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A flexible operation organization of container terminals considering intermodal transport demand

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Abstract: *The operation organization of loading, unloading, and transshipment (LUT) is of great importance in managing, configuring resources, and scheduling container tasks for strengthening competitiveness in intermodal container terminals (ICTs). This study concludes the seven existing intermodal transportation LUT routes for sea-road, sea-rail, and road rail intermodal LUT methods in ports. In the past decade, container terminals usually operate container tasks based on a traditional operation organization by separating the 7 types of LUT routes. However, the traditional operation organization could not satisfy variable intermodal container transshipment simultaneously nor provide more choice of transshipment routes. A novel distributed parallel flexible operation organization with reentrant equipment (DPFOM_RE) for ICTs is constructed. Based on DPFOM_RE, ICTs can handle different intermodal container tasks at the same time with facility by multiple transshipment routes. The benefits for stakeholders and future directions for the proposed operation organization are discussed.*

Keywords: *Intermodal transport; Container terminal; Operation organization; Flexible operation; Reentrant equipment*

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Introduction

Intermodal transportation is the movement of containers by a sequence of at least two transport modes (Crainic et al.,2007). Compared to unimodal transportation, intermodal transportation has the flexibility to use different modes considering the specific characteristics of containers (SteadieSeifi et al., 2014). In Europe, the growth of intermodal tonne-kilometer performance was 6.77% in 2021, with a 1.02% growth in the number of consignments transported (UIRR Report., 2021). A typical sea-rail application is the Eurasia Land Bridge, which connects Europe and China. It transports imported cargo from China and other far east countries. On its return from central Europe, the train transports European products, which are then loaded on feeder vessels to travel to China. Although the intermodal transportation brings convenience to global trade, it also brings great pressure to automated container terminals. Different intermodal containers need to be transferred to specific intermodal operation areas in container terminals, which makes the container transshipment process more complex. A more intelligent decision system for automated container terminals in the context of intermodal (ICTs) is urgently needed.

ICTs are the key elements in intermodal transportation, managing the transfer from one transport mode to another. As shown in Figure 1, ICTs consist of yard operation areas in railway station (rail access area), internal trucks, yard operation areas (including yard crane handling area and containers storage area), check-in/out area (gate), external trucks (road access area), and berth operation areas (including quay crane handling area and truck transportation area). We can find that many blocks are used as yard operation areas; and they are regularly distributed at terminals and do not interfere with each other during work. For most of ICTs, the external trucks and rails have access to the ports, which is becoming a trend of terminals. The multiple intermodal containers are not only between vessels and road, but also between vessels and rails. These additional areas and access make the transshipment situations more complex.

Figure 1: An illustration of an intermodal container terminal layout.

ICTs are urged to find an integrated operation organization that can manage different areas and equipment better for more effective intermodal container transshipment. Recently, container terminals have been continuously working in three technology areas: automation, electrification, and digitalization; the most important being the development of automation and digitalization in container terminals, which has been enabled in part by operational organization (Zhou et al., 2022). Therefore, it is of great practical significance to study the novel operational organization of ICTs.

In ICTs, the operation of loading, unloading, and transshipment (LUT) is completed through the cooperation of different areas and equipment. The LUT is a complex operation process with multiple stages for containers transshipment. In general, the LUT process includes QC handling, IT horizontal traveling, and RC handling. Ordinary CTs only provide one type of transshipment route, which is regarded as the execution order of LUT process, for one type containers. However, at intermodal container terminals, there are more than one type intermodal containers (such as sea-road intermodal containers, sea-rail intermodal containers) to be meet at the same time. Only few studies have contributed to this research area. In the state-of-the-art study of Liu et al. (2020), three categories of container tasks including import, export and transfer container tasks were considered together.

To date, the existing operation organization of LUT process is based on the hybrid flow shop operation mode (HFSOM). The HFSOM is a production organization widely used in industrial manufacturing, which can only deal with one type of fixed production process at a time (Pinedo et al., 2008). The hybrid flow shop problem is, in most cases, NP-hard (Ruiz et al., 2010). In recent decades, the academia has analyzed some problems at CTs based on the

HFSOM. Lu et al. (2019) integrated QC handling and IT horizontal traveling as a two-stage hybrid flow shop scheduling problem. Chen et al. (2007), Sun et al. (2023) and Zhong et al. (2022) constructed three-stage LUT scheduling models which root from HFSOM. Although the HFSOM can integrate the processes with strong couplings well, it cannot simultaneously solve the flexible transshipment routes problem for various intermodal container tasks.

Based on the above considerations, we conducted a deep analysis from the following aspects. First, during loading, unloading, and transshipment, the distributed operation characteristics must be seriously considered for operation areas with homogeneous and heterogeneous equipment. Secondly, due to intermodal transportation, the types of intermodal containers and terminal operation areas will increase, followed by the diversification of transshipment routes. The new mode must be able to cope with transshipment for various tasks and provide sufficient flexible transshipment routes for multiple classes of containers. Third, the characteristics of critical equipment that occur many times during transshipment need to be properly defined to improve effective utilization.

Motivated by the above considerations, this paper proposes a comprehensive and effective novel LUT operation organization, named distributed parallel flexible operation mode with reentrant equipment (DPFOM_RE), with the following main innovations and contributions: 1) The seven types of LUT routes are concluded for the three intermodal methods for the first time. 2) The characteristics of hybrid LUT routes transshipment are extracted, including flexible LUT routes for variable intermodal containers, distributed multiple parallel operations for areas with homogeneous and heterogeneous equipment, reentrant equipment for the organization.

Related works

Traditional LUT operation organization

To date, the modeling and scheduling of LUT processes have been based on the HFSOM. Lu et al. (2019) studied a two-stage optimization problem on QC and RC scheduling in CTs. Sun et al. (2023) proposed a multi-resource collaborative scheduling optimization model, rooted in the principle of the blocking-type hybrid flow shop problem, with the objectives of minimizing the makespan of QC and the transportation energy consumption. Zhong et al. (2022) proposed a multi-objective optimization for integrated QC handling, IT traveling and RC handling operation considering no-idle QC operation in a container terminal. Lee et al. (2008) considered the comprehensive scheduling of QCs and RCs as a hybrid flow shop with sequence-dependent setup time. Xin et al. (2015) studied the joint scheduling of QCs, ITs, and automatic stackers, and introduced a hybrid flow shop scheduling model to represent discrete events.

In the above studies, the mathematical models of joint scheduling were all built based on the HFSOM. It can be seen that they abstract each operation stage of LUT as multiple parallel machines operation and assume that the LUT processes of all containers are consistent. However, this kind of study based on HFSOM ignores the distributed characteristics of equipment in all operation areas, and also ignores the diversity of LUT routes due to intermodal transportation.

Scheduling mode in distributed manufacturing

In practice, distributed manufacturing has been widely used in various types of industrial scenes, such as semiconductor wafer manufacturing (Dong et al., 2019), advanced computer-aided process planning (Mishra et al., 2012), production monitoring and scheduling in the distributed garment manufacturing environment (Guo et al., 2015). Many studies have been conducted on the scheduling of distributed manufacturing.

Wu et al. (2019) introduced the distributed flexible job shop scheduling to study the manufacturing problems of building materials and equipment manufacturing enterprises. There are also relevant researches that combine the distributed scheduling problem with other problems, such as the distributed problem with multi-factory manufacturing (Gharaei et al., 2018).

In particular, research on distributed job shop scheduling for factories began in the 1980s. Most of the studies focused on homogeneous factories or machines, and only a few studies discussed heterogeneous machines in heterogeneous factories. Researchers have made some progress on distributed heterogeneous parallel devices.

In most of the ICTs, there are at least two homogeneous pieces of equipment configured in each LUT operation area, and each stage operation area is divided into at least two parts, each of which has the same function and can work at the same time (Yu et al., 2021). However, few relevant researchers have considered resource allocation and job scheduling from the perspective of distributed scheduling, which makes the transshipment execution low and unbalanced between resources and consumption.

Reentrant operations

As important horizontal traveling equipment in ICTs, the trucks often interact with QCs and RCs. Therefore, most studies on trucks are conducted from the perspective of integrated scheduling. There are even more complex multi-stage integrated scheduling problems that simultaneously scheduled the QCs, ITs, and RCs in ICTs (Luo et al., 2020; He et al., 2015; Yang et al., 2018). In the models, the three types of equipment are assigned to container tasks, and the paths of ITs are planned at the same time.

In these models, the limited number of ITs requires the transportation of multiple container tasks (Luo et al., 2020). It can be seen that the current research on the vehicle path is limited to the closed-loop cycle between the endpoints of the two operation areas. However, it seldom considers how to use the non-circulating path to improve the utilization efficiency and turnover rate of ITs when more work areas have a demand for the internal truck.

Research gap

In the current research, the characteristics of distributed multiple parallel operations of ICTs have not been fully reflected in the traditional operational organization. The traditional organization cannot manage all different intermodal containers simultaneously, and the classification and definition methods for intermodal containers' LUT routes are not unified. Some critical equipment in ICTs may occur twice during LUT processing, and related studies have not researched this equipment.

Although the proposal and construction of the novel organization bring many challenges, for the intermodal transport network, the safe and efficient operation of ICTs can significantly improve the stability of container transportation. For ICTs, the change of operation organization can reduce effectively the waiting time of containers, and improve the competitiveness of terminals. For clients, the efficiency of ICTs can provide them with a reduction in logistics costs.

Construction of DPFOM_RE

LUT routes

Considering the combinations of intermodal transport, this section analyzes the transshipment routes (TR) during the process of LUT in ICTs. As shown in figure 2, the interaction diagram shows the traveling areas of ITs and external trucks (ETs) in some operation areas when the combination transport consists of sea, road, and rail. Among these operation areas, the yard operation area is the most popular for ITs and ETs. The second popular area is the railway station. The types of intermodal containers' TR are shown in figure 4 - figure 6, the arrows in these figures indicate the flow direction of the containers.

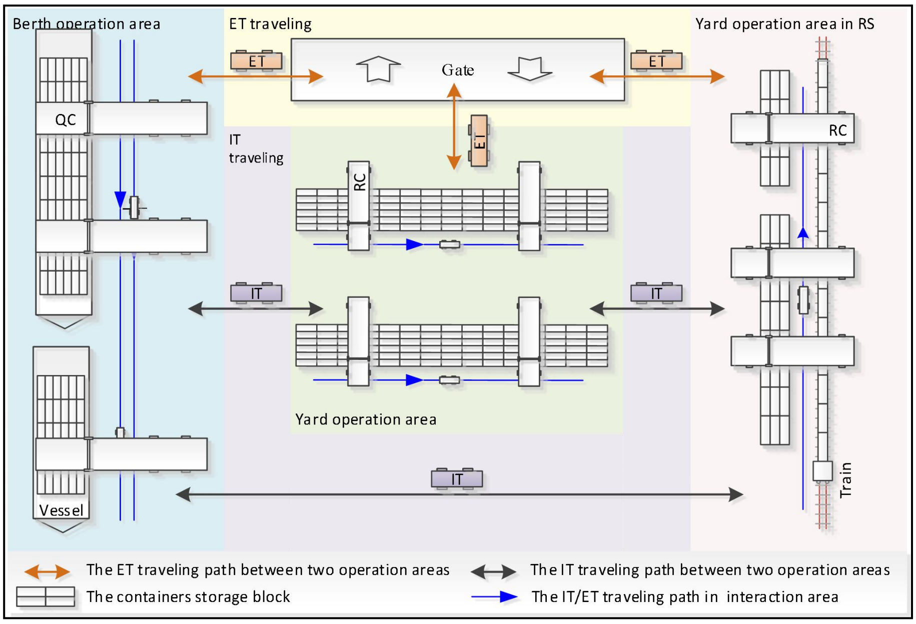


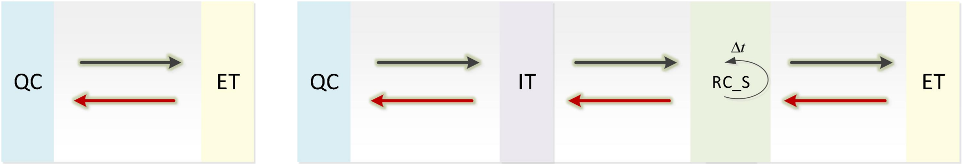
Figure 2: The interaction diagram among operation areas in an ICT.

For sea-road coordination, containers need to be transferred between vessels and ETs. Figure 3 shows two types of TRs for sea-road container (S-D container) tasks:

Type 1: If ETs are allowed to enter the berth operation area, the containers are handled by QCs between vessels and ETs directly. The TR is shown in figure 3 (a).

Type 2: The containers are first transported from the berth operation area to the yard operation area through ITs, and then carried to ETs by RCs in the yard, or the opposite LUT process. The TR is shown in figure 3 (b). It is worth noting that there is a temporary storage time Δt for containers in the yard.

The type 2 route is a standard TR in the actual operation of ICTs, alleviating the pressure on resources. For example, the excessive container transfer tasks may be limited by the quantities or capacity of the equipment. Therefore, some containers may be stored in the yard temporarily.



(a) (b)

Figure 3: The TRs of sea-road containers. (a) Type 1 of TR; (b) Type 2 of TR

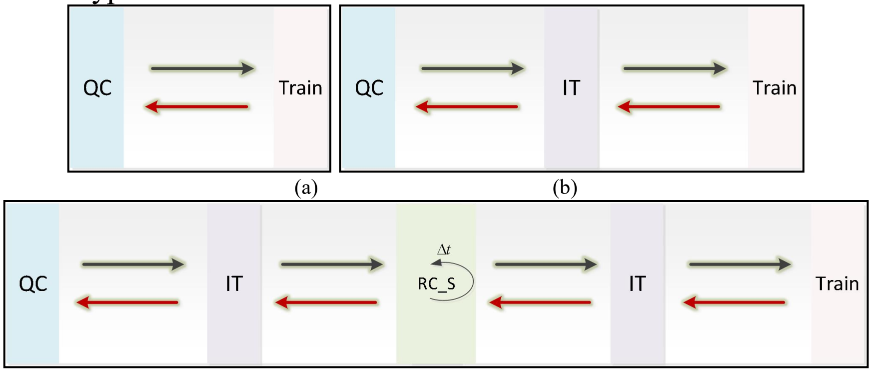
The LUT process between vessels and trains in the ICT is required for sea-rail intermodal containers. Figure 4 shows three types of TRs for sea-rail container (S-L container) tasks:

Type 3: If the railway connects to the berth operation area directly, the containers can be carried between the vessels and the trains by QCs without horizontal trucks travel. The TR is shown in figure 4 (a).

Type 4: Unlike type 3, if the train is not allowed to enter the berth operation area directly, the containers need to be transferred between the berth operation area and the railway station by the ITs. The TR is shown in figure 4 (b).

Type 5: The containers are first transported from the berth operation area to the yard operation area by ITs, and then stored in the yard temporarily. Until the railway station can receive the containers, the containers will be transferred between the berth operation area and the railway station by ITs, or the opposite LUT process. It is worth noting that the storage time Δt is generated by the storage procedure in yard areas, and the transfer process of ITs has been completed twice. The TR is shown in figure 4 (c).

Likewise, some S-L containers will be stored in the yard areas temporarily. Therefore, there is a storage time Δt in type 5.



(a) (b)

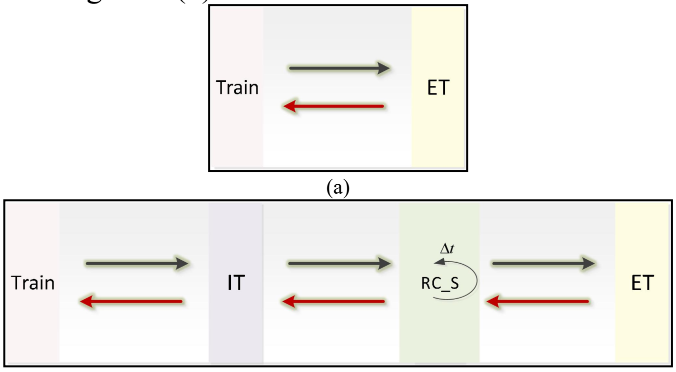
(c)

Figure 4: The TRs of sea-rail containers. (a) Type 3 of TR; (b) Type 4 of TR; (c) Type 5 of TR.

Sometimes, the same batch of intermodal containers in the railway station area is not only transported to vessels but also transported to ETs. For the sea-road-rail coordination, except for S-D container, and S-L container tasks, there are some road-rail container (D-L container) tasks. These D-L containers are transported between trains and ETs. Figure 5 shows two types of TRs for D-L container tasks:

Type 6: If the ETs have the access to enter the railway station area directly, the D-L containers are carried from the train to ETs by the RCs in the rail station directly without other transfer. In contrast, the transfer is from ETs to trains. The TR is shown in figure 5 (a).

Type 7: The containers are first transported from the rail station to the storage yard area by ITs, then stored in the yard temporarily until the ETs arrive at ICTs or the opposite LUT process. Similar to type 5, it is worth noting that Δt is generated by storage procedures in the yard. The TR is shown in figure 5 (b).



(a)

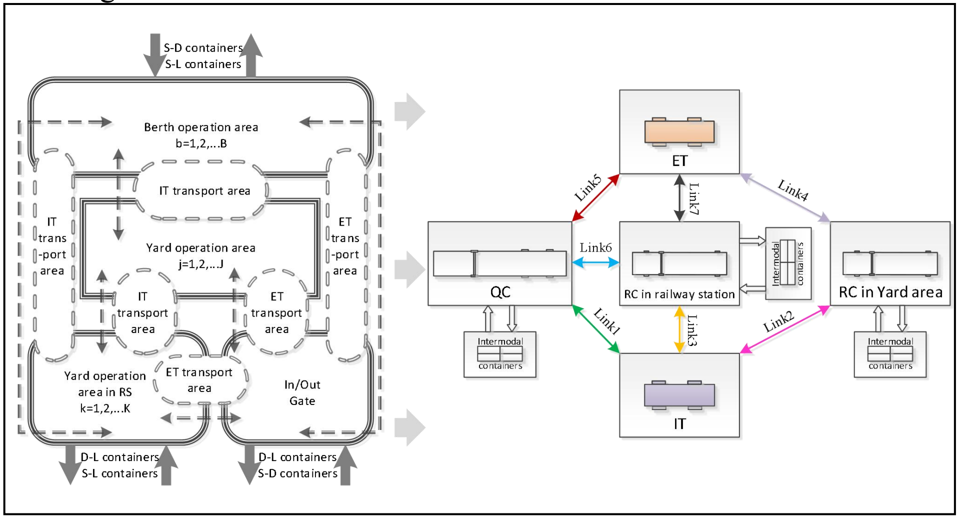
(b)

Figure 5: The TRs of road-rail containers. (a) Type 6 of TR; (b) Type 7 of TR.

In order to illustrate the flexible operation more clearly, the relationships between operational areas and container flows, and between each operational process, are shown in Fig. 6. The figure 6(a) shows important areas that are used during LUT, and the dashed double arrows indicate intermodal container flows between two different areas. It is noteworthy that two operation areas are related through IT/ET transport areas. The figure 6(b) gives the LUT process, which is divided into five common operational processes, and the seven colored double arrows link every two relational processes. The five common operational processes are QC handling, reentrant IT travelling, RC handling in storage yard, RC handling in the railway station, and ET travelling. All of the types of TR are composed of these processes. Each TR can be represented by a combination of these links. The following are the combinations: Type 1 consists of link 5; Type 2 consists of link 1, link 2, and link 4; Type 3 consists of link 6; Type 4 consists of link 1 and link 3; Type 5 consists of link 1, double link 2, and link 3; Type 6 consists of link 7; Type 7 consists of link 3, link 2, and link 4.

In this subsection, we discuss various operation areas in ICTs. The S-D, S-L, and D-L containers are considered, and seven types of TR are defined, respectively. Each type of TR includes a unique LUT process, and each intermodal container can be assigned to at least two types of TR. Both of them reflect the flexible transshipment operation of the intermodal container tasks in ICTs. Finally, the flexible LUT route is defined as follows:

Definition 2 *The Flexible LUT route* (FT) means that each type of TR has a unique LUT process, and the TR assignment is flexible. Considering the distributed characteristics of equipment proposed in Section III. *A* and the limitations of equipment resources, each container is allowed to choose the appropriate TR type from the above definitions to complete the transfer. Before the transshipment start of each container, its selection of TR can be adjusted according to the current situation of resources.



(a) (b)

Figure 6: The flexible operational processes of LUT in ICTs.

Distributed multiple parallel operations

In this subsection, we take the sea-rail transshipment as an example to characterize the feature of distributed multiple parallel transfers of equipment.

As shown in figure 2, we can observe that a variety of equipment for different processes is distributed in multiple areas in batches, and the equipment can be used at the same time. This constitutes the distributed feature of heterogeneous transfer equipment. And in each distributed interaction areas, there are at least two sets of homogeneous equipment.

The feature of distributed configuration provides the basis of distributed parallel machine operation. It can provide the flexible operation with different scales or emergencies. Therefore, the distributed parallel machine operation is introduced to characterize the LUT. The k and s mean the total number of interaction areas in the operation area l and w, respectively. The nlth machine exists in the interaction area j. The interaction area j exists in the operation area i. The definition of distributed multiple parallel operations is given below.

Definition1 *Distributed Multiple Parallel Operations* (DMPO) means that the homogeneous equipment is configured in distributed interaction areas, and heterogeneous equipment is configured in different operation areas. The transfer operations between different areas will not affect one another. In the face of changing tasks or uncertainty, the most suitable equipment can be assigned to synchronize multiple tasks from distributed areas for LUT. Let S be a closed set, which means the operation area set. $S = \{So_1, \ldots, So_i, \ldots, So_n\}$, $|S| \geq 1$, $i=1, 2, \ldots, n$, and So_i is also a closed set, which means the operation area i in ICT. The set $So_i = \{St_{i1}, \ldots, St_{ij}, \ldots, St_{im}\}$, $|\ So_i\ | \geq 2$, $j=1, 2, \ldots, m$, and St_{ij} is also a closed set, means the distributed interaction area j exist in So_i.

Reentrant operations

As important horizontal transportation equipment of the ICT, the IT plays an important role during the LUT process. It can be seen from figure 2 and figure 6 that IT can travel in every operational area and execute twice within one type of TR. In addition, there is a temporary storage time Δt in type 2, type 5, and type 7 of TR. At the start time and end time of Δt , the container needs to be handled by RC. Therefore, the container is handled by RC at least twice during these types of TR. Based on the above factors, we define reentrant equipment:

Definition 3 *Reentrant equipment* (RE) can undertake multiple operation processes in a TR for a container. Let r_{ij} be a finite-dimensional vector, $r_{ij} = [r_{ij}^1, \ldots, r_{ij}^y, \ldots, r_{ij}^Y]$, where the r_{ij}^y is the yth dimension in r_{ij}, $Y = |\ r_{ij}\ |$, $Y \in \mathbb{R}^n$. Elements $|w_{ij}|$ are extracted from r_{ij} and represented as the closed set w_{ij}, where $|w_{ij}| \geq 2$. Let $E = \{e_1, \ldots, e_i, \ldots, e_n\}$ be a closed set. If e_i is mapped to w_{ij} , then the e_i is RE.

In ICTs, RC and IT are REs. Then, another question comes. What effect will be triggered for the LUT when REs operating? To answer this question, we make the following analysis.

The number of operation processes assigned to REs will be increasing. Usually, the REs accept more instructions than ordinary equipment. The increasing instructions make that REs need to respond to the order and complete the previous transfer process in a timely manner. Additionally, if there is no idle equipment available to process the containers when the ITs arrive at the operation area, the ITs need to wait in the area. During this time, ITs continue to carry containers and cannot leave until the containers are unloaded by idle equipment.

Taking the above into consideration, it is necessary to account for the idle state of REs during transshipment and the potential strong coupling of space-time constraints that may arise when RE interacts with equipment in other operational areas.

Discussion

It can be seen from the above results that DPFOM_RE differs greatly from HFSOM in terms of the LUT process and performance. Further, we discuss the advantages, future work, and challenges of the novel organization from the following points.

Distribution. The intermodal container tasks are transmitted by the same LUT process based on HFSOM. Although the same type of equipment in ICTs is usually enough to complete the tasks, it can be challenging to handle, transfer, classify and store tens of thousands of containers simultaneously. With distributed operation organization, the DPFOM_RE distributes the container tasks to the equipment in different areas, which effectively relieves the pressure on the handling equipment.

Flexibility. In the intermodal container task, the choice of TR may be changed with the variety of the combination of intermodal. However, HFSOM cannot satisfy the flexible TR. For intermodal containers, the destinations of containers always depend on clients, which are diversified. Unlike the HFSOM, DPFOM_RE not only can provide the traditional TR to intermodal containers but also can meet other intermodal demands for clients. In addition, DPFOM_RE introduces the routes selection mechanism, which allows the terminal manager to choose the optimum TR. DPFOM_RE coordinates and utilizes terminal resources flexibly.

Complexity. The calculation of the TR combination of multiple intermodal container tasks is given above. Let $H \in \mathbb{R}^n$ be a closed set, let $H_{S-D}, H_{S-L}, H_{D-L} \in \mathbb{R}^n$ be a closed subset, and $H_{S-D} \cup H_{S-L} \cup H_{D-L} \in H$, $H_{S-D} \cap H_{S-L} = \varnothing$, $H_{S-D} \cap H_{D-L} = \varnothing$, $H_{S-L} \cap H_{D-L} = \varnothing$. As we know, there are two types of TRs that can be selected by S-D container, thus there are $2^{|H_{S-D}|}$ TRs combinations for $|H_{S-D}|$ S-D containers. In a similar way, there are $3^{|H_{S-L}|}$ TR combinations for $|H_{S-L}|$ S-L containers and $2^{|H_{D-L}|}$ TR combinations for $|H_{D-L}|$ D-L containers. Therefore, the total number of TR combinations of container tasks is $2^{|H_{S-D}|} \bullet 3^{|H_{S-L}|} \bullet 2^{|H_{D-L}|} = 2^{|H|-|H_{S-L}|} \bullet 3^{|H_{S-L}|}$.

Stakeholders. It is always important for each carrier to complete the container tasks as soon as possible since that has a direct bearing on their profits. Similarly, for terminal operators, the operation efficiency of terminals is the key competitive indicator among peers. For shippers and logistics service providers, the resource loss generated during the LUT process is also worth considering (e.g., container wear). For customs agencies and their agents, the speed of customs declaration has an impact on the storage time of containers and then changes the choice of TR.

Conclusion

In this study, we propose an innovative LUT operation organization named DPFOM_RE, to enhance the containers transshipment in the context of intermodal transportation. The DPFOM_RE consists of distributed multiple parallel operation, flexible LUT route and reentrant equipment. The novel organization, which can cope with the variable demand of transshipment efficiently.

The DPFOM_RE can provide operation guidance to enhance the competitiveness of the terminals, and reduce the container wear, which are good news for shippers and logistics service providers. Additionally, the selection of TR can give a better advice to terminal operators to reduce the impact of customs declaration delay. This has a great attraction for customs agencies. For the terminal layout, the TRs can be used as references for designers during the initial design of terminals.

In the future, the types of TRs will become changeable with the development of ICTs and intermodal transportation modes. Therefore, it is significant to explore and expand the TR category library. Furthermore, a new direction of mathematical modeling and optimization based on DPFOM_RE for the ICTs' transshipment scheduling. The management framework based on DPFOM_RE provides new ideas for terminal managers.

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