Journal of Artificial Intelligence for Automation
https://www.sciltp.com/journals/jaia

Article

A Novel Operation Mode for Container Terminal with Changeable Intermodal Transport Demand: Distribution, Flexibility, and Reentrancy

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How To Cite: Li, W.; Zhong, L.; He, L.; et al. A Novel Operation Mode for Container Terminal with Changeable Intermodal Transport Demand: Distribution, Flexibility, and Reentrancy. *Journal of Artificial Intelligence for Automation* **2026**, *1*(2), 10. https://doi.org/10.53941/jaia.2026.100010

Received: 4 January 2026
Revised: 3 April 2026
Accepted: 8 April 2026
Published: 10 June 2026

Abstract: The operation mode of loading, unloading, and transshipment (LUT) is of great importance in managing/configuring resources and scheduling container tasks to maximize the operational efficiency of intermodal container terminals (ICTs). In the past decade, terminals have typically adopted a traditional operation mode, mainly the hybrid flow shop mode with fixed routing and non-reentrant processing, for container task operations. However, this mode cannot adequately meet the variable intermodal container transshipment demands, nor provide optimal transshipment routes to cope with the flexible intermodal transport needs. This study constructs a novel Distributed Parallel Flexible Operation Mode with Reentrant Equipment (DPFOM-RE) for ICTs, which includes three components: distributed multi-parallel operations, flexible LUT routes, and reentrant equipment. Based on DPFOM-RE, ICTs can efficiently handle different intermodal container tasks (e.g., import/export and transshipment containers) simultaneously via multiple transshipment routes. In addition, a generic LUT management framework is proposed. A simulation case is conducted and the results show that DPFOM-RE outperforms the traditional mode in terms of makespan, average handling frequency per container, and turnover rate of internal trucks. The benefits for stakeholders are demonstrated, and future research directions are discussed.

Keywords: intermodal transport; container terminal; operation mode; distributed operation; flexible operation; reentrant equipment

1. Introduction

Intermodal transportation refers to the movement of containers through a sequence of at least two distinct transport modes [1]. Compared with unimodal transportation, intermodal transportation offers greater flexibility in selecting transport modes based on the specific characteristics of containers [2]. In 2024, combined transport operators that are members of the International Union for Road-Rail Combined Transport (UIRR) recorded a 5.19% increase in the number of consignments transported via their intermodal networks. The growth in tonne-kilometres was even higher, reaching 8.41%, driven by an increase in the average weight of individual consignments [3]. While sea-road and rail-road intermodal systems have been well established at major Chinese ports (e.g., Yangshan, Ningbo-Zhoushan, Dalian, Qingdao, and Guangzhou), sea-rail intermodal transportation has garnered growing attention in recent years. As of 4 September 2025, the New International Land-Sea Trade Corridor in China had handled over 1 million twenty-foot equivalent units (TEUs) via rail-sea intermodal freight trains, representing a year-on-year increase of 72.5% [4]. A typical application of sea-rail intermodal transportation is the Eurasian Land Bridge, which links Europe and China. This corridor facilitates the transport of imported goods to China and other

Far Eastern countries; on its return leg from Central Europe, the network carries European products that are subsequently loaded onto feeder vessels for final delivery to China. Although intermodal transportation enhances the efficiency of global trade, it also imposes significant operational pressure on container terminals. Different types of intermodal containers must be transferred to designated intermodal operation zones within terminals, thereby increasing the complexity of container transshipment processes.

Intermodal container terminals (ICTs) serve as the core nodes of intermodal transportation systems and are responsible for managing the transfer of containers between different transport modes. As illustrated in Figure 1, ICTs comprise several key components: railway yard operation zones (rail access areas), internal trucks (ITs), general yard operation zones (including yard crane handling areas and container storage areas), gate check-in/out zones, external trucks (road access areas), and berth operation zones (including quay crane (QC) handling areas and truck transfer zones). Notably, multiple yard operation blocks are typically arranged in a regular, non-interfering layout within terminals. For most ICTs, direct access to external trucks and railway networks has become a standard design trend. Intermodal container flows are not limited to vessel-road connections but also include vessel-rail links. The addition of dedicated operation zones and transport access points further increases the complexity of terminal transshipment operations.

Figure 1. Layout of the container terminal and functional operation areas (Qingdao container terminal).

Against this backdrop, ICTs are increasingly compelled to adopt integrated operational modes that can effectively coordinate diverse zones and equipment to optimize intermodal container transshipment processes. In recent years, container terminal development has focused on three core technology domains: automation, electrification, and digitalization. Among these, automation and digitalization have emerged as the most critical drivers of progress, with their implementation partially facilitated by innovations in operational modes [5]. Consequently, the study of novel operational modes for ICTs is of substantial practical significance.

In ICTs, loading, unloading, and transshipment (LUT) operations are completed through the collaborative interaction of different terminal zones and equipment. The LUT process is a complex, multi-stage workflow for container transshipment, which generally consists of three key steps: QC handling, IT horizontal transportation, and railway crane (RC) handling. Conventional container terminals (CTs) typically provide only a single transshipment route—defined as the specific execution sequence of the LUT process—for each type of container. In contrast, ICTs must simultaneously handle multiple types of intermodal containers (e.g., sea-road and sea-rail intermodal containers). Several studies have addressed this research gap [6,7]. Specifically, the LUT execution sequence for import container tasks follows the order of QC handling, IT horizontal transportation, and RC handling. Whereas for export container tasks, the sequence is reversed: RC handling, IT horizontal transportation, and QC handling. For containers of the same type, import and export tasks employ an identical combination of LUT process steps.

In previous years, the existing operation mode for the LUT process was based on the hybrid flow shop operation mode (HFSOM). The HFSOM is a production mode widely used in industrial manufacturing, capable of handling only one type of fixed production process at a time [8]. The hybrid flow shop problem is, in most cases, NP-hard [9]. In recent decades, academia has analyzed several problems in container terminals (CTs) based on the HFSOM. For instance, Chen et al., Sun et al., and Zhong et al. [10–12] constructed three-stage LUT scheduling models derived from the HFSOM. Although the HFSOM can effectively integrate processes with strong couplings, it can only handle container tasks with a single transshipment route and cannot simultaneously accommodate flexible transshipment routes for diverse intermodal container tasks.

Recently, Zhong et al. [13] addressed an integrated container scheduling problem involving two transshipment routes for sea-road containers. Li et al. [14] considered flexible transshipment routes for sea-rail container transshipment operations involving four types of equipment. Both studies highlight the limitation of a single transshipment route in the HFSOM. However, while these studies discuss different transportation routes, they focus exclusively on the transportation of a single type of intermodal container. It should be noted that the management of transshipment in CTs becomes more challenging when intermodal transshipment processes are considered. To date, no research has been able to integrate all types of transshipment routes into a single integrated operation mode.

Based on the above considerations, we conducted an in-depth analysis of the following aspects: First, during loading, unloading, and transshipment (LUT), the distributed operation characteristics must be carefully considered for operation areas equipped with both homogeneous and heterogeneous equipment. Second, due to intermodal transportation, the types of intermodal containers and terminal operation areas increase, which, in turn, leads to the diversification of transshipment routes. The new model must be capable of handling transshipment for various tasks and providing sufficient flexible transshipment routes for multiple classes of containers. Third, the characteristics of critical equipment that is utilized multiple times during transshipment need to be properly defined to improve their effective utilization.

Motivated by the above considerations, this paper proposes a comprehensive and effective novel LUT operation mode. Its main innovations and contributions are as follows:

(1) Distributed multi-parallel operations are constructed for areas equipped with both homogeneous and heterogeneous equipment.
(2) Flexible LUT routes in intermodal container terminals (ICTs) are proposed for sea-rail-road intermodal containers.
(3) Reentrant equipment is selected, and the concept of reentry is defined for the proposed mode.
(4) A management framework for ICT managers is constructed based on this novel mode.

The rest of this paper is organized as follows: Section 2 reviews research on distributed scheduling, provides more detailed background on the traditional operation mode and reentrant operations, and identifies existing research gaps. Section 3 presents the construction of the DPFOM-RE. Section 4 designs a simulation study for mode comparison. Section 5 discusses the advantages of the proposed mode and elaborates on future research perspectives for modeling and scheduling based on the proposed mode. Section 6 concludes the paper.

2. Related Work

This section presents the related works on distributed scheduling, traditional LUT operation mode, and reentrant operations in CTs. Finally, the research gaps are identified.

For each type of container, Liu et al. [6] integrated the analysis of import/export railway containers and import/export highway containers; however, their framework only considered three types of equipment: railway container gantry cranes, yard stacking cranes, and internal trucks. Liu et al. [7] further explored the coexistence of railway and road containers in shared yard spaces, but their flexible scheduling model was restricted to a single type of equipment.

2.1. Distributed Scheduling

In practice, distributed manufacturing has been widely applied in various industrial scenarios, such as semiconductor wafer manufacturing [15], distributed multi-agent manufacturing scenario of new energy vehicles [14], distributed manufacturing with fuzzy PID control [16], and scheduling IoT applications in edge and cloud computing environments [17]. Extensive research has been conducted on scheduling in distributed manufacturing systems.

Wu et al. [18] introduced distributed flexible job shop scheduling to address manufacturing challenges in building materials and equipment manufacturing enterprises. Additionally, relevant studies have integrated distributed scheduling problems with other research topics, such as multi-factory manufacturing [19,20] and vehicle routing problems [21].

Notably, research on distributed job shop scheduling in factories originated in the 1980s. Most early studies focused on homogeneous factories or machines, with only a limited number addressing heterogeneous machines in heterogeneous factories. Researchers have achieved some progress in the field of distributed heterogeneous parallel machine scheduling.

Behnamian et al. [22,23] solved distributed heterogeneous parallel machine problems involving different processing speeds and heterogeneous factories. Marzouki et al. [24] studied the distributed flexible job shop scheduling problem with transportation time in a collection of factories that are distributed geographically.

In most ICTs, each LUT operation area is equipped with at least two units of homogeneous equipment. Each stage-specific operation area is divided into at least two functional units, each with the same operational capabilities and the ability to work simultaneously [25,26]. However, few researchers have considered resource allocation and task scheduling from the perspective of distributed scheduling. This oversight results in low transshipment efficiency and an imbalance between resource supply and demand.

2.2. Traditional LUT Operation Mode

To date, the modeling and scheduling of LUT processes have been based on the HFSOM [10–12,27–33]. Chen et al. [10] studied the three-stage integrated scheduling problem of QCs, ITs, and RCs as a hybrid flow shop scheduling problem with blocking and sequence-dependent setup times. Lee et al. [27] considered the comprehensive scheduling of QCs and RCs as a hybrid flow shop with sequence-dependent setup times. Xin et al. [28] studied the joint scheduling of QCs, ITs, and automatic stackers, and proposed a hybrid flow shop scheduling model to represent discrete events. Yang et al. [29] proposed a bi-objective integrated optimization model for the three-stage handling operations among QCs, ITs, and reach stackers, based on the hybrid flow shop scheduling problem. Qin et al. [30] regarded the three-stage operations of QCs, ITs, and RCs as a hybrid assembly line operation problem. Jonker et al. [31] developed a scheduling model involving QCs, ITs, and RCs. Sun et al. [11] proposed a multi-resource collaborative scheduling optimization model based on the principle of the blocking-type hybrid flow shop problem. Zhuang et al. [32] formulated the integrated scheduling of intelligent handling equipment as a blocking hybrid flow shop scheduling problem with bidirectional flows and limited buffers. Zhong et al. [12] proposed a multi-objective optimization model for the integrated operations of QC handling, IT traveling, and RC handling, considering no-idle QC operations in a container terminal. Shi et al. [33] developed a hybrid flow shop scheduling model that utilizes vehicle transportation to maximize operational efficiency.

In the aforementioned studies, mathematical models for joint scheduling were all established based on the HFSOM. These studies abstract each operation stage of the LUT process as a multi-parallel machine operation and assume that the LUT processes of all containers are consistent. However, such studies based on the HFSOM overlook both the distributed characteristics of equipment across all operation areas and the diversity of LUT routes that result from intermodal transportation.

2.3. Reentrant Operations

As critical horizontal traveling equipment in ICTs, ITs frequently interact with QCs and RCs. Accordingly, most studies on ITs have been conducted from the perspective of integrated scheduling. Notably, more complex multi-stage integrated scheduling problems have been investigated, which simultaneously schedule QCs, ITs, and RCs in ICTs [34,35]. In these models, the three types of equipment are assigned to container tasks, and the routes of ITs are planned at the same time.

Within these models, the limited number of ITs necessitates the transportation of multiple container tasks. Yang et al. [35] pointed out that the waiting time of ITs can be eliminated during their interaction with RCs, thereby achieving spatiotemporal synchronization and minimizing the completion time of all tasks. In these studies, the traveling routes of ITs follow a loop rule, i.e., cycling back and forth between two operation areas [34–36].

It is evident that current research on IT routing is limited to closed-loop cycles between the endpoints of two operation areas. However, few studies have explored how to utilize non-circulating routes to improve the utilization efficiency and turnover rate of ITs when multiple operation areas require IT services. A non-circulating traveling route refers to a route where ITs have more than two endpoints in the terminal's operation areas and can shuttle between any number of these endpoints, rather than traveling sequentially between only two.

2.4. Research Gap

In current research, the characteristics of distributed multi-parallel operations are not fully reflected in traditional operational modes adopted by ICTs. Such modes cannot simultaneously handle different types of intermodal containers, and the classification and definition of LUT routes for intermodal containers remain inconsistent. Moreover, some critical equipment in ICTs may be deployed multiple times during LUT processes, a characteristic that has not been adequately investigated in existing studies.

Although the proposal and construction of this novel mode pose several challenges, its implementation yields notable benefits across multiple stakeholders: for the intermodal transport network, the safe and efficient operation of ICTs can significantly enhance the stability of container transportation; for ICTs themselves, the shift in operational mode can effectively reduce container waiting times and boost terminal competitiveness; for terminal clients, improved operational efficiency of ICTs translates into tangible reductions in logistics costs.

3. Construction of DPFOM-RE

In this section, we study the feature extraction in LUT system in the context of ICTs. Three parts of the DPFOM-RE are constructed as follows: (1) Distributed multiple parallel operations; (2) Flexible LUT route; (3) Reentrant equipment.

3.1. Distributed Multiple Parallel Operations

In this subsection, we use sea-rail transshipment as a case study to characterize the attributes of distributed multiple parallel equipment operations in ICTs.

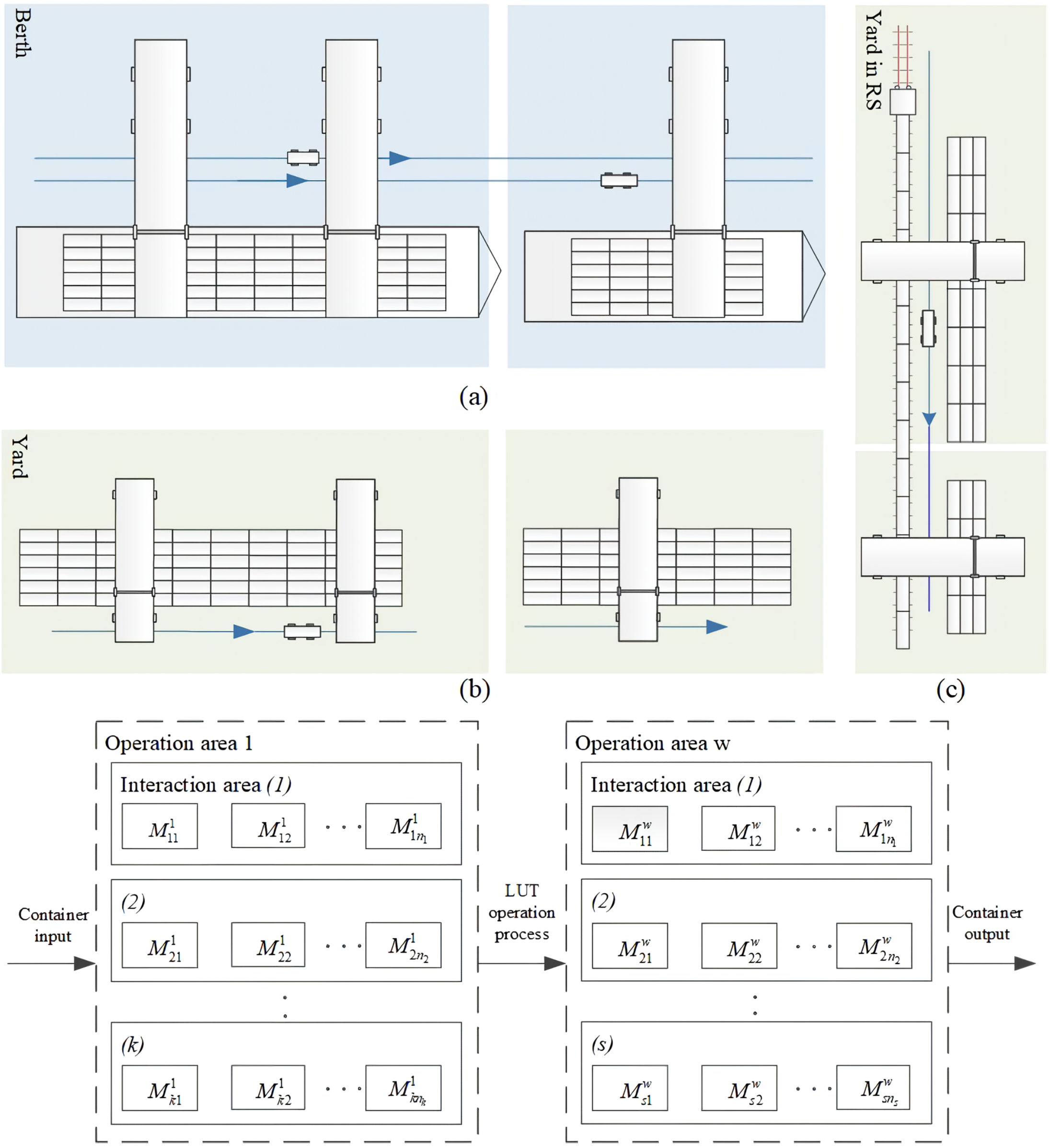
As shown in Figure 2a–c, we can observe that a variety of equipment for different processes is distributed in multiple areas in batches, and the equipment can operate simultaneously. This constitutes the distributed feature of heterogeneous transfer equipment.

In each area, there are at least two sets of homogeneous equipment. For example, as shown in Figure 2a, berth 1 in the berth operation area is equipped with two QCs, and berth 2 is equipped with one QC.

Figure 2b,c shows that yards 1–2 are each equipped with two RCs respectively in the storage yard area, which have the same storage capability. In the railway station area, however, the operation capability of yard 1 is greater than that of yard 2, because yard 1 has more RCs.

As evidenced by the above examples, multiple distributed interaction zones of varying scales exist within the same operation area of ICTs. Each of these distributed interaction zones is equipped with an appropriate number of homogeneous equipment. The distributed configuration characteristic provides a foundation for distributed parallel machine operations. This configuration enables flexible handling of container tasks of different scales or in response to emergencies. Accordingly, the distributed parallel machine operation concept is introduced to characterize the fundamental transfer characteristics of LUT processes, as illustrated in Figure 2d. The k and s denote the total number of interaction areas in the operation area 1 and w respectively, and the means that the n_l-th machine exists in the interaction area j, which exists in the operation area i. The definition of distributed multiple parallel operations is presented below.

Definition 1. *Distributed Multiple Parallel Operations (DMPO) in ICTs refers to the configuration of homogeneous equipment in distributed interaction zones and heterogeneous equipment across different operation zones, where transfer operations between distinct zones do not interfere with one another. When confronted with changing tasks or uncertainties, the most appropriate equipment can be allocated to simultaneously handle multiple tasks from distributed zones during LUT processes. Let* S *denote a closed set, representing the set of operation zones, where* $S = So_1, \ldots, So_i, \ldots, So_n$*,* $|S| \geq 1$*,* $i = 1, 2, \ldots, n$*. Each* So_i *is also a closed set, representing the operation area* i *in ICT. Additionally, The set* $So_i = St_{i1}, \ldots, St_{ij}, \ldots, St_{im}$*,* $|So_i| \geq 2, j = 1, 2, \ldots, m,$*, where each* St_{ij} *is also a closed set, indicationg the distributed interaction area* j *within* So_i*.*



(a)

(b) (c)

(d)

Figure 2. The characteristics of DMPO of equipment in ICTs. (**a**) Berth operation area; (**b**) Yard operation area; (**c**) Yard operation area in rail station; (**d**) The flow of distributed multiple parallel operations.

3.2. Flexible LUT Route

Considering the combinations of intermodal transportation, this section analyzes the transshipment routes (TR) during the LUT processes in ICTs. As illustrated in Figure 3, the interaction diagram depicts the traveling zones of internal trucks (ITs) and external trucks (ETs) across selected operation zones for the sea-road-rail intermodal transportation combination. Among these operation zones, the yard operation zone is the most frequently accessed by ITs and ETs, followed by the railway station zone. The types of transshipment routes (TR) for intermodal containers are presented in Figures 4–7, where the arrows in these figures indicate the container flow directions.

For sea-road coordination, containers need to be transferred between vessels and ETs. Figure 4 illustrates two types of TRs for sea-road container (S-D container) tasks:

- Type 1: If ETs are allowed to enter the berth operation area, QCs handle containers directly between the vessel and the ETs. This route is depicted in Figure 4a.
- Type 2: Containers are first transported from the berth to the yard by ITs and then loaded onto ETs by RCs, or vice versa for the land-to-sea direction. The route is shown in Figure 4b. Notably, this type involves temporary container storage time within the yard.
- Type 2 is the standard operational practice in most ICTs as it effectively alleviates resource constraints. Specifically, when the volume of transfer tasks exceeds the immediate handling capacity of the equipment at the berth, the yard serves as a buffer, allowing for the temporary storage of containers to maintain operational efficiency.

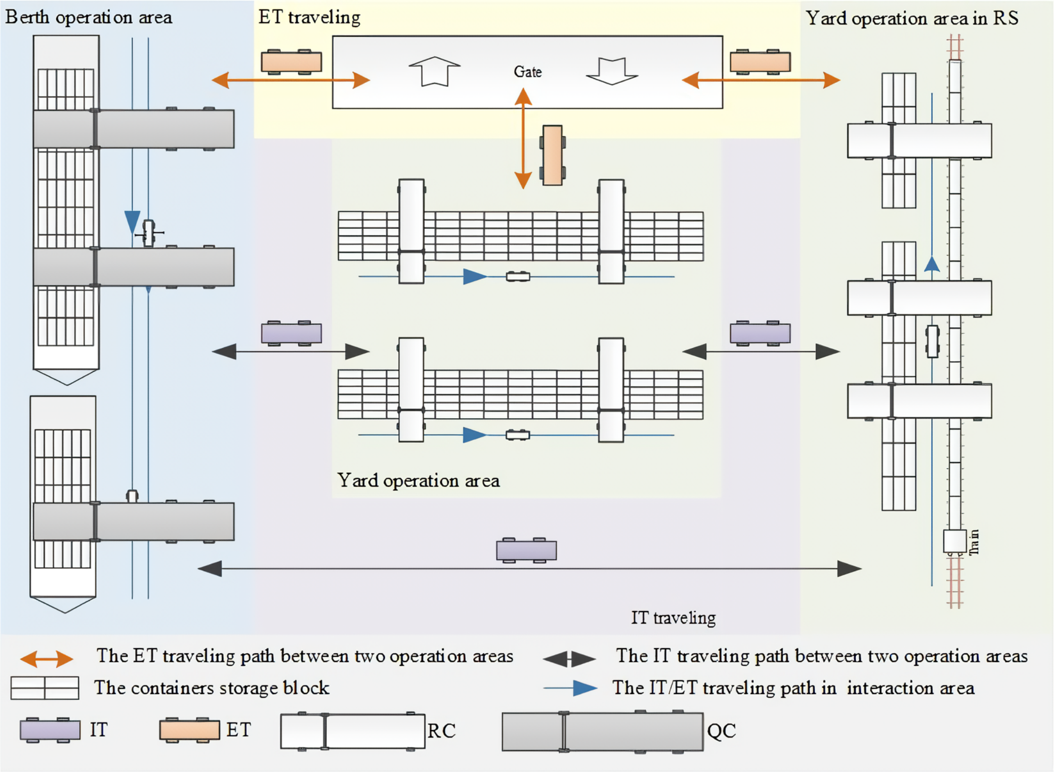


Figure 3. Interaction diagram among operation areas in an ICT.

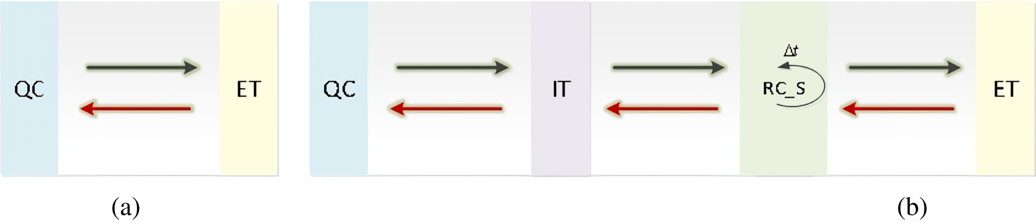


Figure 4. The TRs of sea-road containers. (**a**) Type 1 of TR; and (**b**) Type 2 of TR.

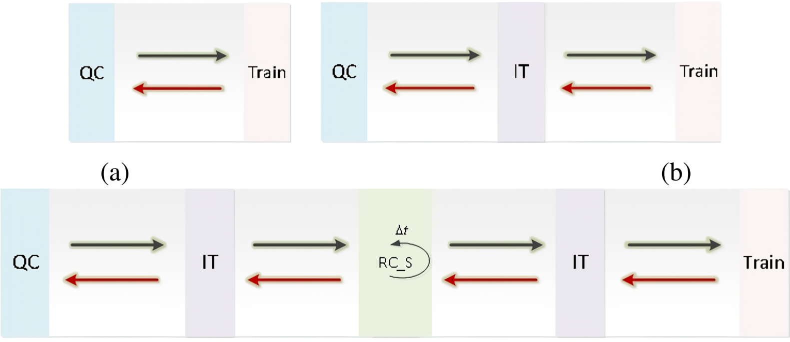
The LUT process between vessels and trains in the ICT is required for sea-rail intermodal containers. Figure 5 shows three types of TRs for sea-rail container (S-L container) tasks:

- Type 3: If the railway line connects directly to the berth operation area, QCs can transfer containers directly between vessels and trains without the need for horizontal transportation by ITs. This route is depicted in Figure 5a.
- Type 4: In contrast to Type 3, if trains are not permitted to enter the berth area, containers must be transported between the berth and the railway station via ITs. This route is shown in Figure 5b.
- Type 5: Containers are first transported from the berth to the yard by ITs for temporary storage. When the railway station is ready to receive them, the containers are then moved from the yard to the railway station by ITs (or vice versa). As shown in Figure 5c, this route involves temporary yard storage and requires ITs to complete two separate transfer legs (Berth-Yard and Yard-Station).

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

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, in addition to S-D container and S-L container tasks, there are road-rail container (D-L container) tasks. These D-L containers are transported between trains and ETs. Figure 6 shows two types of TRs for D-L container tasks:

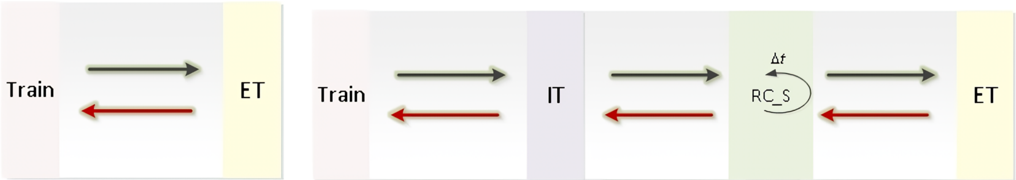
- Type 6: If the ETs have access to enter the railway station area directly, the D-L containers are carried from the train to ETs by the RCs in the rail station directly without other transfer. In contrast, the transfer is from ETs to trains. The TR is shown in Figure 6a.
- Type 7: The containers are 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 incurred due to storage procedures in the yard. The TR is shown in Figure 6b.



(a) (b)

(c)

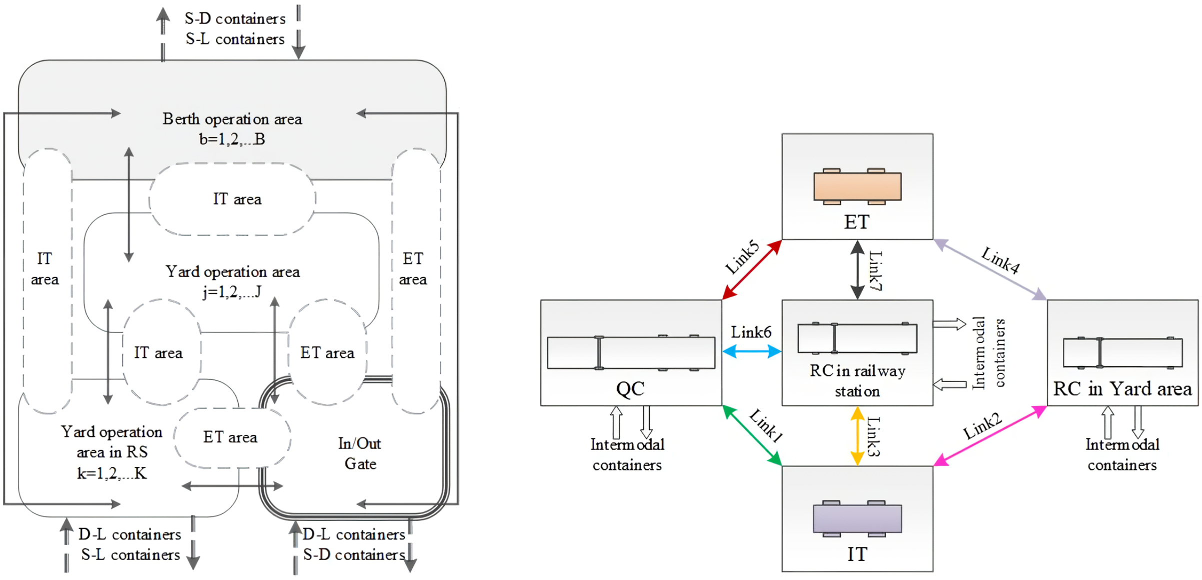
Figure 5. The TRs of sea-rail containers. (**a**) Type 3 of TR; (**b**) Type 4 of TR; (**c**) Type 5 of TR.



(a) (b)

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

Figure 7 illustrates the flexible operational logic, showing the relationships between operational areas, container flows, and individual processes. Figure 7a highlights the key areas used during intermodal operations, with dashed arrows denoting container flows between areas. These areas are connected via IT and ET transport links. Figure 7b breaks down the process into five common subprocesses, connected by seven colored links. These subprocesses are: QC handling, reentrant IT travel, RC handling (yard), RC handling (railway station), and ET travel. Each TR type is represented as a combination of these links, as below: 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; and Type 7 consists of link 3, link 2, and link 4.



(a) (b)

Figure 7. The flexible operational processes of LUT in ICTs.

In this subsection, we discuss various operation areas in ICTs. The three types of intermodal transporations, S-D, S-L, and D-L, 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 aspects reflect the flexible transshipment operation of the intermodal container tasks in ICTs. Finally, the flexible LUT route is defined as follows:

Definition 2. *A Flexible LUT Route (FT) is defined as a dynamic assignment strategy where each Transfer Route (TR) corresponds to a unique LUT process. Considering the distributed equipment characteristics proposed in Section 3.1 and the constraints of equipment resources, the system allows each container to select the most appropriate TR type from the options defined above to complete its transfer. Furthermore, the selected TR for each container can be adjusted based on the real-time resource status prior to the commencement of transshipment.*

3.3. Reentrant Equipment

As a critical component of horizontal transportation within the ICT, the IT plays a crucial role in the LUT process. As illustrated in Figures 3 and 7, ITs are capable of traveling across all operational areas and may be deployed for two distinct trips within a single TR. Furthermore, temporary storage time Δt is incurred in type 2, type 5, and type 7 of a TR. Because RCs are needed to handle containers at both the start and end of Δt, these routes necessitate two RC handling tasks per container.

Based on the above factors, we define reentrant equipment:

Definition 3. *Reentrant equipment (RE) refers to equipment that executes multiple operational processes for a single container transfer task. Let* $r_ij = \left[r_{ij}^1, \ldots, r_{ij}^y, \ldots, r_{ij}^Y\right]$ *be the finite-dimensional process sequence vector for equipment* e_i *handling container* j*,where* Y *is the total number of processes. Let* $|w_{ij}|$ *be a subset of elements extracted from* r_ij*, such that the cardinality* $|w_{ij}| \geq 2$*. Let* $E = \{e_1, \ldots, e_i, \ldots, e_n\}$*be the set of all quipment. If there exists a mapping from equipment* e_i *to a subset* w_{ij} *, then* e_i *is defined as RE.*

In conclusion, both RCs and ITs are classified as REs. This raises a critical question: what implications does the operation of REs have for the LUT system? The analysis is as follows:

Firstly, as REs are assigned an increasing number of operational processes, they must process more instructions than non-reentrant equipment. Secondly, this heightened instruction load requires REs to respond promptly to directives from the equipment that performed the preceding transfer process. Simultaneously, an appropriate idle RE must be allocated in a timely manner to maintain workflow continuity. Thirdly, if no idle equipment is available to service an IT upon its arrival at an operational area, the IT must wait. Consequently, the IT, still laden with containers, cannot depart until the containers are unloaded by an available piece of equipment in that area.

To summarize, it is imperative to consider the idle states of REs during operations. Furthermore, the tightly coupled spatiotemporal constraints that may arise when REs interact with equipment in other operational areas must also be taken into account.

3.4. Management Framework of LUT Based on DPFOM-RE

In the preceding sections, we identified three key features of the LUT system within ICTs: distributed multi-parallel operations, flexible LUT routes, and reentrant equipment. These features collectively constitute the novel DPFOM-RE, which integrates all operational processes flexibly to efficiently handle diverse intermodal container tasks.

To complete the LUT process, it is essential to select a TR for each container, assign equipment to each stage of the TR, and schedule the processing sequence. These decisions are derived through mathematical modeling and optimization based on DPFOM-RE. Although this approach exhibits higher computational complexity than methods based on traditional HFSOM, recent advancements in terminal layout optimization, 5G transmission technology, and large artificial intelligence (AI) models provide the necessary support for complex modeling and real-time optimization. As shown in Figure 8, the management framework of LUT based on DPFOM-RE consists of three parts: (1) enabling technologies for ICT management; (2) operation mode-based modeling and optimization; and (3) the actual execution of the LUT process.

Enabling Technologies. Layout optimization, 5G+ICT integration, and large AI models are the cornerstones for both solving container terminal optimization problems and realizing smart terminals. Layout optimization has the most significant impact on the LUT process, as TR types are inherently determined by the terminal layout—encompassing the apron, storage yard, and other collection/distribution (C/D) points. Furthermore, during large-scale container transfers, terminal operators must manage vast resources while collecting real-time equipment operational data and environmental data. Fast and stable data transmission, enabled by 5G+ICTs, is critical for supervising operations. However, raw collected data often cannot directly reflect the actual operational status due to noise. Therefore, large AI models are necessary to filter noise and extract valuable insights from the operation data.

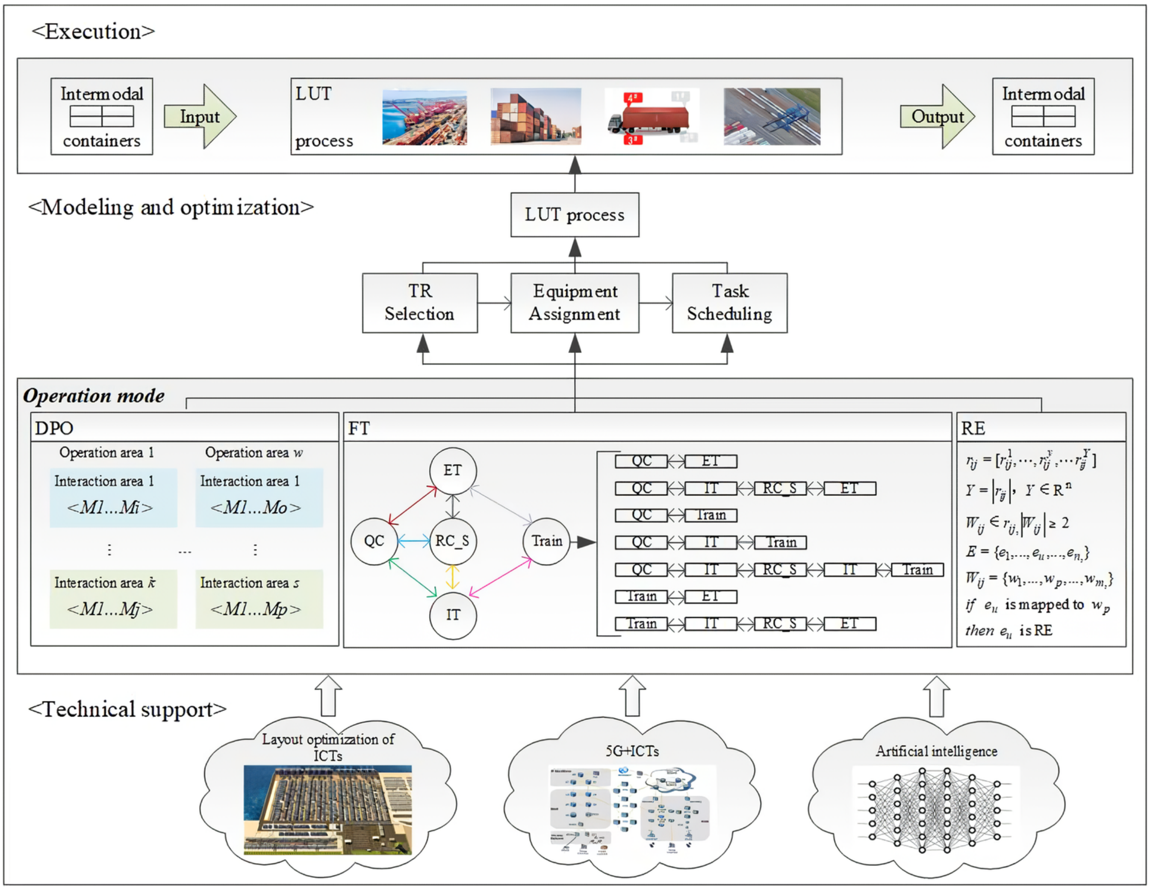


Figure 8. The management framework of LUT based on DPFOM-RE.

Secondly, once these foundational technologies meet the operational requirements of container terminals—including the handling of large-scale container transfer tasks and reliable data transmission—the optimal transfer route (TR) for the LUT process, resource allocation scheme, and container task execution plan can be derived through operation mode-based modeling and optimization. Among these steps, establishing a rational operation mode serves as the fundamental premise for solving ICT-related optimization problems. Developing an innovative operation mode is also crucial for formulating efficient and actionable LUT procedures. The novel operation mode proposed in this study fully incorporates key characteristics such as the layout and organizational structure of intermodal transportation, resource distribution, and operational capacity. This design enables the full exploitation of terminal operational potential and adapts to the dynamic LUT demands of intermodal container tasks. Specifically, the operation mode encompasses the three core features identified earlier: distributed multi-parallel operations, flexible LUT routes, and reentrant equipment (RE). Once the operation mode is determined, TR selection, equipment allocation, and container task scheduling are sequentially implemented based on this mode to generate an efficient and executable LUT process scheme for containers.

Finally, the resource allocation and scheduling plans, which include detailed LUT procedures, are submitted to the execution management department. Subsequently, the on-site equipment receives operational instructions and completes the LUT process for container tasks in accordance with the approved plans.

4. Case Study

HFSOM is a traditional LUT operation mode, and it is used to construct mathematical models for the assignment and scheduling of QCs, RCs, or trucks. To compare DPFOM-RE and HFSOM in the context of ICTs, a simulation case study is designed including S-D, S-L, and D-L containers. Three comparison indicators, namely makespan, average handling frequency per container, and turnover rate of IT, are defined in Subsection 4.2.

4.1. Benchmark System

This case is studied on a simulated U-shaped ICT, as shown in Figure 9. In the U-shaped ICT, there are many operation areas, including one ET parking lot area, one IT parking lot area, two berth operation areas, six storage yard areas, and one railway station. The traveling areas of the ETs (black path) and the ITs (gray path) are physically isolated. The design ensures conflict-free operation between ETs and ITs and enhances the safety of

ETs within the ICTs.

We use BQ_i to represent the number of QCs equipped in berth i. $BQ_1 = 2$, $BQ_2 = 3$. YR_i represents the number of RCs equipped in the yard area i, $YR_i = 2$. The train station is equipped with one storage yard, one RC, one train track, and one train with 66 cars. The number of ITs is limited. The number of ETs is equal to the number of S-D and S-L containers. The parameters of equipment used in the simulation are referred from actual values.

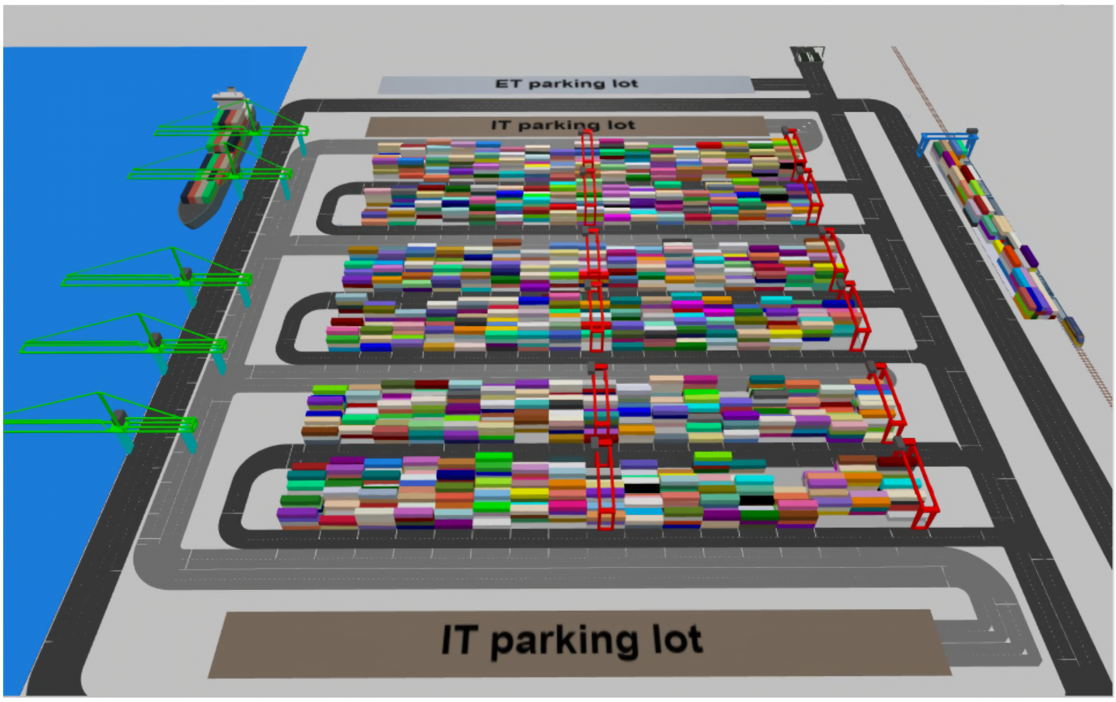


Figure 9. 3D layout view of the U-shaped ICT.

4.2. Performance Indicators

The following three indicators are designed from the perspective of the time dimension, operation dimension, and equipment utilization dimension.

(1) Makespan— C_{max}

The makespan is the completion time of LUT process for all intermodal container tasks. The result of C_{max} is calculated by Gantt charts.

In addition, the makespan is directly related to the turnaround time of vessels and the sequence scheme for vessels entering the berth areas. Furthermore, C_{max} affects the number of vessels operating in ICT per unit of time indirectly. It will have an impact of economic on the operators of ICTs, vessels, clients, and other stakeholders at the same time. Its average value reflects the competitiveness of the terminal among peers.

(2) The average frequency of each container be handled— $Fcon$

$Fcon$ is calculated as the total handling times of all containers handled divided by the total of containers. The lower value of $Fcon$, the better. The calculation formula of $Fcon$ based on DPFOM-RE is defined as follows:

$$Fcon = \frac{1}{\sum_{i=1}^{7} Htr_i} \sum_{i=1}^{7} Htr_i \cdot Ftr_i \tag{1}$$

where Ftr_i means the total times that one container is handled by equipment under type i of TR. The specific values of Ftr_i are given in the Table 1. Htr_i represents the number of containers assigned to type i of TR.

Table 1. The total times of one container be handled with the type i of TR.

Ftr$_1$	**Ftr$_2$**	**Ftr$_3$**	**Ftr$_4$**	**Ftr$_5$**	**Ftr$_6$**	**Ftr$_7$**
1	2	3	4	5	6	7

The calculation formula of Fcon based on HFSOM is defined as follows:

$$Fcon = \frac{1}{H_{S-D} + H_{S-L} + H_{D-L}} \left(H_{S-D} \cdot F_{S-D} + H_{S-L} \cdot F_{S-L} + H_{D-L} \cdot F_{D-L} \right) \tag{2}$$

where H_{S-D},H_{S-L} , and H_{D-L} are the number of S-D, S-L, and D-L containers, respectively. F_{S-D} is the total handling times that one S-D container is handled by equipment based on HFSOM. Likewise, F_{S-L} is the total handling times of one S-L container and the F_{D-L} is the total handling times of one D-L container.

Based on the survey of actual ICTs operations, we set the relevant parameters as follows: F_{S-D} = F_{tr2} = 3, F_{S-L} = F_{tr4} = 4, and F_{D-L} = F_{tr7} = 3.

A lower value of $Fcon$ can reduce the logistics costs of containers, and increase the trust of container clients in ICTs. It also reflects the efficiency of an ICT. If a terminal can minimize $Fcon$, it can get more attention from its customers and gain higher competitiveness than its peers.

(3) Turnover rate of IT—$Trate$

$Trate$ means the average value of all ITs' usage per unit time. For DPFOM-RE and HFSOM, the formula of $Trate$ is defined as follows:

$$Trate = \frac{1}{IT\_num} \sum_{i=1}^{IT} T_i \tag{3}$$

where T_i is the total number of tasks completed by the i-th IT per unit time. The IT_num is the total number of working ITs.

The turnover rate of IT reflects the efficiency of ITs in dealing with container tasks comprehensively.

4.3. Container Task Description

4.3.1. Processing Time

The completion time of the LUT process is closely related to several key factors: the terminal layout, equipment parameters, the stowage position of each container, and the destination location (or ID of the receiving intermodal equipment), and other factors.

For the case study, the processing times for these stages are assumed to follow specific distributions. The QC handling time follows a uniform distribution over [95, 145], while the RC handling time ranges from 135 to 175. Furthermore, given that only two yard blocks are utilized in this instance, the IT travel time between the berth and yard areas is uniformly distributed over [130, 150]. The ET travel time between the gate and the berth area is uniformly distributed over [140, 150], and between the gate and the yard area is uniformly distributed over [100, 110]. All processing times are generated randomly from the specified ranges. The time unit is seconds.

Additionally, the temporary storage time Δt , which is inherent in TR Types 2, 5, and 7, is influenced by various real-world factors. To simplify the computational complexity, Δt is set to 0 in all scenarios.

4.3.2. Selection of TRs

In the U-shaped ICT, a container task comprises 20 S-D containers and 20 S-L containers, all of which are unloaded from the vessel. According to DPFOM-RE, seven types of TRs are available for this task.

The assignment scheme of TR for the containers is shown in Table 2. To validate the performance of DPFOM-RE, the LUT processes of the containers are executed under two operational modes: DPFOM-RE and HFSOM [10]. Notably, under HFSOM, yard storage time is inherently incorporated into the LUT process. Consequently, if the containers are transferred under HFSOM, type 2 of TR will be assigned to 20 S-D containers, while type 5 of TR is assigned to 20 S-L containers.

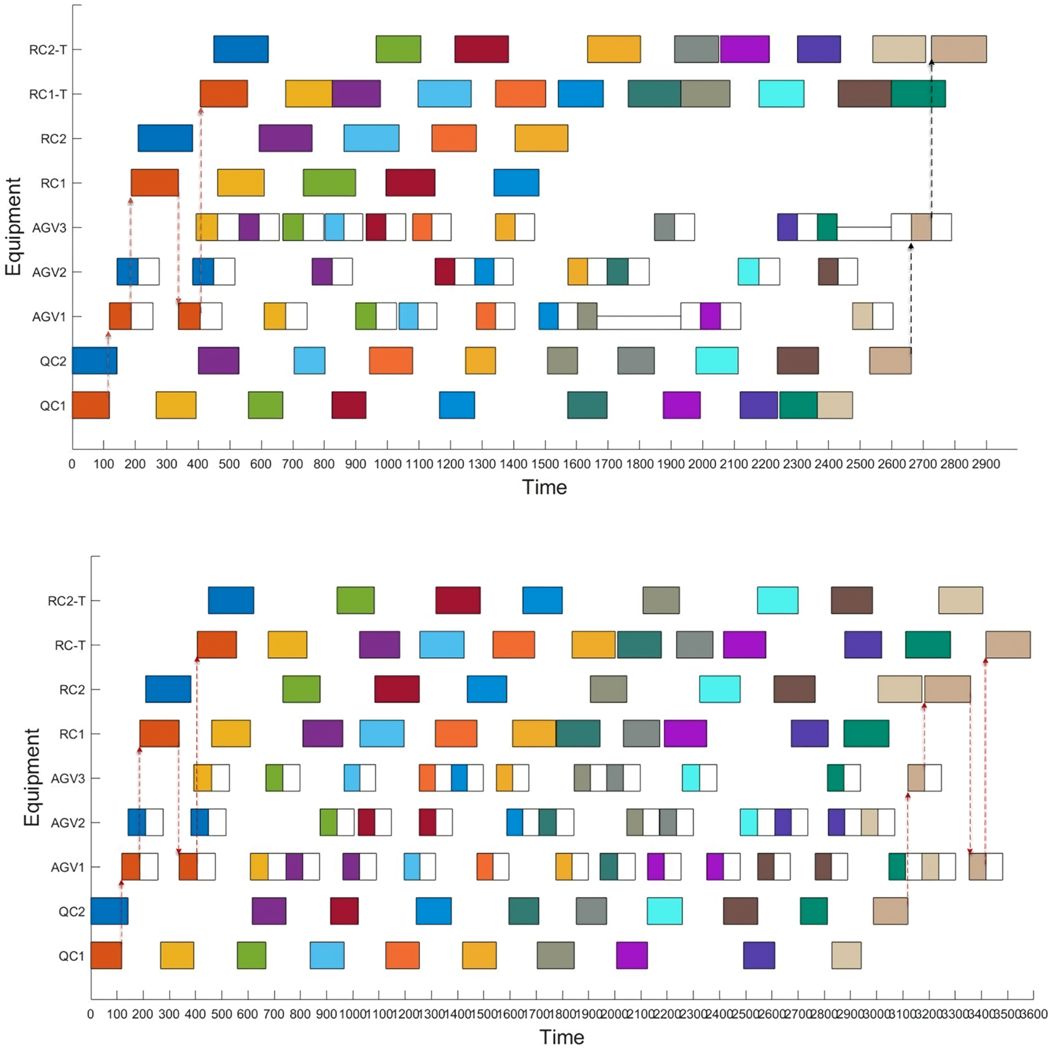
Table 2. The assignment of TR for each container based on DPFOM-RE and HFSOM, respectively.

Container Task	**S-D**		**S-L**	
ID of container	1–10	11–20	21–30	31–40
TR assigned by DPFOM-RE	Type 1	Type 2	Type 4	Type 5
TR assigned by HFSOM	Type 2	Type 2	Type 5	Type 5

4.4. Comparison Results and Analysis

For this container handling task, we computed the aforementioned performance indicators separately for S-D containers and S-L containers. To more intuitively illustrate the operational processes of different TR types, Container 1 and Container 20 were selected as examples. Two colors of dashed lines are plotted in Figure 10a: reddish-brown denotes the process of TR Type 5, while black represents that of TR Type 4. In contrast, only reddish-brown dashed lines are shown in Figure 10b, as only TR Type 5 is executed under HFSOM.

Figure 11a presents the LUT scheme for the 20 S-D containers under DPFOM-RE: TR Type 1 is assigned to the first 10 S-D containers, and TR Type 2 to the remaining 10.



(b)

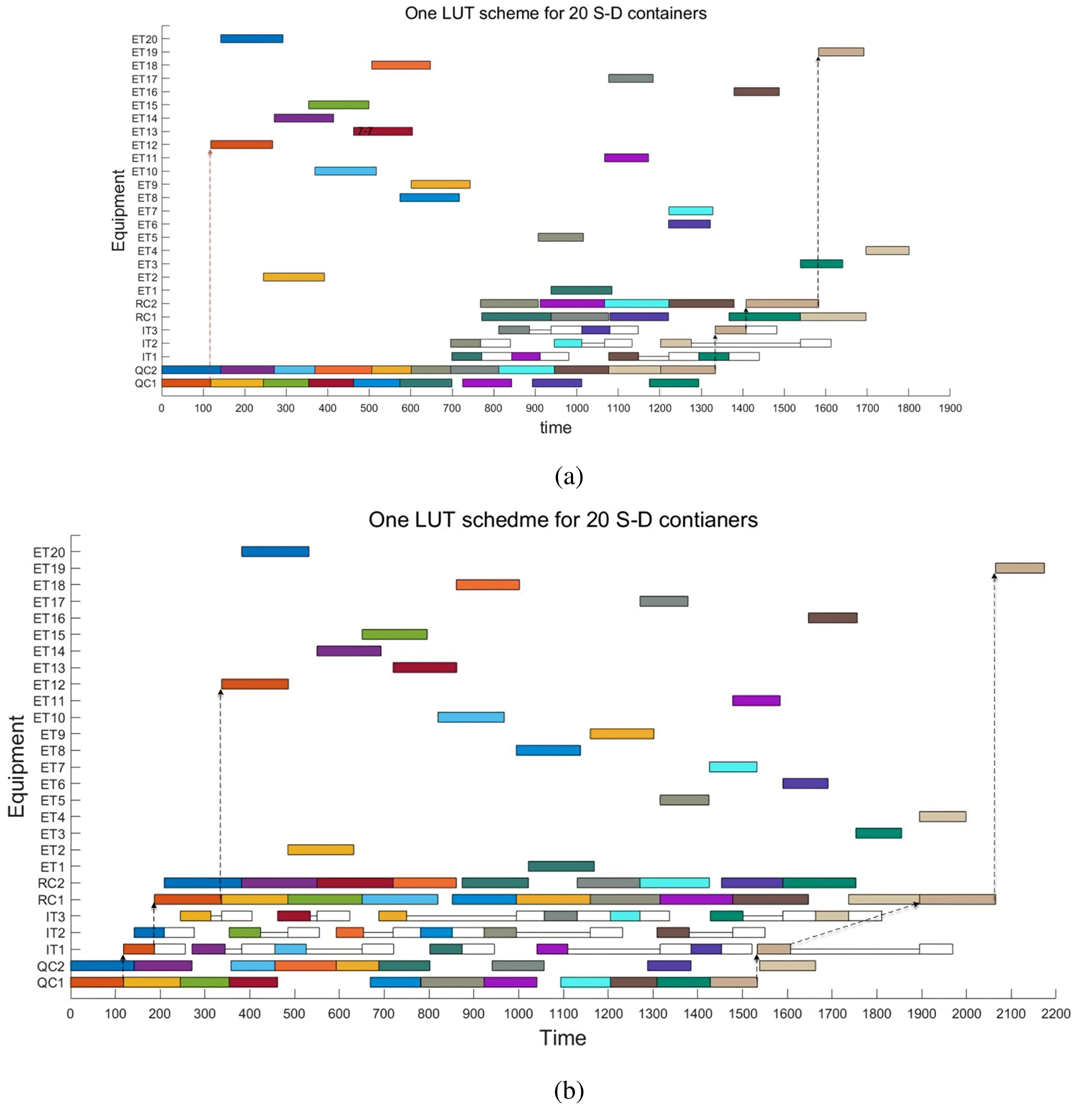
Figure 10. The Gantt charts for 20 S-L containers. (**a**) The LUT scheme obtained by DPFOM-RE; (**b**) The LUT scheme obtained by HFSOM.

As illustrated in Figure 11b, under HFSOM, all containers must be transported by ITs and temporarily stored in the yard. This results in unnecessary time consumption for certain containers, as direct transfer (without yard storage) would be feasible for them.

The C_{max1} under DPFOM-RE is 1724 s, while that under HFSOM C_{max2} is 2073 s. It is evident that C_{max1} is less than C_{max2}. This is because the traveling and waiting times of ITs for the first 10 S-R containers are saved—a benefit not achievable under HFSOM.

Furthermore, QCs only experienced 4 idle periods under DPFOM-RE. In contrast, QCs under HFSOM had 5 idle periods, with unbalanced utilization rates between the two QCs. Consequently, the utilization of the QCs under DPFOM-RE is higher than that under HFSOM.

Figure 10a further illustrates the LUT scheme for the 20 sea-rail (S-L) containers under DPFOM-RE: TR Type 5 is assigned to the first 10 S-L containers, and TR Type 4 to the last 10 S-L containers. The maximum completion time for S-L containers under DPFOM-RE (C_{max3}) is 2901 s, compared to 3543 s under HFSOM (C_{max4}). Clearly, $C_{max3} < C_{max4}$, which is attributed to the saved IT traveling and waiting times for the last 10 S-L containers under DPFOM-RE.



(a)

(b)

Figure 11. The Gantt charts for 20 S-D containers. (**a**) The LUT scheme obtained by DPFOM-RE; (**b**) The LUT scheme obtained by HFSOM.

In addition, under DPFOM-RE, RCs can complete assigned tasks ahead of schedule, significantly improving their turnover rate. In contrast, when handling the same tasks under HFSOM, each piece of equipment is occupied for a longer duration. Collectively, the performance data demonstrate that DPFOM-RE is more efficient than HFSOM for the same container handling tasks in a U-shaped ICT.

As shown in Tables 3 and 4, for 20 S-D containers, it can be seen that the $Fcon1$ = 2 and $Fcon2$ = 3, where $Htr1$ = 10, $Htr2$ = 10, H_{S-D} =20, H_{S-L} = 0 and H_{D-L} = 0. For 20 S-L containers, it is observed that the $Fcon1$ = 3 and $Fcon2$ = 4, with $Htr4$ = 10, $Htr5$ = 10, H_{S-D} = 0, H_{S-L} = 20 and H_{D-L} = 0. DPFOM-RE can significantly reduce the loss and cost of containers for logistics service providers, since the average handling times of QCs and RCs are reduced.

As shown in Figures 11 and 10, for 20 S-D containers, the $Trate_{11}$ = 15.29 and $Trate_{12}$ = 14.50, where $Trate_{11}$ is derived from Figure 11 a and $Trate_{12}$ from Figure 11b. For 20 S-L containers, the $Trate_{21}$ = 15.19 and $Trate_{22}$ = 16.34, with $Trate_{21}$ calculated from Figure 10a and $Trate_{22}$ from Figure 10b. A higher value of $Trate$ indicates a higher IT workload. Notably, the variance of $Trate$ values under DPFOM-RE is smaller than that under HFSOM, indicating more stable IT management under DPFOM-RE. Additionally, DPFOM-RE eliminates invalid IT travel for the same container tasks. Given that RE is a core component of the proposed mode, the aforementioned results highlight the necessity of improving the effective utilization rate of RE, reducing invalid occupancy, and avoiding resource waste.

Table 3. The assignment of TR for each container based on DPFOM-RE and HFSOM, respectively.

	Cmax/(Seconds)	**Fcon/(Frequencies)**	**Trate/(Times/Hour)**
DPFOM-RE	1707	2	15.29
HFSOM	2178	3	14.50

Table 4. The comparison results of DPFOM-RE and HFSOM for 20 S-L containers.

	Cmax/(Seconds)	**Fcon/(Frequencies)**	**Trate/(Times/Hour)**
DPFOM-RE	2901	3	15.19
HFSOM	3543	4	16.34

5. Discussion

It is evident from the aforementioned results that DPFOM-RE exhibits significant differences from HFSOM in both the LUT process and performance. Below, we discuss the advantages, challenges, and future work of the proposed novel mode from the following perspectives.

Distribution. Under HFSOM, intermodal container tasks are processed through the same LUT process. Although homogeneous equipment in an ICT is typically sufficient to complete these tasks, simultaneously handling, transferring, classifying, and storing tens of thousands of containers poses considerable challenges. In contrast, DPFOM-RE adopts a distributed operation mode, which distributes container tasks to equipment in different areas. This effectively alleviates the workload pressure on handling equipment.

Flexibility. In intermodal container operations, TR selection may vary with intermodal combinations. However, HFSOM cannot accommodate flexible TR selection. The destinations of intermodal containers are client-dependent and thus diversified. Unlike HFSOM, DPFOM-RE not only provides traditional TRs for intermodal containers but also meets other customized intermodal demands of clients. Additionally, DPFOM-RE introduces a route selection mechanism that enables terminal managers to select the optimal TR, thereby realizing flexible coordination and utilization of terminal resources.

Complexity. Notably, constructing a mathematical model based on the novel DPFOM-RE will result in higher model complexity compared to that based on the traditional HFSOM. Two primary factors contribute to this: first, DPFOM-RE incorporates more operational areas and equipment simultaneously, leading to an increased number of indices, variables, and constants; second, it can handle multiple intermodal container tasks concurrently, involving more computational objects. Nevertheless, within the same computation time, the distributed and flexible nature of DPFOM-RE yields more accurate solutions than HFSOM.

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 $H_{S-D} \cup H_{S-L} \cup H_{D-L} \in H$, $H_{S-D} \cap H_{S-L} = \emptyset$, $H_{S-D} \cap H_{D-L} = \emptyset$, $H_{S-L} \cap H_{D-L} = \emptyset$. As we know, there are two types of TRs that can be selected for each S-D container, thus, there are $2^{|H_{S-D}|}$ TR combinations for $|H_{S-D}|$ S-D containers. Similarly, 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 $2^{|H_{S-D}|} \cdot 2^{|H_{D-L}|} \cdot 3^{|H_{S-L}|} = 2^{|H|-|H_{S-L}|} \cdot 3^{|H_{S-L}|}$.

Stakeholders. For carriers, completing container tasks promptly directly affects their profitability, making it a critical objective. For terminal operators, terminal operational efficiency is a core competitive indicator among peers. For shippers and logistics service providers, resource losses during the LUT process (e.g., container wear) are also a key concern. For customs authorities and their agents, the speed of customs declaration impacts container storage time, which in turn influences TR selection. The comparative results between HFSOM and DPFOM-RE demonstrate that DPFOM-RE can minimize the aforementioned adverse impacts for all stakeholders, owing to its superior operational efficiency and resource utilization.

6. Conclusions

In this study, we propose, for the first time, an innovative LUT operation mode for container terminals in the context of intermodal transportation, termed the Distributed Parallel Flexible Operation Mode with Reentrant Equipment (DPFOM-RE). DPFOM-RE encompasses three core components: distributed multi-parallel operations, flexible LUT routes, and reentrant equipment (RE). This novel mode is capable of accommodating the variable demands of intermodal transportation, as it fully considers the layout, resource distribution, and operational capacity of an ICT. Following the proposal of DPFOM-RE, a corresponding management framework has been constructed, which elaborates on the role of DPFOM-RE in ICT transshipment operations. To verify the advantages and effectiveness of the proposed mode, a simulation experiment was conducted based on a U-shaped ICT. The experimental results confirm the feasibility of DPFOM-RE and demonstrate its superior performance compared to the traditional HFSOM. Specifically, for S-L and S-R container tasks, DPFOM-RE achieves a shorter makespan, lower average handling frequency per container, and a more stable turnover rate of ITs.

From the perspective of stakeholders: for container terminal managers, DPFOM-RE provides more efficient operational guidance, thereby enhancing terminal competitiveness. For shippers and logistics service providers, the novel mode reduces container wear, which is beneficial for their cost control. For customs authorities and their agents, the speed of customs declaration affects container storage time; DPFOM-RE's flexible TR selection mechanism enables terminal operators to adjust routes in a timely manner, thereby mitigating the adverse impacts of customs declaration delays. Collectively, DPFOM-RE can minimize the aforementioned negative impacts for all stakeholders. Additionally, from the perspective of intermodal transportation development, since TR selection is influenced by terminal layout, the popular TRs identified under DPFOM-RE can serve as valuable references for ICT designers during the initial terminal planning phase.

In the future, with the advancement of container terminals and intermodal transportation, the types of TRs are expected to diversify, which will require future researchers to further explore and enrich the TR category library. Furthermore, DPFOM-RE's three core components (distributed multi-parallel operations, flexible routes, and RE integration) provide new directions for future terminal mathematical modeling and optimization studies. For example, future work will focus on constructing a corresponding mixed-integer programming model that satisfies practical operational requirements, followed by the development of more efficient solution algorithms. Extensive computational experiments will then be conducted to systematically evaluate the robustness and generalizability of the proposed DPFOM-RE. In addition, the LUT management framework based on DPFOM-RE offers novel insights for terminal managers to improve operational efficiency.

Author Contributions

W.L.: conceptualization, supervision. W.L. and L.Z.: research framework, development. L.Z.: data curation, expriments, visualization, investigation, validation, original draft. W.L., L.Z., L.H. and W.G.: reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported in part by the National Natural Science Foundation of China (62173263), the National Key Research and Development Program of China (2019YFB1600400), and the Innovation Research Team Project of Natural Science Foundation of Hainan, China (621CXTD1013).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors of the paper would like to acknowledge the "Logistics and Robotics Technology Laboratory" for providing the solid foundation for the research work in this paper, and express gratitude to the relevant members, experts, and cooperative enterprises who provided cases, data, and revision suggestions during the research and writting process.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Crainic, T.; Kim, K. Intermodal Transportation. In *Transportation, Handbooks in Operations Research and Management Science*; Barnhart, C., Laporte, G., Eds.; Elsevier Science Ltd.: Amsterdam, The Netherlands, 2007; Volume 14, pp. 467–537.
2. SteadieSeifi, M.; Dellaert, N.; Nuijten, W.; et al. Multimodal Freight Transportation Planning: A Literature Review. *Eur. J. Oper. Res.* **2014**, *233*, 1–15.
3. UIRR. 55 Years of the European Combined Transport Community, 2024–2025. Available online: https://www.uirr.com/sites/default/files/documents/UIRR_RA_2025_V10def.pdf (accessed on 1 November 2025).
4. SCIO. China's Landmark Trade Corridor Freight Tops 1 Million TEUs in 2025. Available online: http://english.scio.gov.cn/m/beltandroad/2025-09/08/content_118065912_3.html (accessed on on 8 september 2025).
5. Zhou, C.H.; Zhu, S.D.; Bell, M.G.H.; et al. Emerging Technology and Management Research in the Container Terminals: Trends and the COVID-19 Pandemic Impacts. *Ocean Coast. Manag.* **2022**, *230*, 106318.
6. Liu, W.Q.; Zhu, X.N.; Wang, L.; et al. Integrated Scheduling of Yard and Rail Container Handling Equipment and Internal Trucks in a Multimodal Port. *IEEE Trans. Intell. Transp. Syst.* **2023**, *25*, 2987–3008.
7. Liu, W.; Zhu, X.; Wang, L.; et al. Flexible Yard Crane Scheduling for Mixed Railway and Road Container Operations in Sea-Rail Intermodal Ports with the Sharing Storage Yard. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *190*, 103714.
8. Pinedo, M.L. *Scheduling: Theory, Algorithms, and Systems*; Springer: Berlin/Heidelberg, Germany, 2008.
9. Ruiz, R.; Vázquez-Rodríguez, J.A. The Hybrid Flow Shop Scheduling Problem. *Eur. J. Oper. Res.* **2010**, *205*, 1–18.
10. Chen, L.B.; Nathalie, D.; Dejax, P.; et al. A Tabu Search Algorithm for the Integrated Scheduling Problem of Container Handling Systems in a Maritime Terminal. *Eur. J. Oper. Res.* **2007**, *181*, 40–58.
11. Sun, B.F.; Zhai, G.S.; Li, S.; et al. Multi-Resource Collaborative Scheduling Problem of Automated Terminal Considering the AGV Charging Effect under COVID-19. *Ocean Coast. Manag.* **2023**, *232*, 106422.
12. Zhong, L.C.; Li, W.F.; He, L.J.; et al. Optimization of Mixed No-Idle Flexible Flow Scheduling in Container Terminal. *Comput. Integr. Manuf. Syst.* **2022**, 28, 3421–3433.
13. Zhong, L.C.; Li, W.F.; Gao, K.Z.; et al. An Improved NSGA-II for Integrated Container Scheduling Problems with Two Transshipment Routes. *IEEE Trans. Intell. Transp. Syst.* **2024**, *25*, 14586–14599.
14. Li, W.F.; Zhong, L.C.; He, L.J.; et al. Integrated Scheduling in Sea-Rail Intermodal Terminals with Flexible Transshipment Routes. *Swarm Evol. Comput.* **2025**, *93*, 101852.
15. Dong, J.; Ye, C.M. Research on Collaborative Optimization of Green Manufacturing in Semiconductor Wafer Distributed Heterogeneous Factory. *Appl. Sci.* **2019**, *9*, 2879.
16. Kang, S. Blockchain-Secured Multi-Agent Digital Twin Framework for Distributed Manufacturing with Fuzzy PID Control. *IEEE Commun. Stand. Mag.* **2026**, 1–9. https://doi.org/10.53941/jaia.2026.100010.
17. Wang, Z.; Goudarzi, M.; Buyya, R. TF-DDRL: A Transformer-Enhanced Distributed DRL Technique for Scheduling IoT Applications in Edge and Cloud Computing Environments. *IEEE Trans. Serv. Comput.* **2025**, *18*, 1039–1053.
18. Wu, R. Study on Distributed and Flexible Job Shop Scheduling Problems for Building Material Equipment Manufacturing Enterprise. Ph.D. Thesis, Wuhan University of Technology, Wuhan, China, 2019.
19. Fu, Y.; Li, Z.; Gao, K.; et al. Integrated Scheduling of Distributed Manufacturing with Assembly and Distribution: State of the Art, Challenges, and Future Directions. *Int. J. Prod. Res.* **2025**. https://doi.org/10.1080/00207543.2025.2602898.
20. Tavana, M.; Hajipour, V.; Abdollahzadeh, V.; et al. An Integrated Bi-Objective Multi-Factory Production and Distribution Model with Direct Shipments. *Comput. Ind. Eng.* **2026**, *212*, 111668.
21. Sadok, A.; Euchi, J.; Siarry, P.; et al. Vehicle Routing with Multiple UAVs for the Last-Mile Logistics Distribution Problem: Hybrid Distributed Optimization. *Ann. Oper. Res.* **2025**, *351*, 59–99.
22. Behnamian, J. Graph Colouring-Based Algorithm to Parallel Jobs Scheduling on Parallel Factories. *Int. J. Comput. Integr. Manuf.* **2016**, *29*, 622–635.
23. Behnamian, J.G.; Seyyed, M.T.F. Multi-Objective Multi-Factory Scheduling. *RAIRO-Oper. Res.* **2021**, *55*, 1447–1467.
24. Marzouki, B.; Belkahla Driss, O.; Ghédira, K. Modeling and Solving the Distributed Flexible Job Shop Scheduling Problem with Transportation Time. *Knowl. Inf. Syst.* **2025**, *67*, 10451–10490.
25. Yu, H.; Ning, J.; Wang, Y.; et al. Flexible Yard Management in Container Terminals for Uncertain Retrieving Sequence. *Ocean Coast. Manag.* **2021**, *212*, 105794.
26. Tao, Y.; Zhang, S.L.; Lin, C.H.; et al. A Bi-Objective Optimization for Integrated Truck Operation and Storage Allocation Considering Traffic Congestion in Container Terminals. *Ocean Coast. Manag.* **2023**, *232*, 106417.
27. Lee, D.H.; Cao, J.X.; Shi, Q.X. Integrated Quay Crane and Yard Truck Schedule for Inbound Containers. In 2008 IEEE International Conference on Industrial Engineering and Engineering Management, Singapore, 8–11 December 2008; pp. 1219–1223.

28. Xin, J.; Negenborn, R.R.; Corman, F.; et al. Control of Interacting Machines in Automated Container Terminals Using a Sequential Planning Approach for Collision Avoidance. *Transp. Res. Part C Emerg. Technol.* **2015**, *60*, 377–396.
29. Yang, Y.J.; Zhu, X.N.; Yan, B.C.; et al. Integrated Scheduling of Rail-Water Containers Handling Operations in Intermodal Terminals Considering Energy-Efficiency. *J. Transp. Syst. Eng. Inf. Technol.* **2018**, *18*, 215–221.
30. Qin, T.B.; Du, Y.Q.; Chen, J.H.; et al. Combining Mixed Integer Programming and Constraint Programming to Solve the Integrated Scheduling Problem of Container Handling Operations of a Single Vessel. *Eur. J. Oper. Res.* **2020**, *285*, 884–901.
31. Jonker, T.; Duinkerken, M.B. Coordinated Optimization of Equipment Operations in a Container Terminal. *Expert Syst. Appl.* **2021**, *33*, 281–311.
32. Zhuang, Z. Optimization for Integrated Scheduling of Intelligent Handling Equipment with Bidirectional Flows and Limited Buffers at Automated Container Terminals. *Comput. Oper. Res.* **2022**, *145*, 105863.
33. Shi, H.; Si, H.; Qin, J. Energy-Efficient Scheduling for Resilient Container-Supply Hybrid Flow Shops under Transportation Constraints and Stochastic Arrivals. *J. Mar. Sci. Eng.* **2025**, *13*, 1153.
34. He, J.L.; Huang, Y.F.; et al. Integrated Internal Truck, Yard Crane and Quay Crane Scheduling in a Container Terminal Considering Energy Consumption. *Expert Syst. Appl.* **2015**, *42*, 2464–2487.
35. Yang, Y.; Zhong, M.; Dessouky, Y.; et al. An Integrated Scheduling Method for AGV Routing in Automated Container Terminals. *Comput. Ind. Eng.* **2018**, *126*, 482–493.
36. Xu, B.; Jie, D.; Li, J.; et al. Integrated Scheduling Optimization of U-Shaped Automated Container Terminal Under Loading and Unloading Mode. *Comput. Ind. Eng.* **2021**, *162*, 107695.