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# Research Article

# A Cooperative Intermodal Transportation Network Flow Control Method Based on Model Predictive Control

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With the development of information technology, intermodal transport research pays more attention to dynamic optimization and multi-role cooperation. The core issue of this paper was to realize container routing with dynamic adjustment, real-time optimization, and multi-role cooperation characteristics in the intermodal transport network. This paper first introduces the Intermodal Transport Cooperation Protocol (ITCP) that describes the operation and analysis of intermodal transport systems with the concept of encapsulation and layering. Then, a new network flow control method was built based on Model Predictive Control (MPC) in the ITCP framework. The method takes real-time information from all ITCP layers as input and generates flow control decisions for containers. To evaluate the method's effectiveness, a discrete event simulation experiment is applied. The results show that the proposed method outperforms the all-or-nothing method in scenarios with high freight volume, which means the method proposed in this paper can effectively balance the network transport load and reduce network operating costs. The research of this paper may throw some new light on intermodal transport research from the perspectives of digitization, multi-role cooperation, dynamic optimization, and system standardization.

#### 1. Introduction

As an important part of logistics, transportation is of great importance to social development. The way to realize green, efficient, and safe transportation is an important research topic in recent years. As a kind of comprehensive transport, intermodal transport realizes the complementary advantages among different modes of transport, which leads to more efficient and economical transportation. Since the 1960s, intermodal transport has effectively promoted the prosperity of international trade and accelerated globalization.

Although intermodal transport is of great significance to the development of human society, there are still many unresolved problems: the ever-increasing global transportation demand has brought about excessive carbon emissions and environmental pollution, which has caused a great burden on the earth's ecology; the container space utilization rate is low, and there are even a great number of empty containers during transportation; cooperation between different stakeholders is difficult; the transportation load is unbalancing. . . The above problems seem to be the bottleneck of existing intermodal transport systems.

With the development of information technology and its application in transportation, the situation has been partly improved. However, the improvement of transportation due to information technology is often local and independent, so transportation systems need a radical change to adapt to the information age. Therefore, it is necessary to introduce innovative logistics concepts to meet this challenge. Physical Internet (PI) [1] and synchromodal transport [2] are the typical representatives. For all innovative logistics concepts, they share a common aspect, that is, they all take dynamic adjustment, real-time optimization, and multi-role cooperation as important parts of their core perspectives.

The core issue of this paper is to realize container routing with dynamic adjustment, real-time optimization, and

multi-role cooperation characteristics in the intermodal transport network. The dynamic adjustment and real-time optimization require the system to have the ability to process real-time data and make decisions quickly. Multi-role cooperation requires that not only stakeholders in the network can cooperate but also different decision modules can participate in cooperative decision-making, which will provide more supporting data and thus make better decisions. To solve the container routing problem on this premise, we need to build a framework to ensure cooperation between different modules as well as real-time information processing, and then plan routes for containers in this framework.

Inspired by PI and synchromodal transport, we proposed Intermodal Transport Cooperation Protocol (ITCP) to describe the operation and analysis of the intermodal transport system by analogy with the Internet. ITCP provides a cooperative paradigm for roles in intermodal transport, and pays more attention to real-time control and dynamic adjustment of the transportation plan, which leads to easier cooperation and better decision-making. Then, this paper will discuss the container routing problem in the framework of ITCP from a flow control perspective. The problem was solved with the Model Predictive Control (MPC) method. Simulation experiments verify the effectiveness of the method.

The contributions of this paper are as follows: (1) We propose an innovative logistics framework ITCP to describe the operation and analysis of intermodal transport. (2) We present a new intermodal transport flow control model based on MPC in the ITCP framework. In the model, besides the basic mathematical model of network flow control, we also model the queuing process of loading and unloading, and different characteristics of various transport modes are fully considered. (3) We conducted a discrete event simulation to test the effectiveness of the method under different transport loads.

The structure of this paper is as follows. Section 2 briefly reviews the research of container routing, innovation logistics concepts, and model predictive control. Section 3 presents the innovative logistics framework ITCP and the flow control method running in the framework based on MPC. Section 4 contains the mathematical programming model of MPC. Section 5 verifies the effectiveness of the method through a discrete event simulation experiment and has a discussion. Section 6 concludes the study.

## 2. Literature Review

As the main issue discussed in this paper is the container routing problem, this section first reviews the commonly used route planning methods in intermodal transport. Afterward, because dynamic adjustment, real-time optimization, and multi-role cooperation often rely on innovative logistics frameworks, this section reviews the existing mainstream innovative logistics concepts and frameworks. Finally, this chapter reviews the application of the MPC method in the field of transportation.

2.1. Container Routing Problem. The container routing problem selects the transportation channels and terminals in an intermodal transportation network. In the existing literature, service network design (SND) and network flow planning (NFP) are regarded as two solutions to container routing problems. SND focuses on the transportation service selection for constructing transportation schemes [3–5], while NFP regards containers as cargo flow, and its planning focuses on the impact of cargo flow within the entire network [6–8].

With the development of information technologies, the real-time data in intermodal transportation networks become available for dynamic decision-making. Some researches focus on online decision-making. For instance, Chang presented a dynamic path selection method based on real-time information on a rolling horizon [9]. In the research of van Riessen [10], the real-time container transport planning was realized by a decision support system (DSS), which is based on decision trees trained with solutions from a centralized optimization method. Some other studies focus on using real-time information to dynamically adjust previously generated schemes. In the study of Hrušovský et al. [11], a decision support system based on hybrid simulation and service network design achieves real-time allocation combining offline planning with online replanning. In Bock's research [12], the decisions in a horizon of the theoretical plan are changeable to adapt the transportation processes in the real-time control system.

In addition to decision-making based on real-time information, information technologies also promote cooperation among different roles in intermodal transportation. Some researches focus on the construction of intermodal transport cooperation platform to realize the information communication of different roles. For instance, Ding [13] built an information communication platform for the relatively independent information systems of different transportation modes, to realize the unified management of multimodal transportation. Some research also focuses on cooperative decision-making among different decision modules, such as the cloud-based cooperative decision support system proposed by Fanti et al. [14]. The platform integrates modules including cargo transport optimization, intelligent truck parking, CO2 monitoring, etc. Multiple modules realize data exchange and cooperative decisionmaking through the platform. What's more, the cooperation can also be carried out in the form of distributed optimization [15, 16].

2.2. Innovation Logistics Concepts. As information technology has penetrated all aspects of logistics systems, further researches began to pay attention to some innovative logistics concepts. Physical Internet (PI) and synchromodal transport are the typical representatives.

Markillie first proposed the concept of PI in 2006, and Professor Benoit Montreuil formed the complete theoretical system in the following years to meet the challenges of sustainable development of logistics [1]. PI applies the idea of the Internet to the logistics system. It creates an open

global logistics network through encapsulation, interface, and protocol. The transport units with goods inside are regarded as the "data packages" in the logistics network. An Open Logistics Interconnection (OLI) model was proposed to enable interconnecting logistics services within PI [17].

The concept of PI is disruptive, and its core components are still in the research stage, including PI containers [18, 19], global interconnection [20, 21], and platform architecture [22, 23]. Therefore, most of the researches based on the concept of PI focus on the theoretical level [24, 25]. In the innovative logistics development roadmap of ALICE [26], PI is the long-term goal to be achieved by 2050. It is worth mentioning that PI covers all logistics scenarios and is not limited to intermodal transport.

Synchromodal transport, which appears in ALICE's roadmap as a short-term goal, is also a new concept in recent years. It refers to the cooperation of various roles in an intermodal transport network through information and communication technology and intelligent transportation technology to achieve efficient, reliable, flexible, and sustainable transportation services [27]. The cornerstone of synchromodal transport is an integrated view in the planning and management of different modalities to provide flexibility in handling transport demand [2]. Synchromodal transport gives a new connotation to intermodal transport. It implements real-time route planning, seamless switching of transport mode, and real-time equipment scheduling based on the original intermodal transport. Synchromodal transport can be understood as real-time, dynamic, optimized, and integrated intermodal transport.

Most of the research about synchromodal transport is related to dynamic transportation planning based on realtime information. In the research by Qu et al. [28], under the framework of synchromodal, a replanning model for uncertain disturbances was proposed to improve the flexibility of the network. Yee et al. [29] presented a synchromodal decision support model based on the Markov decision process, and it allows adaptations to the modal choice based on real-time information on the travel time. Guo et al. [30] proposed an online match platform between shipment requests and transportation services, and a rolling horizon approach and a heuristic algorithm were developed to handle the matching problems in hinterland synchromodal transportation dynamically. What's more, they also presented approaches with predictive information that perform better and proposed an anticipatory optimization approach for the matching problems [31]. Some other researches focus on the construction of integration platform [32].

In general, PI is controversial because of its subversive ideas [33], and synchromodal transport is regarded as the next generation of intermodal transport. Compared with synchromodal transport, PI has a wider range of application scenarios and is more forward-looking, but synchromodal transport has a more solid theoretical and application foundation.

Based on the concepts of PI and synchromodal transport, ITCP is proposed to describe the operation and decision-making of intermodal transportation systems hierarchically. Although both refer to the TCP/IP protocol,

the difference between ITCP and OLI is that ITCP emphasizes the continuity of the transport process. The flow of containers between ITCP layers represents the handover of different transport processes, just like data packages in Internet protocols. In addition, ITCP inherits the characteristics of synchromodal transport real-time decision-making, dynamic optimization, and integration.

2.3. Model Predictive Control. In this paper, the MPC method is used to realize the network flow control decision in the network layer of ITCP. In the MPC, the controlled object's state is sampled at the decision-making point, and the optimal control is carried out for a relatively short time horizon in the future. Only the first step of the decision will be applied, and the rest will be abandoned [34]. Then, the system repeats the above operations at the next planning horizon. MPC is a common method in process control systems and has recently been applied in traffic control systems [35, 36].

MPC method also has many applications in intermodal transport. In the research of Larsen et al. [37], a model predictive controller was presented to solve an integration problem about transport mode combination selection and truck route planning in a synchromodal transport network. The research of Nabais et al. [38] presents a hierarchical model predictive control framework for addressing flow assignments in intermodal container terminals. As for the study of Li et al. [6], a receding horizon intermodal container flow control method was developed to realize intermodal freight transport planning with dynamic transport demand and dynamic traffic conditions. The method control and reassign container flows in a receding horizon way, solving linear programming problems in every planning horizon.

Similar to Li's research, the model in this paper also applies MPC to the flow control of containers. However, this paper no longer solves the problem by a single decision module. Placing more emphasis on the cooperation of different modules, this paper proposes the ITCP framework to support cooperation and decision-making. In addition, the mathematical model in MPC models the queuing process of containers when unloading or loading in the terminals, and explains the transfer process. The modal also considered the existing goods in the channel before the decision-making. These improvements make the model more practical. What's more, this paper also describes the simulation method in detail, and the simulation experiment pays more attention to the performance of the method under different loads.

### 3. Network Flow Control Method

The core issue of this paper is to realize container routing in the intermodal transport network with dynamic adjustment, real-time optimization, and multi-role cooperation characteristics. Firstly, we propose a framework named Intermodal Transport Cooperation Protocol (ITCP) to ensure real-time data collection, optimization decision-making, and cooperation of different roles. Then, we present the construction of the container routing module.

3.1. Intermodal Transport Cooperation Protocol. Inspired by Physical Internet and synchromodal transport, we built the ITCP to describe the operation and analysis of the intermodal transport system by analogy with the Internet, and the containers are regarded as "data packages" in the ITCP, which makes intermodal transport systems' operation process follow the unified encapsulation method, interactive interface, and cooperation protocol. The goal of the ITCP is to realize the cooperation of multiple stakeholders in the network and achieve efficient and sustainable transportation systems. Unlike the OLI protocol [17] raised in Physical Internet, ITCP abandons ideas that are too idealistic from the perspective of the existing transportation system and pays more attention to the circulation of containers in the intermodal network. In other words, ITCP is a synchromodal transport inheriting the idea of PI.

ITCP is a framework that contains modules about intermodal transport network analysis and decision-making. The unified encapsulation method, interactive interface, and cooperation protocol ensure the data interaction between different modules. Each decision and analysis module follows the principle of program reuse and the design idea of high cohesion and low coupling.

Similar to TCP/IP protocol, the ITCP divides the intermodal transport system into five layers, namely, Transport Layer, Transfer Layer, Network Layer, Encapsulation Layer, and Consignor Layer from bottom to top, as shown in Figure 1. Among them, the Consigner Layer interacts with the consignor to generate transportation demand; the Encapsulation Layer realizes the packaging of the containers, including cargo collection, packing, unpacking, distribution; the Network Layer realizes the dynamic routing of the containers to ensure the efficient flow of the network; the Transfer Layer implements the operation and management of the intermodal transport terminals; the Transport Layer realizes the transportation of containers between terminals.

It is worth mentioning that the ITCP is not an information network protocol but a protocol about the operation of physical intermodal transport. It not only divides the operation of the intermodal transport system hierarchically but also divides the functional hierarchy of decision-making. ITCP is a unified framework for complex intermodal transport systems, and roles can make full use of existing resources and provide better services in the framework. Besides, ITCP also guarantees the scalability of the intermodal transport network. Any role can participate in the cooperative operation of the network as long as the uniform protocol is observed. ITCP facilitates hierarchical control, and only necessary information will be exchanged between roles at necessary layers. It not only ensures sufficient information exchange in the network but also protects the business privacy of all stakeholders. In general, ITCP standardizes intermodal transport networks to maximize resource sharing and operational optimization.

In each layer of the Internet protocol, like TCP/IP, the information is added to the head and tail of the data packet, and then the data package is sent through the physical link to another node. After the next node receives the packet, the

packet is disassembled layer by layer. This process ensures the independence of each layer. In the ITCP, containers are regarded as data packets. The shipments from consignors are encapsulated, routed, and transferred through the operation of various layers and then transported to another terminal as containers in channels. Then, the next terminal operates layer by layer from the bottom to the top of the protocol after receiving containers, just like the Internet.

Each layer of ITCP contained various function modules, as shown in Table 1, and the modules can improve the operation effect through data interaction with each other. As one of the most important parts of intermodal transportation, the network routing of containers is the focus of this paper. This paper chooses to deal with the problem from the perspective of network flow planning. In the ITCP, the Network Layer received containers from the Encapsulation Layer and realized container route planning. Then, containers are transferred to the next port and loaded to the right vehicle in the Transfer Layer.

3.2. Container Routing Module. In the Network Layer of ITCP, the network flow control method needs to deal with uncertain events dynamically, such as the dynamic transport demand, the dynamic change of network condition, etc. Besides, it needs to realize the global optimization of the whole network, which is difficult because the intermodal transport network is too complex to obtain an accurate optimization model. However, the MPC method can provide a good solution. The MPC method divides continuous time into time intervals, and flow control decisions are made in each period with the auxiliary information from other layers of ITCP. But, only the first time interval decision will be executed. Because of this characteristic, the MPC method can overcome the disadvantages of an inaccurate model. This method fully considers all participants in the whole network to guarantee global optimization, and its periodic optimization process ensures the timeliness of decisionmaking. Moreover, the method can obtain better optimization performance through short-term prediction of future system states. This chapter will specifically describe the flow control method.

Under the framework of ITCP, the network flow control problem is a decision support module that runs in the Network Layer, and other layers cooperatively participate in. The structure of the decision model is shown in Figure 2. After finishing operations in the Encapsulation Layer, the container routing module in the Network Layer, which MPC realizes, makes a decision based on the system states and auxiliary information from other modules.

To be specific, the network flow control method proposed in this paper utilized six kinds of information to make a decision, as shown in Figure 2. Because of the complexity of intermodal transport, it is not easy to discuss all these information acquisition methods in one paper. So, we consider this information available in Intelligent Transportation System (ITS), which is the basis of the ITCP.

The channel speed estimation is used in the container routing module to estimate the transport time. It is driven by

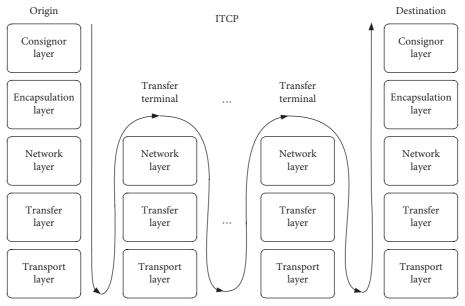


FIGURE 1: Intermodal transport cooperation protocol.

TABLE 1: Function modules in each layer.

Layers	Function modules in each layer		
Consignor layer	Pricing strategy and benefit distribution; consignor demand forecast, etc.		
Encapsulation layer	Packing calculation and LCL calculation; dispatching of empty containers, etc.		
Network layer	Network design and hub layout; network routing of containers, etc.		
Transfer layer	Operation resource dispatching; terminal monitoring, etc.		
Transport layer	Transport resource scheduling, transport monitoring, channel speed estimation, etc.		

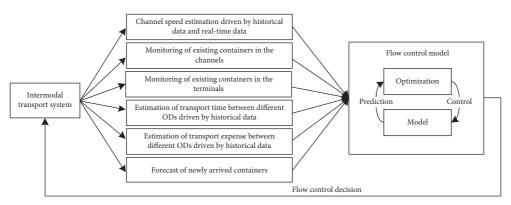


FIGURE 2: Container routing module.

the fusion of historical data and real-time data in the Transport Layer. The estimation module might contain a traffic speed model and a traffic forecast model of the channel, and the research of Guo et al. [39] and Zhao et al. [40] is related to this field. The monitoring data of the container number in channels and terminals are from the real-time monitoring modules of the Transport Layer and Transfer Layer, respectively. The integration of these data helps to build the network monitoring information.

Moreover, the estimated time and estimated expense between different OD come from the Network Layer's historical transport data, which help the container routing module calculate the expected cost of unfinished container transportation. The newly arrived containers' forecast module predicts the new transportation demand by analyzing the consignors' information in the Consignor Layer and getting information about containers to be packed from the Encapsulation Layer. This module improves the accuracy of future network behavior prediction in MPC. There are many related studies, for instance, the study of Moscoso-López et al. [41]. Some of the above information is the basic data of the MPC model, and others help make the model more practical and get better optimization results. Furthermore, all this information is updated in real-time and

delivered to the MPC model at the beginning of the planning horizon.

The container routing module makes decisions for container flow with the above information as input. We assume the parameter t as the time of the decision-making moment, and the planning horizon is a short period from moment t. As we set Ts as time step and N as step number of MPC, the time horizon for planning is  $N \times Ts$ . In the MPC, only system behaviors in the planning horizon are considered. The operation of intermodal transport is described in the flow control model, which assesses the control objective of specific flow control decisions, and the optimization process adjusts the flow control decision. With the iteration of assessment and adjustment, MPC chooses the best flow control decision, but only the first time step flow control will be applied in the time interval [t, t + Ts]. In this paper, the flow control model is a linear programming model, and Section 4 explains the model in detail.

After finishing decision implementation in the time interval [t, t + Ts], a new round of state sampling, data acquisition, and decision-making are executed in the next planning horizon. The receding horizon control ensures the timeliness of decision-making.

# 4. The Mathematical Programming Model in MPC

A mathematical programming model was built to describe the network's operation for implementing the flow control method. As mentioned before, the planning horizon was divided into *N* time intervals, and the model finds the network flow decision of each period. Therefore, we refer to the network flow planning to build the mathematical programming model in MPC, and we take the container flow leaving terminals in every time interval as decision variables. In general, the model finds a container flow allocation result under the intermodal transport network's constraints to minimize the whole network's cost.

4.1. Network Description and Assumptions. Compared with the common transportation network, the characteristic of the intermodal transport network lies in the diversity of transportation modes, including railway, road, and waterway. The different organization modes and transportation characteristics of these kinds of transportation modes bring difficulties to a unified network model.

For the convenience of analyzing the transportation modes, the network is described by a directed graph in graph theory, as shown in Figure 3. The terminals are denoted as vertices, and channels are denoted as edges. The network is denoted as G(V,E), in which vertices set are  $V=V_{\rm road}\cup V_{\rm rail}\cup V_{\rm water}\cup V_{\rm store}$  and edges set are  $E=E_{\rm road}\cup E_{\rm rail}\cup E_{\rm water}\cup E_{\rm tran}$ .

The intermodal transport hub in the network was split according to transport modes. For example, the intermodal transport hub A provides port services for trucks, barges, and trains, as well as container storage service, so we split the hub into four terminals: "3W" terminal for water transport

service, "3T" terminal for railway transport service, "3R" terminal for road transport service, and "3S" terminal for storage service. The transfer channels link the terminals in the same hub, and other types of channels link two terminals providing corresponding services from different hubs.

If vehicles can run in two channels without berthing at the joint terminal, the topology of the network should add a new channel between the nonadjacent terminals of the two channels. For example, if the barge can sail from terminal "2W" to terminal "4W" passing terminal "3W" without berthing, we should add a new channel "2W-4W" in the network topology.

Before the specific discussion of the method, the assumptions about the container flow control model are listed:

- (i) The intermodal transport system has an ITS, and transportation operation in the system follows the ITCP framework, and the basic information mentioned above for flow control is available.
- (ii) Only standard containers are considered in this paper.
- (iii) The module does not consider packing and unpacking of containers, which is accomplished in the Encapsulation Layer.
- (iv) The container arrives at its departure node at the beginning of the transportation and leaves its destination node at the end of transportation. The cost of arriving at the departure node and leaving the departure node is ignored.
- (v) For the sake of convenience, in this paper, the channels not indicating a direction in network topology are bidirectional channels.

4.2. Initial Parameters. Before the flow decision-making, the Network Layer takes auxiliary information from other layers as input, and all of this information constitutes the initial parameter of the flow control model. The initial parameters are stated separately based on sources.

The initial parameters artificially set are listed as follows:

- (i) Ts is the length of an MPC time step
- (ii) N is the time steps number in the planning horizon

The initial parameters from Transport Layer are listed as follows:

- (i)  $x_{j,c}^m(0)$ ,  $\forall c \in C_{od}$ ,  $\forall j \in E$  is the container number of consignor c in channel j at the beginning of the planning horizon
- (ii)  $s_{j,c}(k)$ ,  $\forall c \in C_{od}$ ,  $\forall j \in E$ ,  $\forall k$  is the forecast number of the container, which is in channel j at beginning of the planning horizon, flowing out of the channel in the time step k
- (iii)  $td_j$ ,  $\forall j \in E$  is the departure time list of the trains (barges) in the planning horizon, and  $td_j[n]$ ,  $n \in \mathbb{N}$  is the departure time of the n+1th train (barge)
- (iv)  $ct_j[k]$ ,  $\forall j \in E$ ,  $\forall k$  is the estimated transport time of the channel j when departure is at the k time step

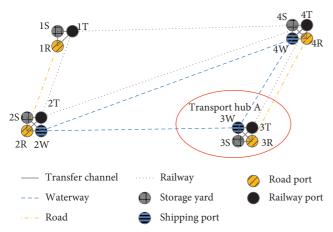


FIGURE 3: Intermodal transport network.

- (v)  $tc_i$ ,  $\forall j \in E$  is the vehicle capacity limit of channel j
- (vi)  $cp_j$ ,  $\forall j \in E_{\text{road}} \cup E_{\text{tran}}$  is the container number limit of channel j

The initial parameters from Transfer Layer are listed as follows:

- (i)  $x_{i,c}(0)$ ,  $\forall c \in C_{od}$ ,  $\forall i \in V$  is the number of containers of consignor c in terminal i at the beginning of the planning horizon
- (ii)  $S_i$ ,  $\forall i \in V$  is the capacity limit of terminal i
- (iii)  $h_i^{\text{in}}$ ,  $\forall i \in V$  is the unloading speed limit of terminal i
- (iv)  $h_i^{\text{out}}$ ,  $\forall i \in V$  is the loading speed limit of terminal i

The initial parameters from Network Layer are listed as follows:

- (i)  $rt_{i,c}$ ,  $\forall c \in C_{od}$ ,  $\forall i \in V$  is the estimated transport time from terminal i to the destination of consignor c
- (ii)  $rc_{j,c}$ ,  $\forall c \in C_{od}$ ,  $\forall j \in E$  is the estimated transport time from channel j to the destination of consignor c
- (iii)  $et_{i,c}$ ,  $\forall c \in C_{od}$ ,  $\forall i \in V$  is the estimated transport cost from terminal i to the destination of consignor c
- (iv)  $ec_{j,c}$ ,  $\forall c \in C_{od}$ ,  $\forall j \in E$  is the estimated transport cost from channel j to the destination of consignor c
- (v) t is the time of the decision-making moment

The initial parameters from Consignor Layer and Encapsulation Layer are listed as follows:

- (i)  $d_{i,c}^{\text{in}}(k)$ ,  $\forall c \in C_{\text{od}}$ ,  $\forall i \in V$  is the estimated transportation demand of consignor c in terminal i within step k
- (ii)  $d_{i,c}^{\text{out}}$ ,  $\forall c \in C_{\text{od}}$ ,  $\forall i \in V$  is a binary parameter describing whether terminal i is the destination of consignor c
- 4.3. Dynamics Model of Network. In the MPC method, network state changes between different time intervals are illustrated by dynamic equations. The dynamic equation of terminal container number is formulated as follows:

$$x_{i,c}\left(k+1\right) = d_{i,c}^{\text{out}} \times \left(x_{i,c}\left(k\right) + \sum_{j \in N_{i}^{\text{in}}} q_{j,c}\left(k\right) \times Ts - \sum_{j \in N_{i}^{\text{out}}} u_{j,c}\left(k\right) \times Ts + d_{i,c}^{\text{in}}\left(k\right) \times Ts\right),$$

$$\forall c \in C_{\text{od}}, \ \forall i \in V, \ \forall k,$$

$$(1)$$

where  $x_{i,c}(k)$  (TEU) is the container number in the terminal i at time step k under the demand of consignor c;  $q_{j,c}(k)$  (TEU/h) is the container flow that leaves channel j at time step k under the demand of consignor c;  $u_{j,c}(k)$  (TEU/h) is the container flow that enters channel j at

time step k under the demand of consignor c;  $N_i^{in}$  is the set of input channels of terminal i;  $N_i^{out}$  is the set of output channels of terminal i;

The dynamic equation of container number in the channel is formulated as follows:

$$y_{j,c}(k+1) = y_{j,c}(k) + \left(u_{j,c}(k) - q_{j,c}(k)\right) \times Ts, \quad \forall j \in E, \ \forall c \in C_{\text{od}}, \ \forall k,$$

$$\tag{2}$$

where  $y_{j,c}(k)$  (TEU) is the container number in the channel j at time step k under the demand of consignor c.

Then, the outflow of channels is described. The following mathematical model describes the coupling relationship of the channel's inflow and outflow, and it is divided into two types. In the first type, the channel is a roadway or a transfer path, and the vehicles might be container trucks in the roadway or Auto Guiding Vehicles (AGV), forklifts in the

transfer path. They can leave the terminal as soon as loaded with a container.

$$q_{j,c}^{u}(kt) = \begin{cases} \sum_{k|k_{t}=t(k)} u_{j,c}(k), & \forall j \in E_{\text{road}} \cup E_{\text{tran}}, \ \forall c \in C_{\text{od}}, \\ 0, & \text{else}, \end{cases}$$

(3)

where t(k) is the outflowing time step at which containers flow into channel j at time step k; and int indicates rounding down.

$$t(k) = \inf\left(\frac{k \times Ts + ct_j[k]}{Ts}\right), \quad \forall k.$$
 (4)

The second type of channel is railways or waterways, and the vehicles are the trains or barges that depart from terminals according to the timetable.

Because of the vehicles' waiting time, there is some difference between the first shift and the others within the planning horizon. If it is the first shift of the channel in the planning horizon, the containers having been loaded before planning should be counted as part of the shipment on the train (barge). If it is not the first shift, only containers that flow into the channel between two shifts should be counted. The outflow volume of vehicles departing at the planning horizon should be calculated based on the container number and estimated finishing time step of every train (barge) shift.

$$q_{j,c}^{u}(k) = \begin{cases} \sum_{i=0}^{td'_{j}[0]} u_{j,c}(i) + \frac{ws_{j,c}}{Ts}, & \text{if } k = ke_{j}[0], \\ \\ \sum_{i=td'_{j}[n]}^{td'_{j}[n+1]} u_{j,c}(i), & \text{if } k = ke_{j}[n], \quad n \in \mathbb{N}\{0\}, \\ \\ 0, & \text{else.} \end{cases}$$

 $\forall j \in E_{\text{rail}} \cup E_{\text{water}}$ 

$$\forall c \in C_{\text{od}},$$

where  $td'_j$  is the time step list at which the trains (barges) depart from terminals, and  $td'_j[n]$ ,  $n \in \mathbb{N}$  is the departure time step of the n+1th train (barge).

$$td'_{j}[n] = \operatorname{int}\left(\frac{td_{j}[n]}{Ts}\right), \quad n \in \mathbb{N}.$$
 (6)

 $ke_j[n]$  is the estimated time step list of the n+1th train (barge) finishing the transportation in channel j.

$$ke_{j}[n] = \operatorname{int}\left(\frac{td_{j}[n] - t + ct_{j}[td'_{j}[n]]}{Ts}\right), \quad n \in \mathbb{N}.$$
 (7)

Because of the queuing process before unloading to terminals, every time step's outflow volume should be no more than all queuing containers. It should be described in the following form:

$$\sum_{i\leq k}q_{j,c}\left(i\right)\leq\sum_{i\leq k}q_{j,c}^{u}\left(i\right)+\sum_{i\leq k}s_{j,c}\left(i\right),\quad\forall j\in E,\,\forall c\in C_{\mathrm{od}},\,\forall k.$$

4.4. Constrains. In consideration of intermodal transport operation in practice, there are some constraints in the model.

Due to the limited capacity of vehicles, there are capacity constraints in trains and barges:

$$q_{j,c}^{u}(k) \le tc_{j}, \quad \forall j \in E_{\text{rail}} \cup E_{\text{water}}.$$
 (9)

As for trucks and vehicles in the transfer channel, it is assumed that they can only be loaded with one container, which means no additional constraints are required here.

As container handling equipment is finite in terminals, there are unloading and loading speed limits:

$$\begin{split} & \sum_{c \in C_{\text{od}}} \sum_{j \in N_{i}^{\text{in}}} q_{j,c}\left(k\right) \leq h_{i}^{\text{in}}, \quad \forall i \in V, \ \forall k, \\ & \sum_{c \in C_{\text{od}}} \sum_{j \in N_{i}^{\text{out}}} u_{j,c}\left(k\right) \leq h_{i}^{\text{out}}, \quad \forall i \in V, \ \forall k. \end{split} \tag{10}$$

There are capacity limits of terminals because of finite storage area:

$$\sum_{c \in C_{od}} x_{i,c}(k) \le S_i, \quad \forall i \in V, \ \forall k.$$
 (11)

As the truck fleet completes the transport of containers on the roads, there are vehicle number limits. Moreover, the transfer channels are limited in the same way because the vehicles for transferring are finite. As vehicles on roads and transfer channels can only be loaded with one container, these constraints can also be regarded as container number limits of channels:

$$y_{j,c}(k) \le cp_j, \quad \forall j \in E_{\text{road}} \cup E_{\text{tran}}, \ \forall c \in C_{\text{od}}.$$
 (12)

4.5. Cost Function. The cost function of this model contains two parts: the expense cost and the time cost. Because the MPC method only takes an appropriate time horizon from the decision-making point into account, the time cost and expense cost of the executed transportation operation is not enough, and the estimated remaining transportation cost of the unfinished containers should also be taken into account. Therefore, the cost function can be described as follows:

$$J = \alpha (J_1 + J_2) + J_3 + J_4, \tag{13}$$

 $\alpha$  is the coefficient that converts the time cost into the expense cost, so the multi-objective optimization problem is converted into a single-objective problem.

 $J_1$  is the time cost of executed transportation operation, and is calculated by the sum of total container numbers in every time step.

$$J_{1} = \sum_{c \in C_{\text{od}}} w_{c} \left[ \sum_{k=1}^{N-1} \left[ \sum_{i \in V} x_{i,c}(k) T s + \sum_{j \in E} y_{j,c}(k) T s \right] \right].$$
 (14)

 $J_2$  is the estimated remaining transportation time of unfinished containers at the end of the planning horizon.

$$J_{2} = \sum_{c \in C_{c,d}} w_{c} \left[ \sum_{i \in V} x_{i,c}(N) r t_{i,c} + \sum_{j \in E} y_{j,c}(k) r c_{j,c} \right].$$
 (15)

 $J_3$  is the expense cost of executed transportation operation, and is calculated by the sum of total container operation expense in every time step

$$J_{3} = \sum_{c \in C_{\text{od}}} w_{c} \left[ \sum_{k=1}^{N-1} \left[ \sum_{i \in V} x_{i,c}(k) \times Ts \times sc_{i} + \sum_{j \in E} q_{j,c}(k) \times Ts \times L_{j} \times dc_{j} \right] \right], \tag{16}$$

where  $sc_i$  is the storage cost at terminals i.  $dc_j$  is the distance-dependent transport cost of channel j.

 $J_4$  is the estimated remaining transportation expense cost of unfinished containers at the end of the planning horizon

$$J_4 = \sum_{c \in C_{\text{od}}} w_c \left[ \sum_{i \in V} x_{i,c}(N) \times et_{i,c} + \sum_{j \in E} y_{j,c}(k) \times Ts \times ec_{j,c} \right].$$

$$(17)$$

The mathematical programming model illustrated in this chapter is the container routing module's decision-making process. It is a linear programming model that can be quickly solved with the simplex method. After the decision-making process, the container flow  $u_{j,c}(k)$  is the result, but only the first time interval's container flow decision  $u_{j,c}(0)$  will be executed. Then, the container routing module will repeat state sampling, data acquisition, and flow control at the next decision point.

# 5. Simulation Experiment

The proposed container flow control method's effectiveness is proved by a simulation experiment, which is the most commonly used verification method in transportation studies. The Discrete Event Simulation was applied to simulate the intermodal transport network's operation. The MPC and all-or-nothing (AON) approach were used as flow control methods for contrast analysis.

5.1. Simulation Method. The experiment uses the Simpy module in the Python environment to realize the simulation. Simpy is a discrete event simulation framework, which simulates multiple components of the system through multiple processes, and process in Simpy is a kind of Python generator. All processes run in the same environment, and each one interacts with the environment or another process through events to realize the system's simulation. The process generates events and waits for the event to trigger through the "yield" method. When the process yields an event, the process is suspended. As soon as the event is triggered, the process is resumed.

The simulation uses object-oriented programming to describe the intermodal transport system. There are five classes in the simulation environment as the basic elements, including Terminal, Channel, Container, Vehicle, and Consignor. The simulation then uses the attributes and functions of each class to represent the properties and

processes of each element. The class diagram in Figure 4 illustrates the attributes and functions of each class.

Figure 5 shows the operation of the simulation. After initialization, all consignors in the network execute the demand generation process in parallel and generate different kinds of container transportation demand regularly, once, or randomly. Then, the initial positions of the newly generated containers are their origin terminals' yard. Meanwhile, all terminals in the network run the loading and transfer process in parallel. In the loading process, the containers with transportation permission are loaded onto the chosen channel's vehicle. In the transfer process, transfer channels linking terminals in an intermodal transport hub realize the transshipment of containers.

As for the channels in the simulation, each of them runs three processes in parallel. In the vehicle departure process, trains and barges depart according to time table while trucks leave as soon as they get loaded. When vehicles complete the transportation, they are queuing to get their containers unloaded, and the unloading process realizes the simulation of these operations. Finally, the vehicle arrival process deals with vehicles finishing unloading.

The flow control process is the decision-making module, and the control of containers is modeled as flow permission of every channel. The flow control process works at every time step and the MPC method solves the mathematical programming model to get the container's dispatching plan.

5.2. Experiment. In the experiment, we take the intermodal transport network in the middle section of the Yangtze River Basin as an example. The intermodal transportation network and the topology are shown in Figure 6. There are two parts in the experiment conducted in this paper. The first part compared AON and MPC strategies in the container routing module with different freight volumes, while the second part compared the running results under different step length *Ts* and step number *N*.

All-or-nothing (AON) is a heuristic strategy frequently used in transport flow distribution. All of the transport between a specific origin and destination will take the shortest route. If transportation demand is out of the shortest route capacity, AON will choose the suboptimal route.

There are some assumptions in the simulation experiment. Firstly, the distance-dependent transport costs are 0.2758 €/TEU/km for road transport, 0.0635 €/TEU/km for railway transport, and 0.0213 €/TEU/km for waterway

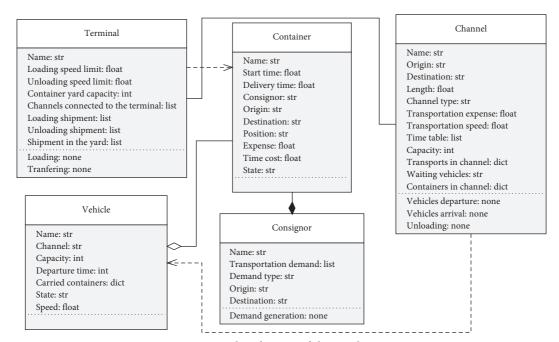


FIGURE 4: Class diagram of the simulation.

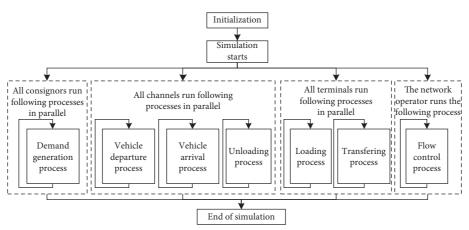


FIGURE 5: Block diagram of simulation.

transport. Moreover, the mode changes between storage yard and ports in one hub cost 11.945 €/TEU and 1h, while the mode changes between two ports cost 23.89 €/TEU and 2h [42]. The storage cost at terminals for a relatively short period is very small or even free, which is set as 0.0001 €/TEU/h in the simulation. What is more, we set the speed of channels as fixed values in the simulation, and the speed of trains, barges, and trucks is, respectively, 40 km/h, 20 km/h, and 50 km/h.

Moreover, there is some randomness in the transport simulation. The transportation time obeys the normal distribution with  $\sigma$  as standard deviation. The channel length is divided by the channel speed as expected, and  $\sigma$  is 0.01 for trains and 0.1 for trucks and barge. We set the time-expense coefficient  $\alpha$  to  $5 \in h$ .

The capacity of the storage yard is infinite, and port terminals' capacity is set to 100TEU. The loading and unloading time is 0.02 h/TEU in terminals. As for vehicles'

capacity limit, trucks can be loaded with one container, trains' capacity is 100TEU, and barges' capacity is 250TEU. The vehicles in the transfer channels are regarded as AGV, which can be loaded with one container. There are capacity limits for transfer channels and roads, and the limits are 10 and 30 vehicles, respectively. The trains and barges depart based on schedule, and trains only depart at 7, 12, 17, and 22 o'clock while barges depart at 8, 15, 22 o'clock.

There are three consignors in the network to generate transportation demands, as shown in Table 2. In the table, i indicates the amplification factor of freight volume.

In the MPC method, some system states and auxiliary information should be transmitted to the optimization process. In the simulation experiment, the speed estimation for every channel is set as a constant number. The real-time container number in the channels and terminals are sampled from the simulation. The estimation of transport time and expense between different ODs is acquired from a

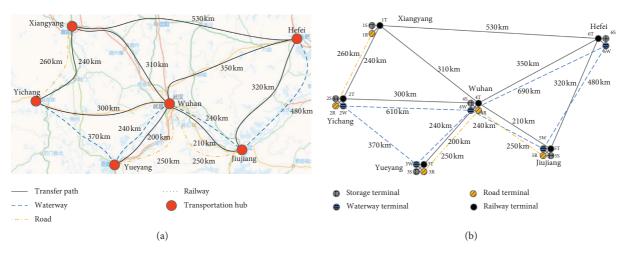


FIGURE 6: The intermodal transport network in the middle section of the Yangtze River Basin.

Table 2: Consignors information.

Consignor	Origin	Destination	Freight volume (i indicates amplification factor)	Start time	Periodicity
No. 1	1S	3S	$10 \mathrm{TEU}  imes i$	10	Once
No. 2	6S	2S	$8\text{TEU} \times i$	0	Regular, $T = 20 \text{ h}$
No. 3	3S	5S	$15 \text{TEU} \times i$	15	Once

preliminary experiment. As for the forecast of the transport demand, only consignors with regular transport demand are considered.

The simulation experiments are conducted using a desktop computer with an Intel (R) Xeon (R) CPU with 3.30 GHz and 8 GB RAM. The linear programming is solved with the Gurobi solver.

5.3. Results and Analysis. The first part of the experiment compares the effects of different methods in different freight volume scenarios, which is controlled by amplification factor *i*. And, the step size and step number of MPC are 4 h and 10 h, respectively. The entire time of the experiment is 100 h. The simulation experiment tests the total delivery cost of the MPC method and the AON method in the scenarios of factor *i* from 1 to 100 and draws the curve in Figure 7.

In the small freight volume scenarios, the MPC method is almost as good as the effect of the AON strategy. With the growth of transport load, the MPC method outperforms the AON. The total delivery cost of the MPC method can even be 25% less than the AON method in the scenario with the amplification factor of 100.

With small freight volume, the AON method is slightly better than the MPC Method in some cases. For example, in the scenario with the amplification factor of 5, the total cost of the MPC method is about 2% higher than that of the AON method, which may be difficult to detect in Figure 7. The main reason is that the MPC method can only make decisions at the decision-making point. For dynamic events that occur in the middle of a step, it can only react at the next decision-making point, which causes a delay. Because of the AON method's flexible characteristics, it can react

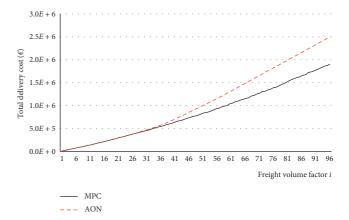


FIGURE 7: Total transport cost comparison in different freight volume scenarios.

immediately. Fortunately, this defect of MPC has little impact on the cost.

As for scenarios with high freight volume, some reasons may explain the better performance of MPC. Firstly, the MPC method can dynamically consider the congestion situation, departure timetable, transportation capacity of each channel, and each terminal's state to make a flow control decision. It is different from AON, which only selects the suboptimal route when the transportation demand exceeds the optimal route's capacity. Secondly, the MPC model will predict the system's future evolution within the planning horizon according to the current state and other layers' input information. It evaluates different flow control decisions to find the optimal decision (corresponding to the situation that the linear programming model seeks the

optimal solution when solved by the simplex method), rather than only relying on the current system state. Moreover, in the flow control process, the decisions of each terminal will affect each other. In the MPC method, the interaction between flow control of different terminals will be considered to obtain the optimal global solution, rather than a greedy strategy of a single terminal like AON.

In the second part of the experiment, the length of the planning horizon  $N \times T_s$  should be determined first. Generally, the planning horizon should be greater than the full transport time of containers, and we set the planning horizon length to be 40 h. The experiment's entire time horizon is still 100 h, and the consignor information is displayed in Table 2 with amplification factor i as 50. Four MPC methods with different parameter selection of N and  $T_s$  were applied to the same scenario to compare control performance, which is shown in Table 3.

Table 3 shows the total transport cost, mean optimization time, max optimization time, and distribution proportion of different modes. As we can see, the four MPC methods all outperform the AON method from the perspective of total transport cost in this experiment, and the method with a shorter time step size has better performance. However, the method with a shorter step size also means more optimization time, and the operation time for AON is almost negligible.

The MPC method can deal with dynamic events, such as the stochastic arrival of transport demand. The reason is that MPC gets real-time information of the network in every decision-making process. Therefore, a shorter step means a higher frequency of information acquisition, which leads to a faster response to random events. Moreover, a shorter time step makes planning horizon division more precise and makes the more accurate part of the decision adopted due to the deviation between model and reality. So, the shorter time step also means better modeling accuracy, which leads to a better optimization effect. However, in the same planning horizon, the calculation time of single optimization increases twice with the increase of the step number N, not to mention that smaller *Ts* means higher predictive control frequency. Therefore, the choice of *Ts* and *N* is a trade-off between the control effect and computing resource consumption.

5.4. Discussion. Realizing container routing with dynamic adjustment, real-time optimization and multi-role cooperation characteristics is the research issue of this paper. Considering this issue, ITCP was proposed as a framework to ensure multi-role cooperation, real-time data acquisition, and optimization of decision-making in intermodal transport systems. As the MPC method makes a decision for the controlled object in a receding horizon way, which enables systems to handle the real-time information, it was chosen to deal with the container routing problem in the ITCP framework. The simulation results show that the MPC method's overall cost in network flow control is lower than that of AON when the transport load is high, verifying the MPC-based flow control method's effectiveness. In general, the container routing method proposed in this paper can

balance the network load and find the flow control decision with the lowest overall cost in the planning horizon by forecasting the future evolution of the network.

5.4.1. Research Comparison. In contrast with the model in Li's research [6], we made some improvements to the mathematical model of MPC, including modeling the queuing process of containers when unloading or loading in the terminals, describing the transfer process, and considering the existing goods in the channel before. These improvements make the model more practical. In addition, in Li's research, a single model is used to control the container flow. While this paper prefers the cooperation of different decision and analysis modules, and all of them working in the ITCP framework.

It is worth mentioning that if the model in MPC describes the controlled object more accurately, the control effect will be better. It is very difficult to experiment in the real intermodal transport network. Therefore, in our research and Li's research, the experimental verification is carried out by simulation methods. This situation leads to the fact that the conclusion reflected by the experiment results only shows the fit degree between the MPC mathematical model and the simulation model, instead of the real intermodal transportation. So, the simulation should fit the real intermodal transport network well to make the experimental results meaningful. Based on this scenario, this paper presents the simulation method in detail. However, Li's simulation method is not described in detail, and in the simulation environment of this paper, the effect of Li's method is not ideal, and is even worse than AON in most cases. This is why there is no comparison with Li's method in our experiment.

5.4.2. Implications of Research. The research in this paper may throw some new light on the development of intermodal transport in the information age.

In the information age, the importance of data is selfevident, and data are the basis for analysis and decisionmaking. With the further development of digitization, decision-making in intermodal transport systems involves massive heterogeneous data. Layering and encapsulation of the system are good solutions to the situation, which is achieved in ITCP.

In the existing systems, cooperation and optimization are often limited to a small part of the system, which is far from enough to reduce the global cost or improve global efficiency. The proposed ITCP provides a global cooperation paradigm and breaks the separation between subsystems. And, the MPC-based flow control method fully considers the various stakeholders in the network to ensure the overall optimization of the decision-making.

In actual systems, a lot of uncertainty is inevitable. Realtime decision-making can eliminate the negative impact of uncertainty. In the research of this article, the real-time feature is embodied in the real-time data collection in ITCP and the real-time decision-making of MPC.

Strategy	Ts (h)	N	J (€)	T_mean (ms)	T_max (ms)	Road (%)	Rail (%)	Water (%)
AON	_	_	9.13E + 5	_	_	0	100	0
MPC1	1	40	7.64E + 5	1639.7	2540.0	5.0	85.3	9.7
MPC2	2	20	7.68E + 5	403.7	696.1	5.2	89.0	5.8
MPC4	4	10	7.73E + 5	117.4	145.8	5.7	89.0	5.3
MPC5	5	8	7.92E + 5	88.1	100.7	10.0	88.6	1.4

Table 3: Comparative experiment of different MPC parameters.

Thanks to the ITCP framework, the operation of intermodal transport systems is standardized, and the transmission of information in the simulation experiment is carried out under the assumption of this framework, which also protects the data privacy of all stakeholders. ITCP also guarantees the scalability of the intermodal transport network. Any role or module can participate in the cooperative operation of the network as long as a uniform protocol is observed. Although the above benefits are not reflected by the simulation results, this premise ensures the data interaction and cooperation in intermodal transport networks.

5.4.3. Future Research Directions. However, this method can still be improved in the following aspects. Because of the receding horizon way of MPC, there is a delay between the appearance and disposal of random events, which leads to insufficient optimization effect, and some hybrid methods may eliminate these delays. Besides, there is a huge consumption of computing resources when the network is extensive or when the consignor quantity is large. At the same time, the optimization effect of flow control still needs to be improved. Meanwhile, as environmental protection is also important, more environmental factors need to be considered in the flow control model and ITCP. In the case of incomplete information sharing, how to carry out cooperative optimization is also a problem to be solved. Finally, the development of the other modules in ITCP is also significant to improve one module's effectiveness.

### 6. Conclusion

The core issue of this paper is to realize container routing with dynamic adjustment, real-time optimization, and multi-role cooperation characteristics in the intermodal transport network.

With the guidance of PI and synchromodal transport, we proposed ITCP in this paper to realize the standardization of the operation, analysis of the intermodal transportation system, and the cooperation of different roles in the system. The container routing module in ITCP's Network Layer is the major research object. In the module, an MPC method dealing with real-time information in a rolling horizon way was built to realize the dynamic routing of containers. In the MPC method, we built a flow control model to describe intermodal transport system dynamics and make the optimal flow control decision for the planning horizon.

To verify the effectiveness of the method, we constructed a simulation experiment based on discrete event simulation. Based on the experiment, we get the following results. The experiment compares the MPC-based method in the ITCP framework and the AON method. In the small freight volume scenarios, the MPC method is almost as good as the AON method. With the growth of transport load, the MPC method outperforms the AON method. And, the choice of step length and step number in the MPC method is a trade-off between the control effect and computing resource consumption.

In general, the container routing method proposed in this paper can balance the network load when the transport demand is high and find the flow control decision with the lowest overall cost in the planning horizon by forecasting the future evolution of the network. The research in this paper may throw some new light on the development of intermodal transport in the information age.

# **Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

## **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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