Using path optimum algorithm to solve slot selection problems for outbound containers of different attributes in container terminals

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Abstract

The outbound container slot selection problem (OCSSP) is a hot topic in the field of port research and of great significance to improving the operational efficiency of container yards. With the initial stacking state and extractive sequence of containers being known, the goal is to accomplish the task of extracting all containers in the container block with a minimum number of container relocations. OCSSP is an NP-hard problem. To obtain more practical research results, this paper proposes an improvement to the existing model and presents an improved version of the path optimum algorithm that considers container attributes. With the objective of improving the overall operational efficiency of container terminal yards, this study analyzed some practical issues related to container extraction by taking into consideration the influences of extraction priority levels, movements of obstruct containers, the Manhattan distances of gantry crane, and other factors on the model. Finally, the paper distills some scheduling strategies applicable to OCSSP in the hope of providing a theoretical basis and practical guidance to container port operators for the better allocation and optimization of coastal container ports resources.

Keywords Extraction priority levels · The number of relocations · Manhattan distances of gantry cranes · Path optimum algorithm

1 Introduction

The emergence of the container, a box that would change the world, in the 1950s brought a sea of change to the economics of the shipping industry and ushered the industry into an era of fast development. As the shipping industry is closely related to economic development, global trade flows have also changed as a result. Hence, the rise and fall of container ports clearly reflect the patterns of worldwide industry transfers. Over the past 40 years, China's economy and international trade have been growing rapidly thanks to economic reforms and liberalization while a cluster of coastal container ports has emerged and developed as a result. As of 2017, China boasts seven of the world's top ten biggest container ports with a container throughput of more than 160 million TEUs (accounting for 70.02% of

the world's total),¹ demonstrating that China's container ports have strengthened their position in the container ports worldwide industry during a time of weak global economic recovery.

While the rapid development of the container port industry promotes international trade, the industry is plagued by a host of problems, such as homogenization and structural excess. Taking the Pearl River Delta region as an example, the theoretical throughput of the container ports, which have a total capacity of more than 50,000 tons,² has exceeded the total demand for container service in Guangdong Province. For several reasons, most

¹ Data source: <https://largest.org/structures/ports/>.

² Data source: <http://en.pkulaw.cn/display.aspx?cgid=112309&lib=law>.

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container terminal yards in the Pearl River Delta are small. Under the pressure of slowing down imports and exports, the port operators are offering much longer free storage periods than before as a measure for increasing competitiveness. Thus, the problem of slot selection is becoming an increasingly important issue for the ports.

OCSSP is the focus of attention for container port operators. However, the problem is difficult to solve because of the problem's NP-hard nature. As a result, high-level slot selection has not yet been attained in most container ports. In view of this situation and centering on the problem of outbound container relocation rates, the authors explored the problem of modeling and optimizing the container extraction process in gantry crane yards on the basis of a survey of a group of container ports in the Pearl River Delta Region. This study made use of the multi-bay container extraction model developed in a previous study conducted by members of the same research team [20–23]. The construction of the model helped to form a systematic understanding of OCSSP. However, the model is based on stringent assumptions (e.g. all containers have the same attributes), which is far divorced from the complex operations of a container yard.

To better suit the practical needs of container slot selection in port yard management, the authors have improved the existing model regarding several attribute dimensions of containers and the influences of extraction priority levels, container relocations within a block, the Manhattan distances of gantry crane movements, and other factors on the model. As an extension to the existing model, the improved model has inherited the basic concepts, definitions, and descriptions but has a much higher algorithmic complexity. The goal of the improved model is to provide a scientific basis on which port operators can conduct effective scheduling and further improve the overall operational efficiency of their container port yards.

In the container retrieval operation model with considering containers' different attributes, the research content further changes from considering different flow directions to different attributes, the research scope ranges from single attribute to multi-attributes. The factors taken into account are more comprehensive and closer to the container terminal operation scene, but it makes the study more difficult. Hence, it is necessary to judge the importance of different attributes, and make better combination of attributes of different flows, so as to make the theoretical research more applicable to management practice.

1.1 Literature review

Scholars have focused their attention on selecting the right relocation strategies and optimizing container extraction. The number of relocations can be reduced by

combining the optimal relocation strategy and extraction process with different algorithms.

About the selection of relocation strategy, Kim and Park [12] conducted an in-depth analysis of the export container slot selection problem in a container terminal yard by dividing the entire planned time period into multiple stages and constructing a mixed integer linear planning model, then suggested solving the model by a method based on the minimum duration principle and the sub-gradient heuristic algorithm. Kim and Lee [11] proposed a container extraction optimization model for selecting slots for export containers according to the operational efficiency of the container trucks and gantry cranes, as well as designed a corresponding solution to the model in compliance with a multitude of constraints. Zhou and Li [25] considered the optimization of selecting the relocation positions in the pick-up process of inbound container and built a simulation model based on Petri net. Considering the path planning problem of gantry cranes, the simultaneous operation of multiple gantry cranes to improve loading efficiency was analyzed in depth [3]. An optimization model of gantry crane path network was constructed and a two-stage dynamic programming algorithm based on greedy algorithm was adopted to solve the pick-up problems.

About the selection of the container locations, a heuristic algorithm H and an improved algorithm IH were designed for the problem of container location selection [18]. The numerical results showed that H and IH were better than branch and bound algorithm (B&B). Park et al. [14] believed that choosing the right stacking position for the import containers would not only affect the productivity of stacking but also subsequent container extraction, which is one of the most important jobs of a container terminal. Simulation experiments have proven that the proposed algorithm could effectively improve the operational efficiency of a container yard. Aiming at the multi-stage characteristic features of outbound containers relocation problems, Jin et al. [8] assumed that the specific stacking positions and the pick-up sequences of containers in the container yards were known and transformed this problem into dynamic shortest path problem. A parallel processing calculation method was used to solve this kind of problem, and heuristic rules were used to reduce the solution space of dynamic programming, which became the highlights.

About the optimization of the extraction process, Kim and Bae [9] divided the extraction problem into three small problems to be solved separately and applied dynamic planning technique and traffic technology to reorganize the mixed container stacks in each bay of a container port with the optimization goal of minimizing the ship's port time. To reduce the number of container relocations, Yang and Kim [19] applied the proposed method to container

extraction scenarios from the perspective of stacking containers in groups. Based on this study, Kim and Hong [10] after having studied the export container extraction procedure, proposed a method to improve the efficiency of handling export containers. For a scenario in which the export containers arrive at a terminal yard randomly, they proposed two algorithms, the branch & bound (B&B) and heuristic (OH). Considering the dynamics of containers' extracted operation, Shao et al. [15] started their research under the premise of extracting containers in groups, and generated the arrival time of the external trucks by statistical distribution.

In summary, most scholars considered a container retrieval problem at the container yard. The objective is to minimize relocations when all containers at a yard-bay are retrieved according to a predetermined precedence. In this study, we also consider the same problem proposed by Kim and Hong [10] and Wu and Ting [17], but we use a new heuristic algorithm to solve this problem. Because of the problem's NP-hard attribute, this dissertation puts forward several retrieval rules and builds a rule base according to terminal technology, parallelly using multiple rules to select suitable locations for obstructed containers, which is different from existing studies. The problem of multi-rules used in parallel is solved successfully: the time complexity of the algorithm increases at least one order, and balance the relationship between solving precision and CPU time. The numerical results show that our proposed algorithm is superior to KH, DH, CM, and LA algorithms under the same condition where the bay size of the yard is the same.

1.2 Contributions of this study

This paper enriches the existing research in two ways.

- (1) Because of this problem's NP-hard attribute, this dissertation puts forward several retrieval rules and builds a rule base according to terminal technology, parallelly using multiple rules to select suitable locations for obstructed containers, which is different from existing studies. The problem of multi-rules used in parallel is solved successfully: the time complexity of the algorithm increases at least one order, and balance the relationship between solving precision and CPU time. The numerical results show that our proposed algorithm is superior to KH, DH, CM, and LA algorithms under the same condition where the bay size of the yard is the same.
- (2) The research content has changed from neglected container flow to taking the flow into consideration, and the research scene further improved from being theoretical to actual. The difficulty of the research

is how to put every added attribute into the theoretical model. Based on the theoretical model and in combination with the practical operation situation of container terminals, the dissertation integrates each additional element into the model by setting the priorities, changing the initial storage states and refining containers' retrieval rules. The comparison between the results of the examples including specific information and the random generated examples shows that the relocation number of the model considering container flow is lower than the base model.

Therefore, this paper conducts an in-depth study on the effect of different attributes of the OCSSP, which can be crucial for the development of coastal research worldwide.

2 Materials and methods

2.1 Basic problem descriptions

The storage yard is usually divided into different blocks, bays, stacks, and tiers according to the different attributes of containers. An ordinary block is shown in Fig. 1a. The handling equipment commonly used in the storage yard of a container terminal is the rail-mounted gantry crane (RMGC). The movement of the RMGC includes horizontal and vertical directions. The horizontal movement is completed by the gantry of RMGC, which refers to the operation between different bays. The vertical movement is completed by the trolley of RMGC, which refers to the operation between different stacks in the same bay. The RMGC block is shown in Fig. 1b.

According to the operations plan, each container has a planned extractive date. Based on the date sequence, the container with the highest priority is the first one to leave the storage yard; this container is called the target container. If a container is placed above the target container, resulting in the obstruction; this container is called the obstructive container or reshuffled container.

2.2 Basic notations

Priority Suppose there are S containers in a block and the specific slot of each container has been determined. Combined with the storage state and the extractive sequence of these containers, they are represented by $1, 2, \dots, S$ respectively to form a slot matrix T . Each container corresponds to a unique number, and this number is the priority of the container. No. 1 is the highest priority, which means that this container is the target container in the initial state

Fig. 1 Images of **a** the schematic diagram of a block in a container yard; **b** the schematic diagram of a gantry crane block

and needs to be extracted at first. The container S is given the lowest priority, which will be finally retrieved.

Matrix of slots If a block has M bays, N stacks, and K tiers, a three-dimensional matrix T can be used to represent the storage status of each container. Any element of the matrix T indicates that there is a container in a slot, and the slot is assigned a priority t ($0 \leq t \leq M \times N \times K$), which is denoted by $slot(m, n, k)$, ($m=0, 1, 2, \dots, M; n=0, 1, 2, \dots, N; k=0, 1, 2, \dots, K$). $T(m, n, k) = t > 0$ indicates that the $slot(m, n, k)$ is occupied by a container of extractive sequence t . $T(m, n, k) = 0$ indicates that there is no container in the $slot(m, n, k)$, and it is an empty slot.

2.3 Different flow directions of the containers

The transfer of containers to a dock is an important flow direction of which the most prominent feature is the batching of the containers. The departure of containers from a port gate is another important flow direction, of which the most prominent feature is the containers' leaving singly. Because of the different characteristics of these two flow directions, the characteristics of containers leaving in batches or singly can be reflected in the priority levels of the containers if the departure sequence is used as the key criterion for setting the priority levels.

The details are as follows: (1) Containers in the same batch to be loaded onto a ship have the same priority level regardless of size; (2) Containers to be transferred from a yard to a port gate at different times have different priority levels and their sizes will be taken into consideration.

The priority level is no longer unique now. The priority of the container is given according to the time of extracting and affected by two different flow directions. It should be noted that different extraction plans generate different priority orders. Once the extraction plan is determined, the priority of the container is fixed.

2.4 Different sizes of the containers

It should be noted that there are different sizes of containers: 20 feet, 40 feet, 45 feet, etc. Generally, a 20-foot container occupies one slot and a 40-foot container occupies two slots. If the gantry crane spreaders are frequently switched between 20 feet and 40 feet, they are more likely to be damaged. Therefore, 20-foot and 40-foot containers should be stacked separately and not stacked one on top of each other generally. The RMGC block is shown in Fig. 2.

To avoiding the mixed storage of containers of different sizes, container ports usually have bays in the same container area grouped into sub-blocks. For example, in Foshan Gaoming Container Port, a container area has been partitioned into two smaller areas at a ratio of 3:4 for 40-foot containers and 20-foot containers, respectively. Specifically, when there are 10 bays, 6 bays would be allocated to 3 columns of 40-foot containers while 4 bays would be allocated to 4 columns of 20-foot containers. Since containers of different sizes are not mixed, the setting of the container priority level would not be affected, but there is a certain difference in the setting of the container slot matrix. According to the characteristics

Fig. 2 20-foot and 40-foot containers stacked separately in a gantry crane block

of the container matrix setting, each element no longer corresponds to only one container.

2.5 Multiple factors of containers

Considering that the expected departure time, destination port, customer information, and other factors have different influences on the selection of container slots, the authors decided to incorporate these influences into the priority level of a container. Under normal circumstances, the expected departure time is the most important information for container extractions, followed by the destination port and customer information. Therefore, the priority level is no longer a known value. The order of container extractions is determined by the priority level.

- (1) Time: Since the expected departure time is of the highest importance, the container extraction sequence presented previously in this paper was used to indicate the times of containers leaving a yard during actual operations.
- (2) Destination port and customer information: These two factors have less influence on the extraction operation than does the time factor, but they cannot be ignored. They have the same level of influence. Their priority levels are calculated by weight addition as follows:

$$P_2 = w_1 \bar{T} + w_2 \bar{C} \quad (w_1 + w_2 = 1) \quad (1)$$

where P_2 represents the priority level of both the destination port and customer information, $\bar{T}$ represents the priority level of the destination port, and $\bar{C}$ represents the priority level of the customer information. Due to the difficulty of synchronously and precisely quantifying information such as the type, size and value of containers, they are collectively referred to as customer information.

After considering the expected departure time, destination port, and customer information, Eq. (2) for calculating the multi-bay container priority level P is obtained:

$$P = \tilde{\lambda} \times P_1 + P_2 \quad (2)$$

where P represents the multi-bay container priority level with the container attributes taken into consideration. Container attributes include the expected departure time, the destination port and customer information. P_1 represents the priority level of the expected departure time, P_2 represents the priority level of the destination port and customer information, and $\tilde{\lambda}$ indicates the importance of P_1 relative to P_2 for P . According to the actual operation of the container terminal, $\tilde{\lambda} = 10$. Note that the smaller the P value, the higher is the priority level of the container.

This calculation method suits busy container terminals. Firstly, attaching great importance to the time factor indicates that the terminal conducts container extractions with high efficiency. Secondly, paying attention to the destination port allows the terminal operator to arrange the orders of container loading properly for different shipment routes, for which forward-looking plans for the subsequent container loading operations must be made.

Lastly, paying attention to customer information allows the terminal operators to meet different customer needs so that the terminal can provide diverse services to the customers. In summary, this method pays more attention to timeliness and forward-looking arrangements, which are conducive to improving the quality of service and promoting the long-term development of container terminals.

2.6 Basic frameworks of existing algorithms

The NP-hard nature of the container relocation problem has been confirmed [1, 2, 4–7, 13, 16, 24]. Container extraction operations involve container relocation problems, which are also NP-hard. There is an urgent need to study various problems (including slot selection for blocking containers, selection of relocation paths, selection of optimization targets, and patterns of container departures) arising in container extraction and offer scientifically sound answers. After literature combing and site surveying, the authors designed an optimization algorithm for solving OCSP.

2.6.1 Basic framework of the algorithms in the existing literature

We divide the existing solution algorithms into four categories: design an accurate algorithm to solve the number of relocations on a small scale; enumerate the relocation paths on a small scale; design an intelligent algorithm to solve the number of relocations on a large scale; optimally select the relocation paths on a large scale. According to different scale and different target, the algorithm features are different. The detailed characteristics are shown as follows.

- (1) The first category is to find the exact solution to the number of container relocations in small-scale extractive operations. Kim and Hong [10] mentioned that a yard bay usually contained 4–7 tiers with 6–10 stacks. Wu and Ting [17] generated 48 problem classes, and each of them has 40 instances. Many scholars cited their literature and argued that 4–50 containers are small-scale problems. Scholars usually adopt CPLEX to find the exact solution to the problem. When the number of extractive operations reaches 50, CPLEX is often unable to obtain accurate solutions for large-scale examples within an acceptable computer running time.
- (2) The second category is to solve the optimum path in small-scale extractive operations. Scholars usually traverse all the nodes to find the optimal results without the prompt message in order to obtain the optimal solution of path planning. The solution scale

is generally within 8 stacks and 8 tiers of a single bay. Beyond this scale, it is difficult to find an exact solution within an acceptable time range.

- (3) The third category is to find an optimized solution to the number of container relocations in large-scale extractive operations. Since the problem of storage space selection for outbound containers has the NP-hard attribute, scholars usually establish mathematical programming models and develop heuristic algorithms for solving them. The typical algorithm is an intelligent algorithm. By simulating the natural process, it has a guiding search for the optimal solution, and the constant mutation and iteration are approaches to the optimal solution.
- (4) The fourth category is to solve the optimum path for large-scale extractive operations. Regarding intelligent algorithms, only multi-objective optimal solutions, such as the specific number of relocations and equipment operational time can be obtained. Scholars typically use the prompt message for searching and evolve it into a heuristic search algorithm. Among them, the algorithm considering the container relocation rule is the most commonly used method. In the same experimental scenario, scholars refine the relocation strategy and embed the heuristic algorithm to obtain an optimized relocation path planning solution.

2.6.2 Basic framework of the algorithms in this paper

Based on the research ideas of the existing algorithms, this study focused on solving the problem of optimizing large-scale container extractions and planning container relocation paths. Combining the perspectives of container relocation path searching and solving the mathematical programming model, the authors planned to solve the problem by using nested relocation rules that could provide an optimization strategy and solve the problem with exponential time complexity by using an algorithm with polynomial time complexity. The specific research ideas are as follows:

- (1) The authors designed an optimization algorithm and tested its accuracy and running time by using the existing example library as the test benchmark. Several valuable inspirations for management were obtained by comparing the results of the example calculations incorporating the relevant information with those of randomly generated example calculations.
- (2) The authors employed the strategy of embedding container relocation rules into the design of the algorithm. Several rules were formulated on the basis of

the results of previous research and actual operation scenarios in the terminal yards. Also, a rule base, which is of great practical significance, was built. Most previous studies used only a single rule to simplify the problem. The difficulty of using multiple rules in parallel lies in converting each rule into computer language.

- (3) An experiment is performed to test the effects of using multiple rules in different orders. The obtained optimal sequence of rules will incorporate into the algorithm, thereby reducing redundant paths for container extraction and time complexity of the container extraction operation, and ultimately, improving the efficiency of container handling operations.

In the author's existing research [20–23], a path optimum algorithm (POA) based upon heuristics was proposed to solve optimal solution for any-scale instances in a shorter CPU runtime. Numerical experiments and comparisons with the other algorithms from the literature show the superiority, high efficiency, robustness and accuracy of this algorithm. However, POA cannot be solved the slot selection problems for outbound containers of different attributes. POA must be improved to solve the problem.

This paper makes an in-depth discussion on the basis of the author's existing research and proposes an improved POA for containers with different attributes. The POA is used to obtain the number of movements, relocations, movement paths, relative container relocation rates, Manhattan distances of gantry crane movements, and costs of gantry crane operations under different initial states. Multiple rule use consequences are ranked to obtain the optimal sequence that yields the smallest number of container relocations. The algorithm was improved for different operation scenarios. The basic features of the algorithm are shown in Fig. 3.

2.6.3 Build the rule library

The core part of the algorithm's design is to build a rule base. To this end, the authors combined the research results of previous studies and the data obtained from a field survey of several container ports to distill multiple container relocation rules and build a rule base.

- (1) *Same bay first and neighboring bays second rule (SFNS)* RMGC could work in both horizontal and vertical directions, however, moving vertically takes a much longer time. In order to save operation time, we consider the horizontal movement of the gantry crane first, and then the vertical movement, i.e., This rule preferentially relocates the obstructive container in

the same bay, and the gantry crane moves in a horizontal direction at this moment, so as to save the moving distance of gantry cranes. That is, a block container should be moved to another slot in the same bay if one or more empty slots are available in the same bay. If there are no empty slots in the same bay, it is preferable to move the blocking container to an empty slot in a neighboring bay.

- (2) *Minimum obstructive rule (MOR)* For container ports, higher turnover rates mean higher performance of port operations. Time is one of the factors that cannot be ignored. After a blocking container is placed onto a destination stack, having fewer containers under the blocking container means shorter operating times.
- (3) *Nearest slot rule (NSR)* For convenience, a gantry crane operator usually moves a blocking container directly to the lowest empty slot of another stack in the same bay. The shorter the horizontal distance traveled to place the blocking container onto a destination stack, the shorter is the operating time.
- (4) *Lowest stack rule (LSR)* To ensure safe operation, a gantry crane operator usually moves a blocking container to the lowest empty slot of the lowest stack in the same bay so as to ensure the minimum average height of the stacks in the same bay after the blocking container has been placed onto the destination stack.

A practical and effective container relocation rule is introduced to optimize the selection of slots for blocking containers in order to reduce redundant paths and the computational complexity of container extraction so as to improve the efficiency of container handling.

3 Results

Based on the multi-bay POA, the authors propose a POA that takes into consideration the multiple attributes of a container for solving the problem of selecting slots for outbound containers of different attributes. Figure 4 shows the pseudocode of a POA with multiple container attributes taken into consideration. When a set of initial container storage status matrices are fed in, the code will output the number of container moves, container extraction paths, running times, and container relocations under the given initial status. By incorporating multiple container attributes (container size, expected departure time, destination port, customer information, etc.), the proposed algorithm is better suited to the real-world scenarios of container handling.

Fig. 3 A basic characteristic diagram of path optimum algorithm (POA)

3.1 Departure rules

Taking Foshan Gaoming Container Terminal in the Pearl River Delta as an example, the authors chose the relevant data gathered in October 2018 for analysis. Firstly, the ratio of to-gate containers (containers to be transferred to a port gate) to to-dock containers (containers to be transferred to a dock) was discussed. Secondly, the time intervals within which the containers were transferred to a terminal gate and a dock were analyzed. Then, the number of containers in the same batch transferred to a dock was analyzed. Lastly, the percentages of containers of different sizes were analyzed. Next, the authors analyzed these four rules in detail to ensure that the initial state conformed with these four rules. The obtained results were applied to the generated initial state matrix so that the numerical experiment would better reflect the actual scene.

- (1) *Ratio of to-gate to to-dock containers* First, the authors accounted for the number of containers transferred to a gate and the number of containers transferred to a dock, then calculated the ratio between the two numbers. According to the accounting result, the ratio of to-gate containers to to-dock containers is 4:5.

- (2) *Time intervals within which the containers were transferred to a terminal gate and to a dock* Next, the authors conducted a statistical analysis of the time intervals within which the containers were transferred to a terminal gate and a dock in order to obtain the time distribution of the container departures in both flow directions. According to the results, the time distribution of transferring containers to a terminal gate is $51 + 930 * \text{BETA}(1.24, 1.18)$ and to a dock is $6 + 1.42e+003 * \text{BETA}(2.01, 1.25)$.
- (3) *Number of containers in the same batch transferred to a dock* The authors conducted a statistical analysis of the number of containers in the same batch transferred to a dock in order to obtain the quantity distribution. According to the results, the quantity distribution is $-0.001 + 240 * \text{BETA}(1.57, 5.5)$.
- (4) *Percentages of containers of different sizes* Finally, the container area was divided into two sections with their areas at a ratio of 6:4, which resulted in a ratio of 3:4 between the 40-foot and 20-foot containers. This ratio setting is taking a small and medium-sized container terminal as an example. The container of 20-foot and 40-foot are stacked according to the ratio of 4:3 in this terminal. Since the container of 40-foot occupies two container slots, the ratio of container block division is 4–6.

Fig. 4 A pseudo-code of path optimum algorithms considering different attributes of containers

Algorithms: path optimum algorithms considering different attributes of containers.

Variable: (1) V represents the matrix of slots; (2) V_1 represents the 20-foot container slot matrix; (3) V_2 represents the 40-foot container slot matrix; (4) $V(bay, stack, tier)$ represent the container slots; (5) S represents the total number of containers; (6) $vth\ container$ represents the container priority, i.e., No. v container; (7) $N(sm)$ represents the total number of container movements; (8) $N(sr)$ represents the total number of container relocations;

$$(9) G(n) = \begin{cases} 1 & \text{Move to other bays.} \\ 0 & \text{Otherwise.} \end{cases} \quad (10) F(g) = \begin{cases} 1 & \text{Extract the target box directly.} \\ 0 & \text{Otherwise.} \end{cases}$$

Output: the total number of container movement, the total number of container relocation, the optimal relocated paths and the computer's running time.

- 1: Set the size of the three-dimensional matrix V to $M \times N \times K$ (i.e., M bays, N stacks, K tiers), and **start the timer**.
- 2: Initial setting: $N(sm) \leftarrow 0$, $N(sr) \leftarrow 0$, $vth\ container \leftarrow 1$, $G(n) \leftarrow 1$, $F(g) \leftarrow 1$ {Reset the Counter.}
- 3: Since V_2 represents the 40-foot container slot matrix, and every two matrixes' elements are exactly the same, so only one of every two identical matrixes is selected to form the new container slot matrix V_3 .
- 4: Merge matrix V_1 and matrix V_3 into a new matrix Z , and transform matrix Z into a row matrix K .
- 5: The elements of the row matrix K are arranged in the order from smallest to largest, and zero elements are removed, denote as matrix R .
- 6: **for** the number of stacks $\leq (N-1)$ **do**
- 7: Determine whether move the container to another bay or not?
- 8: **if** $U(bay, n, tier) = 0$ **then**
- 9: Place the obstructive container on the n th stack of the bay ($n=1, 2, \dots, N$).
- 10: **for** the container $\in R_i$ ($i=1, 2, \dots, g$) **do**
- 11: Find the target container and record $V(bay, stack, tier)$ and $vth\ container$.
- 12: **if** $F(g) = 1$ **then**
- 13: $V(bay, stack, tier) := 0$
- 14: $N(sm) \leftarrow N(sm) + 1$
- 15: Record $V(bay, stack, tier)$ and $vth\ container$, and update the matrix V . If this is a 40-foot container, then update the slot of $V(bay-1, stack, tier)$ or $V(bay+1, stack, tier)$ to 0.
- 16: **else**
- 17: Move the obstructive container and record the relocative paths, i.e., from $(ath\ bay, ath\ stack, ath\ tier)$ to $(bth\ bay, bth\ stack, bth\ tier)$.
- 18: $N(sm) \leftarrow N(sm) + 1$
- 19: $N(sr) \leftarrow N(sr) + 1$
- 20: Record $V(bay, stack, tier)$ and $vth\ container$, and update the matrix V . If this is a 40-foot container, then update the slot of $V(bay-1, stack, tier)$ or $V(bay+1, stack, tier)$ to 0.
- 21: **end if**
- 22: **end for**
- 23: **else**
- 24: Determine whether there are empty slots in other stacks in the bay.
- 25: **if** $G(n) = 1$ {The other stacks in the bay do not have empty slots available for stacking the obstructive container, hence this obstructive container needs to be relocated to another bay.}
- 26: **if** $bay > 1$ or $bay < m$ **then**
- 27: **for** $a=1:1:(bay-1)$ or $b=(bay+1):1:m$ **do**
- 28: Judge whether there are empty slots in $ath\ bay$ or $bth\ bay$.
- 29: **if** $G(n) = 0$ **then**
- 30: This obstructive container can be placed in $ath\ bay$ or $bth\ bay$.
- 31: **end if**
- 32: **end for**
- 33: **end if**
- 34: $N(sm) \leftarrow N(sm) + 1$
- 35: $N(sr) \leftarrow N(sr) + 1$
- 36: **end if**
- 37: **end if**
- 38: **end for**
- 39: **Until** there is no container in the system.
- 40: **Return** the total number of container movement, the total number of container relocation, the optimal relocated paths and the computer's running time.
- 41: **Stop the timer**.

3.2 Numerical experiment

The first part of the numerical experiment is to compare the performance of POA with the LL, B&J and LL heuristic algorithms. All the test instances were generated randomly and from Lee and Lee [13]. The numerical results are

shown in Tables 1, 2 and 3. The test instances in Tables 1 and 2 are more random. The test instances in Table 3, the extracting time of the upper container is later than that of the bottom container, and the number of relocations is larger.

Table 1 The average number of movements of the four algorithms under Lee and Lee instances (Unit: TEU)

Instances	Bays	Stacks	Tiers	Containers	L&L	B&J	LL Heuristic	POA	Lower than LL Heuristic (%)
R011606_0070	1	16	6	70	125.4	108.2	110.2	90.6	17.79
R021606_0140	2	16	6	140	230.2	211.4	213.4	189.8	11.06
R041606_0280	4	16	6	280	454.2	427.6	433	388.6	10.25
R061606_0430	6	16	6	430	709.8	658.8	657.4	619	5.84
R081606_0570	8	16	6	570	945.4	875.6	876.2	810.6	7.49
R101606_0720	10	16	6	720	1169.2	1095.8	1093	1002	8.33
R011608_0090	1	16	8	90	191.4	142	152	130.4	14.21
R021608_0190	2	16	8	190	367.8	307.6	315.2	302.8	3.93
R041608_0380	4	16	8	380	768.6	610.6	623.8	600.6	3.72
R061608_0570	6	16	8	570	1242	907.6	926.2	894.2	3.45

Table 2 The computer running time of the four algorithms under Lee and Lee instances (Unit: seconds)

Instances	Bays	Stacks	Tiers	Containers	L&L	B&J	LL Heuristic	POA	Lower than LL Heuristic (%)
R011606_0070	1	16	6	70	8204.324	2.65	0.09	0.012	650
R021606_0140	2	16	6	140	21,579.552	10.602	0.084	0.033	154.50
R041606_0280	4	16	6	280	21522.112	180.206	0.085	0.069	23.20
R061606_0430	6	16	6	430	21,358.796	199.796	0.087	0.072	20.80
R081606_0570	8	16	6	570	21,200.966	198.602	0.084	0.075	12.00
R101606_0720	10	16	6	720	20,844.76	284.342	0.085	0.079	7.60
R011608_0090	1	16	8	90	13,353.362	7.028	0.078	0.047	66
R021608_0190	2	16	8	190	21,527.714	10.992	0.086	0.059	45.80
R041608_0380	4	16	8	380	21,231.078	163.284	0.088	0.066	33.30
R061608_0570	6	16	8	570	20,874.034	189.76	0.087	0.074	17.60

As can be seen from Table 1, POA has an absolute advantage in the average number of movements. Compared with LL heuristic (the best of the other three algorithms), under the scale of 570 containers, POA is reduced by at least 3.45%.

As can be seen from Table 2, POA has an absolute advantage in computer running time. Compared with the LL heuristic (the best of the other three algorithms), under the scale of 570 containers, POA is reduced by at least 17.6%.

As can be seen from Tables 1, 2 and 3, POA is significantly better than other algorithms in performance. Therefore, POA has a relatively better performance and is capable of handling container terminal yard operations.

In the second part of the numerical experiment, under the condition of conforming with the four departure rules, 100 initial matrixes were randomly generated. By observing the variation of the container area utilization rate and comparing the number of container relocations and lengths of CPU running times, the authors assessed the performance of the POA while considering the container

attributes. In the first case that was analyzed, the 20-foot containers and 40-foot containers were extracted separately according to their priority levels (separate extractions). The results of the numerical test are shown in Table 4.

As can be seen in the table, after the container attributes and the four rules of the terminal operations captured by the field survey were taken into consideration, the container area utilization rate could no longer reach 90% all the time and even the utilization rate of the 40-foot container area could barely reach 80%. These results demonstrate that the container area utilization rate cannot be too high; otherwise, the container yard system would not be able to operate normally. On this basis, the authors analyzed the case in which all the 20-foot and 40-foot containers were extracted in sequence according to the priority level without distinguishing container size (mixed extraction). The container relocation quantities and running times of the two cases were compared. The results of the numerical test are shown in Table 5.

Table 3 The average number of movements of the two algorithms under Lee and Lee instances (Unit: TEU)

Instances	Bays	Stacks	Tiers	Containers	L&L	POA	Lower than LL Heuristic (%)
U011606_0070_001	1	16	6	70	125	110	12.00
U011606_0070_002	1	16	6	70	130	112	13.85
U021606_0140_001	2	16	6	140	255	226	11.37
U021606_0140_002	2	16	6	140	259	222	14.29
U041606_0280_001	4	16	6	280	505	438	13.27
U041606_0280_002	4	16	6	280	510	444	12.94
U061606_0430_001	6	16	6	430	789	688	12.80
U061606_0430_002	6	16	6	430	797	678	14.93
U081606_0570_001	8	16	6	570	1059	898	15.20
U081606_0570_002	8	16	6	570	1029	877	14.77
U101606_0720_001	10	16	6	720	1368	1150	15.94
U101606_0720_002	10	16	6	720	1322	1106	16.34
U011608_0090_001	1	16	8	90	175	150	14.29
U011608_0090_002	1	16	8	90	180	152	15.56
U021608_0190_001	2	16	8	190	387	341	11.89
U021608_0190_002	2	16	8	190	414	338	18.36
U041608_0380_001	4	16	8	380	848	655	22.76
U041608_0380_002	4	16	8	380	752	616	18.09
U061608_0570_001	6	16	8	570	1230	976	20.65
U061608_0570_002	6	16	8	570	1238	944	23.75

Table 4 The average number of relocations (Unit: TEU) of 20-foot and 40-foot of containers respectively taken under different attributes of containers

Utiliza- tions (%)	Sizes of container	The sizes of the blocks (bays × stacks × tiers)					
		11*5*3	13*6*4	15*7*5	17×8×6	19*9*7	21×10×8
50	20-foot	8.25	26.75	43.25	101	144	252.75
	40-foot	7.5	17.5	53.5	80.75	148	224.25
60	20-foot	14.25	44	67.5	159.5	222.75	432.75
	40-foot	14.75	33	76.5	125	248.5	369.25
70	20-foot	20.25	67.5	117.75	216.75	336.75	637.75
	40-foot	22	50	104.25	186.75	380.75	553.25
80	20-foot	30	–	150.75	350	480.25	913
	40-foot	–	68	–	–	–	–
90	20-foot	–	–	227	–	687.75	–
	40-foot	–	–	–	–	–	–

The following conclusions can be drawn according to the results of the numerical experiment:

- (1) The sum of the average container relocation quantities of the 20-foot and 40-foot containers in the case of separate extractions is the same as the average container relocation quantity in the case of mixed extractions. Hence, in the scenario where there is only one container area and one gantry crane, whether the separate or mixed extraction mode is used makes no difference to the number of container relocations. However, as the size of the container area becomes larger, the mixed extraction mode requires a longer
- (2) Because of the initial setting constraints of containers of different sizes when multiple container attributes are taken into consideration, the container area utilization rate cannot exceed 70%. Once it exceeds

computer running time than does the separate extraction mode. In the scenario where the containers of different sizes are stored together and there is only one gantry crane, it is impossible to perform separate extractions. The only choice is the mixed extraction mode, which means a longer decision time. If more than one gantry crane is available for extracting containers of different sizes, the decision time will be shorter.

Table 5 The comparisons between the average number of relocations No. (Unit: TEU) and the computer running time (Unit: seconds) when extracted different size of containers separately or in priority order

Extractive ways	Utilizations (%)	Parameters	The sizes of the blocks (bays × stacks × tiers)				
			13 × 6 × 4	15 × 7 × 5	17 × 8 × 6	19 × 9 × 7	21 × 10 × 8
Different sizes of containers are extracted respectively	50	No.	44.25	96.75	181.75	292	477
		Time	0.2657	0.5807	0.7789	1.5341	2.674
	60	No.	77	144	284.5	471.25	802
		Time	0.347	0.7085	1.0427	2.0826	3.7388
	70	No.	117.5	222	403.5	717.5	1191
		Time	0.4558	0.9171	1.2514	2.5829	4.8764
Different sizes of containers are extracted in order of priority	50	No.	44.25	96.75	181.75	292	477
		Time	0.3342	0.7103	1.0992	2.5414	4.9694
	60	No.	77	144	284.5	471.25	802
		Time	0.4204	0.731	1.5016	3.5626	6.2963
	70	No.	117.5	222	403.5	717.5	1191
		Time	0.532	0.9789	1.907	4.581	7.9451

70%, multiple initial settings cannot be satisfied at the same time, *i.e.*, a container area utilization rate of 70% accurately reflects the actual operations of Foshan Gaoming Container Terminal.

In order to analyze the variations in the number of container relocations at different utilization rates, the average container relocation quantity and the relative relocation rate of containers corresponding to different container area utilization rates were calculated by using the operation data yielded by the container extraction model with multiple container attributes taken into consideration. The result is shown in Fig. 5. Note that Tables 4 and 5 in the graph are average values.

Because of the multiple initial container settings set with multiple container attributes taken into consideration, the performance of the outbound container slot selection model considering container attributes under the container area utilization rate of 80–90% will not be studied. As the container area utilization rate increases, the number of container relocations increases sharply, but the relative container relocation rate varies at the same pace despite the differences in the initial values. A comprehensive analysis of both Tables 4 and 5 reveals that when the initial settings of the containers (which are set with multiple container attributes) are considered, the optimal outcome can be obtained when the container area utilization rate is 70%.

In summary, the setting of the initial state matrix of the containers has a great influence on container relocation. Different container terminals could distill different rules and an effective algorithm could be used to obtain the number of container moves, the number of container relocations, the computer running times, the container relocation paths, and other figures in a short time. Therefore,

the container extraction operation model considering container attributes better suits the container terminal operating system. With the long-term operational pattern of the container terminal being known, this model can produce a container extraction scheme within a short decision time, which helps improve the overall operational efficiency of the yard, as well as saves operating time and costs. Hence, this method can contribute to coastal research worldwide.

4 Discussion

Considering that the initial states of the containers have a great influence on the number of container relocations, the authors investigated the number of container relocations and the relative relocation rate under different rule use sequences and assessed the extent of the influences of these sequences on these two parameters. Since only SFNS involves multi-bay switching, it has the highest priority level, *i.e.*, it is applied preferentially in container extraction. Therefore, the position of the SFNS is fixed. Six different rule use sequences can be obtained by changing the positions of the remaining three rules.

- (1) SFNS → MOR → LSR → NSR (S&M&L&N);
- (2) SFNS → MOR → NSR → LSR (S&M&N&L);
- (3) SFNS → LSR → NSR → MOR (S&L&N&M);
- (4) SFNS → LSR → MOR → NSR (S&L&M&N);
- (5) SFNS → NSR → LSR → MOR (S&N&L&M);
- (6) SFNS → NSR → MOR → LSR (S&N&M&L).

The most fundamental improvements achieved by the outbound container slot selection model considering container attributes are reflected in the following three areas:

Fig. 5 Comparisons of the average number of relocations (Unit: TEU) and relative relocation ratio (RRR) in different sizes of the blocks (bays $\times$ stacks $\times$ tiers)

- (1) The bays of the container area are divided into a certain proportion for storing 20-foot and 40-foot containers separately. Container terminals can set different proportions according to the actual situation of yard operations.
- (2) The priority level of a container is determined by multiple factors, including expected departure time, destination port, and customer information. Container terminals can adjust the weights of the factors according to the importance of each influencing factor.
- (3) To improve the practicality of the container extraction model, multiple constraints are taken into consideration: the ratio of to-gate to to-dock containers, time distribution of container transfers, number of containers in the same batch transferred to a dock, and percentages of containers of different sizes. Container terminals can change the relevant data of the rules according to the actual situation of yard operations.

The improvements in several areas are reflected in the setting of the initial matrix. By comparing the performance of the six rule use sequences, the optimal rule use sequences under different initial state matrices can be obtained. So, the numerical test will compare the two important parameters: the number of container relocations and the relative relocation rate. The test results are shown in Table 6. (Text in bold italics indicates the minimum number of container relocations yielded by the six rule use sequences with different container area sizes. The container block size = bays $\times$ stacks $\times$ tiers).

Table 6 shows the ranking of the six rule use sequences determined by a numerical test in which the performance of a rule use sequence is measured by the number of container relocations (the container attributes were taken into consideration). The descending order of the six rule use sequences is (1) $\rightarrow$ (2) $\rightarrow$ (6) $\rightarrow$ (5) $\rightarrow$ (4) $\rightarrow$ (3), i.e., with the minimum number of container relocations as the objective, the performance of the POA considering container attributes is optimal when the rule use sequence is S&M&L&N.

In order to analyze the variations in the number of container relocations during container extraction under different container area utilization rates, the container relocation quantities corresponding to the six rule use sequences with container area utilization rates of 50%, 60%, and 70% were calculated. The results are shown in Fig. 6, of which (a), (b), and (c) compare the container relocation quantities corresponding to the six rule use sequences obtained with different container area utilization rates. As the utilization rate increases, the slope of each curve becomes steeper, which means that the number of container relocations rises at an accelerated pace. Note that sequences (1) and (2) are always lower than the average, whereas sequences (3) and (4) are much higher. Figure 6d clearly shows that the gaps between sequences (1) and (2), (6) and (5), and (4) and (3) are small, indicating that when SFNS is given the first position, the selection of the second container's relocation rule is of particular importance. This phenomenon can be considered from the following angles:

- (1) When the number of container relocations is the optimization goal, the second position should be given

Table 6 The average number of relocations (No., Unit: TEU) and relative relocation ratio (RRR) in different rule set orders

Rule set orders	S&M & L&N						S&M & N&L					
Utilizations	50%		60%		70%		50%		60%		70%	
Parameters	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)
11*5*3	15.75	19.3	29	26.1	42.25	29.9	15.75	19.3	29	26.1	42.75	30.2
13*6*4	44.25	26.3	77	33.1	117.5	38.6	44.25	26.3	79	33.6	119.5	39.0
15*7*5	96.75	31.5	144	35.5	222	41.3	100.75	32.4	149.25	36.3	226.5	41.8
17×8×6	181.75	35.8	284.5	41.1	403.5	45.2	188	36.6	299.5	42.3	424.25	46.5
19*9*7	292	37.9	471.25	44.1	717.5	50.0	298	38.4	491	45.1	765	51.6
21×10×8	477	41.5	802	48.8	1191	54.2	506.5	43.0	852	50.4	1258.75	55.5
Rule set orders	S&L & N&M						S&L & M&N					
Utilizations	50%		60%		70%		50%		60%		70%	
Parameters	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)
11*5*3	21	24.1	33.5	29.0	49	33.1	20.75	23.9	33.5	29.0	48.75	33.0
13*6*4	56	31.1	101.3	39.4	143.5	43.4	55.75	31.0	99.75	39.0	141.25	43.0
15*7*5	133	38.8	201	43.4	289.75	47.9	130	38.2	198.25	43.1	288	47.8
17×8×6	256	44.0	417.5	50.6	575.25	54.1	248.5	43.3	411	50.2	565.5	53.6
19*9*7	435.5	47.7	708.5	54.2	1016.3	58.6	426	47.1	690.5	53.6	994.25	58.1
21×10×8	745.25	52.6	1204	58.9	1757.75	63.6	726.75	52.0	1167.8	58.2	1739.8	63.3
Rule set orders	S&N & L&M						S&N & M&L					
Utilizations	50%		60%		70%		50%		60%		70%	
Parameters	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)	No.	RRR (%)
11*5*3	18.5	21.9	29.25	26.3	45.75	31.6	17.25	20.7	29.5	26.5	44.5	31.0
13*6*4	48	27.9	86.25	35.6	126.25	40.3	47.25	27.6	84.25	35.1	125	40.1
15*7*5	112.75	34.9	167	38.9	249	44.2	108	34.0	165.25	38.7	247	44.0
17×8×6	209.25	39.1	345.25	45.8	489.25	50.0	204.5	38.6	333	44.9	469.75	49.0
19*9*7	349.75	42.3	578.25	49.2	858	54.4	339.75	41.6	561.5	48.4	844.5	54.1
21×10×8	594.25	46.9	992	54.2	1480.25	59.5	571.75	46.0	969.25	53.6	1430.5	58.7

to MOR. Note that sequences (1) and (2) arranged in this way yielded a smaller number of container relocations than did the remaining four sequences. A smaller number of container relocations means higher efficiency and lower costs of container relocations, and hence, lower operating costs. Therefore, placing MOR at the second position of the rule use sequence is conducive to achieving high efficiency and saving costs in operations, which are desirable outcomes for any container terminal operator.

- (2) When the optimization goal is to keep the gravity of the container block as low as possible, NSR should be given the second position from the perspective of safety. Note that sequences (6) and (5) arranged in this way yielded container relocation quantities higher than that of sequence (1) by 13.16% and 16.20%, respectively. For container terminals where high efficiency is of great importance, many container relocations will result in reduced efficiency and increased costs. Therefore, NSR should not be placed in the second position of the sequence.
- (3) When the optimization goal is to minimize the travel distance required by job switching, the second position should be given to LSR from the perspective of operator convenience. However, sequences (4) and (3) arranged in this way yielded container relocation quantities higher than that of sequence (1) by 35.36% and 37.66%, respectively. As with the second scenario, LSR should not be given the second position of the sequence.
- (4) Therefore, MOR should be given a position second only to SFNS.

The last step is to decide the positions of LSR and NSR. A comparison of sequences (1) and (2) shows that sequence (1) outperformed sequence (2) by a large margin in the number of container relocations with different container area utilization rates and container area sizes.

Fig. 6 Comparisons of the average number of relocations (Unit: TEU) and relative relocation ratio (RRR) in different rule set orders

In summary, the optimal rule use sequence is S&M&L&N when the optimization goal is to minimize the number of container relocations. This conclusion is consistent with that produced by the multi-bay container extraction operation model and further proves that the proposed algorithm, while still undergoing gradual improvement, can produce conclusions in good agreement with those produced by the existing algorithms. Although the container extraction operation model considering container attributes incurs a larger number of container relocations and longer computer running times, it is more comprehensive and better suited for container handling in container yards because it takes multiple initial settings into consideration.

From the results of numerical test shows that if the sizes of the blocks (i.e., bays × stacks × tiers), the number of outgoing container, the ratio of to-gate to to-dock containers, the number of containers in the same batch transferred to a dock, the percentages of containers of different sizes are different, the number of relocations will be different. In our algorithm, the application of different rules and the different order of multiple rules will also affect the number of relocations, and thus the operation efficiency of the yard.

Therefore, the initial setting of the container yard has a significant impact on the operation of the ports.

In conclusion, since a major improvement of the model is reflected in the setting of the initial state of the containers, the initial state matrix has a great influence on container extraction. It is especially important to form the initial state matrix according to data gathered from the daily operations of the container terminal. In all, the proposed model is more practical, scientific, and forward-looking than existing models, and therefore, can be used to improve the overall efficiency of container ports.

5 Conclusion

In this study, the authors analyzed the influences of a host of factors (flow direction, size, expected departure time, destination port, and customer information) on the selection of container slots, reflected this influence in the priority levels of the container, and further improved the model and algorithm for container extraction. Four container departure rules were distilled, on the basis of which the

performance of the container extraction model considering container attributes was tested. The test results show that the utilization rate of a container area cannot exceed 70% because of the initial setting constraints of containers of different sizes. Once the utilization rate exceeds 70%, multiple initial settings cannot be satisfied at the same time. The container extraction model considering container attributes is more comprehensive and better suited to actual container handling in terminal yards, and shows an important practical significance in coastal container ports worldwide. Although the authors have conducted a comprehensive analysis of container extraction, distilled some common strategies applicable to the selection of container slots, and achieved the goal of optimizing container extraction, there are still some flaws in the obtained conclusions because this study had been conducted under certain assumptions.

To increase the comprehensiveness of the research and make the algorithm better suited to the actual operation of the container terminal, more attention should be paid to uncertain factors and container dynamic operation in the future studies. Although a port receives information about the containers before a container ship arrives, there are still uncertainties, including customs inspections, placing special containers, and weighing containers, after arrival. Besides, in addition to the extraction of containers from the yard, the allocation of the containers is also a classic problem. Simultaneous consideration of the operation of lifting and putting containers in the storage yard is also the future research direction. Therefore, conducting more field surveys on more ports and distilling more operational patterns for improving the model will be the focus of future studies.

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Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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