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Simulation Study on Sea-Rail Intermodal Diversion Operation of Container Terminal in the Beilun Port Area of Ningbo Zhoushan Port

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Abstract: With the continuous development of global trade, the Beilun port area of Ningbo Zhoushan Port, as an important node of international shipping, its efficient and orderly container dredging operation is crucial to ensure the overall operational efficiency of the port and the stability of the regional supply chain. However, the actual operation is faced with multiple constraints such as fluctuating berth utilization rate, complex truck scheduling, tight yard space, and so on, which need to be optimized by scientific means. To achieve more efficient container transport, it is necessary to further optimize and improve sea-rail intermodal transport to improve the efficiency of port container operations. Therefore, this paper is based on the background of the rapid development of sea-rail intermodal transport of port containers, focusing on the problem of dredging operation of container terminals in the Beilun port area of Ningbo Zhoushan Port, through the analysis of the characteristics and influencing factors of container dredging operation, research on the optimization of container dredging scheme and put forward optimization scheme for the problem of dredging in Beilun Port Area of Ningbo Zhoushan Port, which is aimed at improving the efficiency and economy of container dredging operation and the efficiency of container dredging operation in Beilun port area through the advanced modeling and simulation technology. Through advanced modeling and simulation technology, it aims to effectively improve the efficiency and economy of container dredging operations in the Beilun port area, to cope with the increasing throughput pressure and the challenges of a complex logistics environment, and to provide theoretical support and practical guidance for the development of China's sea-railway intermodal transport.

Keywords: Beilun port area of Ningbo Zhoushan Port; Container terminal; Sea-rail intermodal transport; Harbour dredging operation; System simulation

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1. Introduction

Ports have long been valued by all countries as an important hub for land and water transport. Actively improving the port development strategy and maximizing the role of the port, is essential to ensure the survival and development of the port. The development of ports cannot be separated from the port transport to improve the quality of the port container system. To achieve the efficient development of port transport, it is imperative to build and improve the infrastructure network, including the construction of transport corridors based on multiple modes of transport, and to strengthen the links between the corridors, in which the links between ports and railways and highways are also crucial, through which a series of initiatives to gradually establish a well-connected transport system to provide strong support for the smooth operation of ports [1].

Ningbo Zhoushan Port is located in the middle of China's mainland coast. It is a deep-water port integrating inland river port and estuary port and occupies an important position among China's coastal ports [2–3]. The data released by Zhejiang Province Port and Navigation Management Centre on January 10th shows that in 2023, Ningbo Zhoushan Port had completed 1.324 billion tonnes of cargo throughput, an increase of 4.94% compared with 2022; complete the container throughput of 35.301 million TEUs, a year-on-year increase of 5.85%, and the competitiveness of Ningbo Zhoushan Port in the world's ports continues to increase [4].

2. Analysis of the current situation of port dredging operations in the Beilun port area

2.1. Beilun port area container terminal layout structure

Container terminals in the Beilun port area of Ningbo Zhoushan Port include terminal berths, terminal front operation areas, storage yards, railway port stations, railway lines, and loading and unloading areas. The business scope involved in the cargo terminal includes loading and unloading of containers, railway port station inspection, and extended empty container management. The railway port station handles the arrival and departure and transport business of railway containers and completes the loading and unloading transit of railway containers. The inspection yard provides customers with national inspection, sorting, pick-up, and other businesses. Extended empty container management provides customers with container management services [5].

2.2. Beilun port area container terminal facilities and equipment

Huge empty container yards and heavy container yards have been planned to meet the temporary storage needs of large quantities of cargo and achieve an orderly turnover of cargo in the Beilun harbor area. There is a perfect road network in and around the port area to ensure the effective connection of cargoes with ships, railways, and container trucks to meet the transport needs of different customers. Production auxiliary facilities and container gates are equipped with professional production operating systems. The gates are upgraded into intelligent gates around the collection and transport efficiency and other needs, realizing digital online services, and achieving a zero-contact centralized management model through the interactive docking of hardware and software with the data of the terminal's production system [6].

When the required train is scheduled to depart, the internal collector goes to the yard again to pick up the containers to be transferred and transports them to the railway operation area, where the rail crane is responsible for loading the containers on the collector to the container train. When the container arrival time is just in line with the train departure time, the articulation of good coordination is required for the change of different transport methods. Through the ship-train transfer method, in which the container does not go through the yard for storage, the container is directly transported, loaded, and unloaded through the bridge cranes and gantry cranes [7].

This thesis assumes that containers need to be temporarily stored in the yard for all ways of port shipment, so it analyses the common process from the ship entering the yard to the completion of port shipment. Two major factors affecting the container dredging operation are discussed in detail based on the actual Beilun port area, with the terminal-installed railway line mode as the background

2.2.1. Capacity of port facilities and equipment

Through the above analysis of the container dredging operation process, it can be seen that the terminal facilities and equipment space configuration for the control of containers in its range of mobile trajectory and the implementation of the operation has a decisive role. At the same time, this layout shows the operational efficiency, which has a significant impact on the overall container dredging efficiency. This includes yard storage capacity, capacity of loading and unloading equipment, and train running conditions.

2.2.2. The level of port-sparing operation equipment connection

The interface level of dredging operation equipment refers to the degree of cooperation and interface between the various links of equipment in the process of port dredging operations, with the measurement index being the interface time. This includes the interface level of transport and handling equipment within the terminal and the container and port transport equipment connection level.

2.2.3. Container port demand information

Port container dredging demand information involves several aspects, including container arrival time, quantity, transport distance, the direction of container transport, the urgency of the container cargo, and the number of transported containers.

3. Optimization modeling of dredging operations

3.1. Definition of symbols

The symbols of the container port operation model are defined as shown in **Table 1** below.

Table 1. Definitions of model ensemble symbols

Symbol	Description
Set	
M	Indicates a collection of modes of transport for port transport
m	Indicates the mode of transport for port shipping $m \in M$
R	Indicates a collection of containers in order of arrival
r	Indicates container arrival batch number $r \in R$
Z	Indicates a collection of sea-rail intermodal container trains
z	Indicates container train number $z \in Z$
H	Indicates a collection of port destination cities
h	Indicates port destination city $h \in H$
Parametric	
Q	Total number of shipment containers arriving at the port (boxes)
Q_z	Maximum number of containers loaded on container block train z (boxes)
Q_{max}	Maximum number of containers stacked in the yard (boxes)
T_r	Moment of the arrival of the rth container in the harbor
T_m^r	Containers with serial number r are shipped by way of transportation m at the moment of transport
C_a	Cost of loading and unloading a single container by gantry crane in the railway loading and unloading operation area (¥)
C_y	Cost of in-terminal yard storage of containers per unit of time in the harbor (¥/(box*hours))

Table 1 (Continued)

Symbol	Description
C_{mh}	Transport cost per unit of container transported to destination city h by transport mode *m* (¥)
C_v^n	Container time cost for port transport with serial number n (¥/(box*hours))
Q_h^r	Number of containers arriving in batch *r* with port clearance direction *h* (boxes)
V_m	Container transport speed for port clearance by m-transport (kilometers per hour)
P_{mh}^r	Transport distance (in kilometers) from the port container *r* to the destination city *h* by the m-porting mode of transport
Decision variables	
x_{mh}^r	Container No. *r* is transported to destination city h by port clearance m, then $x_{mh}^r = 0$, otherwise 0
y_{mz}^r	No. for *r* dredging container from *h* to *z* frequency container train for dredging, then $y_{mz}^r = 0$, otherwise 0

3.2. Objective function

Minimize the total cost of port container dredging operation as the model objective function, considering the total cost of dredging operation and the cost of the time value of goods.

3.2.1. Total operation cost

The total cost of dredging operation refers to the sum of all relevant costs incurred in the process of container dredging operation, which is mainly composed of the following elements:

Yard storage cost C_1: The total cost of container storage during the planning cycle can be expressed by the following **Formula 1**.

$$C_1 = C_y \cdot \sum_{r \in R} \sum_{h \in H} \sum_{m \in M} \left((T_m^r - T_r) \cdot x_{mh}^r \cdot q_h^r \right) \tag{1}$$

Port clearance transport cost C_2: The transport cost is directly related to the spatial distance it crosses, and the formula for container port clearance transport cost C_2 is shown in **Formula 2** below.

$$C_2 = \sum_{r \in R} \sum_{h \in H} \sum_{m \in M} (C_{mh} \cdot P_{mh}^r \cdot x_{mh}^r \cdot q_h^r) \tag{2}$$

Railway operation area container handling cost C_3: Railway operation area container handling cost C_3 is related to the number of times of loading and unloading of rail-type gantry cranes, which can be expressed by the following **Formula 3.**

$$C_3 = C_a \cdot \sum_{r \in R} \sum_{h \in H} (x_{1h}^r \cdot q_h^r) \tag{3}$$

3.2.2. Container port cargo time value cost

The time value cost of containerized cargo is shown in **Formula 4** below.

$$C_4 = \sum_{r \in R} \sum_{h \in H} \sum_{m \in M} \left(\left(\frac{P_{mh}^r}{V_m} + T_m^r - T_r \right) \cdot C_v^r \cdot x_{mh}^r \cdot q_h^r \right) \tag{4}$$

Therefore, the total cost of dredging transport is the sum of the total cost of dredging operations and the time value cost of dredging goods. The objective function of the model is shown in **Formula 5**.

$$
\begin{aligned}
minZ &= C_1 + C_2 + C_3 + C_4 \\
&= C_y \cdot \sum_{r\in R}\sum_{h\in H}\sum_{m\in M}\left((T_m^r - T_r)\cdot x_{mh}^r \cdot q_h^r\right) \\
&+ \sum_{r\in R}\sum_{h\in H}\sum_{m\in M}(C_{mh}\cdot P_{mh}^r \cdot x_{mh}^r \cdot q_h^r) + C_a \cdot \sum_{r\in R}\sum_{h\in H}(x_{1h}^r \cdot q_h^r) \\
&+ \sum_{r\in R}\sum_{h\in H}\sum_{m\in M}\left(\left(\frac{P_{mh}^r}{V_m} + T_m^r - T_r\right)\cdot C_v^r \cdot x_{mh}^r \cdot q_h^r\right) \\
&= \sum_{r\in R}\sum_{h\in H}\sum_{m\in M}\left(\left((T_m^r - T_r)\cdot C_y + C_{mh}\cdot P_{mh}^r + \left(\frac{P_{mh}^r}{V_m} + T_m^r - T_r\right)\cdot C_v^r\right)\right. \\
&\left.\cdot x_{mh}^r \cdot q_h^r\right) + C_a \cdot \sum_{r\in R}\sum_{h\in H}(x_{1h}^r \cdot q_h^r)
\end{aligned} \tag{5}
$$

4. Simulation modeling and analysis of container terminals in the Beilun port area

4.1. Simulation model of dredging operation process: Modelling methods and ideas

The simulation steps are as follows.

4.1.1. Establish container port simulation model entity

According to the layout of the port, introduce the basic entity of the simulation model, including each functional operation area and related facilities and equipment, this setting directly affects the subsequent simulation effect.

4.1.2. Establish the simulation logic process model

Define the relationship between the elements, construct the port container dredging operation process framework, ensure the correct operation of the simulation model at the logical level, and provide the basis for the subsequent 3D entity movement process.

4.1.3. Establishment of collaborative operation of each entity

Establishment of information transfer and processing mechanism, which involves not only the cooperation between equipment but also the information system and other aspects. Through the collaborative operation, the connection between entities is established, and the dynamic simulation operation of the whole system is realized so that the system can more realistically simulate the actual operation of the port.

4.1.4. Controlling the movement of 3D entities

Determine the actual displacement trajectories of loading and unloading equipment and carriers in the terminal according to the framework of the operation process, and plan the collaboration rules between intelligent entities to ensure that each entity can synchronize and cooperate with the operation.

4.1.5. Setting simulation parameters

Setting the relevant parameters of each operating entity according to the specific information of the port to ensure that the simulation data is as close as possible to the actual operation of the port to improve the accuracy of the model.

4.1.6. Simulation

Run the simulation model to simulate the dredging operation process of the port, generate relevant evaluation index data, output them in the form of statistical charts, and record them for subsequent analysis.

4.1.7. Analysis of evaluation indexes

Compare the simulation results with the actual situation, analyze the indexes in-depth, and assess the operational efficiency of the port and the existing problems.

4.2. Logic design of simulation process for port dredging system

The model adopts a 2D and 3D view linking mechanism to guide the behavior of terminal operation equipment in a 3D entity interface through 2D interface logic manipulation to achieve real-time dynamic simulation of container dredging operation in the whole port.

4.2.1. Ship unloading operation on the shore bridge

The intelligent body module box is used to represent the dredging container, and the attributes and behaviors are defined to achieve the generation of containers through the design logic. Through the temporary storage waiting queue for the processing of containers, the use of material handling in the overhead crane entity to simulate the operation of the bridge, writing a logic simulation of the bridge from the queue to extract containers to simulate the process of unloading the ship.

4.2.2. Containers are transported from the quay front to the yard operation

Using the vehicle source model in the road traffic library to simulate the inner container, set up the path of the vehicle and the transport logic, use the overhead crane to simulate the gantry crane, unloading through the split node, write the logic to achieve the loading and unloading of containers when the inner container is unloaded and returned to the quay front to continue to complete the subsequent transport. When the container unloading is completed, it returns to the quay front to continue to complete the subsequent transport.

4.2.3. Railway dredging operation

The use of a train library in the train and track entities to simulate the operation of the railway system and the train and set the train path and transport logic. The use of overhead crane entities to simulate the gantry crane writes the logic to achieve the internal set of trucks needed to carry out railway dredging of containers to be transported to the railway operating area through the gantry crane for the operation process of loading. The study also designs the logic to realize that the train leaves the port after loading a set number of containers.

4.2.4. Road dredging operation

Using the vehicle model in the road traffic library to simulate the external container truck, calling trucks from the truck pool, setting the path and transport mode of the external container truck, and directly entering the yard to extract containers to drive out of the gate for road transport. The overall logic of the harbor container dredging operation is shown in **Figure 1**, the 3D running effect is shown in **Figure 2**.

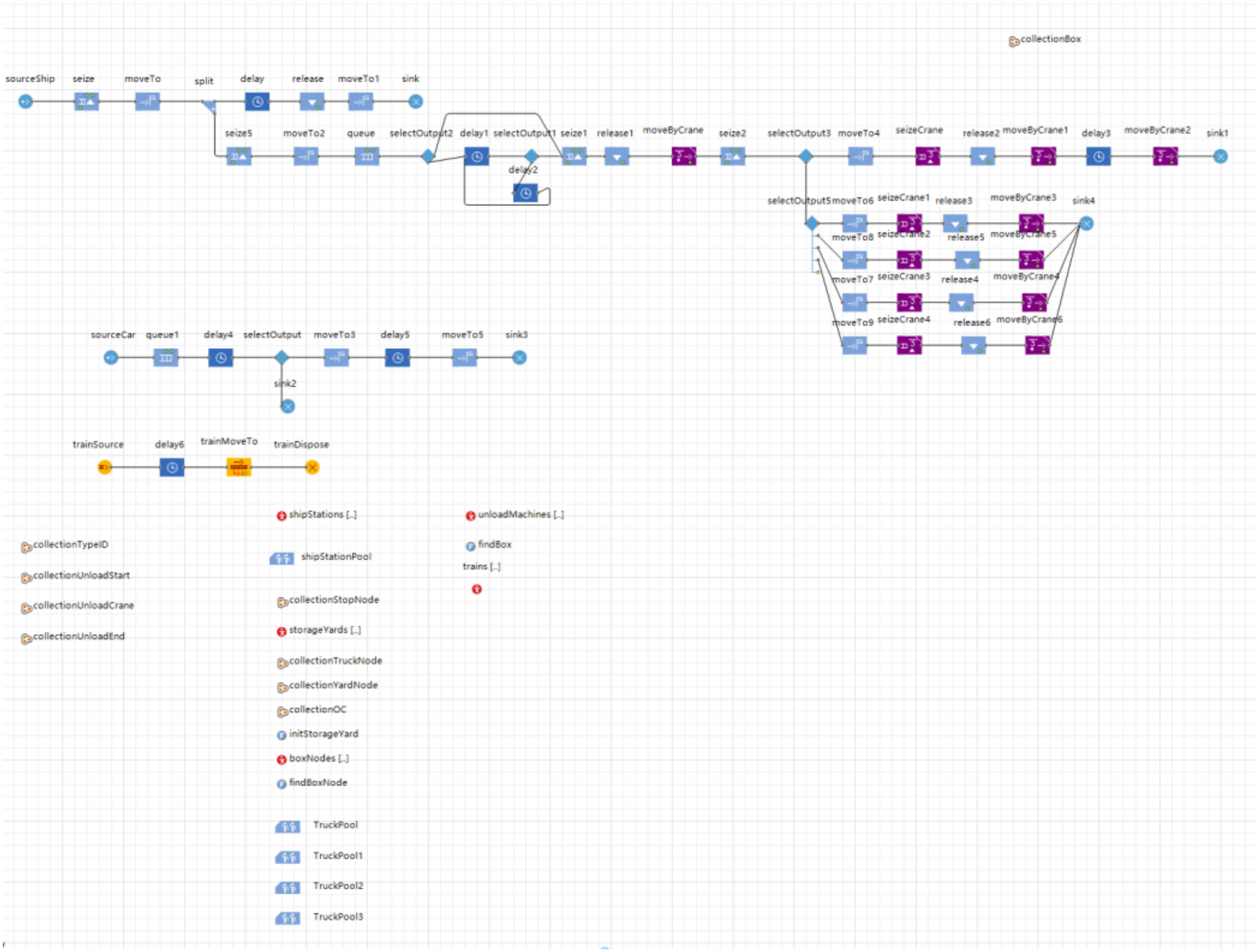

Figure 1. The overall logic of port container dredging operations

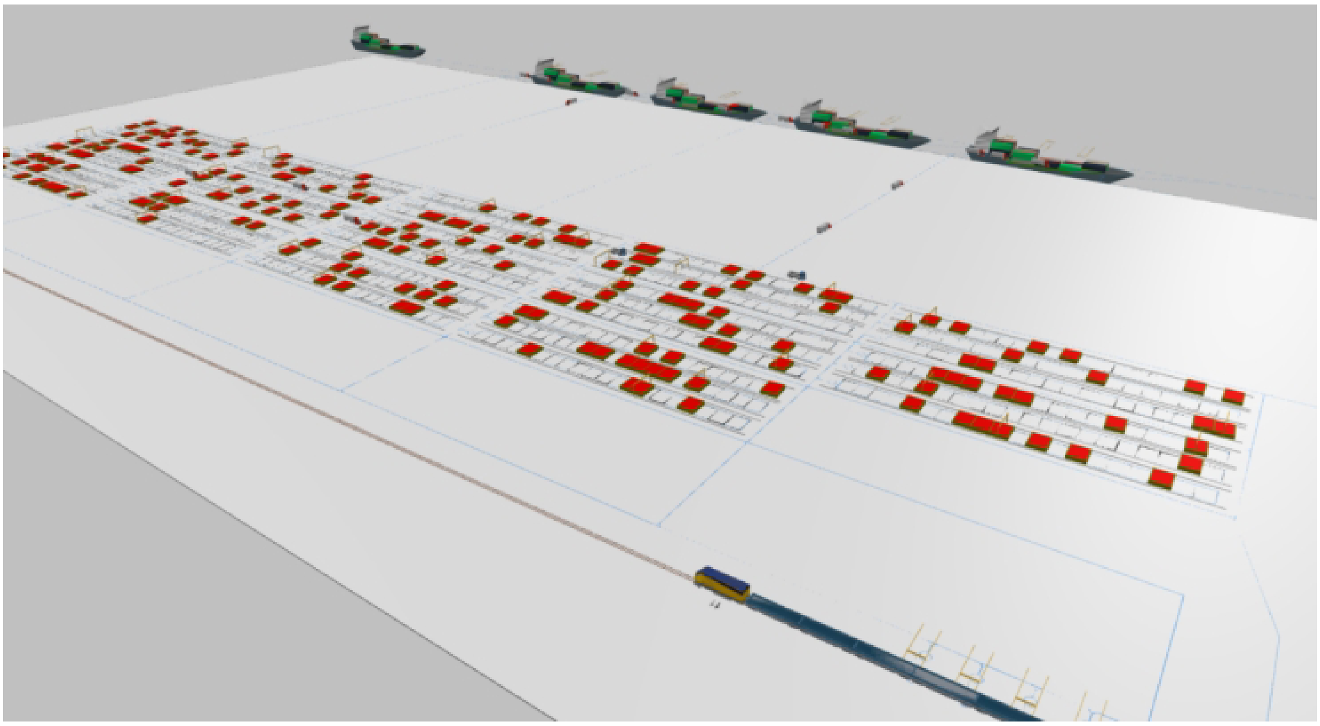

Figure 2. Model 3D running effect diagram

4.3. Analysis of examples

4.3.1. Simulation model data

Combined with the container attributes and the port's specific dredging process, set up the model container-related parameter information through the container-related cost information provided by China Railway 95306 as shown in **Table 2** below.

Table 2. Information on container-related parameters

Cost category	Cost values
Road unit container unit transport distance cost (yuan/box-km)	4.8
Container train running arrival and departure base price (yuan/box)	440
Container train unit distance running base price (yuan/box-km)	3.185
Railway loading and unloading operation area gantry crane single container loading and unloading cost (yuan/box)	120

According to the 2023 operation information provided by the website of the container company of the terminal, the basic parameters of the terminal are set up in the simulation model, the detailed information of the containers to be transported is inputted, and the operation data of each entity is displayed in real-time through the three-dimensional interface. When calculating the storage cost of the yard, a specific yard is selected as the statistical target, the speed and time of the trucks and other parameters are set, and then logical judgment is made to extract the storage data of the yard and the time-consuming data of the operation equipment for statistical analysis.

4.3.2. Comparative analysis of simulation results

In the simulation experiment, the distance and the proportion of railway and road transport are continuously adjusted to explore the effect of using different modes of port transport for bulk arriving containers under specific port transport conditions. The total time and cost of dredging operation under various modes of transport are counted, and the data are shown in **Table 3**. The coordinates of the intersection point of the two linear functions in the figure identify the transport distance where the costs of the two modes of port transport are equal, which is the economic transport distance. Beyond this distance, railway port clearance is more economical; conversely, road port clearance is more advantageous.

The simulation experiment simulates 50 containers as a batch for dredging operation, and according to the optimization model, 100 simulation experiments are conducted to reduce the experimental error. The calculation shows that under the dredging operation conditions, the economic distance of the transport mode is 485.3 km.

When calculating transport costs, the economic efficiency of transport increases significantly with increasing mileage due to fixed base prices for arrivals and departures and low operating base prices. Road transport is the preferred mode of transport for short distances and its cost is directly proportional to the distance. However, when deciding on the optimal mode of transport, ports need to weigh various factors such as transport distance, time, and cargo attributes as shown in **Figure 3**, **Figure 4**, and **Figure 5**. Faced with different transport distances, the most appropriate mode of transport should be flexibly selected to maximize economic benefits.

Table 3. Transport mode comparative analysis

Number of containers removed from the harbor/container	Container distance/ kilometre	Road dredging			Rail dredging		
		Total time/ hour	Total operating cost/¥	Total cost/¥	Total time/ hour	Total operating cost/¥	Total cost/¥
50	200	227	47572	48707	317	59900	61525
	500	477	107572	109807	507	101750	104310
	1000	893	203822	208027	823	185625	189750
	1500	1310	305072	311622	1125	261250	266935
	2000	1727	407572	416207	1437	341000	348250

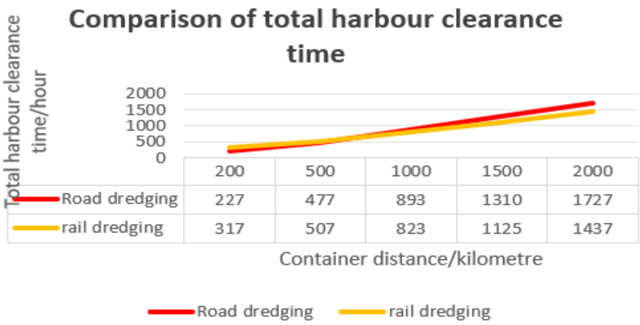

Figure 3. Comparison of total port transport time by different modes of transportation

Figure 4. Comparison of total cost of port transport by different modes of transportation

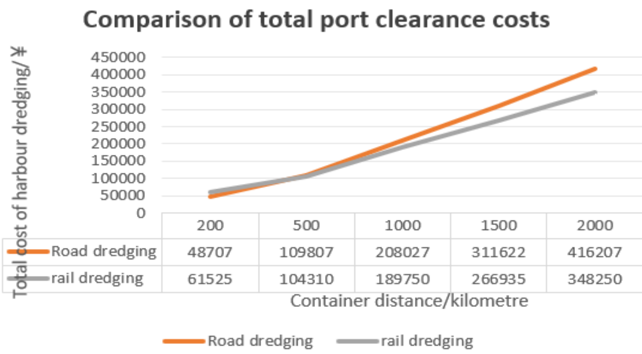

Figure 5. Comparison of total cost of port transport by different modes of transportation

5. Conclusion

In this thesis, the research on the container port dredging operation process is conducted from the perspective of multimodal transport and the establishment of a simulation model to simulate the process of container dredging operation in the Beilun port area of Ningbo Zhoushan Port. The model and genetic algorithm combined with the calculation of the model data are used to explore the economic benefits of different modes of dredging transport. This study compares and analyzes the process of railway transport and road transport in container port dredging operation, summarizes the different layout forms of railway transport, further explores its influence on the process of container port dredging operation, clarifies the optimization framework of the port dredging operation, and come to the conclusion that the efficiency of railway transport is higher than the efficiency of road transport in container port dredging operation. Using Anylogic simulation software, a simulation model of the container dredging operation process is constructed to simulate the dredging operation process of road and railway in the port. Through dynamic simulation analysis, the container transport situation in ports under different modes of transport is studied, and the total time and cost of port dredging operations are counted under different transport distances and different ratios of road and railway transport. Through comparative analysis, the economic transport distance of port container transport modes is derived. In addition, an in-depth study of the impact of dredging container demand information on the operation process provides an important reference for the optimization of the port container transport scheme.

Disclosure statement

The author declares no conflict of interest.

Author contributions

Study idea conceptualization: Xiaoyi Fu
Data analysis: Xiaoyi Fu
Paper writing: Xiaoyi Fu

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