimodal ports.

The rest of this paper is organized as follows. Section 2 provides a literature review and contributions. Section 3 presents the problem description and model development process. Section 4 introduces the algorithm solution process. Section 5 analyzes the numerical experimental results. Section 6 concludes the paper.

2. Literature review

Scholars have carried out extensive research in the field of equipment configuration of molten iron combined transportation.In terms of horizontal transport equipment configuration. Zhang and Pel [2] proposed a hybrid storage strategy and analyzed the impact of hybrid storage strategy on terminal operation in terms of considering the configuration of transportation equipment at hub level. Gharehgozli et al. [3] evaluated the use of different transportation modes and quantities (including IT, Automated Guided Vehicles (AGVs) and multi-trailer systems). Anvari et al. [4] propose and compare several practical approaches to solving the problem of fleet size of horizontal transport equipment at container terminals. Uribe-Martes et al. [5] analyze container transport demand within the port of Barranquilla for straddle carriers moving between container terminals and yards. Stojaković and Twrdy [6] proposed berth-yard operation model focusing on IT type and quantity for yard and terminal bilateral service. Zhang et al. [7] considered yard IT transformation and deployment for green port dangerous goods transportation.

In terms of comprehensive configuration and evaluation of terminal equipment, Li [8] established the quantitative relationship among the possession quantity of port machinery, the intact rate of equipment and the optimal number of equipment on duty. Mi [9] analyzed the configuration scheme of loading and unloading facilities under the premise of comprehensively considering the maximum capacity of main storage yard and auxiliary storage yard. Castilla-Rodríguez et al. [10] considered uncertainties in the application environment and the allocation of quayside cranes and IT involved in optimizing transshipment operations. Mahpour et al. [11] analyzed the number of containers of different size in container ports and the number of equipment allocated to each berth through factor relationships. Zenginz and Hamdoon [12] estimated the optimal IT and crane numbers required for unloading cargo through the DEVS-Suite platform. Li et al. [13] proposed a method of multi-equipment cluster scheduling between U-type automatic freight yard and railway freight yard, and analyzed the influence of equipment quantity on the transfer process.

In terms of rail-water intermodal connectivity, Yao [14] constructed quantity allocation models of Quay Cranes (QC), Yard Cranes (YC) and IT based on "iron-water" and "iron-storage yard-water" modes respectively. Liu et al. [15] considered Rail-Mounted Gantry Cranes (RMGC) allocation from two aspects of RMGC scheduling problem and quantity optimization allocation problem. Wang et al. [16] designed equipment quantity allocation process in the loading and unloading process of "QC, IT and RMGC". Yan et al. [17] proposed a multi-objective model integrating container flow, yard allocation and equipment deployment scheme decision, in which the equipment deployment scheme is to configure an appropriate number of equipment for each transfer node or route in the port. Li et al. [18] built a model based on the collaborative scheduling of IT and RMGC, and analyzed the impact of container quantity, container proportion on shore, IT quantity and RMGC quantity on RMGC and IT completion time. Yang [19] took the optimal configuration scheme of

QC, YC, RMGC and IT as the research object, and analyzed the single and double cycle loading and unloading strategies in the container loading and unloading process. Li et al. [20] established a mixed integer programming model to solve the problem of RMGC and IT collaborative scheduling in iron and steel intermodal ports under the mixed mode of container flow, and decided to take the optimal number of RMGC and IT directly and indirectly under different container number ratios. Yang et al. [21] used Automated Rail-Mounted Gantry Crane (ARMG) and AGV collaborative scheduling model to analyze the impact of ARMG and AGV number and their ratio on total energy consumption under the mixed operation mode of "train-ship" and "train-yard-ship", under the scenario of vertical railway arrival and shared yard between port and railway.

In summary, scholars at home and abroad have conducted extensive research and optimization on the configuration of handling and transportation equipment at hubs. Most studies focus on decision-making for the configuration of a specific type of equipment or consider multiple equipment configurations while neglecting the interdependencies among them. And 'time allocation' and 'carbon emission cost' have not been included in the unified framework. This article will further optimize this issue.

3. Formulation

3.1 *Problem description*

Focusing on the handling tasks of three types of transport units: arriving ships, trains, and container trucks, this paper aims to optimize a specific objective and allocate the limited handling equipment within the terminal. Through the allocation of equipment, the circulation pattern of containers to be loaded and unloaded within the port is determined. The handling and transfer equipment involved for each transport unit include QC, YC, RMGC, and Container Trucks (CT), where CT comprises IT and External Trucks (ET). The transfer of containers between various transport units necessitates loading, unloading, and transportation through the aforementioned equipment, as illustrated in Figure 1.

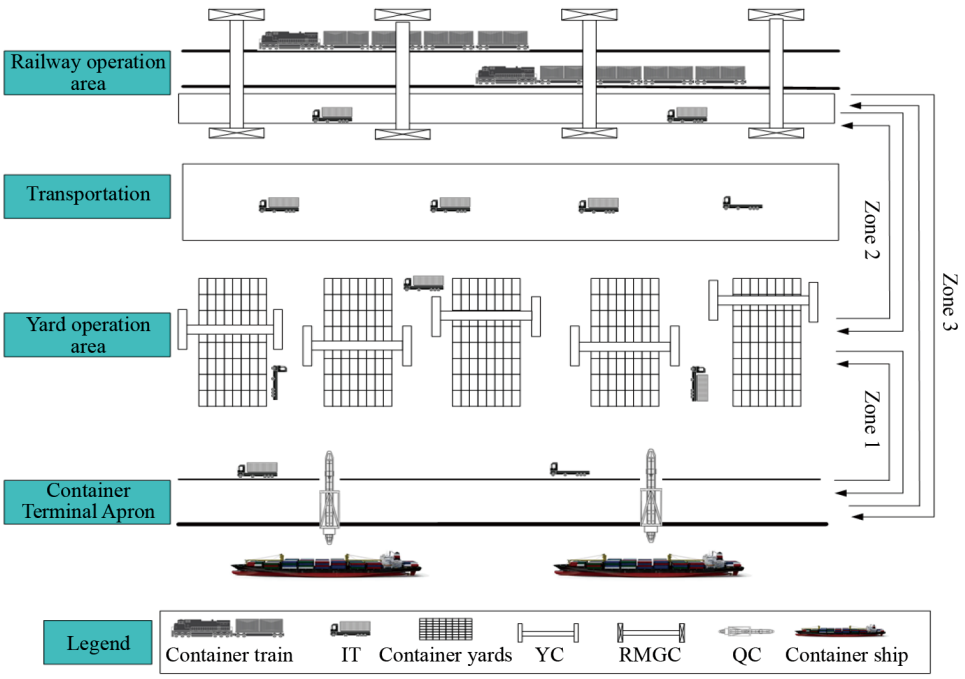


Figure 1. Equipment configuration for loading and unloading in various areas of the rail- water intermodal hub

QC and RMGC are deployed on fixed tracks at the quay front and railway loading/unloading lines, respectively, to load containers from ITs onto trains or ships, or unload containers from trains or ships onto ITs. RMGC provides stacking services for various container zones and can travel between different zones. For ITs, a "double-cycle" operation mode is adopted for loading and unloading transportation, dividing the areas for IT loading and unloading activities among the three functional zones into three parts: zone 1 for "quay front-yard", zone 2 for "yard-railway loading/unloading area", and zone 3 for "quay-railway loading/unloading area". The IT travel paths involved can be classified into two categories: one involves horizontal movement within the yard, such as in zones 1 and 2, where ITs need to provide box delivery and pick-up services within the yard; the other does not involve horizontal movement within the yard, such as in zone 3, which directly provides transportation services between ships and trains.

The decision-making time period is discretized into multiple unit time segments, and container loading and unloading tasks are determined based on the arrival times of ships and trains. Considering the corresponding optimization objectives, by deciding the number of cranes for loading and unloading operations for each ship, train, and container zone within each time segment, the container loading and unloading plans for ships and trains within each time period can be determined. Furthermore, by deciding the number of IT in zones 1, 2, and 3, it can be determined whether to directly load or unload containers when the loading and unloading time windows of ships and trains overlap.

Based on the above description, this paper considers the problem of configuring handling equipment to serve different port collection and distribution transportation modes from the perspective of rail-water intermodal transportation. During the stage of constructing the IT configuration model, carbon emission costs and operating costs are combined to construct a multi-objective optimization IT configuration model. With the total available handling resources of the port known, decisions are made on the number of handling equipment allocated to each arriving ship, train, and functional zone within the port.

3.2 *Notations*

The set of parameters involved in the model is shown in Table 1, the main parameter variables involved are shown in Table 2, and the decision variables involved are shown in Table 3.

Table 1. Description of aggregate parameters

Symbol	Meaning
V	Set of arrived ships, $v \in V$
K	Set of arrived trains, $k \in K$
TU	Set of loading/unloading units, $TU = V \cup K \cup B_d$
d	Set of directions, $d = d_o \cup d_{ir} \cup d_{it}$
B_d	Set of blocks, where block B_d can only store containers of direction d
U	Set of QCs, $u \in U$
R	Set of RMGCs, $r \in R$
Y	Set of YCs, $y \in Y$
TR	Set of ITs, $tr \in TR$
E	Set of equipment types, $e \in E = U \cup R \cup Y \cup TR$
T	Set of time periods, $t \in T$
N	Set of IT travel areas, $n \in N$

Table 2. Description of main parameters

Symbol	Meaning
a_v	Ship arrival time period
l_v	Ship departure time period
a_k	Train arrival time period
l_k	Train departure time period
TN_v^d	Loading/unloading volume of containers in direction d on ship v, $d \in D$
TN_k^d	Loading/unloading volume of containers in direction d on train k, $d \in d_{ir} \cup d_o$
TN_t^d	Loading/unloading volume of road containers in direction d during time period t, $d \in d_{it}$
d_o	Export direction
d_{ir}	Rail import direction
d_{it}	Road import direction
Q_e	Total number of equipment of each type
A_e^{tu}	Maximum allowable configuration quantity of equipment e in handling unit tu
C_e	Operating cost per time period for each type of equipment
W_e	Number of containers that can be loaded/ unloaded per time period for each type of equipment
x_{d0}	Original number of containers in the block for direction d
n	Zone index, n = 1, quay front-yard functional area Zone index, n = 2, yard-railway loading/unloading line functional area Zone index, n = 3, quay front-ailway loading/unloading line functional area
A_{tr}^n	The maximum allowed number of IT configurations for zone n
C_{trn}	Operating cost of IT in zone n during a single time period
em_n	Carbon emission of IT in zone n during a single time period
tt_n	Number of containers that can be loaded/unloaded by IT in zone n during a single time period
ts_n	Percentage of unit time occupied by the total duration for IT in zone n to load/unload a set (two) of containers during a single time period
δ_t	$= 0, t \in [a_v,\ g_v]$ and $\in [a_k,\ g_k]$; otherwise, $= 1$
μ_e	Utilization rate of each equipment
x_{dt}^{tu}	Number of containers loaded/unloaded in direction d by transport unit tu during time period t
z_{dt}^{vk}	Number of containers directly transferred between ship v and train k in direction d during time period t
uz_{dt}^{tu}	Number of containers not directly transferred in direction d by transport unit tu during time period t

Table 3. Description of decision variables

Symbol	Meaning
u_{vt}	Number of QCs allocated to ship v during time period t
r_{kt}	Number of RMGCs allocated to train k during time period t
$y_{B_d t}$	Number of YCs allocated to block B_d during time period t
tr_{nt}	Number of ITs allocated to zone n during time period t
g_{tu}	Completion time period of loading/unloading for transport unit tu

3.3 *Mathematical model*

3.3.1 *Assumption*

Including the following assumptions:

(1) Regarding the service priority of IT, it is assumed that IT operations follow a first-come, first-served principle for loading and unloading, meaning immediate loading/unloading upon arrival without intervals between IT operations.

(2) For YC operations, it is assumed that YC operate continuously without YC waiting for IT and adhere to the principle of "unload first, load later".

(3) In terms of YC task assignment, YC do not need to return to the ends of the yard after each operation. When the next task is required, the nearest YC is moved to perform loading and unloading based on the given starting point and destination of each task.

(4) The yard is divided into storage areas for inbound and outbound containers, specifically including outbound container areas and inbound container areas. The inbound container areas are further divided by import direction into railway inbound container areas and highway inbound container areas.

(5) Throughout the entire homework process, regardless of the performance differences of similar equipment, the vehicle travels at a constant speed with the same carbon emissions and energy consumption.

3.3.2 *Objective function*

The objectives of the optimization scheme for the configuration of handling equipment at the intermodal hub for container rail-water transportation include minimizing the total equipment operating cost, minimizing the cost of berth occupation by trains and ships, and minimizing the carbon tax paid for carbon emissions from IT movements, as shown in Equations (1), (6), and (9), respectively.

$$\min C = \min\left(C_1 + C_2 + C_3 + C_4\right) \tag{1}$$

$$C_1 = \sum_{v=1}^{V}\sum_{t=1}^{T} u_{vt} \cdot C_u \tag{2}$$

$$C_2 = \sum_{k=1}^{K}\sum_{t=1}^{T} r_{kt} \cdot C_r \tag{3}$$

$$C_3 = \sum_{d=1}^{D}\sum_{t=1}^{T} y_{B_{dt}} \cdot C_y \tag{4}$$

$$C_4 = \sum_{n=1}^{N}\sum_{t=1}^{T} tr_{nt} \cdot C_{trn}. \tag{5}$$

In the objective function for equipment operating costs, C represents the total operating cost of each device, C_1 represents the total operating cost of QC, C_2 represents the total operating cost of RMGC, C_3 represents the total operating cost of YC, and C_4 represents the total operating cost of IT.

$$\min P = \min(P_1 + P_2) \tag{6}$$

$$P_1 = \sum_{v=1}^{V} (g_v - a_v) \cdot \alpha \tag{7}$$

$$P_2 = \sum_{k=1}^{K} (g_k - a_k) \cdot \beta. \tag{8}$$

In the objective function for berth or loading/unloading track occupation costs, P represents the total cost of ships occupying berths and trains occupying railway loading and unloading lines, P_1 represents the cost of ships occupying

berths, P_2 represents the cost of trains occupying railway loading/unloading tracks, α denotes the unit time cost for ships occupying berths, and β denotes the unit time cost for trains occupying railway loading/unloading tracks.

$$\min EM = \sum_{n}^{N} \sum_{t=1}^{T} tr_n \cdot em_n \cdot \text{tax}. \tag{9}$$

In the objective function related to carbon emissions from IT movements, EM represents the cost of IT carbon emissions, em_n represents the carbon emissions from ITs in zone n per unit time period, and tax represents the carbon tax fee charged per kilogram of carbon dioxide emitted. The carbon tax indicator is introduced for conversion, i.e., to impose a carbon tax on the total carbon dioxide emissions generated by ITs during the statistical time period.

3.3.3 *Constraints*

Based on the problem description and the establishment of the objective functions, constraints are set in terms of hub operational capacity, container flow, and IT allocation. Equations (10)–(17) represent constraints related to the configuration and scheduling capacity of loading and unloadling equipment at the intermodal hub. Equations (18)–(29) represent constraints related to the input and output container flow within the hub and the internal container flow balance. Equations (30)–(31) represent constraints related to the loading and unloading times of ships and trains arriving at the port. Equations (32)–(36) represent constraints for ITs under different container transfer modes.

$$\sum_{v=1}^{V} u_{vt} \leq Q_u, \ \forall t \tag{10}$$

$$\sum_{k=1}^{K} r_{kt} \leq Q_r, \ \forall t \tag{11}$$

$$\sum_{d=1}^{D} y_{B_d t} \leq Q_y, \ \forall t \tag{12}$$

$$\sum_{n=1}^{N} tr_{nt} \leq Q_{tr}, \ \forall t \tag{13}$$

$$u_{vt} \leq A_u^v, \ \forall t, \ \forall v \tag{14}$$

$$r_{kt} \leq A_r^k, \ \forall t, \ \forall k \tag{15}$$

$$y_{B_d t} \leq A_y^{B_d}, \ \forall t, \ \forall d \tag{16}$$

$$tr_{nt} \leq A_{tr}^n, \ \forall t, \ \forall n. \tag{17}$$

Equations (10)–(13) respectively indicate that the number of QC, RMGC, YC and IT equipment allocated in each time period shall not exceed the total number of equipment of this type. Equations (14)–(17) respectively indicate that

the number of QC, RMGC, YC and IT equipment allocated in each time period shall not exceed the maximum allowable configuration number of equipment of this type.

$$\sum_{d=1}^{D} x_{dt}^{v} = W_u \cdot u_t^v \cdot \mu_u,\ \forall t,\ \forall v, \tag{18}$$

$$\sum_{d=1}^{d_o \cup d_{ir}} x_{dt}^{k} = W_r \cdot r_t^k \cdot \mu_r,\ \forall t,\ \forall k \tag{19}$$

$$TN_t^d + \sum_{k=1}^{k} uz_{d\lfloor t-\frac{ts_2}{2} \rfloor}^{k} + \sum_{v=1}^{V} uz_{d\lfloor t+\frac{ts_1}{2} \rfloor}^{v} = W_y \cdot y_t^{B_d} \cdot \mu_y,\ \forall t,\ \forall d \in d_O \tag{20}$$

$$\sum_{k=1}^{k} uz_{d\lfloor t+\frac{ts_2}{2} \rfloor}^{k} + \sum_{v=1}^{V} uz_{d\lfloor t-\frac{ts_1}{2} \rfloor}^{v} = W_y \cdot y_t^{B_d} \cdot \mu_y,\ \forall t,\ \forall d \in d_{ir} \tag{21}$$

$$TN_t^d + \sum_{v=1}^{V} uz_{d\lfloor t-\frac{ts_1}{2} \rfloor}^{v} = W_y \cdot y_t^{B_d} \cdot \mu_y,\ \forall t,\ \forall d \in d_{it}. \tag{22}$$

Equations (18)–(19) respectively represent the total loading and unloading capacity of QC and RMGC configured correspondingly to the number of containers loaded and unloaded by each ship and train in each time period. Equations (20)–(22) respectively represent the total loading and unloading capacity of YC configured correspondingly to the number of containers loaded and unloaded by each export container area, railway inlet container area and highway inlet container area in each time period. Through Equations (18) to (22), the relationship between containers and handling equipment can be established.

$$\sum_{t=a_v}^{g_v} x_{dt}^{v} \geq TN_v^d,\ \forall v,\ \forall d \in D \tag{23}$$

$$\sum_{t=a_k}^{g_k} x_{dt}^{k} \geq TN_k^d,\ \forall k,\ \forall d \in d_{ir} \cup d_o \tag{24}$$

$$\sum_{k=1}^{K} z_{dt}^{vk} + uz_{dt}^{v} = x_{dt}^{v},\ \forall v,\ \forall t,\ \forall d \in D \tag{25}$$

$$\sum_{v=1}^{V} z_{dt}^{vk} + uz_{dt}^{k} = x_{dt}^{k},\ \forall k,\ \forall t,\ \forall d \in d_{ir} \cup d_o \tag{26}$$

$$\sum_{k=1}^{K} TN_k^d + \sum_{t=1}^{T} TN_t^d + x_{d0} = \sum_{v=1}^{V} TN_v^d,\ \forall d \in d_o \tag{27}$$

$$\sum_{v=1}^{V} TN_v^d + x_{d0} = \sum_{k=1}^{K} TN_k^d,\ \forall d \in d_{ir} \tag{28}$$

$$\sum_{v=1}^{V} TN_v^d + x_{d0} = \sum_{t=1}^{T} TN_t^d,\ \forall d \in d_{it}. \tag{29}$$

Equations (23)–(24) respectively indicate that the container loading and unloading quantity of each ship and train for containers in direction d in the whole time period is equal to the total loading and unloading task quantity in this direction. Equations (25)-(26) respectively indicate that the total number of containers directly taken and not directly taken by each ship and train for containers in direction d in each time period is equal to the container loading and unloading quantity in direction d in each time period. Equations (27)–(29) represent the balance of container flow into and out of the intermodal hub for the export direction, the rail-water intermodal import direction, and the road import direction, respectively, over the entire decision-making time period.

$$a_v < g_v < l_v,\ \forall v \tag{30}$$

$$a_k < g_k < l_k,\ \forall k. \tag{31}$$

Equations (30)–(31) indicate that all ships and trains need to complete their loading and unloading tasks within the time windows defined by their arrival and departure times.

$$2 \cdot \sum_{d=1}^{D} y_{B_d t} \cdot w_y \leq tr_{1t} \cdot tt_1 + tr_{2t} \cdot tt_2,\ \forall t \tag{32}$$

$$2 \cdot \sum_{v=1}^{V} u_{vt} \cdot w_u \leq (tr_{1t} \cdot tt_1) + M(1 - \delta_t),\ \forall t \tag{33}$$

$$2 \cdot \sum_{k=1}^{K} r_{kt} \cdot w_r \leq (tr_{2t} \cdot tt_2) + M(1 - \delta_t),\ \forall t \tag{34}$$

$$2 \cdot \left(\sum_{v=1}^{V} u_{vt} \cdot w_u + \sum_{p=1}^{P} r_{pt} \cdot w_r \right) \leq (tr_{1t} \cdot tt_1 + tr_{2t} \cdot tt_2 + tr_{3t} \cdot tt_3) + M \cdot \delta_t,\ \forall t \tag{35}$$

$$\sum_{d}^{d_{ir} \cup d_o} \sum_{v=1}^{V} \sum_{k}^{K} z_{dt}^{vk} \leq (tr_{3t} \cdot tt_3) + M \cdot \delta_t,\ \forall t. \tag{36}$$

M represents a very large value, which is twice the maximum theoretical loading and unloading capacity of a single type of equipment in a single time period. Equation (32) fulfills the service demand of YC for IT. Regardless of whether only indirect transfers occur or direct transfers are also possible, the number of ITs allocated to zone 1 and 2 within each time period must meet the service demand of YCs in the yard. Equation (33) states that in cases where only indirect transfers take place, since the number of indirect transfers is not less than the number of containers loaded and unloaded

by QC during that period, zone 1 needs to satisfy the service demand of QC. Similarly, Equation (34) indicates that in scenarios where only indirect transfers occur, since the number of indirect transfers is not less than the number of containers loaded and unloaded by RMGC during that period, zone 2 needs to fulfill the service demand of RMGC. However, a correction should be noted here: in a practical sense, zone 2 would likely serve a different set of demands, potentially related to RMGC or another relevant entity. Equation (35) specifies that whenever direct transfers occur, the number of IT in zone 1, 2, and 3 must simultaneously satisfy the service demands of both QC and RMGC. Since the number of containers loaded and unloaded by QC and RMGC within that period may include both direct and indirect transfers, Equation (36) is required to further constrain the direct transfers served by zone 3.

In summary, the objective of the optimization model in this study is represented by Equations (1)–(9), and the constraints are given by Equations (10)–(36).

4. Algorithm design

The optimal strategy for loading and unloading the appropriate number of containers from entire trains and ships across various time periods needs to be harmonized with the most efficient configuration of loading and unloading equipment. As indicated by the aforementioned model, the problem of configuring loading and unloading equipment in container rail-water intermodal transport hubs belongs to the class of NP-hard problems, which means that finding an exact solution within polynomial time is infeasible [22]. Therefore, this paper proposes a genetic algorithm based on specific search rules to address this issue.

To improve the efficiency of population initialization and avoid invalid solutions, three specific search rules are designed:

Time matching rule: QC only sets non-zero values in the corresponding ship arrival time period ($a_v \sim l_v$), and $u_{vt} = 0$ in the non arrival time period; RMGC only configures non-zero values during the corresponding train arrival period ($a_k \sim l_k$), and $r_{kt} = 0$ during the non arrival period;

Zone 3 IT constraint rule: Only when the loading and unloading periods of the ship train overlap ($\delta_t = 0$), the number of Zone 3 IT configurations $tr_{nt} > 0$, otherwise $tr_{nt} = 0$;

Device total quantity constraint rule: When initializing the population, directly filter individuals with "single period device configuration exceeding the total quantity Q_e" (such as the sum of $u_{vt} > Q_e$) to reduce invalid solutions.

(1) Chromosome Encoding

In the process of chromosome encoding, to enhance the efficiency of population iterative optimization, the variables that need to be encoded are divided into the following components: the end loading and unloading time periods for vehicles and ships, denoted as l_k and l_v, respectively; the number of QC allocated to ship v in time period t, denoted as u_{vt}; the number of RMGC allocated to train k in time period t, denoted as r_{kt}; and the number of YC allocated to block B_d in time period t, denoted as $y_{B_d t}$. The structure of the chromosome is illustrated in Figure 2.

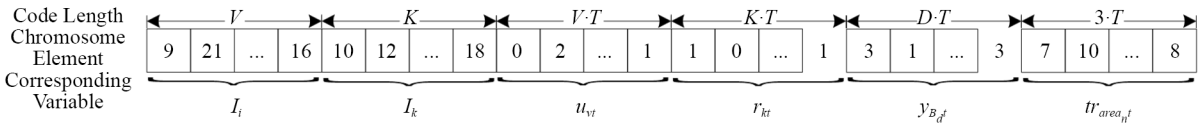


Figure 2. Chromosome structure diagram

Encoding for the end loading and unloading periods specifies that the end times for ships V_1 and V_2 are 9 and 21, respectively, while for trains K_1 and K_2, the end times are 10 and 12, and so on. The number of QC allocated to ship V_1 in time periods 1 and 2 are 0 and 2, respectively, while for train K_1, the number of RMGC allocated in time periods 1 and 2 are 1 and 0, respectively. For the container yard in direction d, the number of YC allocated in time periods 1 and 2 are 3 and 1, respectively, and for zone 1, the number of IT allocated in time periods 1 and 2 are 7 and 10, and so on.

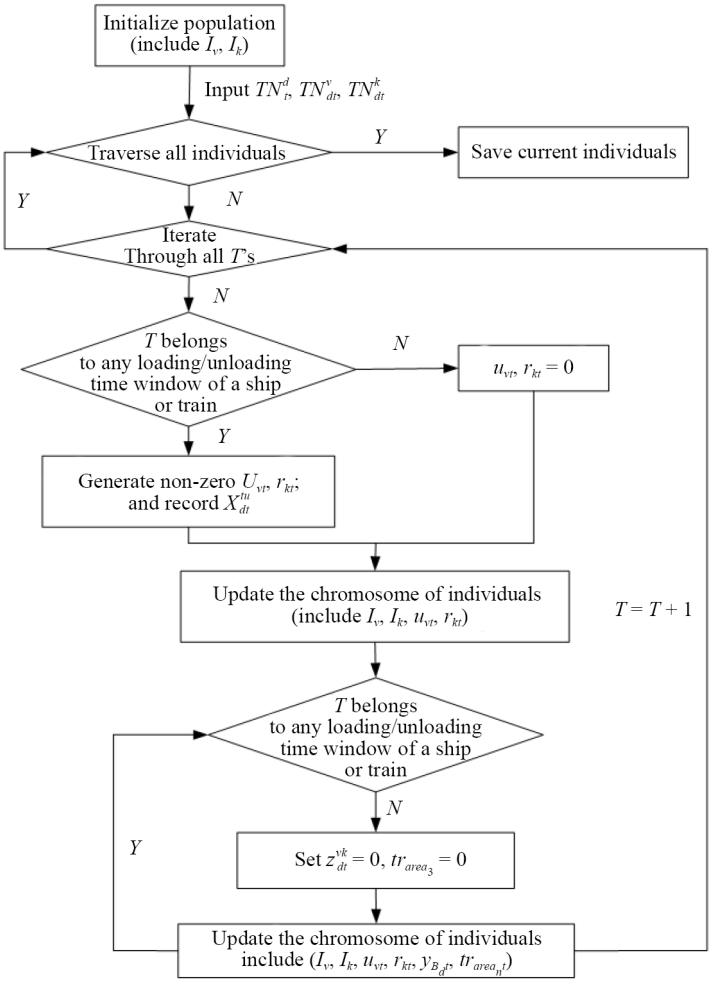


Figure 3. Search allocation algorithm process

By inputting constraints related to the configuration and scheduling capacity of loading and unloading equipment in the intermodal transport hub, as well as constraints related to the loading and unloading times of arriving ships and trains, a population of equipment quantity allocation schemes can be directly generated that meets the loading and unloading requirements for ships and trains departing the port without exceeding the port's production capacity. However, directly generating the population through random encoding would result in an enlarged solution pool, increasing the difficulty of algorithm search. Therefore, the time periods for allocating QC and RMGC to ships and trains must fall within their respective port stay times, with the allocation number for other time periods being 0. For zone 3, during time periods without overlapping loading and unloading activities of ships and trains, the IT allocation number should be 0. In summary, considering the interdependencies among various variables and their association with time periods, a search algorithm is designed during the population initialization phase to improve search efficiency. The search flowchart is shown in Figure 3.

(2) Fitness function calculation

Given that our model encompasses multiple objective functions, namely minimizing the total equipment operating cost, minimizing the cost of berth occupancy by trains and ships, and minimizing the carbon tax cost from IT movements, all of which are minimization problems, the fitness function is designed as the reciprocal of the sum of the products of each objective function and its corresponding weight, as shown in the equation below. Here, ω_1, ω_2, and ω_3 represent the weights of the three objective functions, respectively, with $\omega_1 + \omega_2 + \omega_3 = 1$.

$$fit = \frac{1}{\omega_1 \cdot C + \omega_2 \cdot P + \omega_3 \cdot EM}. \tag{37}$$

(3) Sorting and Selection

Prior to the selection operation, a sorting operator is introduced to arrange the fitness of each individual in the population from high to low, further accelerating the convergence speed. In this paper, the roulette wheel selection algorithm is employed for the selection operation. In algorithms seeking individuals with maximum fitness, the roulette wheel selection algorithm can accelerate the screening process to identify individuals with higher fitness functions.

(4) Crossover and Mutation

A crossover operator based on specific corresponding positions is designed, combined with search rules to update the population.

The allocation of QC and RMGC at each time period depends on the load and unload time windows of the trains and ships. Therefore, the number of QC and RMGC allocated to each train and ship at each time period corresponds one-to-one with the chromosome segments involving the decision variables of departure times. When crossing over the chromosome segments representing departure times, the corresponding segments representing the allocation of QC and RMGC should also undergo crossover processing. As shown in Figure 4, crossover position 1 corresponds to ship 3, and the corresponding crossover position 2 is u_{3t}. After completing the crossover operation, it is necessary to check the total quantity of various loading and unloading equipment allocated to the same time period in the offspring. If the total quantity exceeds the limit, that offspring is discarded. After completing the crossover operation, y_{B_dt} and tr_{area_nt} can be further calculated using search algorithms.

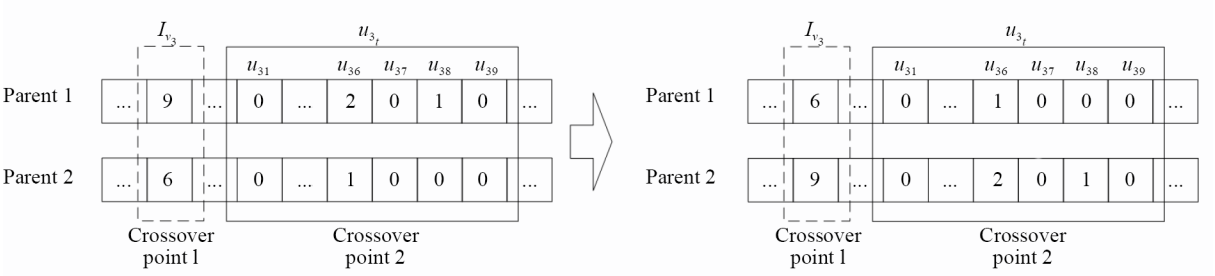


Figure 4. Chromosome crossover

By designing the crossover operator, the population has approached the optimal solution region. At this point, the local search capability of the mutation operator can be utilized to accelerate the convergence to the optimal solution. Considering the correspondence among various chromosome segments, only the single-point mutation operator is employed for mutation within the departure time segments of trains and ships. Specifically, a random mutation point is selected, and the element value at the mutation site is altered within a predefined range, as illustrated in Figure 5.

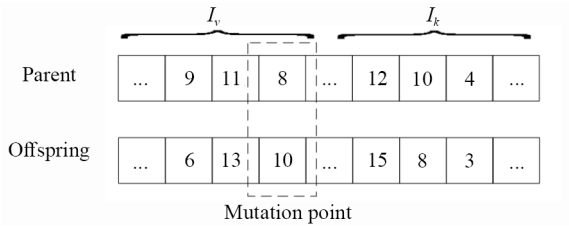


Figure 5. Chromosomal variation

5. Numerical calculation

5.1 *Initial data*

A case study is conducted using data from a specific rail-water intermodal transportation hub.

(1) Information table of incoming transportation units

Incoming transportation units include ships, trains, and ETs. The decision-making duration for loading and unloading equipment is set as $T = 24$ hours. The ship information table is shown in Table 4, the train information table is shown in Table 5, and it can be seen that a total of 5 ships and 4 trains arrived at the hub during the statistical period, with ET transporting containers to the hub in every time period, as shown in Table 6. The above transportation units involve 5 import-export directions, with directions 1 and 2 being export directions, direction 3 being the import direction for highway containers, and directions 4 and 5 being import directions for railway containers. The initial number of containers stranded in each direction's container yard at the beginning of the period is shown in Table 7.

Table 4. Ship information table (unit: Twenty-foot Equivalent Unit (TEU))

Ship number	Arrival time	Departure time	Direction 1	Direction 2	Direction 3	Direction 4	Direction 5
1	22/12:05	23/01:05	92	139	57	23	44
2	22/14:30	23/03:30	82	135	102	34	20
3	22/22:00	23/04:00	90	56	44	12	33
4	23/01:00	23/06:30	166	52	47	18	54
5	23/04:30	23/11:00	62	55	161	34	48

Table 5. Train information table (unit: TEU)

Train number	Arrival time	Departure time	Direction 1	Direction 2	Direction 3	Direction 4	Direction 5
1	22/14:00	22/17:00	33	10	0	45	34
2	22/16:00	22/19:00	22	38	0	18	37
3	23/02:00	23/05:00	32	39	0	22	50
4	23/06:00	23/09:00	57	45	0	29	58

Table 6. ET information table (unit: TEU)

Time	Direction 1	Direction 2	Direction 3	Time	Direction 1	Direction 2	Direction 3
12:00	27	21	14	24:00	21	11	19
13:00	14	22	24	1:00	12	12	19
14:00	7	8	13	2:00	18	8	17
15:00	22	15	6	3:00	25	8	15
16:00	13	10	13	4:00	11	20	19
17:00	20	9	11	5:00	18	12	14
18:00	14	5	25	6:00	25	8	22
19:00	8	7	22	7:00	10	12	19
20:00	9	15	12	8:00	13	10	17
21:00	24	24	16	9:00	7	9	23
22:00	10	10	25	10:00	27	10	11
23:00	16	10	13	11:00	17	10	22

Table 7. Original container quantity of yard (unit: TEU)

Block	Direction 1	Direction 2	Direction 3	Direction 4	Direction 5
Number	14	19	22	7	20

(2) Hub Conditions

The travel path of IT in each zone is mainly related to the layout of the hub, and the main parameters affecting the layout of the travel path are: the number of horizontal container areas on the dock is n, the length of a single block is denoted as l, the width of the entire yard is denoted as w, the distance from the edge of the yard to the front of the quay is denoted as $dist1$, and the distance from the edge of the yard to the railway loading and unloading line is denoted as $dist2$. According to the calculation method proposed by Zhang et al. [23, 24], the average driving distance for other location classifications can also be obtained. Therefore, for zone 1, the average driving distance of IT is:

$$E_1(S) = \frac{32n^2 - 91n + 84}{n^3} \cdot w + \frac{20n^3 + 66n^2 - 386n + 456}{3n^3} \cdot l + 2 \cdot dist1. \tag{38}$$

For zone 2, the average driving distance of IT is:

$$E_2(S) = \frac{32n^2 - 91n + 84}{n^3} \cdot w + \frac{20n^3 + 66n^2 - 386n + 456}{3n^3} \cdot l + 2 \cdot dist2. \tag{39}$$

For zone 3, IT directly transports containers from the QC to the train. Considering the relative position of the QC and the target railway loading and unloading area, the calculation method for the average travel distance of IT in a mixed storage scenario, as described in the works of Zhang et al., can be analogously applied. Therefore, the average travel distance of IT in zone 3 is:

$$E_3(S_n) = 2w + \frac{2n^2 + 3n + 1}{3n} \cdot l + 2 \cdot (dist1 + \cdot dist2). \tag{40}$$

Based on Equations (38)-(40), the travel distances of IT within the three zones are further calculated, as shown in Table 8.

Table 8. Layout information

Attribute	Numerical value	
Number of horizontal blocks, n		5
Length of individual block, l		130 m
Yard width, w		220 m
Distance from the edge of the yard to the front of the quay, $dist1$		200 m
Distance from the edge of the yard to the railway loading and unloading line, $dist2$		100 m
Average travel distance of IT	zone 1	1,927 m
	zone 2	1,727 m
	zone 3	2,041 m

Regarding the occupation costs of loading and unloading areas for incoming ships and trains, we adopt an average tonnage of 6,523.2 tons for incoming ships, with a berthing rate of 0.15 yuan per ton-hour [25], resulting in a ship berthing cost rate of 978.5 yuan per hour. For incoming trains, we consider an average train length of 749.7 meters (including the length of the locomotive and other components). The rate for railway loading and unloading tracks is referenced against the maintenance and overhaul costs of these trains, with the overhaul frequency set to once per year at a rate of 2,048 yuan per meter per year. Consequently, the occupation cost rate for railway loading and unloading trains is 175.2 yuan per hour.

(3) Equipment situation of rail-water intermodal hub

The data on the number of QC, YC, RMGC, and IT in the hub, as well as their equipment scheduling constraints, efficiency, and energy consumption, are presented in Table 9. The average operational cost per container move for IT is 14.5 yuan, with an average traveling speed of 350 m/min [26] and an average energy consumption of 0.81 kg/TEU. The diesel conversion factor is 1.4571 standard coal per kg [27], and the carbon tax is set at 522 yuan per ton. By combining the average traveling distance of IT in each area with its average traveling speed, the loading and unloading capacity, loading and unloading cost, and carbon tax for carbon emissions per unit time in each area can be further calculated, as shown in Table 10.

Table 9. Information on lifting machinery and equipment [28]

Attribute	QC	YC	RMGC
Total number of equipments (units)	6	12	5
Maximum allowable configuration quantity for the same period (units)	3	4	3
Cost per time period (yuan)	735	600	700
Equipment utilization rate	0.8	0.9	0.8
Actual number of loaded and unloaded containers per unit time (TEU)	25	14	20

Table 10. IT load and unload information for various zones

Attribute	Zone 1	Zone 2	Zone 3
Average travel distance of IT (m)	1,927	1,727	2,041
Maximum allowable configuration quantity (units)	10	8	8
Waiting time (min)	2	2	1
Total time required for loading and unloading a pair of containers (min)	7.5	6.9	6.8
Number of TEUs loaded and unloaded per unit time (TEU)	15	17	17
Carbon tax for carbon emissions per unit time (yuan)	9.2	10.4	10.4
Loading and unloading cost per unit Time (yuan)	217.5	246.5	246.5

5.2 *Solution analysis*

Data from a specific rail-water intermodal transportation hub over a 24-hour period were selected as a case study, with each hour representing a time period unit, totaling 24 time periods. Additionally, the initial parameters for the Genetic Algorithm were set as follows: an initial population of 200, a crossover probability of 0.6, a mutation probability of 0.1, and a maximum number of iterations of 350. Considering that the source of carbon emissions in the model presented in this paper only accounts for the movement of IT, when converted into the same cost objective for optimization with other objectives, its quantity level tends to be smaller. Given the current trend in China of promoting rail-water intermodal transportation as a green transportation mode, the weights for the three objectives-equipment loading and unloading costs, berth/loading and unloading line occupancy costs, and carbon emission costs-were set to 0.2, 0.2, and 0.6, respectively. Programming and calculations were performed using MATLAB 2016a on an Intel Core i7-12700H 2.30 GHz CPU with 16.0 GB RAM PC, yielding an optimal result of RMB 55,835.6.

Through solving the model, the loading and unloading time windows for incoming ships and trains are presented in Table 11. Since this paper uses one hour as the unit time period, the specific arrival times in the information tables for ships and trains can be converted into time periods, indicating the range of available loading and unloading time periods.

Table 11. Loading and unloading time windows for each transportation unit

	Serial number	Loading and unloading start period	Loading and unloading end period	Latest loading and unloading end period
Ship	1	1	9	14
	2	3	11	16
	3	11	15	17
	4	14	19	19
	5	17	24	24
Train	1	3	5	6
	2	5	8	8
	3	15	18	18
	4	19	22	22

The number of cranes configured for each transportation unit at each time period is shown in Table 12.

Table 12. Number of cranes allocated to ships and trains at different time periods

Period	Transport unit								
	Ship (Allocate QC quantity)					Train (Allocate RMGC quantity)			
	1	2	3	4	5	1	2	3	4
1	1								
2	3								
3	3	3				2			
4	2	3				2			
5	2					3	2		
6	1	1					1		
7	2								
8	1	1					3		
9	1	3							
10		2							
11		2	1						
12			2						
13			3						
14			2	2					
15			2	3				1	
16				3				3	
17				3	1			3	
18				2	2			1	
19				2	3				2
20					3				3
21					2				2
22					2				3
23					2				
24					1				

The number of YC configured in each block during each time period and the number of IT configured in each zone during each time period are shown in Table 13.

Table 13. Number of cranes or IT assigned to blocks and zones at different time periods

Period	Loading/unloading unit							
	Block (Allocate YC quantity)					Zone (Allocate IT quantity)		
	1	2	3	4	5	1	2	3
1	2	4	3	1	2	2		
2	4	3	3			5		
3	3	3	3	3		8	2	2
4	3	4	2			5		6
5	4	3	1			2	3	4
6	3	3	1			4	1	1
7	1	3	2			3		
8	4	3	3			3	4	
9	4	4	2			6		
10	2	3	4			4		
11	3	2	4			5		
12	4	2	1			4		
13	3	3	2		1	4		
14	3	3	4	1		7		
15	4	4	2			6	1	2
16	4	2	2			1	3	5
17	4	2	3			5	1	5
18	4	1	1			2	1	3
19	4	4	3			7		3
20	3	2	4			5	1	3
21	4	2	3			3	3	
22	3	2	4			3	4	
23	2	1	4			3		
24	2	1	3			2		

(1) Analysis of loading and unloading time window

Upon solving, the proportions of equipment loading and unloading costs, berth/loading and unloading track occupancy costs, and IT travel carbon emission costs are 81.9%, 13.9%, and 4.1%, respectively. Equipment loading and unloading costs account for the largest share of the total costs. Therefore, the optimization results will prioritize maximizing the coordination efficiency of various equipment connections and minimizing costs, while also minimizing the time ships and trains spend in port. A graph depicting the end loading and unloading times of ships and trains for any five optimization results is shown in Figure 6. Due to the larger cargo volumes of V1 and V2 and their longer durations in port, there is more redundant time within their loading and unloading time windows, leading to fluctuations in the optimized departure times. In contrast, for V3, V4, V5, and all arriving trains, the optimized end loading and unloading periods are more stable due to smaller cargo volumes or shorter durations in port. The distribution of the time windows for each ship and train across various time periods for the best optimization result is illustrated in Figure 7.

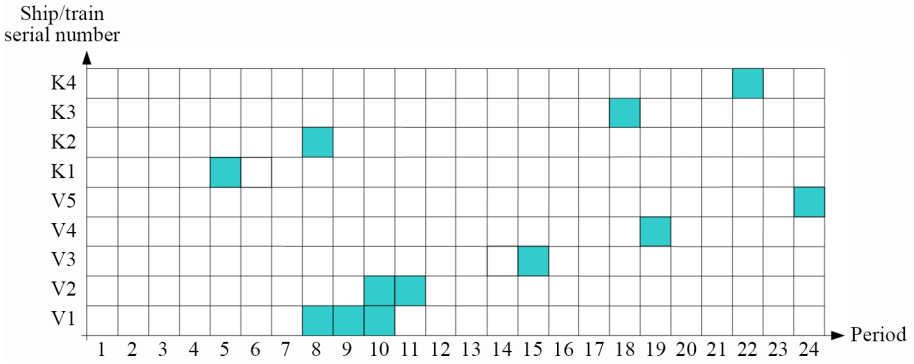


Figure 6. Distribution of end loading and unloading periods for ships and trains

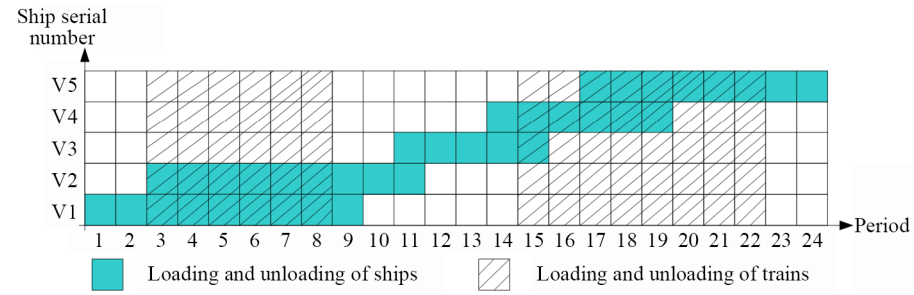


Figure 7. Loading and unloading periods of arriving trains and ships

(2) Analysis of direct load and unload capacity for trains and ships

Given the relatively small volume of intermodal containers handled by the arriving ships and trains discussed in this paper, and the sufficient allowable allocation of IT in each zone in the initial case study, nearly all intermodal containers in the optimization results are directly loaded and unloaded. Additionally, the result shows that the number of IT allocated to zone 3 ranges from 1 to 6. Therefore, an attempt is made to limit the allowable allocation of IT for direct load and unload operations between trains and ships in zone 3, in order to compare its impact on the YC operation volumes across different time periods. By setting the maximum allowable number of IT in zone 3 to 3, as illustrated in Figures 8 to 12, for export directions 1 and 2, there are fluctuations in the YC operation volumes but the overall trends are similar. For highway import direction 3, the YC operation volume fluctuates less and follows a similar trend. For rail-water import directions 4 and 5, the fluctuations in operation volumes are more significant. Further analysis reveals that since the container flow in the export yard originates from both highway and railway containers, with highway containers accounting for a larger proportion, restricting the number of IT in zone 3, which represents direct load and unload capacity, has a certain but limited impact on the YC operation volume in this yard. For highway container yards, as all containers need to enter the yard, this restriction does not directly affect their operation volumes. However, since the loading and unloading equipment group in the intermodal hub is an interconnected system, it has an indirect and relatively minor impact on these yards. For the rail-water import yard, its container flow entirely originates from the railway, making it the yard most affected by the number of IT allocated to zone 3.

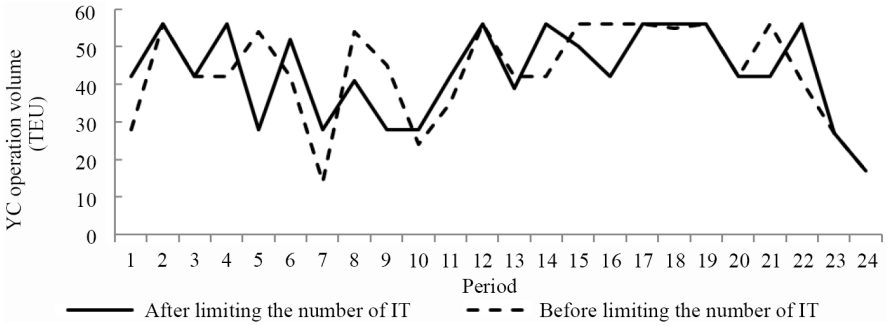


Figure 8. Variation in YC operation volume for yard in export direction 1

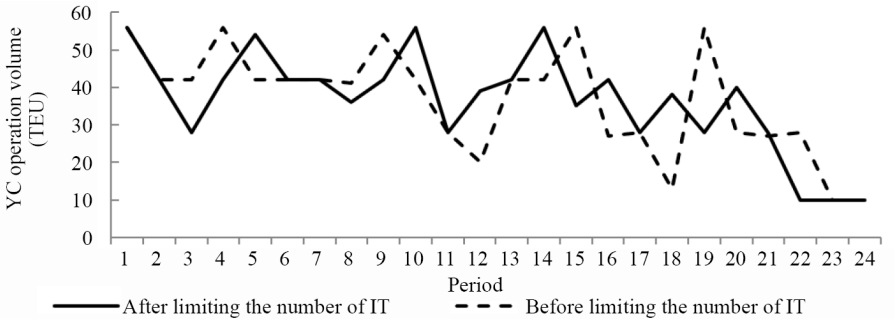


Figure 9. Variation in YC operation volume for yard in export direction 2

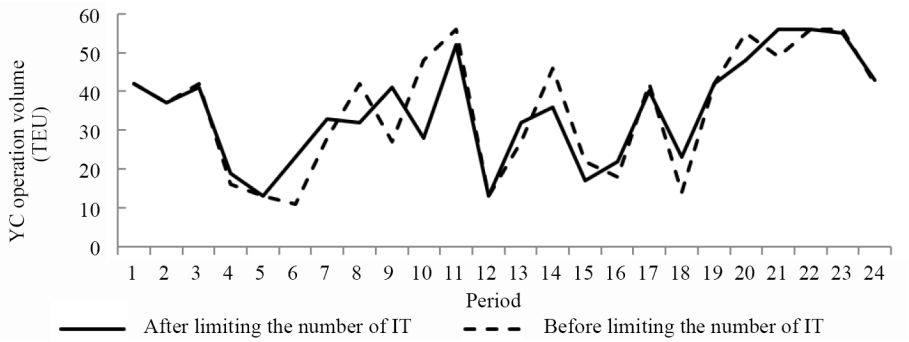


Figure 10. Variation in YC operation volume for yard at highway import direction 3

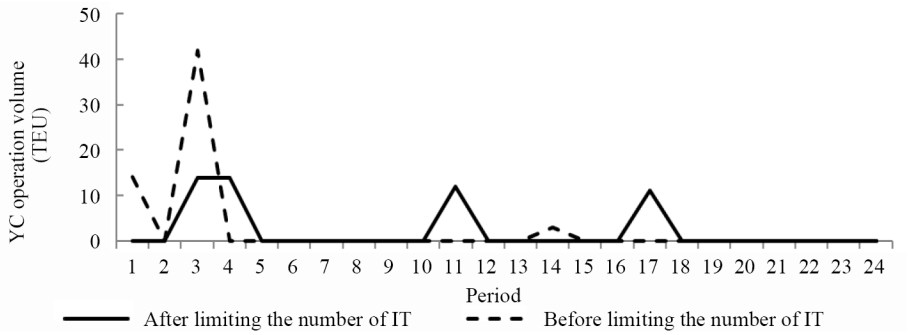


Figure 11. Variation in YC operation volume for yard at railway import direction 4

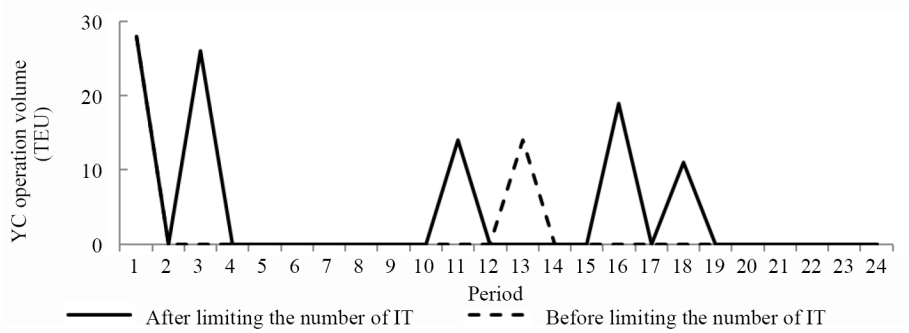


Figure 12. Variation in YC operation volume for yard at railway import direction 5

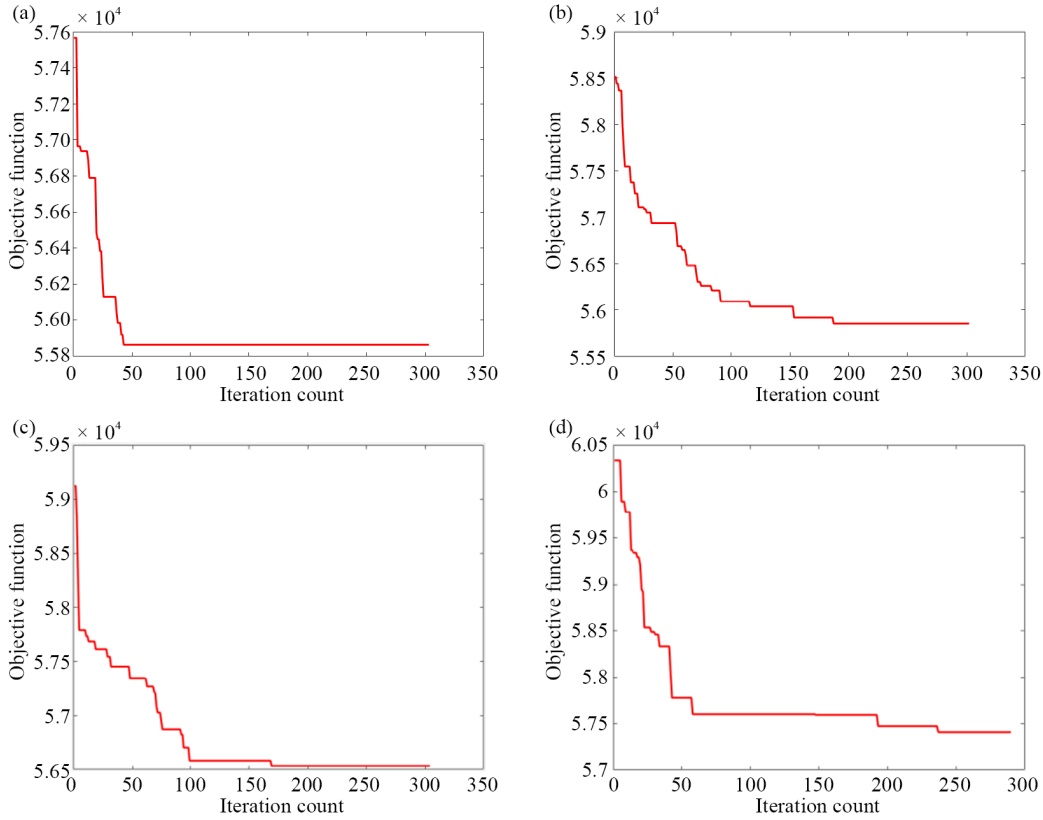


Figure 13. Changes in target cost when the number of IT allowed in zone 3 is 8, 4, 3, and 2, respectively

Based on the analysis of the time windows for loading and unloading of trains and ships presented earlier, it can be concluded that direct transfer between trains and ships in this optimization scheme is the preferred outcome when considering costs. Furthermore, since the IT allocation in zone 3 represents the capacity for direct transfer, different levels of restrictions on the number of IT allowed in zone 3 are set to compare their impact on the total optimization cost. When the number of IT allowed in zone 3 is set to 8, 4, 3, and 2, respectively, the corresponding objective function values with changes in iteration times are shown in Figures 13a-d. The original case with 8 ITs allowed has a cost of 55,835.6 yuan, which changes to 55,852.5 yuan when the number is reduced to 4, 56,519.8 yuan when reduced to 3, and 57,409.7 yuan when reduced to 2. The change in total objective cost with varying numbers of IT allowed is depicted in Figure 14. It can be observed in this case that when the number of IT allowed in zone 3 is greater than 4, the impact on total cost

is insignificant. However, when the number of IT allowed is limited to 4 or fewer and further decreased, the total cost increases significantly. Therefore, it can be concluded that by limiting the number of IT allowed in zone 3, which further restricts the direct transfer capacity of the hub, results in an increased flow of containers entering the yard, leading to higher operational costs and subsequently higher total costs. Hence, to ensure normal loading and unloading in other areas of the hub, the number of IT allowed in zone 3 should be adequately set.

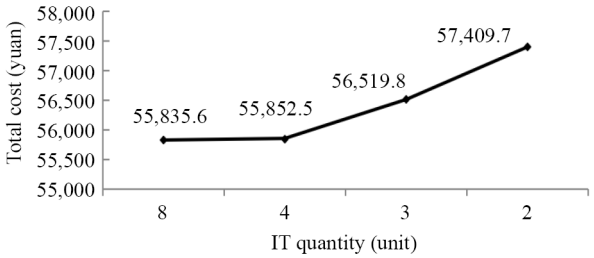


Figure 14. Variation of total cost in zone 3 with the number of IT allowed for allocation

(3) Analysis of the impact of loading and unloading scale

The cases presented here are examples with significant volumes of containers arriving by ship and train. Further, cases with different loading and unloading scales are set up to analyze the impact of varying numbers of arriving ships and trains, as well as container volumes, on the proportions of each sub-objective and the target per container. The scales of each case and their calculation results are shown in Table 14. Figure 15 illustrates the changes in the total objective value and the trends in the proportions of each sub-objective for each case, while Figure 16 depicts the trends in the average cost per container for each case.

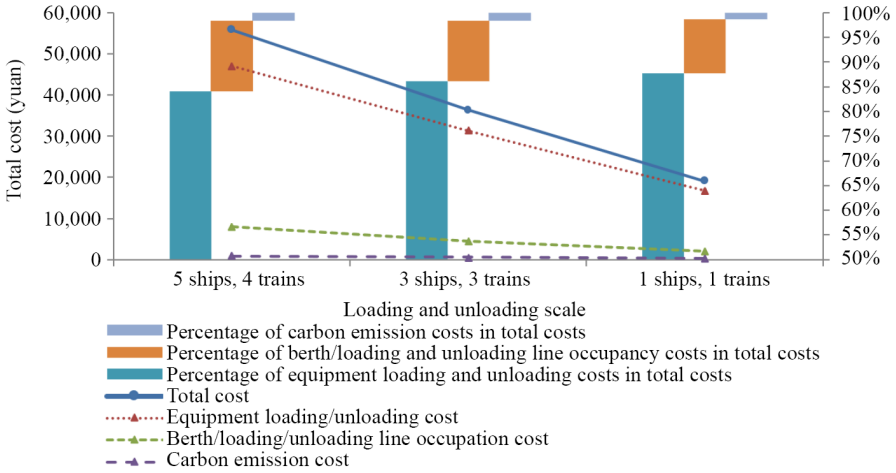


Figure 15. The impact of the number of trains and ships on each sub target

In Table 14 “Cost Optimization Rate”, the equipment loading and unloading cost is 46,971.0 yuan for the 5 ships scenario. Compared with similar scenarios in [20, 24] studies, the multi-objective model proposed in this paper quantifies the cost optimization rate to 8.2%, which is higher than the advantage of 3.8%~5.1% in the literature. This demonstrates the superiority of the method used in this paper.

Based on Figure 15, it can be observed that a reduction in incoming ships and trains, accompanied by a decrease in the volume of containers arriving at the port, leads to a decrease in the total target cost. Simultaneously, the costs of the

three sub-targets also decrease, but the proportions of each sub-target within the total target cost will change. Specifically, the proportion of total costs associated with berth occupancy by ships and loading and unloading line occupancy by trains decreases as the number of incoming ships and trains diminishes. However, the proportions of equipment loading and unloading costs and carbon emission costs increase as the number of ships and trains arriving decreases. As shown in Figure 16, as the volume of containers arriving at the port decreases, the average cost per container also decreases, albeit with a slight overall variation. Compared to the increase in equipment loading and unloading costs, the reduction in berth and loading and unloading line occupancy costs has a greater impact on total costs. In other words, efficient scheduling of ships and trains to reduce loading and unloading times plays a significant role in lowering the average cost per container.

Table 14. Information and calculation results of various scale examples

Numerical example	Total container quantity (TEU)	Total cost	Equipment loading and unloading cost	Berth/loading and unloading line occupation cost	Carbon emission cost	Average cost per container
5 ships, 4 trains (original calculation example)	1,660	55,835.6	46,971.0	7,972.8	891.8	33.64
3 ships, 3 trains	1,089	36,349.13	31,291.3	4,460.1	597.7	33.38
1 ship, 1 train	573	19,100.2	16,769.3	2,062.1	268.7	33.33

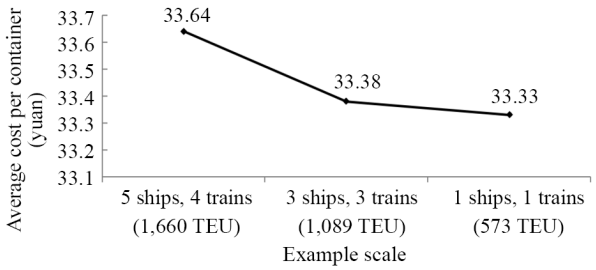


Figure 16. Trend of average cost per container

6. Conclusion

This paper applies the principles of transportation planning and management to investigate the issue of configuring loading and unloading transfer equipment between the frontline of a rail-water intermodal hub terminal and the railway operating area. By allocating a reasonable number of equipment to different loading and unloading zones within the hub based on transportation demand, it aims to reduce the idle rates of various types of equipment, thereby contributing to lowering the hub's operational costs and enhancing its economic benefits. When the IT configuration in Zone 3 should not be less than 4 units, otherwise the total cost will significantly increase. For different loading and unloading scales, the QC and RMGC ratio can be dynamically adjusted, while prioritizing the IT supply during overlapping loading and unloading periods of the ship train to reduce direct transportation delays.

Additionally, the rational allocation of loading and unloading equipment improves the utilization efficiency of such equipment, which can decrease carbon emissions generated during loading and unloading operations at the hub, further facilitating the development of green transportation and green hubs. In subsequent research, the randomness of equipment failures can be included, and multi hub network scenarios can be expanded to include equipment scheduling costs between hubs and consider unplanned arrival events. A dynamic configuration model can be constructed to further optimize the operation of automated container terminals.

Conflict of interest

The authors declare that they have no conflict of interest.

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