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A New Synchronous Handling Technology of Double Stack Container Trains in Sea-Rail Intermodal Terminals

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Abstract: With the advantages of large volume, low unit transportation costs, as well as sustainable and stable transport capacity, China in recent years has actively promoted the innovative pilot of double-stack container sea-rail intermodal transport in the Ningbo-Zhoushan port. In this study, a new synchronous handling technology is proposed to improve the handling efficiency of double-stack container trains at sea-rail intermodal terminals. This research primarily focuses on the design of an LDAGV (Automatic Guided Vehicle with Loading and Discharging Function) and a new special articulated flat car for double-stack container trains, while also optimizing the overall layout of the container terminal yard. It then evaluates nine double-stack container stacking forms based on the requirements of transport gauge and center of gravity height. Finally, using data from the Ningbo Beilun No. 3 container terminal, a cost-benefit analysis is performed to compare the traditional handling scheme for common double-stack container trains and the new synchronous handling scheme for double-stack container trains with new special articulated flat car. The results show that the application of new synchronous handling technology has obvious advantages in terms of reducing the handling time and operation cost of double-stack container trains in sea-rail intermodal container terminals, as well as enriching the stacking forms of double-tier containers on the new special articulated flat car, thus reducing the difficulty of collecting cargoes and the organization of container source.

Keywords: sea-rail intermodal transport; double-stack container trains; synchronous handling technology; container terminals

Citation: Zhao, Z.; Wang, X.; Cheng, S.; Liu, W.; Jiang, L. A New Synchronous Handling Technology of Double Stack Container Trains in Sea-Rail Intermodal Terminals. *Sustainability* **2022**, *14*, 11254. https://doi.org/10.3390/su141811254

Academic Editors: Yi Zuo, Zhuo Sun and Jiaguo Liu

Received: 12 June 2022
Accepted: 5 July 2022
Published: 8 September 2022
Corrected: 23 January 2024

1. Introduction

Container terminals are required to have larger and higher collection and distribution capacity as the global economy recovers in the post-epidemic era and as handling capacity increases due to ship upsizing [1,2]. Construction of the container terminal sea-rail intermodal transport system, as well as operation of double-stack container trains, will help increase the volume of train freight while reducing unit transportation costs and maximizing the benefits of scale economy [3]. As a result, many countries, including the United States, Canada, India and Australia, operate double-stack container trains and conduct research on related topics.

Despite more than ten years of development, double-stack container sea-rail intermodal transport has not gained popularity in China due to national conditions and other considerations. Moreover, in the last five years, the number of containers in sea-rail intermodal transport has accounted for less than 3% of the container throughput of China's main ports, as shown in Figure 1. To address this, the Ministry of Transport of China issued a policy in December 2020: Opinions on the Construction of a Transportation Power in Ningbo to Carry Out the Innovation of Sea-Rail Intermodal Transport of Double stack Containers, agreeing to carry out the innovation pilot of double stack containers in sea-rail intermodal transport in Ningbo. This strategy is well designed to encourage the development of double-stack container sea-rail intermodal transport through design changes, rules improving, transportation adaptation, innovation in handling technology, and other associated technology research.

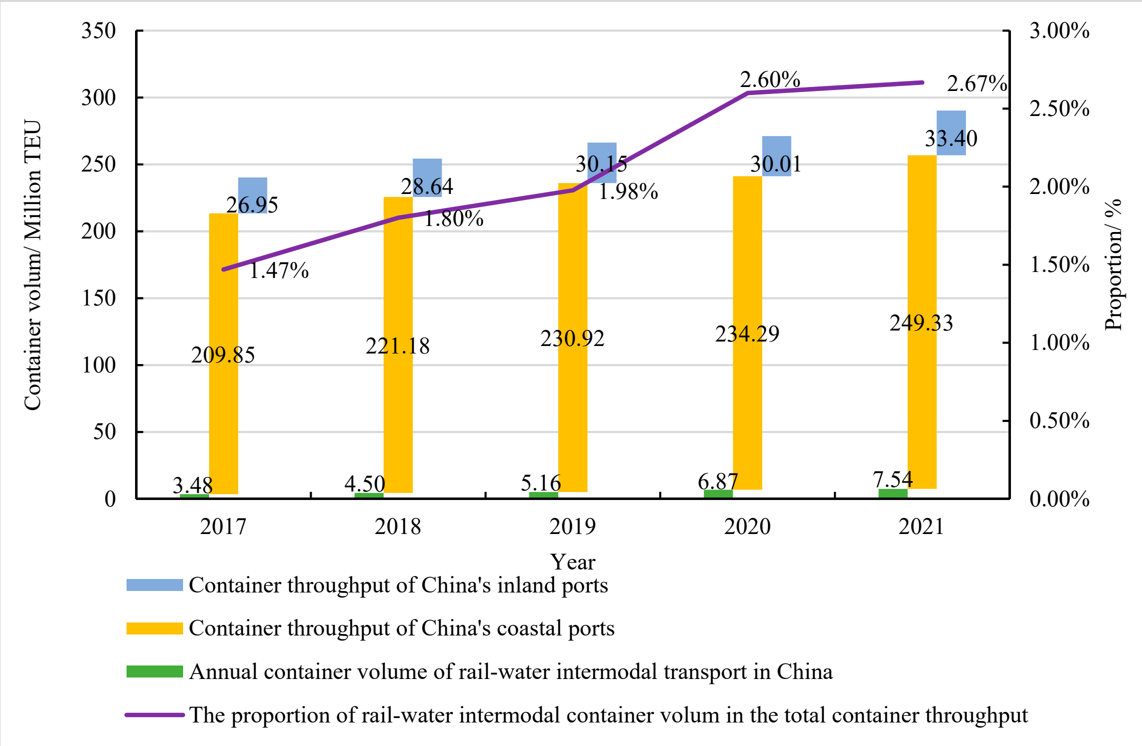

Figure 1. Container volume of rail-water intermodal transport in China. Source: Ministry of Transport of the People's Republic of China.

With the purpose of promoting sea-rail intermodal transport and building a new era of transportation, this research studies the handling and transshipment problem of double-stack container trains in sea-rail intermodal terminals in this circumstance. Based on the traditional double-stack articulated flat car, automatic guided vehicle and container terminal yard layout, this new technology is an innovation that is mainly reflected in a new special articulated flat car for carrying double-stack containers, a new LDAGV, a new yard layout design, and the new workflow of synchronous handling technology for double-stack container trains from the terminal to the inland railway container freight station.

The remaining parts of this paper are organized as follows. Section 2 reviews current studies on the loading strategy of double-stack container trains at terminals and states the problems to be solved. Section 3 covers the design of LDAGV (Automatic Guided Vehicle with Loading and Discharging Function) and a new special articulated flat car of double-stack container trains. Simultaneously, we carry out the optimal design of the overall layout and operation process for the double-stack container yard and terminal. Section 4 evaluates nine double-stack modes of containers in the new special articulated flat car of double-stack container trains under the transport limits and gravity center height requirements. Section 5 performs a cost-benefit analysis between traditional terminal handling technology and new synchronous handling technology to verify the optimization and practicability of the latter, and Section 6 presents the conclusion and further research.

2. Literature Review

Container sea-rail intermodal transport has been a trendy topic that has attracted more attention in recent years [4–7]. However, most existing research is focused on container transshipment and mechanical scheduling optimization in single-stack container trains [8–12], as well as container freight train loading plans and container port area transportation route optimization [13–16]. Furthermore, Guo et al. formulated the operation at intermodal container terminals for China Railway Express and proposed the accelerated accumulation scenario considering the cooperation between a maritime terminal and a railway terminal [17]. Yan et al. developed a tailored rolling horizon approach with adaptive horizon and back-tracking strategy, and suggested prolonging the feasible service time of trains and improving the operational capacity of shunting engines to reduce the negative impact caused by insufficient loading and unloading capacity [18]. Nevertheless, in terms of the handling problem of double-stack container trains, recently both the depth and breadth of the existing research have been very limited, which only study the optimization model of loading plans.

Specifically, Lang et al. established a multi-objective optimization model for the loading problem of double-stack container trains, proving that this method can reduce the gravity center height of articulated flat car after loading under the condition that the container loading capacity is maximized while reducing the bogie load difference [19]; Ng & Talley proposed a loading optimization model that could find the optimal loading scheme of double-stack container trains under reconstruction conditions [20]. Upadhyay et al. established a new double-stack container train loading optimization model considering containers of different types, weights and heights, as well as the loading combination that meets actual constraints, which can reduce transportation cost by about 3% [21]. In view of vehicle weight and center of gravity constraints, stacking rules, container types and loading technology constraints, Mantovani et al. proposed a linear programming model suitable for matching single or double-stack container trains with specific containers, to minimize the loading cost of the train [22].

It is evident that all the above studies are under the constraints of existing technical means, railway lines and related infrastructure, special articulated flat car for double-stack containers, yard handling equipment and management rules, etc. Moreover, these studies have put forward some suggestions for the future development of double-stack container sea-rail intermodal transport or optimization models and methods for loading problems from the perspective of software only. Unfortunately, when it comes to hardware aspects, such as vehicles, handling equipment, and support facilities, as well as technical aspects such as handling efficiency and scheme, no obvious breakthroughs have been made.

Two more issues remain. First, the stacking form of the double-stack container is single. Newly revised in 2018, the existing measures for the Administration of Double-Stack Container Transportation Provisions of China stipulate that when applying double-stack transportation, it is only allowed to use a special articulated flat car with two 20-foot GP (General Purpose Container) at the bottom, the upper limit being one 40-foot GP or one 40-foot HC (High Container), which makes the choice of stack form quite finite. Therefore, a loading plan is even more difficult to come up with, not to mention the difficulty of matching for different container types. Secondly, since more than 80% of the world's trade in the water transport section is completed by 20-foot GP and 40-foot GP, based on this fact, Zhang et al. found that more than 86% of containers in the Shaoxing–Ningbo–Zhoushan port sea-rail intermodal transport section belong to 40-foot HC, making the process of dealing with various containers from different areas more difficult [23]. Meanwhile, it is also unfavorable to the promotion of sea-rail intermodal transport itself. Note that it is not due to the rich source of the 40-foot HC that leads to the current high proportion in railway transportation. Under the condition of the hardware and software, regardless of the economical consideration (freight, container leasing cost allocation, box, etc.) or technical consideration (transportation limits, loading requirements of X2K special articulated flat car, weight, etc.), 40-foot HC transport in railway is much more applicable.

Focusing on the collection and distribution problem of the sea-rail intermodal container terminal, a synchronous handling technology with its related equipment is designed for double stack container trains, which is committed to promoting the handling efficiency of double-stack container trains, as well as pushing the popularity of 20-foot GP and 40-foot GP on double-stack container trains in sea-rail intermodal transport.

3. Optimization Design of Synchronous Handling Technology

3.1. Innovative Design of Equipment

3.1.1. Design of LDAGV

With the objective of realizing container handling while eliminating the use of front lift, tire lift, rail lift or forklift, the LDAGV (Automatic Guided Vehicle with Loading and Discharging Function) with handling function was designed, whose scheme is improved and upgraded based on the traditional AGV (Automatic Guided Vehicle) [24,25]. As shown in the upper part of Figure 2, LDAGV consists of eight automatic button locks, four slide rails, four handling rails, four handling hooks and the main body of the vehicle. The transportation and handling of the vehicle are driven by electricity. It not only undertakes the transport task of containers from the wharf apron to the storage yard and from the storage yard to the double-stack container trains railway platform, but also has the function of loading and unloading containers onto and off the train.

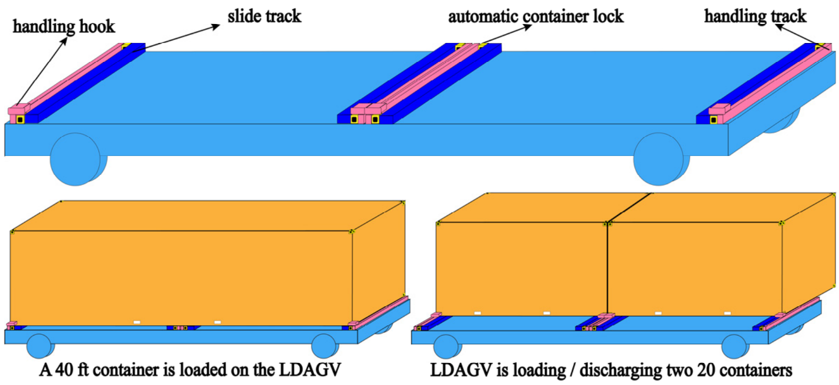

Figure 2. Sketch map of LDAGV.

In particular, automatic button lock is applied to fix the loaded container in LDAGV. Slide rails are equipped with pulleys to guide and facilitate container movement, supplemented by handling rails, handling hooks and motors to drive the handling of each container. During this process, the handling hooks are butted and fixed with the corner pieces on the container. When only facing one 40-foot container, the automatic button locks and handling rails in the middle of the articulated flat car stop working; when facing two 20-foot containers at the same time, four slide rails, stevedoring rails, and stevedorling hook locks work synchronously (see the lower part of Figure 2). The left and right columns represent LDAGV in the state of loading a 40-foot container and unloading double 20-foot containers, respectively. Multiple LDAGVs can perform handling work on the upper and lower platforms on both sides of the train at the same time.

3.1.2. Optimization Design of a Special Double-Stack Container Articulated Flat Car

Considering the convenience of carrying the upper and lower tiers of containers during synchronous handling operation, this study designed and optimized a new type of articulated flat car for double-stack container trains based on the traditional X2K articulated flat car, as illustrated in Figure 3. The biggest characteristic of the new special articulated flat car is to install the upper container loading platform, columns, and the auxiliary frame, no longer subject to strict rules, that is, heavy containers are not loaded on top of lighter ones, and smaller containers cannot be loaded on top of larger ones. Additionally, both the upper and lower bearing platforms are equipped with slide rails and automatic button locks to connect the containers loaded from the ldagv to the train or unload the containers from the train to the LDAGV.

Figure 3. Structural drawing of the new special articulated flat car for double-stack container trains.

The special articulated flat car can load or unload the upper and lower containers simultaneously without affecting each other, but the total weight of the lower containers should not exceed the total weight of the upper containers, and the weight difference between the two 20-foot containers should not exceed 10 tons when loading two 20-foot containers on the same platform. Its design deadweight is 23 tons, marked loading weight is 78 tons, empty car center of gravity is 700 mm high, and slide rail and automatic button lock is 30 mm high. The first floor bearing platform can accommodate a maximum of 40-foot HC, and the second floor bearing platform is 50 mm high. Other parameters including the wagon length, width, distance, the lowest point of the articulated flat car body from the rail surface, and other preliminary designs are consistent with the traditional articulated flat car X2K.

3.2. Optimization of the Yard and Wharf Layout

3.2.1. Design of the Double-Stack Yard Area

Currently, the common arrangement of containers in the world is perpendicular or parallel to the coastline. Traditional sea-rail intermodal terminals mostly use rail cranes to load and unload double stack container trains, but complex loading plans usually need to be made in advance, and containers can only be loaded onto trains layer by layer, which is inefficient. Meanwhile, the AGV in the traditional automated terminal is only responsible for transporting containers in the port area, and the layout of the terminal yard is also wasteful, which does not make full use of space. Therefore, Gharehgozli et al. listed the strategic and tactical layout design problems that need to be solved [26]; Lee and Kim used the construction cost of ground space, the fixed overhead cost of yard cranes, and the operating cost of yard cranes and conveyors to optimize yard layout [27]; Zaerpour et al. proposed a next-generation container terminal consisting of container storage towers, which could increase annual throughput by up to 120% compared to a container block of the same storage capacity [28]. In addition, some researchers also used the optimization model to improve container yard utilization [29–32].

In order to coordinate with the synchronous handling of double-stack container trains, the concepts of a double-tier yard area is proposed. Figure 4 shows that the whole storage yard area is divided into several first-tier yard areas and second-tier yard areas, and the adjacent first-tier yard area and second-tier yard area are shared train track areas. Taking the container loading process as an example, as shown in Figures 4 and 5, the upper and lower tiers of the containers to be loaded are transported, respectively, by LDAGV from the upper-tier yard and the lower-tier yard to the handling platform at the boundary of the railway platform. At this point, the auxiliary parking device is used to assist LDAGV to park automatically and accurately beside the new special wagon and dock with the upper and lower bearing platforms of the new special wagon for subsequent loading and unloading operations (the height of the slide bearing surface of LDAGV is flush with the height of the slide bearing surface of the special articulated flat car for double-stack containers).

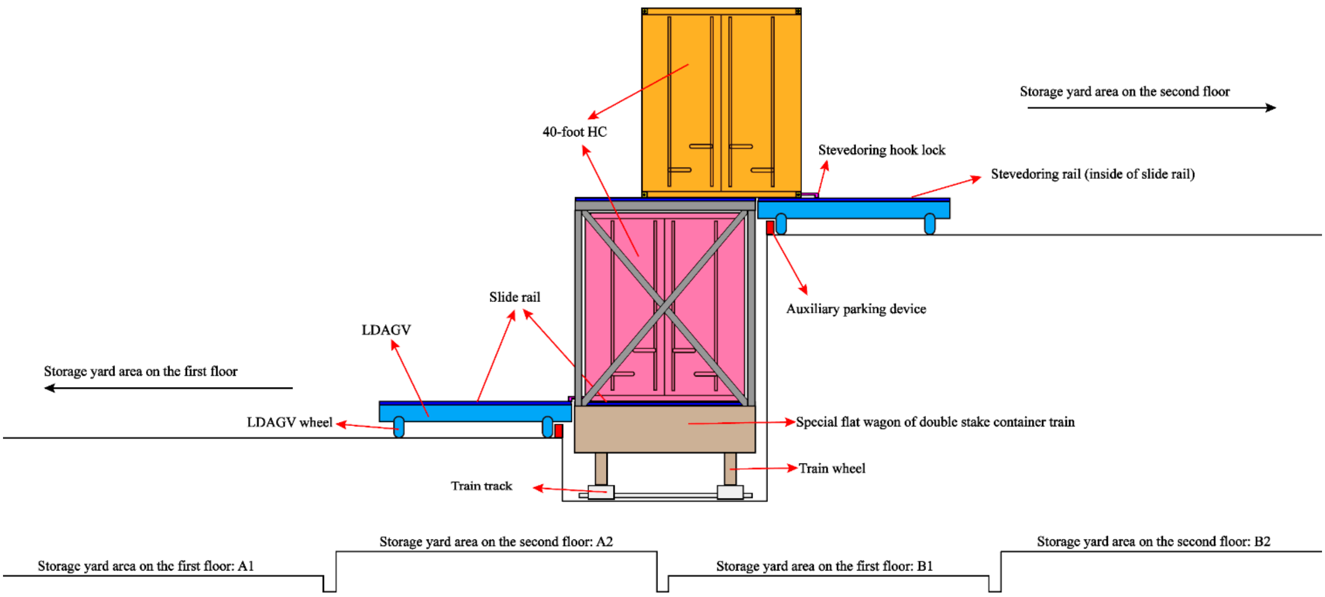

Figure 4. Cross section of the double-tier container terminal yard.

After the LDAGV handling hooks are connected and fixed to the corner pieces at the bottom of the container, driven by the stevedoring rails and motors, the container will be gradually moved to the correct position through the slide rails on the LDAGV loading platform and the special articulated flat car. Then the automatic button locks on the loading platform will connect with the four corner pieces at the bottom of the fixed container to make it safe and stable during transportation. After that, the LDAGV will automatically leave for the wharf apron or container yard to execute the next task instruction.

Similarly, there are two situations that need to be discussed. For the construction of a new double-tier container terminal yard, LDAGV can be equipped in the first and second-tier yards to load or unload containers on the new special wagon, respectively, which can effectively improve handling efficiency. For traditional storage yards or yards with great reconstruction difficulties, instead of using LDAGV, forklifts can be considered to load and unload containers in the lower tier of the special articulated flat car. Reach stackers can be used to load and unload containers in the upper tier of the special articulated flat car.

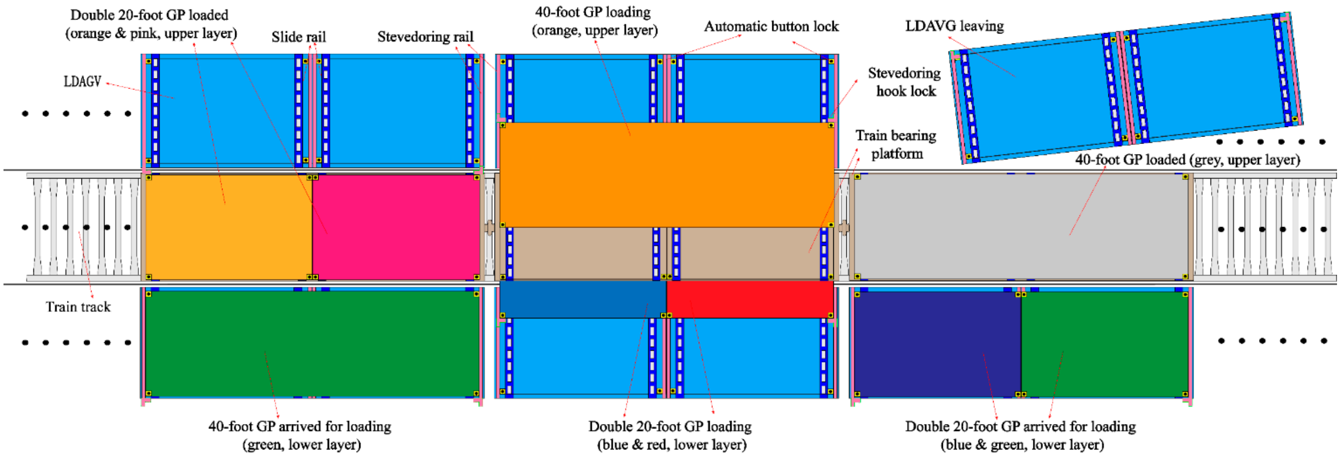

Figure 5. Schematic diagram of the synchronous handling process for the double-stack container train.

In addition, the concept of a stereoscopic storage yard can be taken into account [33]. In this scenario, the lower tier of the yard is designed below the open yard area, which is used mainly to store 20-foot GP or 40-foot GP, while the open storage yard of the upper tier can store 40-foot HC and special containers, such as refrigerated containers, frame containers, and open top containers, as shown in Figure 6. In the future, there are some research challenges about terminal space management, such as housekeeping strategies for yard operations and integrated optimization of space allocation [34].

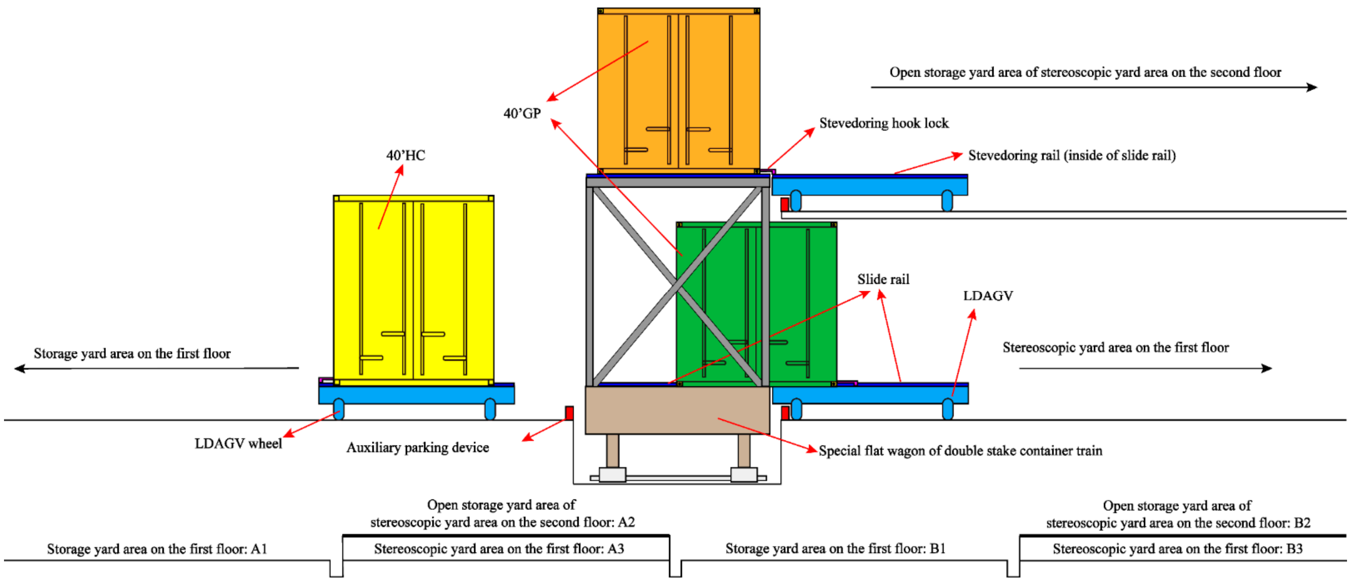

Figure 6. Cross section of the stereoscopic double-stack container terminal yard.

3.2.2. General Layout and Operation Process of the Terminal

Combined with the above two equipment innovations and the design of a double-tier container yard, the overall layout of the container terminal is optimized. Figure 7 clearly illustrates that the entire terminal extends along the coast and the containers on the yard are placed perpendicular to the coastline. The rail tracks of double-stack container trains run through the whole yard and are always consistent with the arrangement direction of the containers.

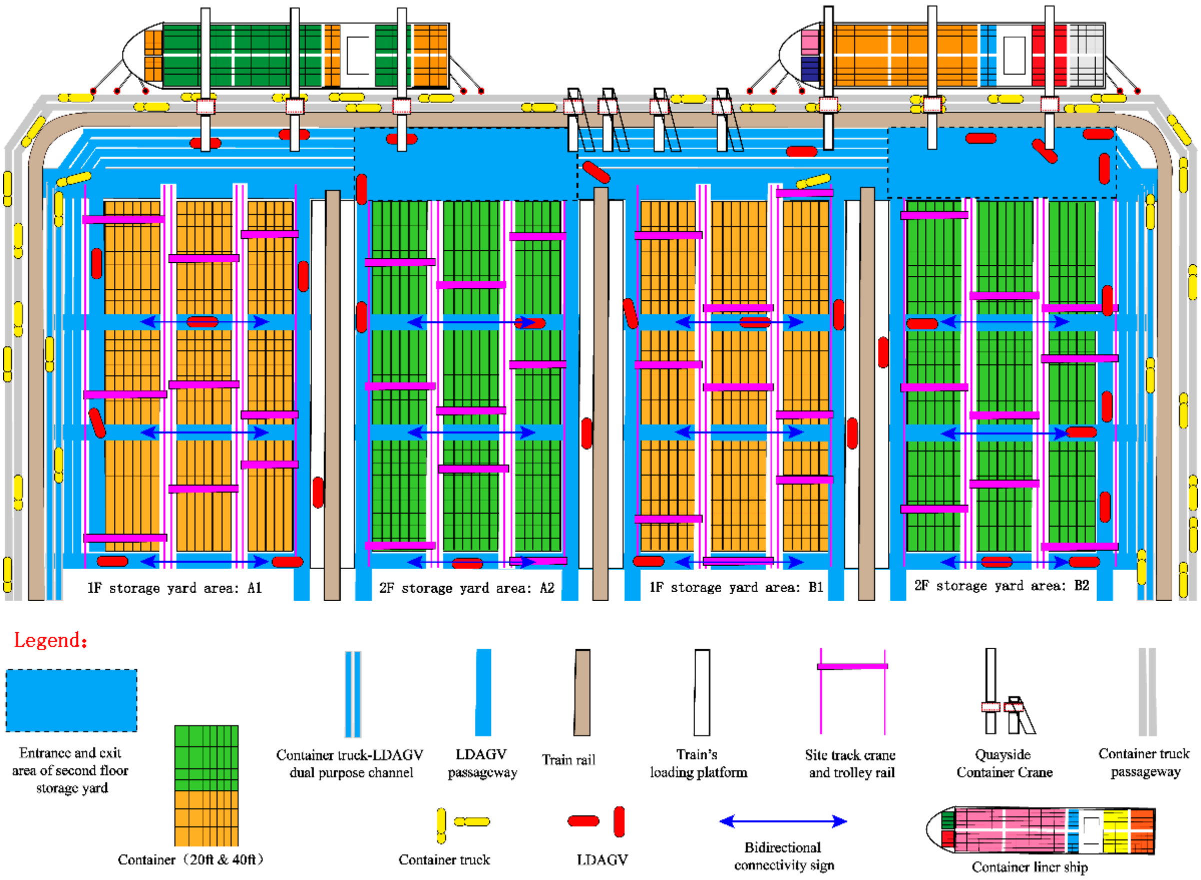

Figure 7. General layout of the wharf.

LDAGV is responsible for the horizontal transport of containers between the storage yard and the quayside container crane, between the storage yard and the railway platform, or directly from the quayside container crane to the railway platform, and it also undertakes the task of loading and unloading containers from double-stack container trains. The container truck undertakes the transportation of containers between the destination outside the port and the crane (in the direct access train-vessel mode) and between the destination and the storage yard (in the normal mode). The yard rail crane is applicable for container entry and exit yard, integration, consolidation, and transfer.

The railway track is designed to direct the rail outside the port. It should be noted that double-stack container trains must be pulled by the diesel locomotive head before entering the port and then changed back to the electric locomotive head after leaving the port area. This updated layout could reduce the need for mechanical equipment while simplifying the whole process.

Figure 8 indicates that when the container is unloaded from the liner ship by a quayside container crane to LDAGV, the container in LDAGV is transported to the rail crane in the corresponding container area according to the instructions and paths and then lifted by the rail crane to the designated container location for storage. When the double-stack container train arrives and is ready, the container will be loaded onto LDAGV by the rail crane and then transported by LDAGV to the railway platform corresponding to the special articulated flat car for the required loading position. After all articulated flat car are loaded, the train will be pulled out of the port by the diesel locomotive. Then driven by the head of the electric locomotive, the train leaves the port area and enters the rear general railway network of the double-stack container freight trains until it arrives at the inland container freight station.

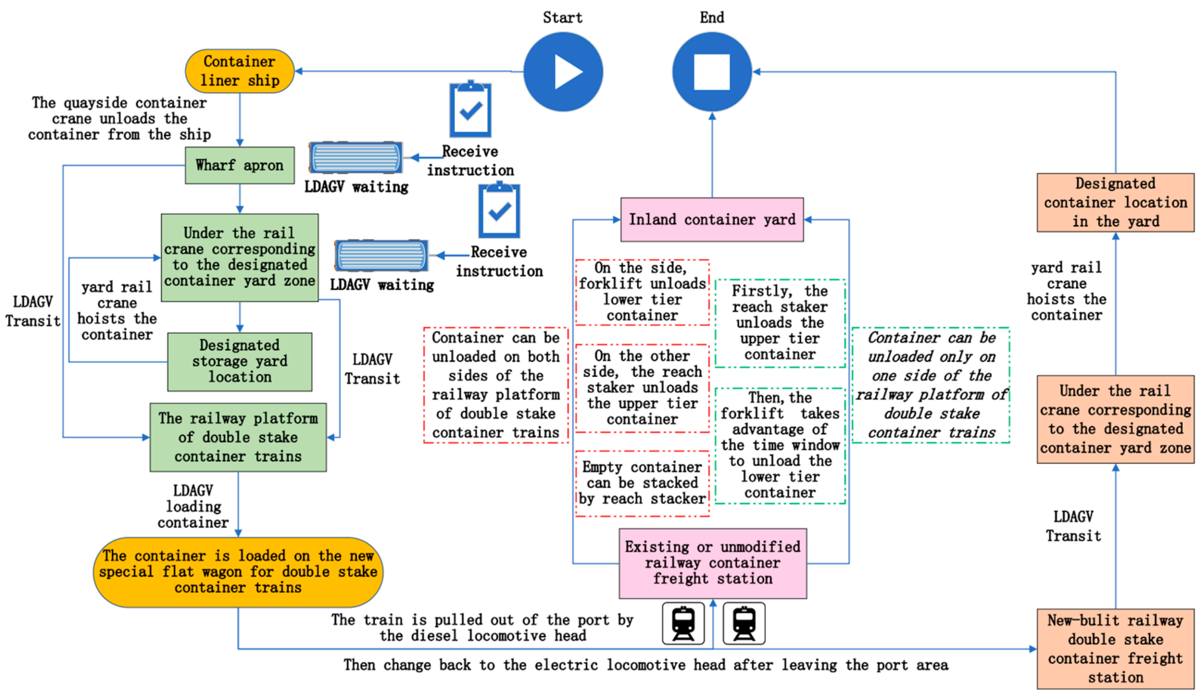

Figure 8. The process of containers from the liner ship to the inland container freight station.

For the construction of the new double-tier container terminal yard, the design layout of the double-tier storage yard area in Section 3.2.1 can be referred to. In this scenario, the LDAGV can be equipped at the first and second-tier yards to load or unload containers on the new special wagon, respectively, which can effectively improve handling efficiency.

For existing traditional railway container freight stations or yards with great difficulty in reconstruction: ① On both sides of double-stack container trains (when the conditions of the railway platforms on both sides are allowed), the container forklifts can be used to unload containers on the first floor, and the reach stackrs are responsible for unloading containers on the second floor, while the stacker can be used for empty containers; ② When only one side of the railway platform is allowed, we can use the reach stackrs to lift the upper-tier containers at one side of the railway platform, and then use the container forklifts to unload the lower-tier containers at the time window when the reach stackrs leave; or use the rail crane to unload the upper container, and use the forklift to unload the lower container.

The conclusion of this section is that the new special articulated flat car is a prerequisite for synchronous loading and unloading of double-stack container trains. LDAGV and double-tier storage yard are auxiliary conditions.

4. Implementation and Evaluation of the Scheme

4.1. Stacking Forms for Containers on Double-Stack Container Articulated Flat Car

Currently, the ISO 1CC 20-foot GP and the 1AA 40-foot GP have a maximum gross weight of 30.48 t and a height of 2591 mm; Model 1AAA 40-foot HC has a maximum gross weight of 30.48 t and a height of 2896 mm. The 40-foot GP and 40-foot HC are usually suitable for lightweight goods with lower density, while the 20-foot GP is accessible for heavy goods with higher density. Meanwhile, the marked loading weight of the new special articulated flat car for double-stack container transportation in this scheme is 78 t. Therefore, the above three types of containers can be combined into nine stacked collocation forms with the support of the new special articulated flat car; see Table 1 and Figure 9.

Table 1. Summary of loading and stacking schemes for double stack containers.

Scheme Serial Number	Lower-Tier Stacking Form	Upper-Tier Stacking Form	Double-Tier Total Weight Requirements	Stack Type
A	20-ft GP×2	20-ft GP×2	78 t	New form
B	20-ft GP×2	40-ft GP	78 t	Traditional form
C	20-ft GP×2	40-ft HC	78 t	Traditional form
D	40-ft GP	20-ft GP×2	78 t	New form
E	40-ft GP	40-ft GP	61 t	New form
F	40-ft GP	40-ft HC	61 t	New form
G	40-ft HC	20-ft GP×2	78 t	New form
H	40-ft HC	40-ft GP	61 t	New form
I	40-ft HC	40-ft HC	61 t	New form

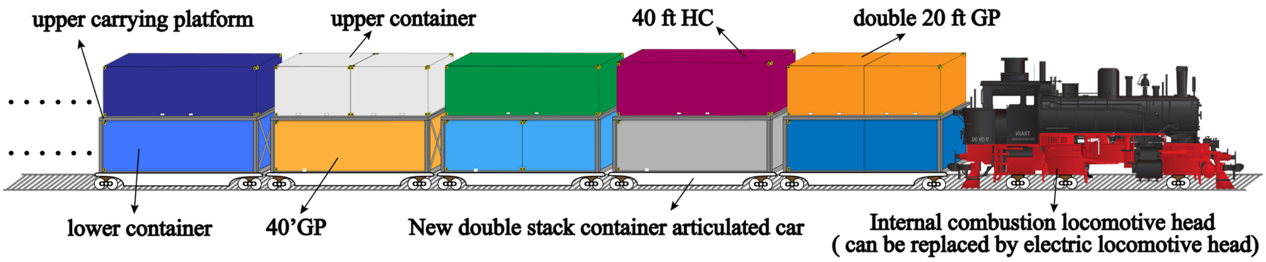

Figure 9. The loading status of the new articulated flat car for the double-stack container train.

4.2. Evaluation of the Program under Transportation Limits and Height Requirements of the Center of Gravity

The China Railway Double-Stack Container Transportation Management Measures (TG/HY203-2018) require that the maximum loading height of double stack containers after being loaded by a special articulated flat car not exceed 5850 mm above the rail surface. At the same time, the China Railway Technical Management Regulations require that the maximum gallop of the overhead contact wire of the electrified railway train does not exceed 6500 mm above the top surface of the rail. According to the method of Zhang et al. [23], the following two equations are used to calculate the gauge height of double stack containers after articulated flat car packing in each stack form of A–I and the clearance height considering the height limit of the catenary conductor. The results are specified in Table 2.

$$h_{zz} = h_{yc} + h_{ec} + h_{yx} + h_{ex} + 2h_{ns} + h_{gc} \quad (1)$$

$$h_{cw} = h_{zz} + h_{aq} + h_{cd} \quad (2)$$

Specifically, h_{zz} is the loading limit. The gauge height between the first floor of the new articulated flat car bearing platform and the rail surface for the transportation of double stack containers is 240 mm, which is represented by h_{yc}. For the gauge height of the double-stack bearing platform of the new special articulated flat car, it is assumed to be 50 mm. h_{yx} indicates the height of the containers on the lower tier bearing platform, while h_{ex} is the height of the containers on the upper tier bearing platform. Speaking of the height gauge for automatic button lock and slide of the new special articulated flat car, this study takes it as h_{ns} with 30 mm high. As for the manufacturing tolerance, we assume that h_{gc} stands for it with 10 mm. h_{cw} demonstrates the height under the height restrictions of the catenary conductor. h_{aq} is the safe distance between the top surface of the upper container and the catenary wire, which is 350 mm. h_{cd} means the conductor slack of the catenary, set at 50 mm [23].

Table 2. Gauge height of each double-stacking scheme.

Stacking Form	Gauge Height after Container Loading	Clearance Height after Considering Catenary Conductor
A	5542 mm	5942 mm
B	5542 mm	5942 mm
C	5847 mm	6247 mm
D	5542 mm	5942 mm
E	5542 mm	5942 mm
F	5847 mm	6247 mm
G	5847 mm	6247 mm
H	5847 mm	6247 mm
I	6152 mm	6552 mm

It is noticeable that the limit height of scheme I after container loading exceeds the specified limit by 302 mm, and the height under the limit of the catenary conductor exceeds by 52 mm. The other eight schemes, except scheme I, all meet the limit requirements of the current regulations. Furthermore, the Measures for the Administration of Railway Double-Stack Container Transportation and the Railway Cargo Loading Reinforcement Rules stipulated that the gross weight of each section within the container articulated flat car that carries cargo is less than 78 tons.

After loading, the vehicle's overall high center of gravity is less than 2400 mm (known to a new type of double-stack container transport, its special articulated flat car weight is 23 tons, and its empty center of gravity height is 700 mm). The total weight of the lower container should be greater than the total weight of the upper container (it is known that the dead weights of the 20-foot GP, 40-foot GP and 40-foot HC are, respectively, 2.24 tons, 3.72 tons and 3.88 tons, and the maximum total weight of each container type should not exceed 30.48 tons). If two 20-foot containers are loaded on the same tier, the weight difference between the two containers should be less than 10 tons. Therefore, in double-stack container rail transport, each stacking scheme must meet the following constraints:

$$G = \frac{16100 + \sum_{i=1}^{2} H_i Q_i + \sum_{j=1}^{2} H_j Q_j}{23 + \sum_{i=1}^{2} H_i + \sum_{j=1}^{2} H_j} \leq 2400 \tag{3}$$

$$\sum_{i=1}^{2} Q_i + \sum_{j=1}^{2} Q_j \leq \begin{cases} 78, scheme\ A, B, C, D, G \\ 61, scheme\ E, F, I \end{cases} \tag{4}$$

$$\sum_{i=1}^{2} Q_i > \sum_{j=1}^{2} Q_j \tag{5}$$

G illustrates the height of the center of gravity of the vehicle and cargo. $\sum_{i=1}^{2} H_i$ and $\sum_{j=1}^{2} H_j$ is the height of the center of gravity of the lower and upper containers and cargo, respectively, while $\sum_{i=1}^{2} Q_i$ and $\sum_{j=1}^{2} Q_j$ represents the weight (it can be considered $H_2 = 0$, $Q_2 = 0$ with only one container loaded onto the lower or upper tier platform). The loading schemes from A to H on the new articulated flat car are found to be in accordance with current standards and specifications, which are helpful in promoting the popularity of

20-foot GP and 40-foot GP in sea-rail intermodal transport. Furthermore, plans *B* to *D* and *F* to *H* mix stacking forms of container type, which can reduce the difficulty of collecting goods and the organization of the container source, pushing forward the balanced and coordinated development of container cargo trade on the container type.

Considering the difficulties in the reconstruction of China's electrified railway (catenary, building clearance along the line, tunnel outline, etc.), mixed passenger and freight lines, large passenger and freight flow, and other factors, the practice of changing the original railway infrastructure to achieve double 40-foot high containers transportation may result in "pull one hair and the whole body is affected". Consequently, it may be appropriate to consider further research and development of a special articulated flat car with a lower center of gravity height, a thinner bearing platform and lower chassis in the near future.

5. Cost-Benefit Analysis

5.1. Data Preparation

Referring to the research of Bruns et al. [35] and Ambrosino et al. [36], this paper compares the different double-stack container handling technologies between the traditional terminal handling scheme for common double-stack container trains (It applied the 5 + 1 operation process, where the container yard can stack four tiers of containers, and the rail crane works normally with room for a fifth tier) and the new synchronous handling scheme for double-stack container trains with new special articulated flat car (It applied the 6 + 1 operation process, where the container yard can stack seven tiers of containers, and the rail crane works normally with room for an eighth tier). Without taking the capital cost into account (equipment purchase cost, site investment, reconstruction cost, depreciation, interest, etc.) and running cost (wages, machinery maintenance cost, insurance cost, etc.), the cost-benefit analysis is performed on the basis of the current market information and related equipment technical parameters.

Next, the operation serial number 1* + 2* + 6* represents the containers that are transported directly between ships and trains, which is defined as the direct access train-vessel mode. The operation serial number 1–6 represents the container that must be stored and transferred through the yard, that is, the normal mode. The correction time refers to the time deviation under the influence of transportation path planning, traffic control, vehicle scheduling, and operational coordination between the quayside gantry crane and the yard rail cranes, and the surplus coefficient is 1.3. The transportation distance from the wharf apron to the yard is set at 300 m, the distance from the yard to the railway platform is 200 m, and the distance from the wharf apron to the railway platform is set at 500 m. The annual throughput of the Ningbo Beilun No. 3 Container Terminal is estimated to be approximately 10 million TEU according to the container throughput data from their official website http://csct.nbport.com.cn/websiteSet/companyPageb (accessed on 28 May 2022). The electric charge provided by the power company to the terminal is 0.85 RMB/KWh, and the price of zero diesel required for container trucks is 7.25 RMB/L.

In addition, because each new special articulated flat car can load at most two 40-foot containers or four 20-foot containers, or two 20-foot containers plus one 40-foot container at one time, we set up three-unit groups: ① double 40-foot containers unit, ② four 20-foot containers unit, and ③ double 20-foot containers + one single 40-foot container unit. This division of three-unit groups makes the calculation results more scientific and closer to the actual situation.

5.2. Calculation of Handling Time and Operation Cost

The handling time in Table 3 is calculated according to the survey data (productivity efficiency/speed). The operation cost in Table 4 is calculated based on the survey data (oil price/electricity price) and the results in Table 3. Table 5 shows the unit time and cost of three groups, respectively, in two modes based on Tables 3 and 4, as well as the comparison of handling time and operation cost between the traditional handling scheme and the new synchronous handling scheme.

Table 3. Comparison of handling time between the new synchronous handling scheme and the traditional scheme.

Scheme	Sequence	Segmented Operation Processes	Group ① Correction Time (min)	Group ② Correction Time (min)	Group ③ Correction Time (min)	Productivity/Speed
Traditional handling scheme for common double-stack container trains	1	Ship-(quayside gantry crane) -container truck	3.9	7.8	5.85	40 natural container/h
	1*	Ship-(quayside gantry crane) -container truck	3.9	7.8	5.85	40 natural container/h
	2	Wharf apron-(container truck) -yard	2.34	2.34	2.34	20 km/h
	2*	Wharf Apron-(container truck) -railway platform	3.9	3.9	3.9	20 km/h
	3	Container truck-(yard tire crane) -container location	7.8	15.6	11.7	20 natural container/h
	4	Container location-(yard tire crane)-container truck	7.8	15.6	11.7	20 natural container/h
	5	Yard-(container truck) -railway platform	1.56	1.56	1.56	20 km/h
	6	Container truck-(rail crane for train's stevedoring) -ordinary articulated flat car	6.24	12.48	9.36	25 natural container/h
	6*	Container truck-(rail crane for train's stevedoring) -ordinary articulated flat car	6.24	12.48	9.36	25 natural container/h
New synchronous handling scheme for double-stack container trains with new special articulated flat car	1	Container ship -(quayside gantry crane)-LDAGV	3.9	7.8	5.85	40 natural container/h
	1*	Container ship-(quayside gantry crane)-LDAGV	3.9	7.8	5.85	40 natural container/h
	2	Wharf apron-(LDAGV)-yard	1.87	1.87	1.87	25 km/h
	2*	Wharf apron-(LDAGV) -railway platform	3.12	3.12	3.12	25 km/h
	3	LDAGV-(yard rail crane) -container location	6.24	12.48	9.36	25 natural container/h
	4	Container location-(yard rail crane)-LDAGV	6.24	12.48	9.36	25 natural container/h
	5	Yard-(LDAGV)-railway platform	1.25	1.25	1.25	25 km/h
	6	LDAGV-(stevedoring device) -new special articulated flat car	2.6	2.6	2.6	30 natural container/h
	6*	LDAGV-(stevedoring device) -new special articulated flat car	2.6	2.6	2.6	30 natural container/h

Consequently, compared to the traditional handling scheme for common double-stack container trains, the new synchronous handling scheme reduces the unit handling time of group ① in normal mode (process 1–6) by 7.54 min, saving 25.44%. The unit handling time of group ② was reduced by 16.90 min, saving approximately 30.52%. The unit operation time of group ③ was reduced by 12.22 min, saving about 28.75%. Moreover, in the direct access train-vessel mode (process 1* + 2* + 6*), the unit handling time of group ① is reduced by 31.48%, group ② is reduced by 44.09%, and group ③ is reduced by 39.46%.

Table 4. Comparison of operation cost between the new synchronous handling scheme and the traditional scheme.

Scheme	Sequence	Total Power/Fuel Consumption	Group ① Operation Cost (RMB)	Group ② Operation Cost (RMB)	Group ③ Operation Cost (RMB)	Electricity Price/Oil Price
Traditional handling scheme for common double-stack container trains	1	500 kw	27.63	55.25	41.44	0.85 RMB/KWh
	1*	500 kw	27.63	55.25	41.44	0.85 RMB/KWh
	2	0.32 L/km	0.7	0.7	0.7	0.3KM (Diesel 7.25 RMB/L)
	2*	0.32 L/km	1.16	1.16	1.16	0.5KM (Diesel 7.25 RMB/L)
	3	210 kw	23.21	46.41	34.81	0.85 RMB/KWh
	4	210 kw	23.21	46.41	34.81	0.85 RMB/KWh
	5	0.32 L/km	0.46	0.46	0.46	0.2KM (Diesel 7.25 RMB/L)
	6	300 kw	26.52	53.04	39.78	0.85 RMB/KWh
	6*	300 kw	26.52	53.04	39.78	0.85 RMB/KWh
New synchronous handling scheme for double-stack container trains with new special articulated flat car	1	500 kw	27.63	55.25	41.44	0.85 RMB/KWh
	1*	500 kw	27.63	55.25	41.44	0.85 RMB/KWh
	2	200 kw	5.3	5.3	5.3	0.3 KM (RMB/KWh)
	2*	200 kw	8.84	8.84	8.84	0.5 KM (0.85 RMB/KWh)
	3	300 kw	26.52	53.04	39.78	0.85 RMB/KWh
	4	300 kw	26.52	53.04	39.78	0.85 RMB/KWh
	5	200 kw	3.54	3.54	3.54	0.2 KM (0.85 RMB/KWh)
	6	100 kw	3.68	3.68	3.68	0.85 RMB/KWh
	6*	100 kw	3.68	3.68	3.68	0.85 RMB/KWh

Table 5. Comparison of the unit time and unit cost of three groups between the synchronous handling scheme and the traditional scheme.

Scheme	Mode	Unit Handling Time of Group ① (min)	Unit Handling Time of Group ② (min)	Unit Handling Time of Group ③ (min)	Unit Operation Cost of Group ① (RMB)	Unit Operation Cost of Group ② (RMB)	Unit Operation Cost of Group ③ (RMB)
Traditional handling scheme for common double-stack container trains	Normal mode	29.64	55.38	42.51	101.73	202.27	152
	Direct access train-vessel mode	14.04	24.18	19.11	55.31	109.45	82.38
New synchronous handling scheme for double-stack container trains with new special articulated flat car	Normal mode	22.1	38.48	30.29	93.19	173.85	133.52
	Direct access train-vessel mode	9.62	13.52	11.57	40.15	67.77	53.96
Time reduction in direct access train-vessel mode		4.42 min	10.66 min	7.54 min	31.48%	44.09%	39.46%
Time reduction in normal mode		7.54 min	16.90 min	12.22 min	25.44%	30.52%	28.75%
Cost reduction in direct access train-vessel mode		15.16 RMB	41.68 RMB	28.42 RMB	27.41%	38.08%	34.50%
Cost reduction in normal mode		8.54 RMB	28.42 RMB	18.48 RMB	8.39%	14.05%	12.16%

Regarding the unit operation cost in the normal mode, the total unit operation cost of group ① was reduced by 8.54 RMB (8.38%) in the new scheme, group ② was reduced by 28.42 RMB, saving approximately 14.05%, and group ③ was reduced by 18.84 RMB. By contrast, in the direct access train-vessel mode, the total unit operating cost of the new scheme is reduced by 27.41% in group ① and 38.08% in group ②, as well as a 34.50% reduction in group ③.

Therefore, the new synchronous handling scheme for double-stack container trains in the sea-rail intermodal terminal has obvious time advantages and cost preponderance over the traditional scheme, which verifies the optimization of this new technology.

5.3. Case Analysis

At the same time, considering the annual throughput of 10 million TEU, 25% of the containers are assumed to be taken directly by train from the ship in the direct access train-vessel mode, and 75% of the containers are transferred after being stored on the yard in the normal mode. At the same time, it is also assumed that 20-foot containers and 40-foot containers (including 40-foot GP and 40-foot HC), respectively, represent 60% (6 million TEU) and 40% (equivalent to 2 million FEU).

The calculation results in Table 6 are based on Table 4 and the assumptions of the case analysis. For example, in the calculation of group ①, there are 250,000 units in the direct access train-vessel mode, and 750,000 units in the normal mode; in group ③, there are 500,000 units in the direct access train-vessel mode and 1.5 million units in the normal mode (every two 20-foot containers and one 40-foot container form a unit). Then, the cost of each process stage can be calculated to obtain the cost of the direct access train-vessel mode, the cost of the normal mode and the total cost, and can further calculate the amount and percentage of cost reduction.

Table 6. Comparison of operation cost between the new synchronous handling scheme and the traditional scheme considering annual container throughput.

Project	**Traditional Handling Scheme for Common Double-Stack Container Trains**			**New Synchronous Handling Scheme for Double-Stack Container Trains with New Special Articulated Flat Car**		
	Group ①	**Group ②**	**Group ③**	**Group ①**	**Group ②**	**Group ③**
Number of units in direct access train-vessel mode	500,000 FEU/2 =250,000 units	1,500,000 TEU/4 =375,000 units	500,000 FEU & 500,000 TEU =500,000 units	500,000 FEU/2 =250,000 units	1,500,000 TEU/4 =375,000 units	500,000 FEU & 500,000 TEU =500,000 units
Number of units in normal mode	1,500,000 FEU/2 =750,000 units	4,500,000 TEU/4 =1,125,000 units	1,500,000 FEU & 4,500,000 TEU =1,500,000 units	1,500,000 FEU/2 =750,000 units	4,500,000 TEU/4 =1,125,000 units	1,500,000 FEU & 4,500,000 TEU =1,500,000 units
Process 1	20,722,500	62,156,250	62,160,000	20,722,500	62,156,250	62,160,000
Process 1*	6,907,500	20,718,750	20,720,000	6,907,500	20,718,750	20,720,000
Process 2	525,000	787,500	1,050,000	3,975,000	5,962,500	7,950,000
Process 2*	290,000	435,000	580,000	2,210,000	3,315,000	4,420,000
Process 3	17,407,500	52,211,250	52,215,000	19,890,000	60,795,000	59,670,000
Process 4	17,407,500	52,211,250	52,215,000	19,890,000	60,795,000	59,670,000
Process 5	345,000	517,500	690,000	2,655,000	3,982,500	5,310,000
Process 6	19,890,000	59,670,000	59,670,000	2,760,000	4,140,000	5,520,000
Process 6*	6,630,000	19,890,000	19,890,000	920,000	1,380,000	1,840,000
Cost in direct access train-vessel mode (RMB)	13,827,500	41,043,750	41,190,000	10,037,500	25,413,750	26,980,000
Cost in normal mode (RMB)	76,297,500	227,553,750	228,000,000	69,892,500	197,831,250	200,280,000
Total cost (RMB)	90,125,000	268,597,500	269,190,000	79,930,000	223,245,000	227,260,000
Cost reduction in direct access train-vessel mode	3,790,000 RMB	15,630,000 RMB	14,210,000 RMB	27.41%	38.08%	34.50%
Cost reduction in normal mode	6,405,000 RMB	29,722,500 RMB	27,720,000 RMB	8.39%	13.06%	12.16%
Total cost reduction	10,195,000 RMB	45,352,500 RMB	41,930,000 RMB	11.31%	16.88%	15.58%

In group ①, it can be seen that the new synchronous handling scheme for double-stack container trains with new special articulated flat car reduces the cost of 3.79 million RMB (27.41%) in the direct access train-vessel mode and 6.41 million RMB (8.39%) in normal mode, and the total cost decreased by 10.195 million RMB (11.31%). In the operation of group ②, the cost of the direct access train-vessel mode was reduced by 15.63 million RMB (38.03%), the cost of the normal mode was reduced by 29.72 million RMB (13.06%), and the total cost was reduced by 45.35 million RMB (16.88%). In group ③, the cost of the direct access train-vessel mode was reduced by 14.21 million RMB (34.50%), while the cost of the normal mode was reduced by 27.72 million RMB (12.16%), and the final total cost decreased by 41.93 million RMB (15.58%). Therefore, it is clear that the application of the new synchronous handling scheme makes the experimental groups ①–③ show brilliant cost advantages in both the direct access train-vessel mode and the normal mode.

6. Conclusions

In the context of the Chinese government supporting the innovation pilot of double-stack container sea-rail intermodal transport in the Ningbo Beilun port area, we studied the problem that the handling efficiency of double-stack container trains in the traditional intermodal terminal is limited and cannot achieve the rapid collection and distribution of container goods in the port. Based on the obtained results, the conclusions can be summarized as follows.

- In this study, a new articulated flat car is developed, which is designed with two-tier bearing platforms to load containers on the upper and lower layers at the same time without affecting each other. This will not only help to increase the number of containers loaded and shipped but will also accelerate the loading and unloading speed. Additionally, eight feasible container stacking modes are realized on the new special articulated flat car of double-stack container trains, which is conducive to mixing and matching different types of containers to reduce the difficulty of making loading plans and organizing the containers and the cargo source.
- At the same time, on the basis of traditional AGV, a new type of electric-powered LDAGV is designed. It can not only transport containers between the yard and the quayside container crane, between the yard and the railway platform, and between the quayside container crane and the railway platform, but it can also load the containers onto the new special articulated flat car without the help of rail cranes, tire cranes, reach stackrs, or forklifts, thus reducing the purchase and use costs of these machines.
- To cooperate with the work of LDAGV and the new special articulated flat car, a new concept of double-tier container yard and double-tier stereoscopic yard used in wharfs and inland railway freight stations is proposed. This can improve the utilization of the container yard and facilitate the loading and unloading of containers on or off double-stack container trains.
- The process of containers from the liner ship to the inland railway container freight station is described in detail, and the loading, unloading and transfer procedure of double-stack container trains at the wharf and the railway freight station are optimized.
- With the help of a scientific and reasonable case analysis, it is shown that the new synchronous handling technology for double-stack container trains is helpful in reducing the handling time and operation cost in the port.
- The application of this new technology is beneficial to improving port collection and distribution capacity, which is conducive to a reduction in the backlog time of containers in ports to ease the pressure of port congestion.

Author Contributions: Data curation, Z.Z. and X.W.; Funding acquisition, Z.Z., X.W. and W.L.; Investigation, Z.Z. and S.C.; Methodology, Z.Z., L.J. and W.L.; Project administration, Z.Z.; Resources, S.C. and L.J.; Software, Z.Z. and L.J.; Supervision, X.W. and W.L.; Validation, S.C.; Writing—original draft, Z.Z. and S.C.; Writing—review and editing, Z.Z., X.W. and W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (71272219; 71601014) and the National College Students Innovation and Entrepreneurship Training Program (202110254009) supported by the Ministry of Education of China.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated during this study are included in this article.

Conflicts of Interest: The authors declare no conflict of interest.

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