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Collaborative Optimization of Berth Allocation and Yard Storage in Container Terminals

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Abstract: Considering the interaction between the berth and the yard, this paper studies the collaborative optimization problem of berth allocation and yard storage from the point of the ships over a certain planning period. This collaborative optimization problem is formulated as the integer programming, which aims at minimizing the total truck travel distance. And decision variables are the berthing positions for visiting ships and the storage positions for export containers. Meanwhile, this paper demonstrates the complexity of the problem in theory. And the hybrid tabu genetic algorithm is designed to solve the problem to obtain the optimal berth allocation position and export container storage position. For this algorithm, the rule is applied to generate the initial feasible solutions, and the crossover and mutation operation are simultaneously applied to optimize the initial solutions. Finally, this paper discusses two different scenes: the same berth scene and the same ship scene. The influence of two different scenes on truck travel distance is analyzed by different numerical examples. Numerical examples' results show that the collaborative optimization of berth allocation and yard storage can effectively shorten the truck travel distance and improve the efficiency of terminal operation, which provides the decision support for terminal operators.

Key words: Export containers, berth allocation, yard storage, collaborative optimization, hybrid tabu genetic algorithm.

1. Introduction

Mega container terminals around the world routinely handle more than 10 million TEU of cargo and serve thousands of vessels in a year [1]. With the rapid increase of container traffic volume, container terminal systems have become more and more busy. Terminal operators and shipping companies are worried about the limited scale of container terminals and the use of various resources. In order to adapt to the development of container transportation, efficient terminal management has gradually attracted the attention of terminal operators and shipping companies [2, 3]. Container terminal is a complex system. The efficiency of container handling and the utilization of terminal resources have a direct impact on the operational efficiency of container terminal. The huge number of containers handling makes the terminal operators always consider simultaneously all kinds of terminal operations in order to achieve the highest operational efficiency and the maximum utilization of resources [4].

As an important part of container terminals, berths and yards are important places for container exchange and storage operations. They mainly decide the allocation of berthing positions for ships arriving at ports and the allocation of storage locations for export containers. As shown in Fig. 1, in the actual terminal operation, the arrival of the ships and containers are uncertain, which is not always appropriate in accordance with a predetermined schedule [5]. During the loading process of export containers, before the ship arrives at the port, the export containers to be loaded onto the ship are entirely already stacked on different yard. When the ship arrives at the port, the ships docked at a particular berth considering the time window. Then, the export containers will be transferred using the trucks from the yard where the containers stack

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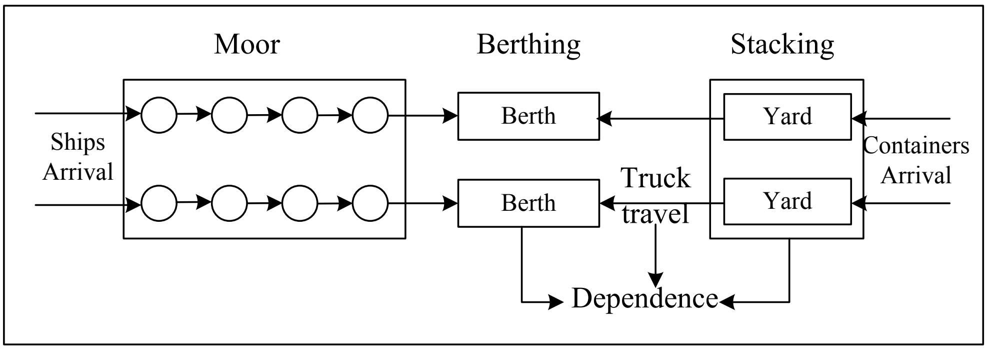


Fig. 1 Port characteristic.

to the berth where the ship is berthing. Considering the difference of containers stacked position and ship berthing position, the distance between the yard and the berth is different. The greater the distance the movement of containers is, the greater the cost of movement. In other words, the truck travel distance is closely related to the ship berthing position and the containers stacking position, which directly influence the efficiency of terminal operation. Meanwhile, the choice of the ship berthing position and the determination of export containers stacking position affect each other and restrict each other. Thus, considering the limitation of berth and yard resources, the collaborative optimization of berth and yard is very important to shorten the truck travel distance and improve the efficiency of terminal operation.

In order to study this problem better, this paper is organized as follows: Section 2 reviews the literature. A detailed description of the problem is given in Section 3. Section 4 presents mathematical model to collaboratively optimize the berth allocation planning and yard storage planning. Section 5 outlines the design of hybrid tabu genetic algorithm to solve the model. Section 6 verifies the effectiveness of the algorithm by different scales of numerical examples. Lastly, this paper presents final conclusions.

2. Literature Review

Generally, after the ship arrives at the terminal, the berthing time and position shall be determined according to the berth allocation planning. A reasonable berth allocation planning can effectively shorten the waiting time of the ship and improve the operational efficiency of ship and terminal. Therefore, the berth allocation problem is an important decision problem for terminal operators, which has attracted the attention of many scholars. Bierwirth and Meisel [6, 7] presented an overview and classification of exiting optimal models and algorithms for the berth allocation problem. Berth allocation problem usually divided into discrete berth allocation problem and continuous berth allocation problem considering the type of berth. Imai et al. [8] studied the discrete static berth allocation problem aiming at minimizing the waiting time and handling time, which used the Hungarian method. Buhrkal et al. [9] discussed three mathematical models of discrete berth and improved the performance of one model. Imai et al. [10] established the mathematical model to minimize the total ships operation time, and designed the heuristic algorithm to solve the continuous berth allocation problem. Ji et al. [11] presented the index system to simulate the continuous berth allocation problem using Monte Carlo. Meanwhile, berth allocation operation faced many uncertain elements, such as ship arriving time, handling time and equipment breakdown. Zhen [12] proposed a stochastic programming formulation and a robust formulation considering the uncertain of ship operation time, and discussed the relationship between them. Xiang et al. [13] established a bi-objective robust berth allocation model with the consideration of the ship arrival and operation time, and developed an adaptive grey wolf optimizer algorithm. However, the research only considers the berth operation, and does not consider the interaction between yard and berth, which directly influence the terminal operation.

In actual terminal operation, the berth operation is not independent. And the berth allocation panning is usually formulated taking into account the stacked position in the yard for export containers, and vice versa. Thus, some scholars have jointly studied the allocation problem of berth and yard in transshipment terminals. Zhen et al. [14] studied the berth template planning and yard template planning in the transshipment hubs, and proposed the integrated model to minimize the service cost and the operation cost. Hendriks et al. [15] presented simultaneous berth allocation and yard planning at tactical level for transshipment ships, and proposed a new method to generate a suitable starting point. Jin et al. [16] studied the berth and yard template design problem for mother ships and feeder ships in container transshipment terminals considering the berthing position and the yard template. Tao and Lee [17] addressed the joint planning problem of berth and yard allocation in transshipment terminals, and formulated a mixed integer quadratic programming model to minimize the total distance of exchanging containers between mother ships and feeder ships.

In a word, some scholars have carried out joint research on berth and yard, but most of these only considered the case of transshipment terminals. Meanwhile, most of these researches studied the berth allocation planning with the certain yard storage planning or studied the yard storage planning with the certain berth allocation planning, which did not literally achieve the coordinated optimization of berth and yard. Therefore, considering the interaction between berth allocation planning and yard storage planning, this paper studies the coordinated optimization of berth and yard for the ships within a certain planning period. A mixed integer programming is established to minimize the total truck travel distance, and a hybrid tabu genetic algorithm is proposed to solve the problem. The optimal ship berthing position and yard storage distribution of export containers are obtained to provide decision-making support for terminal operators and effectively improve the operational efficiency of the terminal.

3. Problem Description

In the process of actual terminal operation, the ships in the planning period arrive in accordance with a predetermined schedule, and the dispatchers make the corresponding berth allocation planning. After the ships determine the berthing positions, the export containers stacked in the yard are transferred by trucks from the yard sub-blocks to the shore to complete the loading operation. During the loading process, taking into account the types of ships and berths, different berth allocation planning leads to different ship berthing positions. In addition, different yard storage planning leads to different stacking positions and stacking quantities of export containers, which leads to different truck travel distances in the transportation process. As shown in Fig. 2, while the ship with number 1 and type 1 determines to dock in the berth with number ① and type 1, if the export containers stack in the sub-block (1), the truck travel distance of each container will be d_{11} in the loading process. And if the export containers stack in the sub-block (6), the truck travel distance will become d_{16}. Therefore, the difference of export containers stacking positions can lead to the difference of truck travel distance. Meanwhile, if the ship with number 1 and type 1 determines to dock in the berth with number ④ and type 2, when the export containers stack in the sub-block (1), the truck travel distance will become d_{41}. Thus, the ship berthing position is another important factor affecting the truck travel distance. That is to say, the berth allocation planning and yard storage planning have the important relationship.

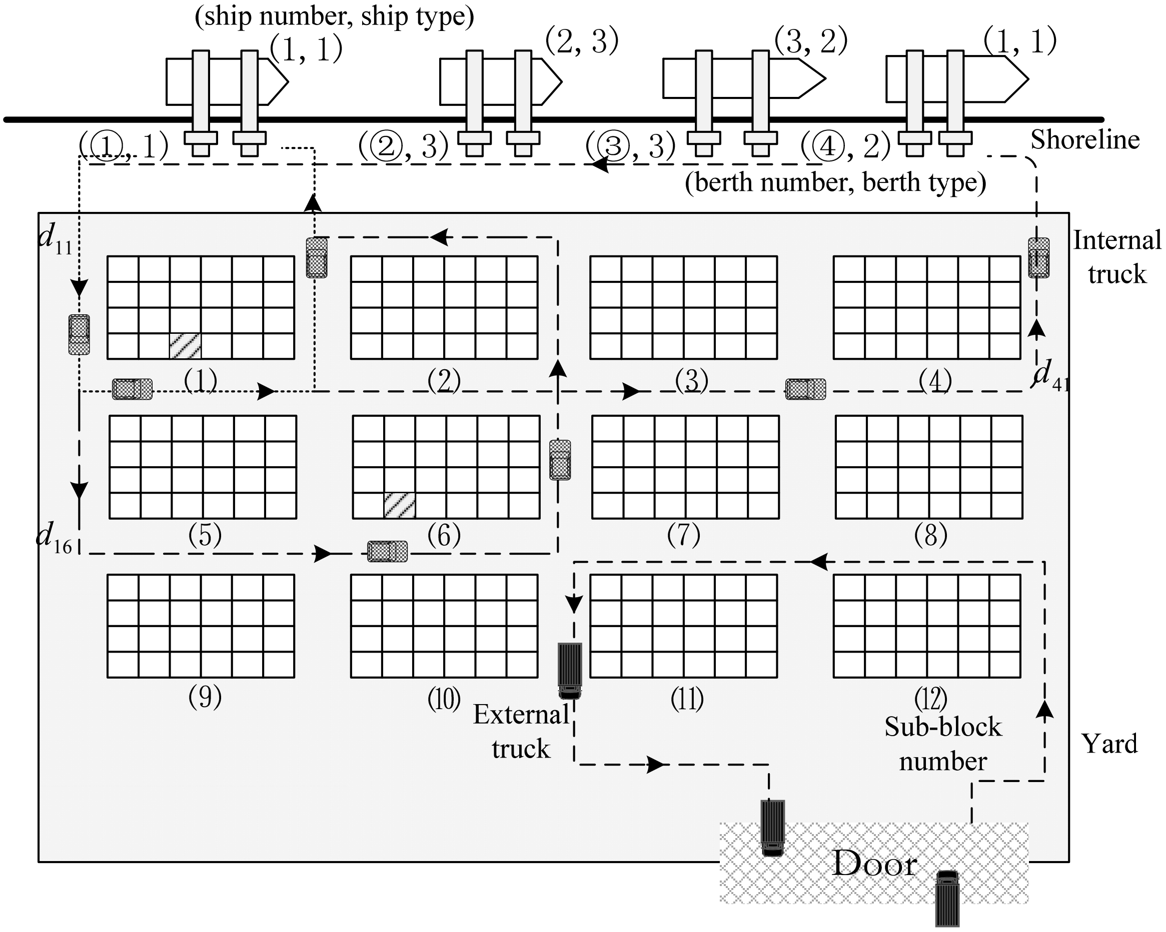


Fig. 2 Loading process diagram for export containers.

Unreasonable berth allocation planning may make the ship berthing position unreasonable, which leads to the increase of truck travel distance and further results in the waiting of quay cranes and yard cranes. And vice versa.

Therefore, berth allocation and yard storage are the key factors affecting the truck travel distance. In order to shorten the truck travel distance and improve the terminal operation efficiency, this paper studies the collaborative optimization problem of berth allocation and yard storage under discrete berths. Define the type of berth is b_j including small berth, middle berth and big berth, which are represented by 1, 2 and 3. Define the type of ship is g_i including small ship, middle ship and big ship, which are represented by 1, 2 and 3. Define the rule of berth allocation is First Come First Served. Besides, the small ship can served by the small, middle and big berth, the middle ship can served by the middle and big berth, and the big ship only can served by big berth. In addition, the limitations, such as the number of berths and sub-blocks, the choice of berths, and stacking locations and quantities of export containers, not only affect the truck travel distance of this ship in the loading process, but also affect the truck travel distance of other ships in the planning period.

As a result, considering the interaction of berth allocation and yard storage among the ships during the planning period, the mixed integer programming model is established aiming at minimizing the total truck travel distance in the loading process. And the hybrid tabu genetic algorithm is designed to solve the problem and obtain the optimal berth number, sub-block number and the number of export containers stacked in the sub-blocks.

4. Mathematical Model

4.1 Model Assumptions

To describe the problem and establish the model conveniently, this paper presents the assumptions as shown as below.

(1) The ship arrival information during the planning period is known, that is, the ship arrival time, ship departure time and the export containers loaded on the ships are known.

(2) The initial stacking status of the terminal yard is known.

(3) The export containers loaded on different ships cannot stack in the same yard sub-block.

(4) The congestion of trucks during the travel process is ignored.

4.2 Model Symbols and Decision Variables

Notations:

T: the planning period

i : the number of ships

V : the set of ship numbers, $i, i' \in V$

B : the set of berth numbers

j : the number of berths, $j \in B$

g_i : the type of ship i , $g_i \in \{1,2,3\}$

b_j : the type of berth j , $b_j \in \{1,2,3\}$

K : the set of yard sub-blocks

k : the number of yard sub-block， $k \in K$

d_{jk} : the distance between berth j and sub-block k

n_i : the number of export containers loaded on ship i

q_i : the maximum number of sub-blocks allowed to serve ship i

Q_k : the total number of export containers stacked in sub-block k

a_i : the arrival time of ship i

l_i : the departure time of ship i

M : a sufficiently large positive number

Dependent variables:

$\delta_{ii'}$: equals to 1 if the type of ship i' is bigger than the type of ship i , and 0 otherwise.

$\xi_{ii'}$: equals to 1 if the departure time of ship i' is latter than the ship i , and 0 otherwise.

Decision variables:

x_{ij} : equals to 1 if ship i determines to berthing the berth j , and 0 otherwise.

y_{ik} : equals to 1 if the container loaded on the ship i is stacked in the sub-block k , and 0 otherwise.

z_{ik} : the number of containers loaded on the ship i to stack in the sub-block k.

4.3 Model Establishment

In this section, we establish the model to collaborative optimize the berth allocation planning and yard storage planning. The objective function of the model aims to minimize the truck travel distance considering the ship berthing position, export containers stacking position and stacking numbers.

$$\min S = \sum_i \sum_j \sum_k d_{jk} \cdot x_{ij} \cdot y_{ik} \cdot z_{ik} \tag{1}$$

$$\sum_k z_{ik} = n_i \quad \forall i \in V \tag{2}$$

$$\sum_j x_{ij} = 1 \quad \forall i \in V \tag{3}$$

$$\sum_i y_{ik} = 1 \quad \forall k \in K \tag{4}$$

$$\sum_k y_{ik} \le q_i \quad \forall i \in V \tag{5}$$

$$\sum_i z_{ik} \le Q_k \quad \forall i \in V \tag{6}$$

$$g_i \cdot x_{ij} \le b_j \quad \forall i \in V \quad \forall j \in B \tag{7}$$

$$(x_{ij} + x_{i'j}) \cdot (g_{i'} - g_i) \cdot \delta_{ii'} \le (g_{i'} - g_i) \cdot \delta_{ii'}$$

$$\forall i, i' \in V \quad \forall j \in B \tag{8}$$

$$(x_{ij} + x_{i'j}) \cdot (g_{i'} - g_i) \cdot (1 - \delta_{ii'}) \cdot (a_{i'} - l_i) \cdot (1 - \xi_{ii'})$$
$$\le (g_{i'} - g_i) \cdot (1 - \delta_{ii'}) \cdot (a_{i'} - l_i) \cdot (1 - \xi_{ii'})$$

$$\forall i, i' \in V \ \forall j \in B \tag{9}$$

$$(g_{i'} - g_i) \cdot \delta_{ii'} \cdot M \geq g_{i'} - g_i \quad \forall i, i' \in V \quad (10)$$

$$(a_{i'} - l_i) \cdot \xi_{ii'} \cdot M \geq a_{i'} - l_i \quad \forall i, i' \in V \quad (11)$$

$$z_{ik} \geq y_{ik} \quad \forall i \in V \quad \forall k \in K \quad (12)$$

$$z_{ik} \leq M \cdot y_{ik} \quad \forall i \in V \quad \forall k \in K \quad (13)$$

$$\delta_{ii'} \in \{0,1\} \quad \forall i, i' \in V \quad (14)$$

$$\xi_{ii'} \in \{0,1\} \quad \forall i, i' \in V \quad (15)$$

$$x_{ij} \in \{0,1\} \quad \forall i \in V \quad \forall j \in B \quad (16)$$

$$y_{ik} \in \{0,1\} \quad \forall i \in V \quad \forall k \in K \quad (17)$$

$$z_{ik} \geq 0 \quad \forall i \in V \quad \forall k \in K \quad (18)$$

Notes: Eq. (1) shows the objective function for minimizing the total truck travel distance. Eq. (2) represents all export containers during the planning period finish loading operation. Eq. (3) expresses each ship only can dock in each berth. Eq. (4) expresses each yard sub-block only can serve each ship. Constraint (5) indicates the number of sub-blocks assigned to a ship cannot exceed the permitted number. Constraint (6) requires the number of export containers stacked in the sub-block shall not exceed the total number of containers allowed to be stacked in the sub-block. Constraint (7) requires each type of ships cannot dock in a berth which the berth type is smaller than that of the ship type. Constraint (8) represents that when the type of latter ship is larger than the type of former ship, it is not allowed for the two ships to dock in the same berth. Constraint (9) represents that when the type of latter ship is smaller than the type of former ship and the arrival time of latter ship is before than the departure time of former ship, it is not allowed for the two ships to dock in the same berth. Constraints (10) to (13) express the relationships among the variables. Constraints (14) to (17) show that the variables are binary-variables. Constraint (18) denotes that the decision variable is a non-negative integer.

5. Hybrid Tabu Genetic Algorithm

5.1 Algorithm Theory

From above analysis about the collaborative optimization problem of berth allocation and yard storage, we can demonstrate the complexity of the problem in theory. If the number of ships is I and the number of berths is J, the complexity of berth allocation planning is $I \times J$. If the number of export containers is N and the number of yard sub-blocks is K, the complexity of yard storage planning is $N \times K$. Hence, considering the interaction between berth and yard operation, the complexity of berth and yard collaborative optimization problem becomes $I \times J \times N \times K$, which is closely related to the number of ships, berths, export containers and sub-blocks. Meanwhile, as the number increases, the complexity accumulation increases and reaches tens or even hundreds of millions, which greatly increases the complexity of the problem and the solving difficulty.

Therefore, the hybrid tabu genetic algorithm is designed considering the coordination optimization feature. During the solving process, berth allocation planning and yard storage planning are changed simultaneously. The export containers loaded on each ship are evenly distributed in the selected sub-blocks, which is designed as the initial solution. Then, the crossover and mutation operation are applied to generate a new feasible solution. Finally, the tabu search table is proposed to choose feasible solution and get the optimal solution, which is the berth allocation planning, the number and position of sub-blocks for export containers storage planning, and the number of export containers for each sub-block.

5.2 Algorithm Design

According to the actual problem characteristics and the algorithm principle, the hybrid tabu genetic algorithm is designed to solve the collaborative optimization problem of berth allocation and yard storage. The algorithm flow chart is shown in Fig. 3.

5.2.1 Basic Data

According to the mathematical model, this paper sets the basic data. The planning period is T. The number of ships is i, and the set of ship numbers is V. The number of berths is j, and the set of berth numbers is B. The type of ship i is g_i, and the type of berth j is b_j. The number of yard sub-block is k, and the set of yard sub-blocks is K. The distance between berth j and sub-block k is d_{jk}. The number of export containers loaded on ship i is n_i. The maximum number of sub-blocks allowed to serve ship i is q_i. The total number of export containers stacked on sub-block is Q_k. The arrival time and departure time of ship i are a_i and l_i.

5.2.2 Initial Population

This paper set the size of initial population as np. Individuals are coded in real numbers. Each gene in the chromosome has the same significance. The genetic elements include the ship number, the berth number, the selected sub-block number of the export containers to be loaded on the ship, the number of export containers to be stacked in the sub-block, and the distance from the berth to the sub-block, as shown in Fig. 4. The chromosome is composed of several such

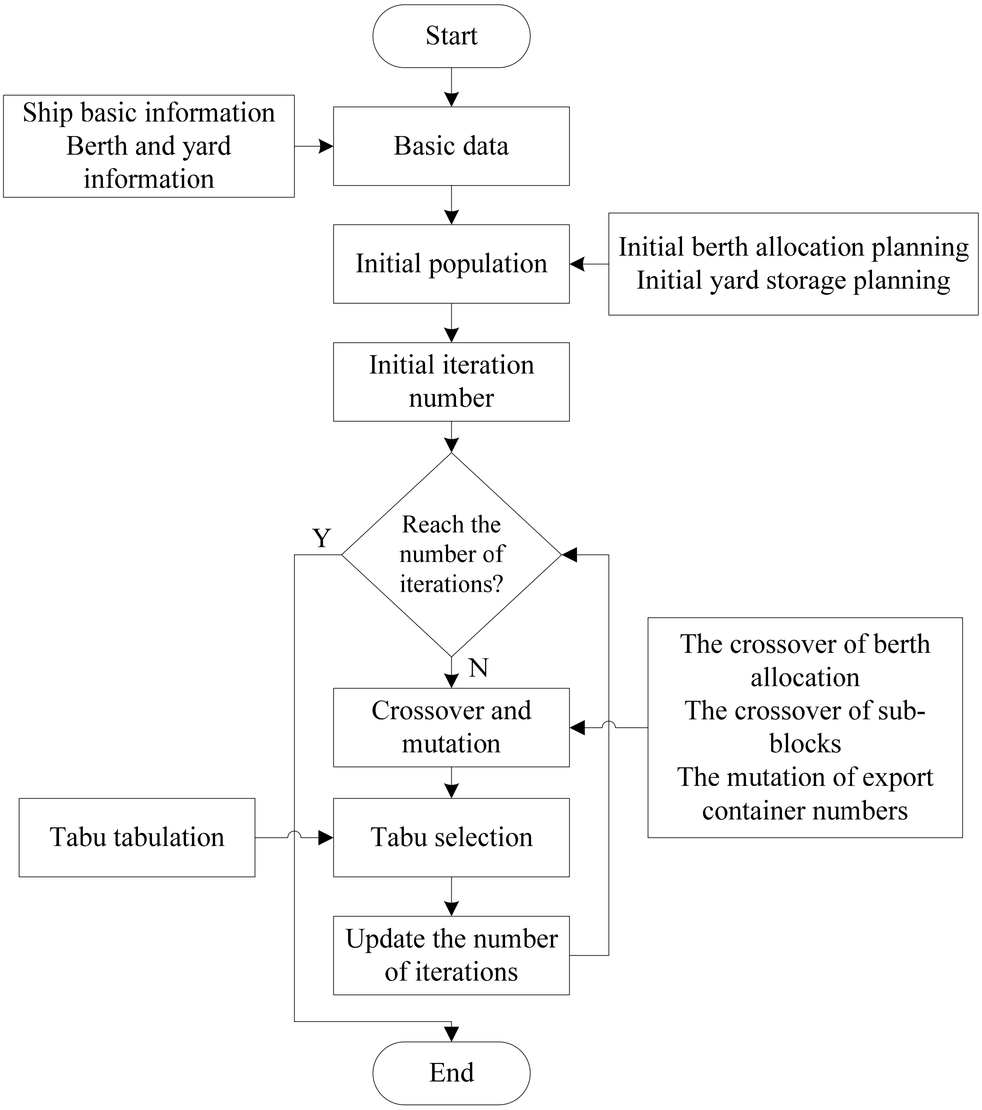


Fig. 3 Algorithm flow.

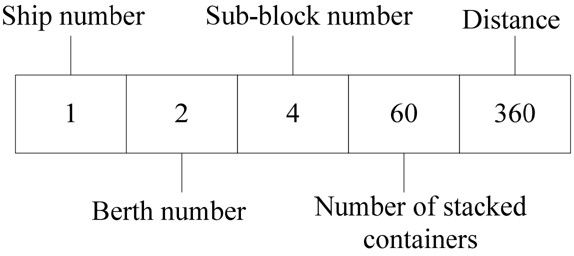


Fig. 4 Gene element.

genes. The gene shown in Fig. 4 indicates that ship 1 docks in the berth 2, the export containers to be loaded on the ship 1 are stacked in the sub-block 4, the number of export containers to be stacked in the sub-block 4 is 60, and the distance between berth 2 and sub-block 4 is 360 m.

The formation of initial population mainly includes berth allocation planning and yard storage planning, which mainly determine the berth number, the sub-block number, and the number of export containers stacked in the sub-blocks. Therefore, the algorithm generates initial berth allocation planning and yard storage planning based on certain rules.

(1) Individual initial berth allocation planning

Step 1: According to the rule of First Come First Served, for a ship numbered i as 1, a valid berth set is formed considering the type of ship and berth, which is defined $AvailableB$. A berth number j is randomly generated in the berth set $AvailableB$, which is to serve the ship 1.

Step 2: For a ship numbered i as 2, according to the type of ship and berth, a valid berth set $AvailableB2$ is determined. Then, we judge whether the berth number j mentioned above exists in this set. If it does not exist, the valid berth set for the ship 2 is $AvailableB2$. If it exists, the arrival time a_2 of the ship is compared with the departure time l_1 of above ship. If $a_2 \geq l_1$, the valid berth set for the ship 2 is $AvailableB2$. Otherwise, the set of berths that the ship 2 can choose to locate is $AvailableB2 \setminus j$. And the berthing position for ship 2 is generated according to Step 1.

Step 3: By analogy, Step 2 is repeated until all ships in the ship set V determine the corresponding berthing position. And the individual initial berth allocation planning is generated.

(2) Individual initial yard storage planning

Step 1: Determine the number of export containers in each sub-block. Considering the maximum number of sub-blocks allowed to serve each ship, as shown as q_i, the export containers n_i shall be distributed to the sub-blocks q_i under the principle of uniform distribution. For the front $q_i - 1$ sub-blocks, the number of export containers stacked is $\lfloor n_i / q_i \rfloor$. For the q_i sub-block, the number of export containers stacked is $n_i - (q_i - 1) \cdot \lfloor n_i / q_i \rfloor$.

Step 2: Determine the sub-block serial number of export containers stacked. In accordance with the principle of First Come First Served, considering the ship serial number i and corresponding berth number j, the smallest sub-block k in the distance matrix d_{jk} is selected as the first sub-block for ship 1. Judge whether the number of containers permitted stacked in the sub-block k is greater than the number of uniformly distributed export containers mentioned above. If it is greater than that, the quantity of stacked export containers shall remain the same. Otherwise, the quantity of stacked export containers in the sub-block k becomes the permitted stacked amount, and adds the excess containers to the next selected sub-block. Similarly, if the last selected sub-block is still not stored, the nearest sub-block that can be permitted stacked is chosen as the last sub-block.

Step 3: Repeat steps 1 and 2 until all ships have completed the yard storage planning for the export containers.

According to the above individual initial generation rules, to some extent, the selection from the sub-block with shorter distance has realized the local optimum, and improves the quality of the feasible solution, which is conducive to reducing the complexity of the optimization process. Repeat it np times, and the initial population P is generated with the size np.

5.2.3 Crossover and Mutation

In order to avoid the generation of unfeasible solutions and realize the coordinated optimization of berth and yard, the crossover and mutation are designed simultaneously for the individuals in initial population. Among them, the crossover is mainly aimed at the berths where the ship docks and the sub-blocks where the export containers are stacked. The mutation is mainly aimed at the number of export containers in each sub-block. The specific process is as follows:

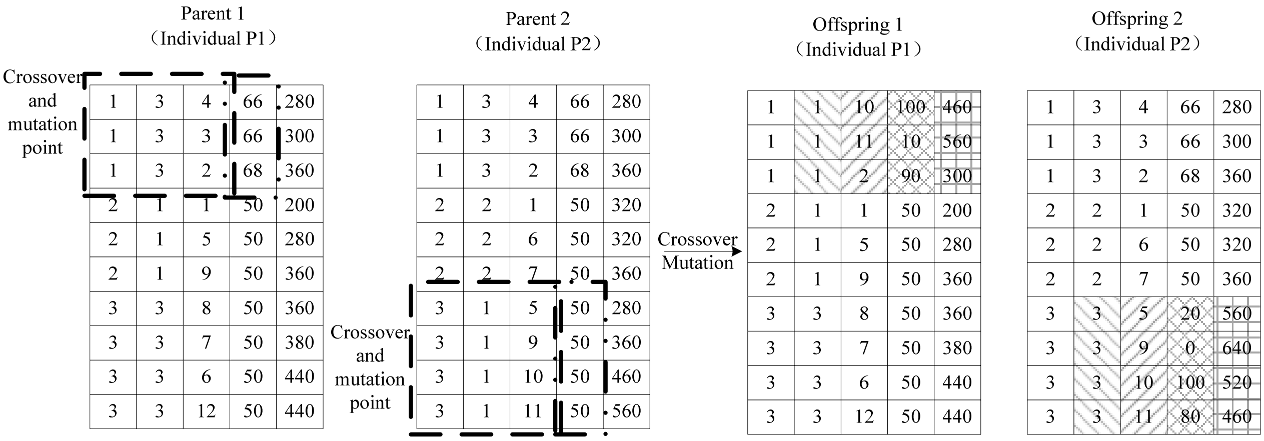
Step 1: Two individuals, $P1$ and $P2$, are selected randomly from the initial population P, which are designed as parents.

Step 2: The selection of crossover and mutation point. Two ships, v_1 and v_2, are selected randomly from the $P1$ and $P2$. And take the rows with two ships as the crossover and mutation point, as shown in Fig. 5.

Step 3: Crossover. According to the selected crossover and mutation point, the parents are cross-operated. Combined with practical problems, the crossover in this algorithm is divided into the crossover of berth and the crossover of sub-blocks.

The crossover of berth: First, change the ships with crossover and mutation point. Then, judge whether the ship after crossing can dock in this berth considering the type of ship and berth. If unfeasible, the changed berth allocation planning should be abandoned. If feasible, the arrival and departure time of all ships should be considered to judge whether the stay time of ships docked in the same berth has coincident time. Further, judge whether the changed berth allocation planning is feasible. If feasible, the new berth allocation planning is generated, otherwise abandoned.

The crossover of sub-blocks: First, record the sub-blocks selected by the ship with the crossover and mutation point of one parent. Then, record the sub-blocks selected by the ship other than the crossover and mutation point of the other parent. Finally, compare these sub-blocks. The different sub-blocks are exchanged in order and the same sub-blocks are retained. As shown in Fig. 4, the sub-blocks selected by the ship with the crossover and mutation point of parent 2 are 5, 9, 10 and 11. Those selected by the ship other than the crossover and mutation point of parent 1 are 1, 5, 9, 8, 7, 6 and 12. The different sub-blocks are 10 and 11. Thus, the



Parent 1 (Individual P1)

1	3	4	66	280
1	3	3	66	300
1	3	2	68	360
2	1	1	50	200
2	1	5	50	280
2	1	9	50	360
3	3	8	50	360
3	3	7	50	380
3	3	6	50	440
3	3	12	50	440

Parent 2 (Individual P2)

1	3	4	66	280
1	3	3	66	300
1	3	2	68	360
2	2	1	50	320
2	2	6	50	320
2	2	7	50	360
3	1	5	50	280
3	1	9	50	360
3	1	10	50	460
3	1	11	50	560

Offspring 1 (Individual P1)

1	1	10	100	460
1	1	11	10	560
1	1	2	90	300
2	1	1	50	200
2	1	5	50	280
2	1	9	50	360
3	3	8	50	360
3	3	7	50	380
3	3	6	50	440
3	3	12	50	440

Offspring 2 (Individual P2)

1	3	4	66	280
1	3	3	66	300
1	3	2	68	360
2	2	1	50	320
2	2	6	50	320
2	2	7	50	360
3	3	5	20	560
3	3	9	0	640
3	3	10	100	520
3	3	11	80	460

Fig. 5 Crossover and mutation.

sub-blocks 4 and 3 of parent 1 are change into 10 and 11. And sub-block 2 remains the same. Parent 2 is the same. Meanwhile, the distance from the berth to sub-block is updated.

Step 4: Mutation. After the crossover of parents, the mutation aims at the number of export containers stacked in the sub-blocks at the crossover and mutation point. Considering the distance from the berth to the sub-block, the permitted maximum number of export containers in each sub-block is stacked from the shortest distance of sub-block. And so on until all the export containers are finished.

Property 1:

The ship i docks in the berth j. The sub-block set of export containers to be loaded on ship i is $\Omega = \{k_1, k_2, \cdots, k_q\}$. The distance from the berth to the sub-block is $\{d_{jk_1}, d_{jk_2}, \cdots, d_{jk_q}\}$. The number of containers stacked in the sub-blocks to be loaded on ship i is $\{z_{k_1}, z_{k_2}, \cdots, z_{k_q}\}$. If $d_{jk_1} < d_{jk_2} < \cdots < d_{jk_q}$, when $z_{k_1} \geq z_{k_2} \geq \cdots \geq z_{k_q}$, $z_{k_1} \cdot d_{jk_1} + z_{k_2} \cdot d_{jk_2} + \cdots + z_{k_q} \cdot d_{jk_q}$ is minimized. In other words, if the sub-block with the shortest distance has the largest number of export containers, the truck travel distance is shortest.

5.2.4 Tabu Selection

In order to keep the superior population and eliminate the inferior solution, the algorithm uses tabu arrangement selection to seek the optimal solution, so as to avoid falling into the local optimal solution

Step 1: Calculate the truck travel distance of all individuals in the initial population, and arrange them in order from large to small, and put them in the tabu table, as shown in Fig. 6. The distance from left to right is getting shorter and shorter.

Step 2: After the crossover and mutation operation, new individuals are generated. Calculate the truck travel distance of new individuals. If the distance of new individuals is smaller than the distance of the initial population, the individuals in the initial population are replaced by the new individuals and the tabu selection list is rearranged. Otherwise the initial population and tabu selection list remain the same.

Step 3: Update the initial population. Record the shortest truck travel distance in the tabu selection list, and obtain the corresponding berth number, sub-block number and the number of export containers stacked in each sub-block.

5.2.5 The Number of Iterations

Set the maximum number of iterations. And the initial population is convergent in the iterative process. The optimal solution that converges is recorded as the solution of the algorithm. Further, record the shortest truck travel distance and the corresponding berth number, sub-block number and the number of export containers stacked in each sub-block

6. Numerical Experiments

In order to further verify the effectiveness of the algorithm, this paper randomly generates numerical examples with different scales and discusses two different scenes: the same berth scene and the same ship scene. Further, the results of the experiments are obtained using a computer with 8 gigabytes of RAM, Windows 7 Professional operating system and an Intel Xeon CPU with 2.8 gigahertz cores. Through the comparisons of experiments, we verify the universality of algorithm and obtain the corresponding conclusions.

Scene 1: The same berth scene

When the types and numbers of berth are the same in different examples, we compare the influence of different ship number and type on the truck travel

1	2	3	4	5	6	……	np-2	np-1	np

Fig. 6 Tabu selection list.

distance. As shown in Table 1, when the number of berth is 4, the berth 1 is the small berth, the berth 2 and 3 are the middle berth, and the berth 4 is the big berth. Meanwhile, when the number of berth is 5, the berth 1 is the small berth, the berth 2 and 3 are the middle berth, and the berth 4 and 5 are the big berth. The numerical examples results are shown in Table 1.

From the Table 1 and Fig. 7, we can obtain the conclusions:

(1) From the Table 1, we can know that the computation time is very short. It means that we can obtain the optimal solution quickly, which implies that the model is valid and the algorithm is reasonable.

(2) From the Fig. 7, it is known that when the number of berth is the same, the more the number of ship is, the greater the truck travel distance. Because the export containers loaded on the different ships must stack in different sub-blocks. When the number of ships becomes more and more, there are fewer valid sub-blocks with shortest distance to choose. Therefore, the total truck travel distance becomes greater.

Table 1 Numerical examples results in Scene 1.

J	I	i	g_i	N	j_i	k	Q_k	S/m	t/s
4	4	1	1	180	1	1/5	100/80	454,600	4.88
		2	2	300	4	4/3/8.2	100/100/90/10		
		3	2	320	2	6/7/10/11	100/80/100/40		
		4	3	400	4	12/16/15/9/14	110/90/100/90/10		
4	5	1	1	140	3	4/3	100/40	463,500	5.74
		2	1	140	1	1/5	100/40		
		3	2	240	2	2/6/7	90/100/50		
		4	2	280	2	10/8/11	100/90/90		
		5	3	400	4	12/16/15/9	110/110/100/80		
4	6	1	1	150	2	2/3	90/60	474,800	5.96
		2	1	150	1	1/5	100/50		
		3	2	160	4	4/8	100/60		
		4	2	160	2	6/7	100/60		
		5	3	280	4	12/11/16	110/110/60		
		6	3	300	4	15/9/14	110/110/90		
5	4	1	1	180	2	2/3	90/90	442,800	5.17
		2	2	300	4	4/8/7	100/110/90		
		3	2	320	2	1/6/5/10	100/100/110/10		
		4	3	400	4	12/11/16/15	110/110/110/70		
5	5	1	1	140	1	1/5	100/40	453,600	3.93
		2	1	140	4	4/3	100/40		
		3	2	240	2	2/7/8	110/90/40		
		4	2	280	2	6/10/11	100/100/80		
		5	3	400	4	12/16/15/9	110/110/100/80		
5	6	1	1	150	1	1/5	100/50	469,000	5.31
		2	1	150	3	4/3	100/50		
		3	2	160	2	2/6	90/70		
		4	2	160	2	7/10	100/60		
		5	3	280	4	8/12/11	110/110/60		
		6	3	300	4	15/9/14	110/110/90		

Notes. J represents the number of berth, I represents the number of ship, i represents the ship serial number, g_i represents the type of ship i, N represents the number of export containers, j_i represents the located berth of ship i, k represents the sub-block number of export container stacked. Q_k represents the number of export containers stacked in the sub-block k. S represents the total truck travel distance, t represents the computation time.

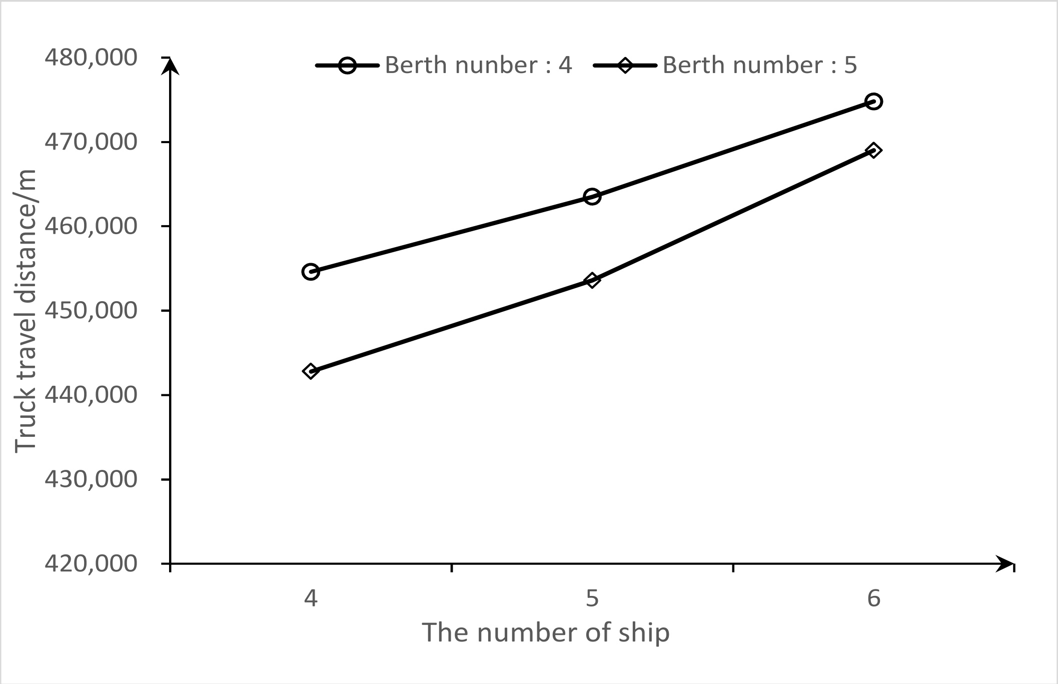


Fig. 7 The truck travel distance with different ship numbers in Scene 1.

Scene 2: The same ship scene

When the types and numbers of ship are the same in different examples, we compare the influence of different berth number and type on the truck travel distance. As shown in Table 2, when the number of ship is 5, the ship 1 and 2 are the small ship, the ship 3 and 4 are the middle ship, and the ship 5 is the big ship. Meanwhile, when the number of ship is 6, the ship 1 and 2 are the small ship, the ship 3 and 4 are the middle ship, and the ship 5 and 6 are the big ship. The numerical examples results are shown in Table 2.

From the Table 2 and Fig. 8, we can obtain the conclusions:

(1) From the Table 2, we can know that the computation time is very short. It means that we can obtain the optimal solution quickly, which implies that the model is valid and the algorithm is reasonable.

(2) From Fig. 8, it shows when the number of ship is the same, the more the number of berth is, the shorter the truck travel distance. Because the number of export container and the ship are the same, if the selected berth is more, the ship can select the berth with the shorter distance from berth to sub-block.

From Scene 1 and Scene 2, we can see that the number of berth and ship has important influence on the truck travel distance. As a result, the collaborative optimization of berth allocation and yard storage is necessary.

7. Conclusions

Based on the interaction of the berth and the yard, this paper studies the collaborative optimization problem of berth allocation and yard storage. Besides, the mixed integer programming is established to minimize the truck travel distance, and the hybrid tabu genetic algorithm is designed to obtain the optimal ship berthing position, yard stacking position and stacking numbers of containers. Further, numerical examples are proposed to compare the same berth scene and the same ship scene. Results show that the model is valid and the algorithm is reasonable. What's more, with the increase of the ship number and the decrease of the berth number, the truck travel distance becomes greater, which provides the decision support for terminal operators.

Table 2 Numerical examples results in Scene 2.

I	J	j	b_j	i	N	j_i	k	Q_k	S/m	t/s
5	3	1	1	1	140	3	4/3	100/40	468,700	5.21
		2	2	2	140	1	1/5	100/40		
		3	3	3	240	2	2/6/7	90/100/50		
		-	-	4	280	2	10/8/11	100/90/90		
		-	-	5	400	3	12/16/15/14	110/110/100/80		
5	4	1	1	1	140	3	4/3	100/40	463,500	5.74
		2	2	2	140	1	1/5	100/40		
		3	2	3	240	2	2/6/7	90/100/50		
		4	3	4	280	2	10/8/11	100/90/90		
		-	-	5	400	4	12/16/15/9	110/110/100/80		
5	5	1	1	1	140	1	1/5	100/40	453,600	3.93
		2	2	2	140	4	4/3	100/40		
		3	2	3	240	2	2/7/8	110/90/40		
		4	3	4	280	2	6/10/11	100/100/80		
		5	3	5	400	4	12/16/15/9	110/110/100/80		
6	3	1	1	1	150	3	4/3	100/50	487,800	5.82
		2	2	2	150	1	1/5	100/50		
		3	3	3	160	2	2/6	90/70		
		-	-	4	160	3	8/7	110/50		
		-	-	5	280	3	12/11/10	110/110/60		
		-	-	6	300	3	15/14/9	100/100/100		
6	4	1	1	1	150	2	2/3	90/60	474,800	5.96
		2	2	2	150	1	1/5	100/50		
		3	2	3	160	4	4/8	100/60		
		4	3	4	160	2	6/7	100/60		
		-	-	5	280	4	12/11/16	110/110/60		
		-	-	6	300	4	15/9/14	110/110/90		
6	5	1	1	1	150	1	1/5	100/50	469,000	5.31
		2	2	2	150	3	4/3	100/50		
		3	2	3	160	2	2/6	90/70		
		4	3	4	160	2	7/10	100/60		
		5	3	5	280	4	8/12/11	110/110/60		
		-	-	6	300	4	15/9/14	110/110/90		

Notes. I represents the number of ship, J represents the number of berth, j represents the berth serial number, b_j represents the type of berth j, i represents the ship serial number, N represents the number of export containers, j_i represents the located berth of ship i, k represents the sub-block number of export container stacked, Q_k represents the number of export containers stacked in the sub-block k, S represents the total truck travel distance, t represents the computation time.

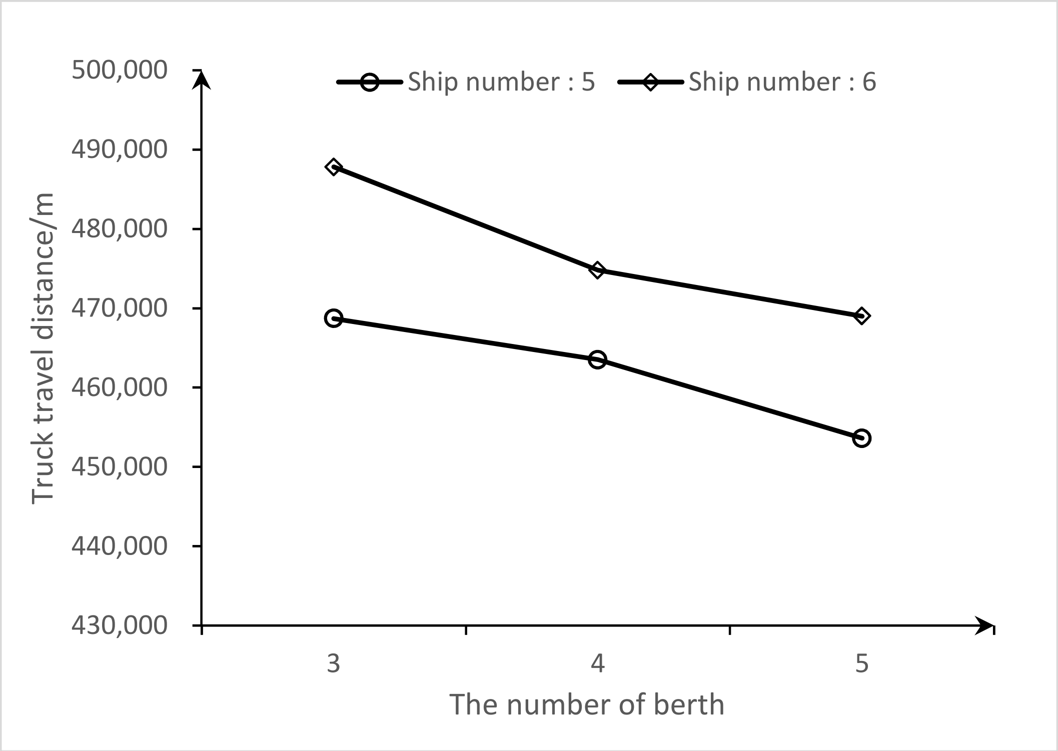


Fig. 8 The truck travel distance with different berth numbers in Scene 2.

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