IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 17, 2020, accepted January 29, 2020, date of publication February 3, 2020, date of current version February 13, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2971027

A Fuzzy Intercontinental Road-Rail Multimodal Routing Model With Time and Train Capacity Uncertainty and Fuzzy Programming Approaches

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This work was supported in part by the National Key Research and Development Program of China under Grant 2016YFE0201700, in part by the National Key Research and Development Program of China under Grant 2018YFB1201402, in part by the Project for Humanities and Social Sciences Research of Ministry of Education of China under Grant 19YJC630149, and in part by the Shandong Provincial Natural Science Foundation of China under Grant ZR2019BG006.

ABSTRACT This paper investigates a fuzzy intercontinental multimodal routing problem with uncertainties in time and train capacity. The transport network has characteristics of a long distance across continents and a road–rail multimodal routing, with four kinds of nodes and three kinds of arcs. Based on a variant of the vehicle routing problem, the tractor and semi-trailer routing problem is considered for the freight collection part for intercontinental trains. Additionally, the rail routing problem includes domestic direct trains, and intercontinental trains with hard time windows of departure. To make this problem more applicable to real-world circumstances, we describe two types of uncertainty parameters, including time and train uncertainties. Based on the transport conditions of stations, the time uncertainty is considered. Due to the multimodal transport stations' operating capacity and container collection methods, train capacity uncertainty is taken into account. Furthermore, we use solution methods based on the defuzzification approach to solve a fuzzy mixed integer linear programming model and generate a series of instances to verify the fuzzy model. We perform sensitivity analyses of the parameters. The results show that different quantities of intercontinental trains can change the performance by 10% to 20%. The objective function may decrease by more than 20% when the service level increases by 0.1. A sensitivity analysis of the time satisfaction confidence level also shows the trends of fuzzy time and the objective function. These analyses can give reference results about timeliness, transport resource allocation and other suggestions for the intercontinental multimodal transport routing problem.

INDEX TERMS Intercontinental road–rail multimodal transport, routing problem, time uncertainty, capacity uncertainty, fuzzy programming.

I. INTRODUCTION

With the development of international production networks and supply chain systems, intercontinental land transport began to occupy a certain position. Transport by land is an effective supplement to sea carriage [1]. Intercontinental land transport includes road and railway transport, in which rail transport is responsible for trunk transport and road transport is responsible for branch transport in most instances. Compared with ocean transport, the timeliness of intercontinental land transport has been significantly enhanced. From a range perspective, intercontinental transport mostly occurs in the Eurasia continents, including East Asia - Europe, East Asia - Central Asia, and Central Asia - Europe. However, because intercontinental transport occurs through a number of countries, there are large differences in terms of their transport infrastructure capacities, transport regulations, station operational capacities, and customs clearance efficiency. Therefore, there can be a series of uncertainties in the transport process.

Multimodal freight transport is defined as the transport of goods by a sequence of at least two different modes

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Liu.

of transportation. Multimodal transport problems are widely used to serve international trade, supply chain management, and urban life. Multimodal transport can effectively reduce costs and improve the timeliness of transport by taking advantage of different modes of transport. However, during the multimodal transport process, multiple transport service providers may be involved, as well as loading and unloading processes involving the conversion of cargoes. This requires the establishment of a multimodal transport coordination mechanism, the promotion of standardized equipment and operational services, and the advantages of different transport entities. Additionally, the basis of multimodal transport is a unified transport unit. In multimodal transport on highways and railways, the transport unit is a container. Container transport plays an important role in international logistics [2]. Under normal circumstances, multimodal transport does not involve freight loading and unloading operations inside containers.

In intercontinental land transport, multimodal transport is represented by road and rail transport. Among such problems, road transport generally assumes the function of collecting goods. To achieve smooth connections in the multimodal transport process, road transport adopts the method of container transport, and the container transport generally includes functions of tractors with semi-trailers and trucks with trailers. The function of a tractor with a semi-trailer can be freely separated and combined due to the power part and the cargo part of the vehicle and is more commonly used for road and rail multimodal transport. Compared with the traditional vehicle scheduling problem, the function of the tractor and semi-trailer also involves the coordinated scheduling of tractors, semi-trailers and commodity sources.

The Euro-China Expressway is an important part of intercontinental multimodal transport [3]. The predecessor of the Euro-China Expressway was the Asia-Europe continental bridge. Compared with the continental bridge, the Euro-China Expressway has significantly improved in several areas, such as the multimodal transport organization, the coordination among different countries and the ability to serve regional economic development. The Euro-China Expressway travels from Chongqing, Chengdu, Zhengzhou, Wuhan, Suzhou and Yiwu to major cities in Germany, Poland, Spain and other countries in Europe. At present, there are 43 cities in China that are connected to the Euro-China Expressways, and it has reached 14 countries and 42 cities in Europe. Compared with maritime transport, the Euro-China Expressway is more suitable for cargo exchange between the inland cities of China and the inland cities of Europe. However, with the increase in the number connected cities in China and Europe, the cities have faced fierce competition. Therefore, related optimization issues in this area will provide useful information for the sustainable development of intercontinental multimodal transport.

Due to the complexity of the intercontinental transportation processes, there are many stations and service enterprises involved, and there are a series of uncertainties in the transport processes. In intercontinental railway transportation, there are some gaps in the operation capacities of different stations, and the congestions at different stations varies. These differences mean that the times of loading and unloading operations are uncertain. In intercontinental rail transport, the railway marshaling capabilities of different stations are different. Furthermore, there may be a situation in which the trains are assembled at different stations, resulting in the number of containers that can be loaded by the trains being insufficient. This leads to uncertainty in the abilities of intercontinental trains. Therefore, using an uncertainty method to summarize the problem will more closely address the actual transportation situation.

In summary, this issue is refined using the Euro-China Expressway. The issue belongs to the vehicle routing problem, which has an intercontinental transport range. The transportation mode is road-rail multimodal routing. There are many uncertainties in this transport. To our knowledge, this category of issues has rarely been mentioned. Therefore, we define this problem as an intercontinental road–rail multimodal routing problem with time and capacity uncertainty.

This paper aims to refine the complex intercontinental multimodal transport problem into a mathematically solvable uncertainty routing model. Then, the effectiveness of the model is verified through fuzzy approaches. From the perspectives of the cost of the multimodal transport system, the method of transport organization, and the plan of operation, some conclusions with reference significance are obtained. Additionally, we hope to provide meaningful experience and ideas for the future intercontinental transport model building and solving such problems.

II. LITERATURE REVIEW

This problem of an intercontinental multimodal routing problem with time and capacity uncertainty is generally similar to the following academic issues. Overall, this problem is a derivative of the vehicle routing problem (VRP). According to the characteristics of this problem, we conduct a literature review on three aspects: the vehicle routing problem with time windows (VRPTW), the intercontinental multimodal routing problem and the fuzzy planning of the routing problem.

A. VEHICLE ROUTING PROBLEM WITH TIME WINDOWS

To solve the VRPTW, the main goal is to rationally plan the vehicle path plan to meet the customer's needs and all constraints, including the time window, so that the total cost is minimized. There are many ways to set the time window, and different types of VRPTWs are derived.

In the VRPTW, there is more than one time window for the customer point, and the vehicle can choose to service the customer nodes in any time window. Therefore, according to the number of customer nodes' time window, the VRPTW can be divided into a single time window and multiple time windows. In an early study of the VRPTW, Azi *et al.* [4] described an exact algorithm for solving a problem with a single time window. Favaretto *et al.* [5] studied the VRP with multiple time windows allowing multiple accesses and proposed an ant colony algorithm for solving it.

According to whether the time window needs to be strictly followed, the VRPTW can be divided into hard time windows and soft time window. In hard time window problems, the service must be satisfied after the time window of the customer node is opened. If the time window of the customer node can be violated, it is called a VRP with soft time windows. In soft time window problems, as long as the vehicle pays the penalty cost, the customer point does not refuse or delay its service. Errico *et al.* [6] constructed a mixed integer programming model of the VRP considering hard time windows and random services. A hard time window problem by Miranda and Conceição [7] considered not only random service time, but also random travel time. Hu *et al.* [8] examined the vehicle routing problem with hard time windows under demand and travel time uncertainty. Compared to the VRP with hard time windows, more research has focused on VRP with soft time windows. Iqbal and Rahman [9] gave mathematical programming models for different soft time windows of the VRP and solved them. In the relevant literature, a model of an open VRP with soft time windows and satisfaction rate was analyzed by Xia and Fu [10], which aimed to reduce the logistics distribution cost. The line-haul feeder vehicle routing problem (LFVRP) is a rather new, and therefore hardly investigated, problem and can be seen as a VRP with synchronization constraints [11]. Brandstätter [12] proposed an LFVRP with time windows. The study introduced a new variable called time window flexibility to describe soft time windows.

In the intercontinental multimodal routing problem studied in this paper, the intercontinental railway departure times belong to hard time windows. The road and railway consolidation process must be completed before an intercontinental departure; otherwise, the next railway will be used to serve unsent containers, which will affect the timeliness of transport.

B. INTERCONTINENTAL MULTIMODAL ROUTING PROBLEM

One of the characteristics of the intercontinental multimodal routing problem is that the transportation distance is very long. For example, in the Euro-China Expressway, the distance between many origin stations and end stations is approximately 10,000 km. This is different from regional multimodal routing problems such as routing problems in Western Europe or Western China. Wolfinger *et al.* [13] designed a multimodal long-haul routing problem, where the origin and the destination of each request are located far apart from each other. Neves-Moreira *et al.* [14] proposed a long-haul transport problem through multiple transshipment points with a tractor and trailer. In response to this type of research, some of the literature has focused on long-distance intercontinental multimodal policies [1].

Inland container transport, as a transport unit, has its academic characteristics. Zhang *et al.* [15], [16] proposed an inland truck scheduling problem, with containers as a resource for transport. Furthermore, they also considered container routing models with inbound full, outbound full, and inbound empty movements. Much of the literature has studied the routing problems of regional multimodal transport systems. Verma *et al.* [17] and Sun *et al.* [18] conducted multiobjective planning research on road-rail multimodal routing. The study found that scheduling direct intermodal trains and unit-trains can reduce rail-haul risk. Steadieseifi *et al.* [19] and Dua and Sinha [20] systematically reviewed multimodal transport planning, and distinguished between different concepts of multimodal transport.

As part of the intercontinental multimodal problem, related research on the tractor and semitrailer routing problem (TSRP) deserves attention. The TSRP is a containerized transportation method for trunk highways [21]. It is a link between road transport and rail container transport and is similar to the truck and trailer routing problem (TTRP). Li *et al.* [22] proposed a TSRP with many-to-many demand in an intercity line-haul network setting. Additionally, it is worth mentioning that the location routing problem (LRP) can also be reflected in multimodal transport. Earlier studies on the LRP by Jacobsen and Madsen [23] and Madsen [24] focused on the distribution of newspapers. Recent research has enriched and expanded the LRP. Fazayeli *et al.* [25] presented an LRP with time windows and fuzzy demand, involving a plan for depot establishment in customer regions. Our study has similarities with the LRP, involving multiple multimodal stations and the selection of multiple intercontinental train departure times.

C. FUZZY PLANNING OF ROUTING PROBLEM

Uncertainties in decision-making can be characterized by random or fuzzy angles. A mathematical plan with random or fuzzy parameters is an uncertain plan. The treatment methods for uncertain planning mainly include the expectation method, opportunistic constraint planning and related opportunity planning [24]. In a function with fuzzy parameters, the mathematical expectation of a fuzzy parameter is used instead of the parameter, thus transforming the fuzzy mathematical programming problem into a deterministic mathematical programming problem. Opportunistic constraint planning is a problem proposed by Williams [26] for making random variables in constraints and making decisions before observing random variables. The principle adopted by this method is that the decision that is made is allowed to satisfy the constraint to a certain extent, but the decision should be made so that the probability of the constraint is not less than a given confidence level. Similarly, Liu and Iwamura [27] proposed a theoretical framework for opportunistic constraint programming with fuzzy parameters. The theory states that the decision making makes the possibility of fuzzy constraints no less than a given level of confidence. For some special cases, we can convert an opportunity-constrained plan into an equivalent mathematical plan [18], which can make the fuzzy plan clear.

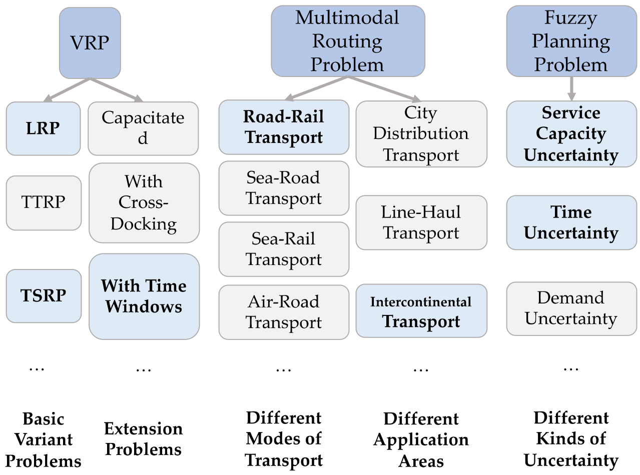

FIGURE 1. Classification of the research areas in this paper.

The fuzzy planning of multimodal routing problems mainly includes uncertain capacity, uncertain demand and uncertain time. In the existing research, various types of problems were often combined. First, in cases of uncertain capacity, Wang [28] studied a stochastic resource containerized cargo transportation problem with random capacities and random demand. Sun *et al.* [29] discussed the intermodal routing problem with service capacity uncertainty and compared a trapezoidal fuzzy number with a triangular fuzzy number. Sun *et al.* [30] proposed a model of a multimodal routing problem with two uncertain factors, including the capacity uncertainty of rail services and the travel time uncertainty of road services. Second, regarding the problem of uncertain time, two types of fuzzy constraints are considered, including uncertain travel time on arcs and uncertain time windows in nodes. Ghannadpour *et al.* [31] proposed a dynamic vehicle routing problem with fuzzy time windows, considering fuzzy travel times and checking the maximum allowable travel time by the concept of fuzzy control. Hrušovský *et al.* [32], Demir *et al.* [33] and Tian and Cao [34] described a multimodal transport problem of time uncertainty in different circumstances. Third, regarding uncertain demand, Erbao and Mingyong [35] proposed a VRP with fuzzy demand and used hybrid differential evolution to solve it. Fazayeli *et al.* [36] set time windows and fuzzy demand in a multimodal LRP. Gaur *et al.* [37], Mendoza *et al.* [38] and Gutierrez *et al.* [39] solved cumulative VRPs with stochastic demand by metaheuristic algorithms.

Consequently, this paper describes a combination problem of the classic VRP, multimodal routing problem, and fuzzy planning problem. As shown by the blue box in Fig. 1, the characteristics of this article are similar to these highlighted issues, which have not been mentioned in existing studies to our knowledge.

III. FUZZY PROBLEM DESCRIPTION

In this section, we propose an intercontinental multimodal network that consists of four kinds of nodes and two kinds of transport modes. Importantly, we refined the timeliness characteristics of the problem based on the actual practices of enterprises to clearly explain the academic problem. Furthermore, time and service capacity uncertainty based on a fuzzy set are shown later.

TABLE 1. Nodes' abbreviations in the problem.

Node	Abbreviation
domestic multimodal station	DMS
domestic highway station	DHS
domestic railway station	DRS
foreign multimodal station	FMS

A. INTERCONTINENTAL MULTIMODAL NETWORK

Based on the Asia-Europe continental bridge, intercontinental rail transport needs to pass through a variety of countries and obey mutually agreed upon transport rules. Intercontinental transport is the main line in this transport network. Consolidation transport composes are the branch lines, which include rail and road transport. Multimodal transport stations are responsible for the functions of consolidation and multimodal transport. In this network, a 40-foot container is the unit that can be transported by tractors and trains. The origin nodes are domestic highway stations and railway stations; the destination nodes are foreign multimodal stations. Therefore, we define four kinds of nodes, which are shown in Table 1.

In the intercontinental multimodal network, transport demand flows from a domestic highway station (DHS) to a foreign multimodal station (FMS) by multimodal transport and from a domestic railway station (DRS) to a foreign multimodal station (FMS) and from a DHS to a DHS by a single mode of transport. As shown in Fig. 2, the road transport network consists of DHSs and DMSs. A tractor departs from a DMS and returns to a DMS after traveling through several nodes. The tractor has two conditions in road arcs, which include the tractor with a semi-trailer and the tractor driving alone. It is worth noting that the tractor can travel through more than one DMS, but the origin and destination stations should be the same. Furthermore, containers from DRSs will be assembled in a direct form. Containers from DHSs and DRSs will be put together in columns after loading and unloading operations in DMSs. Based on the daily departure times in DMSs, intercontinental railway trains will be sent to FMSs. In this problem, we set a hard time window for intercontinental train departure times. Tractors and domestic trains should arrive earlier than these departure times.

In light of the complexity of the highway transport network, we present a flow chart in Fig. 3. In this problem, the two connected highway transport routes cannot be driven by the tractor alone because this situation is equivalent to the tractor not passing through the intermediate station. Since no new container is loaded onto the tractor after the tractor arrives at the DMS, if the DMS is the intermediate node of

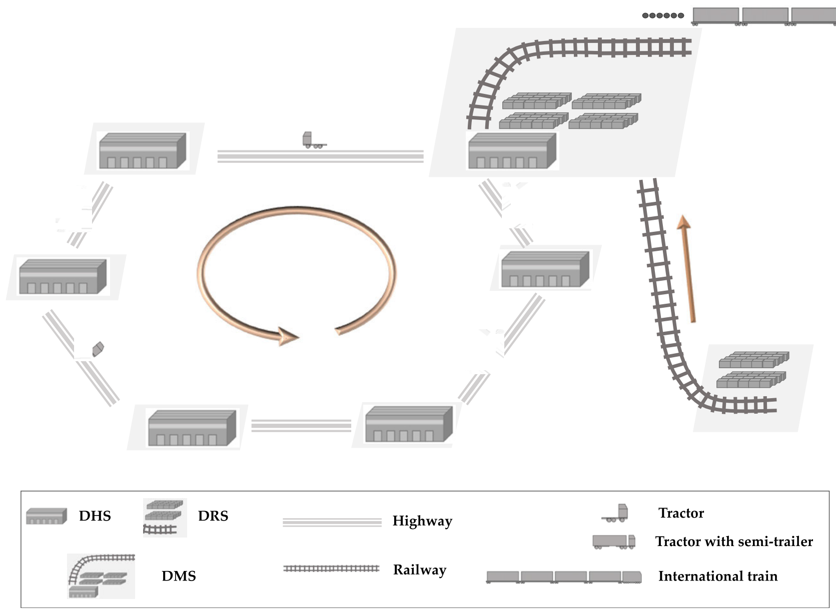

FIGURE 2. An example of a domestic transport network.

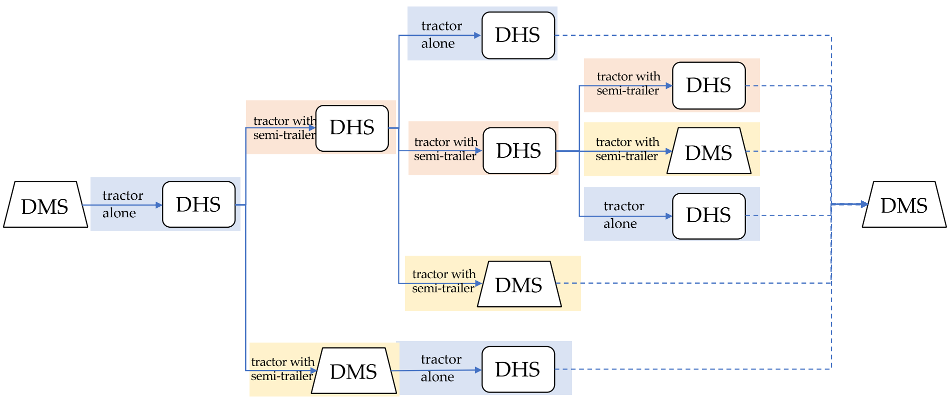

FIGURE 3. Possible routes of vehicles between DHSs and DMSs.

a tractor path, the previous section cannot be driven by the tractor alone, and the tractor cannot continuously pass two DMSs. The figure shows the possible operational choices of the tractor, which are implemented in the subsequent mathematical model.

We need to find the optimal path and allocation scheme between DMSs and FMSs. The intercontinental transport network is shown in Fig. 4. In the example shown in the figure, each FMS has a transport association with two DMSs. In the actual operation of the Euro-China Expressway, after departure from a DMS, a train will reach up to one FMS. The intermediate transport process is guaranteed by transnational transport rules and coordination mechanisms.

B. TIMELINESS OF THE TRANSPORT NETWORK

To clearly show the timeliness of the transport network, we illustrate three relationships between location and time, which include a highway transport echelon and a multimodal transport echelon.

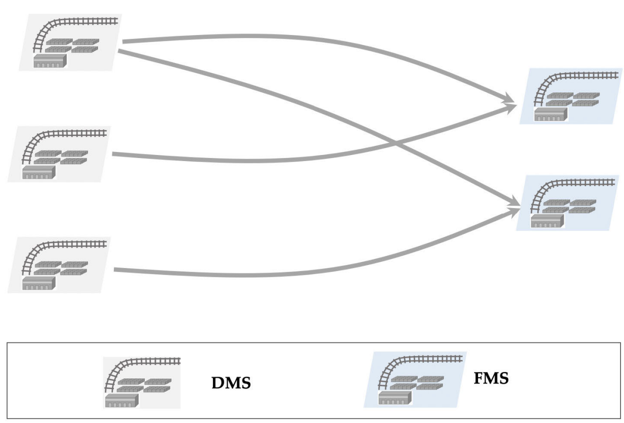

FIGURE 4. An example of the intercontinental transport network.

In light of whether tractors participate in the consolidation of the DMS, we generalize two situations of tractors' route paths. Fig. 5 shows that the tractor departs from the DMS and

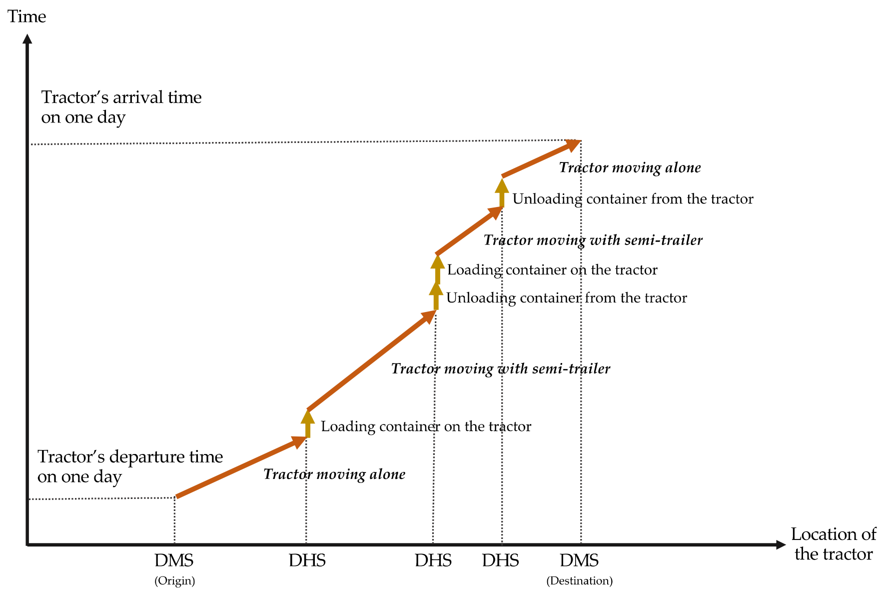

FIGURE 5. The tractor's location changes over time without passing through the station.

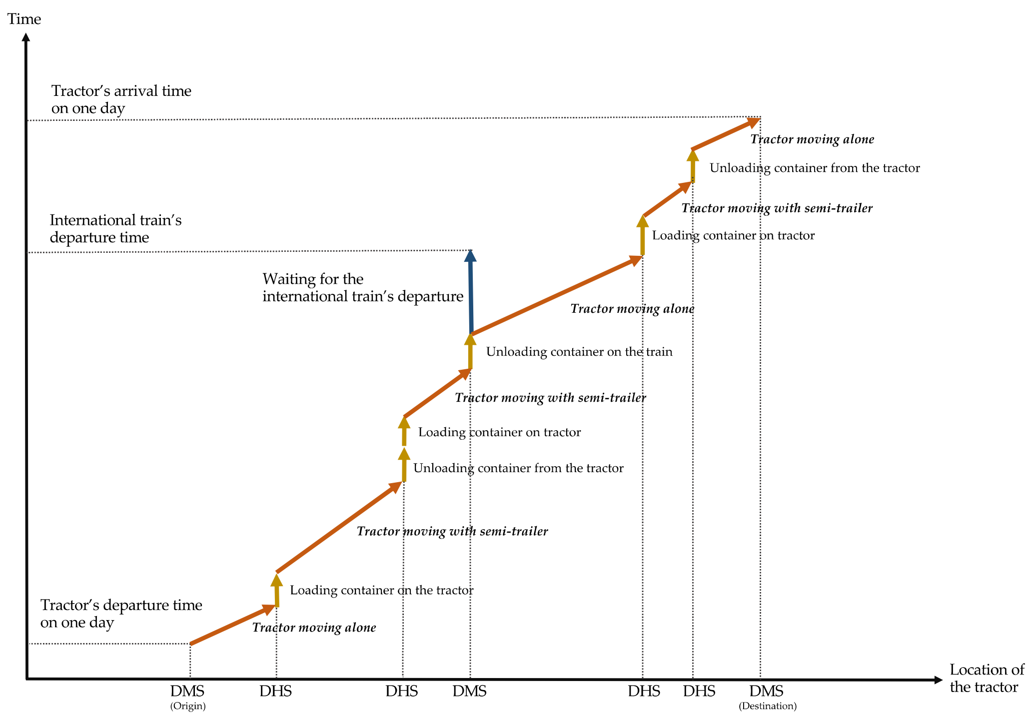

FIGURE 6. The tractor's location changes over time while passing through the station.

returns to the DMS, passing through several DHSs. In this problem, one tractor's route path should be completed in one day. The total time consumption consists of route and node times.

Fig. 5 also shows that tractors driving alone and with semi-trailers exhibit different time consumption in the unit route, which is based on the velocity of the vehicle. The time consumption of nodes corresponds to loading and unloading semi-trailers.

Fig. 6 shows a route with a multimodal consolidation part. When the tractor arrives at a DMS, the container is unloaded for the international train to wait for the train's departure. Then, the tractor continues to the next highway route.

Fig. 7 shows the containers' location changes over time in the multimodal transport system. The containers' departure stations are DRSs and DHSs. The DMS is the station for multimodal transport consolidation. Containers from DRSs and DHSs are loaded on the international trains. The DMS

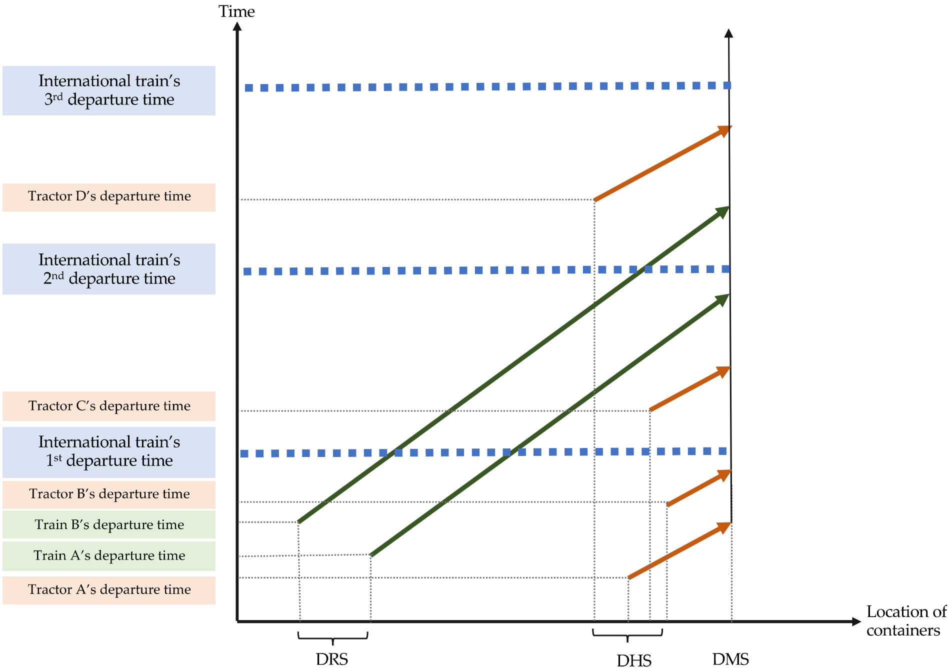

FIGURE 7. Containers' location changes over time in the multimodal transport system.

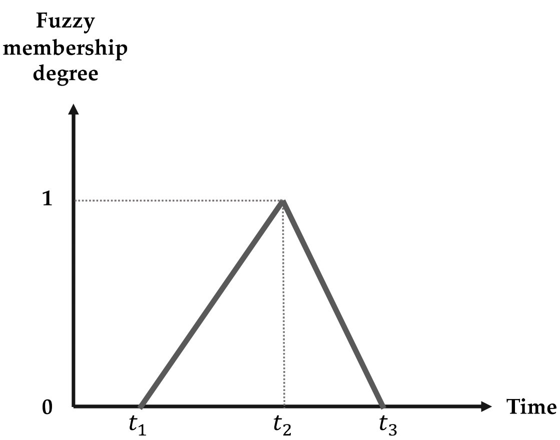

FIGURE 8. Fuzzy membership degree with time by triangular fuzzy time.

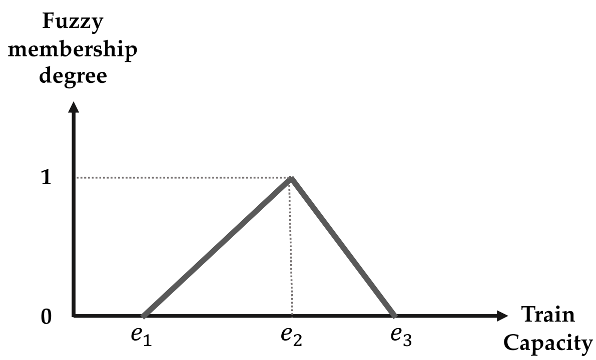

FIGURE 9. Fuzzy membership degree with train capacity by triangular fuzzy capacity.

has three departure times of international trains. Containers may wait for the next train's departure.

C. TIME AND SERVICE CAPACITY UNCERTAINTY BASED ON FUZZY SET

1) TIME UNCERTAINTY IN THE INTERCONTINENTAL MULTIMODAL ROUTING PROBLEM

Due to planning advancement and the real-time status of the transportation network, the intercontinental transport problem has uncertain influencing factors. This problem aims to find the optimal solution for long distances, large areas and different transport modes. Therefore, uncertainty parameters can describe the intercontinental problem more realistically.

Represented by the Euro-China Expressway, intercontinental multimodal transport has obvious advantages in terms of timeliness compared with traditional mode of transport, such as maritime. Accordingly, intercontinental multimodal transport organization has more requirements for timeliness.

In this problem, the fuzzy parameters include the departure time of the tractor, the arrival time of the tractor and the operation times. Among them, the departure time of the tractor and the arrival time of the tractor are decision variables. Parameters include the unloading time in a DHS, the loading time in a DHS, and the time for loading a container from a tractor on an intercontinental train.

Timeliness affects transport service satisfaction, and it can be described by a triangular fuzzy number [40], which is shown in Fig. 8. We set three parameters to describe the fuzzy number, which can be indicated by Equation (1) [41]:

$$\tilde{t} = (t_1, t_2, t_3) \tag{1}$$

In this formula, t_1 is the most optimistic, which can be explained by the shortest time consumption. To reach t_1, stations may need efficient management and intelligent handling equipment. However, the operational efficiency gap between different stations can be large. t_2 is the most likely when transport and station efficiencies are relatively moderate. t_3 is the most pessimistic, which indicates the worst condition of the transport system, with traffic congestion, a low station operation level and concentrated container arrivals.

2) TRAIN CAPACITY UNCERTAINTY IN THE INTERCONTINENTAL MULTIMODAL ROUTING PROBLEM

Compared to regular trains in a domestic railway network, intercontinental trains may be affected by various uncertainties. Customs policies in different countries, transport congestion, container assembly by cargo agents and the level of departure stations are the main factors. The complexity of transshipment operations is the first difficulty when optimizing the multimodal routing problem. To better describe the capacities of intercontinental trains, this paper uses a fuzzy capacity method. According to different stations on the Euro-China Expressway, there are usually fewer than 44 containers in one intercontinental train. Therefore, we choose three numerical values to measure the capacity of intercontinental trains, which include minimum capacity e_1, most likely capacity e_2 and maximum capacity e_3, as shown in Equation (2) and Fig. 9.

$$\tilde{e} = (e_1, e_2, e_3) \tag{2}$$

The Euro-China Expressway represents direct transport between the two stations. With its continuous development, an increasing number of stations strengthen their consolidation function. Through the mode of container assembly, the actual load factor of a train was improved. This mode refers to a train from a station such as Chengdu to a destination such as Nuremberg; if the intercontinental train is not full of containers, it will carry containers from other stations, such as Urumqi, and increase the load factor of the train. As a consequence, the transport organization and stations' capabilities affect the capability of the intercontinental train. Therefore, using an uncertainty method for analysis is necessary.

IV. FUZZY PROBLEM DESCRIPTION

In this section, we propose a mixed integer linear programming (MILP) model with fuzzy parameters and decision variables. The model of the intercontinental multimodal routing problem has a complicated form, so we explain the notations and constraints in several parts.

A. NOTATION

We divide the notation into three parts, including sets, parameters and decision variables.

1) SETS

In sets table describe as shown at the top of next column.

Categories	Sets	Representations
Sets of stations	V_{DMS}	set of DMSs
	V_{DHS}	set of DHSs
	V_{DRS}	set ofDRSs
	V_{FMS}	set ofFMSs
Sets of transport platforms	Q	set of tractors, $q \in Q$
	N	set of intercontinental trains, $n \in N$
Sets of distances	L^h	set of highway distances between nodes, $l_{ij}^h \in L^h$, $i, j \in V_{DHS} \cup V_{DMS}$
	L^r	set of domestic railway distances between nodes, $l_{ij}^r \in L^r, i \in V_{DRS}$, $j \in V_{DMS}$
	L^f	set of intercontinental railway distances between nodes, $l_{jk}^f \in L^f$, $j \in V_{DMS}, k \in V_{FMS}$
Sets of demand	D^d	set of demand between domestic distributions, $d_{ij}^d \in D^d$, $i, j \in V_{DHS}$,
	D^h	set of demand between domestic distributions and foreign multimodal stations, $d_{ik}^h \in D^h$, $i \in V_{DHS}$, $k \in V_{FMS}$,
	D^r	set of demand between domestic railway stations and foreign multimodal stations, $d_{ik}^r \in D^r$, $i \in V_{DRS}, k \in V_{FMS}$,
Sets of time windows	t_{jkn}^p	nth ($n \in N$) train's departure time from node j to $k, j \in V_{DMS}, k \in V_{FMS}$

2) PARAMETERS

In parameters table describe as shown at the top of next page.

3) DECISION VARIABLES

In decision variables table describe as shown at the top of next page of second column.

B. OBJECTIVE FUNCTIONS

$$\begin{aligned}
\min z = &\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}} \\
&\times \sum_{j\in V_{DMS}\cup V_{DHS}} \left(l_{ij}^h \cdot f_t \cdot x_{ijq}^t + l_{ij}^h \cdot f_l \cdot x_{ijq}^l\right) \\
&+\sum_{n\in N}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}} \tilde{e} \cdot l_{jk}^f \cdot f_i \cdot y_{jkn} \\
&+\sum_{n\in N}\sum_{i\in V_{DRS}}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}} d_{ik}^r \cdot l_{ij}^r \cdot f_d \cdot \beta_{ijkn} \\
&+\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}}\sum_{j\in V_{DMS}\cup V_{DHs}} o_l \cdot \left(x_{ijq}^t + x_{ijq}^l\right) \\
&+\sum_{n\in N}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}} o_t \cdot y_{jkn}
\end{aligned}$$

Categories	Parameters	Representations
Operation times	$\widetilde{t^{uh}}$	fuzzy unloading time in DHS, $\widetilde{t^{uh}} = ({t_1}^{uh}, {t_2}^{uh}, {t_3}^{uh})$, h
	$\widetilde{t^{lh}}$	fuzzy loading time in DHS, $\widetilde{t^{lh}} = ({t_1}^{lh}, {t_2}^{lh}, {t_3}^{lh})$, h
	$\widetilde{t^{lm}}$	fuzzy time of loading a container from a tractor on an intercontinental train, $\widetilde{t^{lm}} = ({t_1}^{lm}, {t_2}^{lm}, {t_3}^{lm})$, h
Transport properties and capacities	t^m	maximum time of a tractor's route
	v^{hl}	velocity of a tractor driving alone
	v^{ht}	velocity of a tractor driving with a semi-trailer
	v^{rd}	velocity of domestic railway
	v^{rf}	velocity of intercontinental railway
	$\tilde{e}$	fuzzy number of containers for each intercontinental expressway, $\tilde{e} = (e_1, e_2, e_3)$
Transport costs	f_t	cost of tractor driving 100 kilometers with a semi-trailer [CNY/(100 km·container)]
	f_l	cost of tractor driving 100 kilometers alone [CNY/(100 km·container)]
	f_d	cost of domestic train driving 100 kilometers per container [CNY/(100 km·container)]
	f_i	cost of international train driving 100 kilometers per container [CNY/(100 km·container)]
	o_l	loading and unloading operation cost for a semi-trailer (CNY/container)
	o_t	loading operation cost for a train (CNY/container)
	s	storage cost for a container per hour [CNY/(container·h)]
Other	M	arbitrarily large constant

$$
\begin{aligned}
\min z = &\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}} \\
&\times \sum_{j\in V_{DMS}\cup V_{DHS}} \left[l_{ij}^{h}\cdot f_t \cdot x_{ijq}^{t} + l_{ij}^{h}\cdot f_l \cdot x_{ijq}^{l} + o_l\cdot\left(x_{ijq}^{t}+x_{ijq}^{l}\right)\right] \\
&+\sum_{n\in N}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}}\left[\tilde{e}\cdot l_{jk}^{f}\cdot f_i \cdot y_{jkn} + o_t\cdot y_{jkn}\right] \\
&+\sum_{n\in N}\sum_{i\in V_{DRS}}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}} o_t\cdot\beta_{ijkn} \\
&+\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}}\sum_{j\in V_{DMS}\cup V_{DHS}}(\tilde{t^{uh}}\cdot x_{ijq}^{t}+\tilde{t^{lh}}\cdot x_{ijq}^{l})\cdot s \\
&+\sum_{i\in V_{DRS}}\sum_{k\in V_{FMS}}\tilde{t^{lm}}\cdot d_{ik}^{h}\cdot s
\end{aligned} \tag{3}
$$

Categories	Decision variables	Representations
Routes of tractors	x_{ijq}^{l}	If the qth tractor driving alone covers arc (i, j), then x_{ijq}^{l} is 1; otherwise, it is 0. $i, j \in V_{DMS} \cup V_{DHS}$&$i \neq j$.
	x_{ijq}^{t}	If the qth tractor driving with a loaded container covers arc (i, j), then x_{ijq}^{l} is 1; otherwise, it is 0. $i, j \in V_{DMS} \cup V_{DHS}$&$i \neq j$.
	ε_{jq}	If the qth tractor's originating station is $j \in V_{DMS}$, then ε_{jq} is 1; otherwise, it is 0.
Location and intercontinental train selection of DMS	α_{ijkn}	If domestic multimodal station $j \in V_{DMS}$ serves demand d_{ik}^{h} by the nth train, α_{ijkn} is 1; otherwise, it is 0. $i \in V_{DHS}$, $k \in V_{FMS}$.
	β_{ijkn}	If domestic multimodal station $j \in V_{DMS}$ serves demand d_{ik}^{r} by the nth train, β_{ijkn} is 1; otherwise, it is 0. $i \in V_{DRS}$, $k \in V_{FMS}$.
	y_{jkn}	If the nth train that serves (j, k) is used, y_{jkn} is 1; otherwise, it is 0. $j \in V_{DMS}, k \in V_{FMS}$.
Times of tractors	$\tilde{t}_q^{s}$	Departure time of the qth tractor, $\tilde{t}_q^{s} = ({t_1}_q^{s}, {t_2}_q^{s}, {t_3}_q^{s})$
	$\tilde{t}_{iq}^{a}$	Arrival time at $i \in V_{DMS} \cup V_{DHS}$ of the qth tractor, $\tilde{t}_{iq}^{a} = ({t_1}_{iq}^{a}, {t_2}_{iq}^{a}, {t_3}_{iq}^{a})$

$$
\begin{aligned}
&+\sum_{n\in N}\sum_{i\in V_{DRS}}\sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}}\left(d_{ik}^{r}\cdot l_{ij}^{r}\cdot f_d + o_t\right)\cdot\beta_{ijkn} \\
&+\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}}\sum_{j\in V_{DMS}\cup V_{DHS}}(\tilde{t^{uh}}\cdot x_{ijq}^{t}+\tilde{t^{lh}}\cdot x_{ijq}^{l})\cdot s \\
&+\sum_{i\in V_{DRS}}\sum_{k\in V_{FMS}}\tilde{t^{lm}}\cdot d_{ik}^{h}\cdot s
\end{aligned} \tag{4}
$$

In this objective function, we sum the transport costs in the multimodal system, including the costs of the routes and the costs of the nodes. Depending on the different transport networks, highway and railway transport occupy different shares in the composition of total costs. There are several important factors that affect the total costs, including the complication of highway networks, the distance of the railway, and the operation time at stations. After the merge operation, Equation (3) is transformed into Equation (4).

C. CONSTRAINTS

We divide the constraints into three parts, including the constraints of the highway echelon part, the multimodal echelon part and the fuzzy time part.

1) CONSTRAINTS OF HIGHWAY ECHELON

$$
x_{ijq}^{t}+x_{ijq}^{l}\leq 1, \quad \forall i\in V_{DMS}\cup V_{DHS},\ j\in V_{DMS}\cup V_{DHS},\ q\in Q \tag{5}
$$

Highway echelon constraints reflect the driving conditions of tractors. The constraint (5) is a significant driving characteristic of tractors. Tractors have only one condition on each route: traveling alone or traveling with a semi-trailer.

$$\sum_{i\in V_{DHS}} x_{jiq}^{l} - M\left(1-\varepsilon_{jq}\right) \leq \varepsilon_{jq}, \quad \forall j \in V_{DMS}, q \in Q \quad (6)$$

$$\sum_{i\in V_{DHS}} x_{jiq}^{l} + M\left(1-\varepsilon_{jq}\right) \geq \varepsilon_{jq}, \quad \forall j \in V_{DMS}, q \in Q \quad (7)$$

$$\sum_{i\in V_{DMS}\cup V_{DHS}} \left(x_{ijq}^{t}+x_{ijq}^{l}\right) - M\left(1-\varepsilon_{jq}\right) \leq \varepsilon_{jq}, \quad \forall j \in V_{DMS}, q \in Q \quad (8)$$

$$\sum_{i\in V_{DMS}\cup V_{DHS}} \left(x_{ijq}^{t}+x_{ijq}^{l}\right) + M\left(1-\varepsilon_{jq}\right) \geq \varepsilon_{jq}, \quad \forall j \in V_{DMS}, q \in Q \quad (9)$$

$$\sum_{j\in V_{DMS}} \varepsilon_{jq} = 1, \quad \forall q \in Q. \quad (10)$$

Constraints (6) to (10) describe the origins of tractors, which guarantees that tractors can depart from a DMS and return to the DMS to complete the transport cycle within one day.

Constraints (6) and (7) describe the conditions of the route from the origin station. Constraint (8) and (9) describe the conditions of the route next to the origin route. The parameter M is used to linearize constraints in these constraints. For example, constraints (6) and (7) are equivalent to the description that if $\varepsilon_{jq} = 1$, then $\sum_{i\in V_{DHS}} x_{jiq}^{l} = 1$. It means that if the tractor $q \in Q$ departs from the station $j \in V_{DMS}$, the condition of the arc from j to i of tractor q is driving alone. The constraint (10) guarantees that each tractor $q \in Q$ has only one origin station.

$$\sum_{i\in V_{DMS}\cup V_{DHS}} \left(x_{ijq}^{t}+x_{ijq}^{l}\right) = \sum_{k\in V_{DMS}\cup V_{DHS}} \left(x_{jkq}^{t}+x_{jkq}^{l}\right), \quad \forall j\in V_{DMS}\cup V_{DHS},\ q\in Q \quad (11)$$

The constraint (11) ensures that tractors' travel routes are continuous, and j is their intermediate point to form the route (i, j, k).

$$\sum_{i\in V_{DHS}\cup V_{DMS}} \sum_{j\in V_{DHS}\cup V_{DMS}} l_{ij}^{h}\left(\frac{x_{ijq}^{t}}{v^{ht}}+\frac{x_{ijq}^{l}}{v^{hl}}\right) \leq t^{m}, \quad \forall q \in Q \quad (12)$$

The constraint (12) guarantees that tractors travel within a certain range of time t^m in one day.

$$\sum_{q\in Q} x_{ijq}^{t} = d_{ij}^{d}, \quad \forall i \in V_{DHS},\ j \in V_{DHS} \quad (13)$$

The constraint (13) ensures that the demand of highway transport is fully satisfied.

2) MULTIMODAL ECHELON CONSTRAINTS

$$\sum_{q\in Q} x_{ijq}^{t} - M\left(1-\alpha_{ijkn}\right) \leq d_{ik}^{h}, \quad \forall n\in N,\ i \in V_{DHS},\ j\in V_{DMS},\ k \in V_{FMS} \quad (14)$$

$$\sum_{q\in Q} x_{ijq}^{t} + M\left(1-\alpha_{ijkn}\right) \geq d_{ik}^{h}, \quad \forall n \in N,\ i \in V_{DHS},\ j \in V_{DMS},\ k \in V_{FMS} \quad (15)$$

According to this multimodal transport problem, transport connections between DHSs and FMSs, and between DRSs and FMSs are achieved by the DMS. Constraints (14) and (15) describe that the demand from DHSs to FMSs should be fully satisfied. The parameter M is used to ensure that domestic multimodal station $j \in V_{DMS}$ serves demand d_{ik}^{h} by the nth train.

$$\sum_{n\in N} \sum_{j\in V_{dm}} \alpha_{ijkn} = 1, \quad \forall i \in V_{DHS},\ k \in V_{FMS} \quad (16)$$

$$\sum_{n\in N} \sum_{j\in V_{dm}} \beta_{ijkn} = 1, \quad \forall i \in V_{DRS},\ k \in V_{FMS} \quad (17)$$

$$\sum_{i\in V_{dd}} \alpha_{ijkn} + \sum_{i\in V_{dr}} \beta_{ijkn} \leq y_{jkn}\cdot\left(|V_{dd}|+|V_{dr}|\right), \quad \forall j \in V_{DMS},\ k \in V_{FMS}, n \in N \quad (18)$$

Constraints (16) to (18) describe the characteristics of decision variables α_{ijkn}, β_{ijkn} and y_{jkn}. The constraint (16) guarantees that the multimodal demand from $i \in V_{DHS}$ to $k \in V_{FMS}$ can be served by only one intercontinental train from one station $j \in V_{DMS}$. The constraint (17) guarantees that the railway demand from $i \in V_{DRS}$ to $k \in V_{FMS}$ can be served by only one intercontinental train from one station $j \in V_{DMS}$. The constraint (18) describes the decision variable y_{jkn}.

$$\sum_{l\in V_{dd}} \alpha_{ljkn}\cdot d_{lk}^{h} + \sum_{i\in V_{dr}} \beta_{ijkn}\cdot d_{ik}^{r} \leq \tilde{e}, \quad \forall j \in V_{DMS},\ k \in V_{FMS}, n \in N \quad (19)$$

The constraint (19) is a fuzzy inequality of fuzzy intercontinental train capacity, which ensures the quantities of containers from DHSs and DRSs should not exceed the capacity of the intercontinental train.

3) CONSTRAINTS OF FUZZY TIME

We propose constraints with linearized expressions and use the parameter M to express whether the routes cover and depart from the specific nodes or not. The fuzzy equations are expanded as follows:

$$t1_{q}^{s} + \frac{l_{ij}^{h}}{v^{hl}} - M\left(2-\varepsilon_{iq}-x_{ijq}^{l}\right) \leq t1_{jq}^{a}, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \quad (20)$$

$$t1_{q}^{s} + \frac{l_{ij}^{h}}{v^{hl}} + M\left(2-\varepsilon_{iq}-x_{ijq}^{l}\right) \geq t1_{jq}^{a}, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \quad (21)$$

$$t2_q^s + \frac{l_{ij}^h}{v^{hl}} - M\left(2 - \varepsilon_{iq} - x_{ijq}^l\right) \leq t2_{jq}^a, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \tag{22}$$

$$t2_q^s + \frac{l_{ij}^h}{v^{hl}} + M\left(2 - \varepsilon_{iq} - x_{ijq}^l\right) \geq t2_{jq}^a, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \tag{23}$$

$$t3_q^s + \frac{l_{ij}^h}{v^{hl}} - M\left(2 - \varepsilon_{iq} - x_{ijq}^l\right) \leq t3_{jq}^a, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \tag{24}$$

$$t3_q^s + \frac{l_{ij}^h}{v^{hl}} + M\left(2 - \varepsilon_{iq} - x_{ijq}^l\right) \geq t3_{jq}^a, \quad \forall i \in V_{DMS},\ j \in V_{DHS},\ q \in Q \tag{25}$$

In this problem, tractors depart from the DMS without containers. Constraints (20) to (25) show the relationship between the departure time in the DMS and the arrival time in the next station. According to the constraint where a tractor cannot cover two continuous routes without a semi-trailer, the next station should be a DHS. The constraints are expanded by triangular fuzzy numbers in Equation (1). The parameter M guarantees that this equation holds in circumstances of $\varepsilon_{iq} = 1$ and $x_{ijq}^l = 1$. Constraints (20) and (21) are the cases for the lower bound t_1. Constraints (22) and (23) are the cases for the median bound t_2. Constraints (24) and (25) are the cases for the higher bound t_3.

$$t1_{iq}^a + t_1^{lh} + \frac{l_{ij}^h}{v^{ht}} - M\left(1 - x_{ijq}^t\right) \leq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{26}$$

$$t1_{iq}^a + t_1^{lh} + l_{ij}^h/v^{ht} + M(1 - x_{ijq}^t) \geq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{27}$$

$$t2_{iq}^a + t_2^{lh} + l_{ij}^h/v^{ht} - M(1 - x_{ijq}^t) \leq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{28}$$

$$t2_{iq}^a + t_2^{lh} + l_{ij}^h/v^{ht} + M(1 - x_{ijq}^t) \geq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{29}$$

$$t3_{iq}^a + t_3^{lh} + l_{ij}^h/v^{ht} - M(1 - x_{ijq}^t) \leq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{30}$$

$$t3_{iq}^a + t_3^{lh} + l_{ij}^h/v^{ht} + M(1 - x_{ijq}^t) \geq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{31}$$

$$t1_{iq}^a + t_1^{uh} + l_{ij}^h/v^{hl} - M(1 - x_{ijq}^t) \leq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{32}$$

$$t1_{iq}^a + t_1^{uh} + l_{ij}^h/v^{hl} + M(1 - x_{ijq}^t) \geq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{33}$$

$$t2_{iq}^a + t_2^{uh} + l_{ij}^h/v^{hl} - M(1 - x_{ijq}^t) \leq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{34}$$

$$t2_{iq}^a + t_2^{uh} + l_{ij}^h/v^{hl} + M(1 - x_{ijq}^t) \geq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{35}$$

$$t3_{iq}^a + t_3^{uh} + l_{ij}^h/v^{hl} - M(1 - x_{ijq}^t) \leq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{36}$$

$$t3_{iq}^a + t_3^{uh} + l_{ij}^h/v^{hl} + M(1 - x_{ijq}^t) \geq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS} \cup V_{DHS},\ q \in Q \tag{37}$$

After departure from the DMS, tractors will finish the next route either with a semi-trailer or driving alone. The next nodes could be a DHS or a DMS. Constraints (26) to (37) show the time constraints in highway transport.

Constraints (26) to (31) indicate the time relationship between the front and back arcs when fuzzy loading time exists in the station $i \in V_{DHS}$. Constraints (32) to (37) indicate the time relationship between the front and back arcs when fuzzy unloading time exists in the station $i \in V_{DHS}$. As with the previous constraints, triangular fuzzy numbers are used.

$$t1_{iq}^a + t_1^{lh} + l_{ij}^h/v^{ht} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{38}$$

$$t1_{iq}^a + t_1^{lh} + l_{ij}^h/v^{ht} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{39}$$

$$t2_{iq}^a + t_2^{lh} + l_{ij}^h/v^{ht} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{40}$$

$$t2_{iq}^a + t_2^{lh} + l_{ij}^h/v^{ht} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{41}$$

$$t3_{iq}^a + t_3^{lh} + l_{ij}^h/v^{ht} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{42}$$

$$t3_{iq}^a + t_3^{lh} + l_{ij}^h/v^{ht} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{43}$$

$$t1_{iq}^a + t_1^{uh} + l_{ij}^h/v^{hl} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{44}$$

$$t1_{iq}^a + t_1^{uh} + l_{ij}^h/v^{hl} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t1_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{45}$$

$$t2_{iq}^a + t_2^{uh} + l_{ij}^h/v^{hl} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{46}$$

$$t2_{iq}^a + t_2^{uh} + l_{ij}^h/v^{hl} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t2_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{47}$$

$$t3_{iq}^a + t_3^{uh} + l_{ij}^h/v^{hl} - M(2 - x_{ijq}^t - \varepsilon_{jq}) \leq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{48}$$

$$t3_{iq}^a + t_3^{uh} + l_{ij}^h/v^{hl} + M(2 - x_{ijq}^t - \varepsilon_{jq}) \geq t3_{jq}^a, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ q \in Q \tag{49}$$

When the tractor's route path is finished, the tractor will return to the originating DMS. Constraints (38) to (49) show the time constraint in returning to the originating DMS. In these constraints, fuzzy loading and unloading times are considered. Additionally, triangular fuzzy numbers are used.

$$\tilde{t}_{jq}^a + \tilde{t}^{lm} - M\left(2 - x_{ijq}^t - \alpha_{ijkn}\right) \leq t_{jkn}^p, \quad \forall i \in V_{DHS},\ j \in V_{DMS},\ k \in V_{FMS},\ q \in Q, n \in N \tag{50}$$

The constraint (50) guarantees that the time of tractor arrival should be earlier than the intercontinental train's departure time. It is worth noting that containers from the tractor may be transported by any intercontinental train that meets the time constraints in this problem. If the multimodal transport will be finished by the departure time of the next intercontinental train, the storage costs are lower than those of the other schemes.

V. SOLUTION APPROACHES BASED ON THE DEFUZZIFICATION METHOD

The previous model is an MILP model with fuzzy parameters. To solve this model, defuzzification is required first. This process is divided into two steps: defuzzification approaches for fuzzy constraints, and defuzzification approaches for objective functions.

A. DEFUZZIFICATION APPROACHES OF FUZZY CONSTRAINTS

We use defuzzification approaches from fuzzy credibility measure theory [42]. According to Zheng and Liu [43] and Zarandi *et al.* [44], the possibility and necessity measures lack the self-duality property, while the credibility measure is a self-dual measure. A fuzzy event may fail even if its possibility is equal to one and hold even if its necessity is equal to zero. However, the credibility measure can avoid such consequences [28]. Inequality (19) is a fuzzy constraint, in which $\tilde{e}$ is a fuzzy parameter. Cr$\{\cdot\}$ represents the credibility of the event in $\{\cdot\}$. This process can be expressed by the following formulas. In Equation (51), μ represents the service level of the intercontinental train. In Equation (52), λ represents the time satisfaction confidence level.

$$\mathrm{Cr}\left\{\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}+\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}\leq\tilde{e}\right\}\geq\mu \quad \forall n\in N,\ j\in V_{dm},\ k\in V_{fm} \tag{51}$$

$$\mathrm{Cr}\left\{\tilde{t}_{jq}^{a}+\tilde{t}^{lm}-M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right)\leq t_{jkn}^{p}\right\}\geq\lambda, \quad \forall i\in V_{dd},\ j\in V_{dm},\ k\in V_{fm},\ q\in Q,\ n\in N. \tag{52}$$

Equations (51) and (52) can be rewritten as Equations (53) and (54).

$$\mathrm{Cr}\left\{\begin{Bmatrix} e_1-\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}-\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}, \\ e_2-\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}-\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}, \\ e_3-\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}-\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}, \end{Bmatrix}\geq 0\right\}, \tag{53}$$

$$\mathrm{Cr}\left\{\begin{Bmatrix} t_{jkn}^{p}-t1_{jq}^{a}-t_{1}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right), \\ t_{jkn}^{p}-t2_{jq}^{a}-t_{2}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right), \\ t_{jkn}^{p}-t3_{jq}^{a}-t_{3}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right), \end{Bmatrix}\geq 0\right\}, \tag{54}$$

In Equation (55), a is a deterministic number and b is a triangular fuzzy number, where $\tilde{b}=(b_1,b_2,b_3)$, $b_1<b_2<b_3$ [34].

$$\mathrm{Cr}\left\{\tilde{b}\geq a\right\}=\begin{cases}1, & if\ a\leq b_1\\ \dfrac{2b_2-b_1-a}{2\left(b_2-b_1\right)}, & if\ b_1\leq a\leq b_2\\ \dfrac{b_3-a}{2\left(b_3-b_2\right)} & if\ b_2\leq a\leq b_3\\ 0, & if\ a\geq b_3\end{cases} \tag{55}$$

Furthermore, based on Equation (55), Cr$\left\{\tilde{b}\geq a\right\}$ is equivalent to Equations (56) and (57), according to the proof proposed by Wang *et al.* [45].

$$2a.b_2-(2a-1).b_3\geq a, \quad if\ 0\leq\alpha\leq 0.5 \tag{56}$$

$$2(a-1).b_2+(2a-1).b_1\geq a, \quad if\ 0.5\leq\alpha\leq 1 \tag{57}$$

The constraint (19) can be converted into the following form:

$$2\mu.e_2-(2\mu-1)\,.e_3\geq\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}+\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}, \quad if\ 0\leq\mu\leq 0.5,\ \forall n\in N,\ j\in V_{dm},\ k\in V_{fm}, \tag{58}$$

$$2\left(1-\mu\right).e_2+(2\mu-1)\,.e_1\geq\sum_{l\in V_{dd}}\alpha_{ljkn}\cdot d_{lk}^{h}+\sum_{i\in V_{dr}}\beta_{ijkn}\cdot d_{ik}^{r}, \quad if\ 0.5\leq\mu\leq 1, \forall n\in N,\ j\in V_{dm},\ k\in V_{fm}, \tag{59}$$

The constraint (50) can be converted into the following form:

$$2\lambda\cdot\left[t_{jkn}^{p}-t2_{jq}^{a}-t_{2}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right)\right]\geq(2\lambda-1)\cdot\left[t_{jkn}^{p}-t3_{jq}^{a}-t_{3}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right)\right], \quad if\ 0\leq\lambda\leq 0.5,\ \forall i\in V_{dd},\ j\in V_{dm},\ k\in V_{fm},\ q\in Q, n\in N. \tag{60}$$

$$2\left(\lambda-1\right).\left[t_{jkn}^{p}-t2_{jq}^{a}-t_{2}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right)\right]\geq(1-2\lambda)\cdot\left[t_{jkn}^{p}-t1_{jq}^{a}-t_{1}^{lm}+M\left(2-x_{ijq}^{t}-\alpha_{ijkn}\right)\right], \quad if\ 0.5\leq\lambda\leq 1,\ \forall i\in V_{dd},\ j\in V_{dm},\ k\in V_{fm},\ q\in Q\ n\in N. \tag{61}$$

B. DEFUZZIFICATION APPROACHES FOR OBJECTIVE FUNCTIONS

The fuzzy expected value model is widely acknowledged to be an effective approach to deal with a fuzzy objective [46]. The expected value of a triangular fuzzy number $\tilde{c}=(c_1,c_2,c_3)$ is expressed by Equation (31) [47].

$$E\left[\tilde{c}\right]=\frac{c_1+2c_2+c_3}{4} \tag{62}$$

Therefore, we express the objective function as Equation (63).

$$\min z=\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}}\times\sum_{j\in V_{DMS}\cup V_{DHS}}\left[l_{ij}^{h}\cdot f_t\cdot x_{ijq}^{t}+l_{ij}^{h}\cdot f_l\cdot x_{ijq}^{l}+o_l\left(x_{ijq}^{t}+x_{ijq}^{l}\right)\right]$$

$$+\sum_{n\in N}\sum_{j\in V_{DMS}} \times \sum_{k\in V_{FMS}}\left[\frac{e_1+2e_2+e_3}{4}\cdot l^f_{jk}\cdot f_i\cdot y_{jkn}+o_t\cdot y_{jkn}\right] +\sum_{n\in N}\sum_{i\in V_{DRS}} \times \sum_{j\in V_{DMS}}\sum_{k\in V_{FMS}}\left(d^r_{ik}\cdot l^r_{ij}\cdot f_d+o_t\right)\cdot \beta_{ijkn} +\sum_{q\in Q}\sum_{i\in V_{DMS}\cup V_{DHS}} \times \sum_{j\in V_{DMS}\cup V_{DHS}}\frac{t^{uh}_1+2t^{uh}_2+t^{uh}_3}{4}\cdot x^t_{ijq}+\frac{t^{lh}_1+2t^{lh}_2+t^{lh}_3}{4}\cdot x^l_{ijq}\cdot s +\sum_{i\in V_{DRS}}\sum_{k\in V_{FMS}}\frac{t^{lm}_1+2t^{lm}_2+t^{lm}_3}{4}\cdot d^h_{ik}\cdot s \quad (63)$$

VI. COMPUTATIONAL EXPERIMENTS

Based on the experience of the Euro-China Expressway, we propose a series of instances. Furthermore, we use CPLEX 12.8 with VS2015, and run on a computer with an Intel(R) Core(TM) i5-6200U 2.3 GHz processor and 8 GB of memory, using the Windows 10 operating system. Moreover, we perform sensitivity analysis on these fuzzy parameters.

A. INSTANCES GENERATION AND PARAMETERS VALUES

According to the method of instances generation in Lu *et al.* [48], we generate a series of instances as follows. To verify the influence of the parameters in the model on the objective function and the sensitivity analysis for the fuzzy parameters, we generate the following calculation instances, which are shown in Table 2. Because the size of the CPLEX solution is limited to a certain period of time, we select a relatively suitable calculation example based on experimental experience.

TABLE 2. Characteristics of instances.

instance number	quantity of DMSs	quantity of FMSs	quantity of DHSs	quantity of DRSs	quantity of intercontinental trains per day
instance-a1	2	2	3	3	2
instance-b1~b5	2	2	5	4	2, 4, 6
instance-c1~c5	2	2	5	4	3
instance-d1~d5	2	2	5	4	2

According to the Euro-China Expressway with different departure DMSs, the fuzzy parameter $\tilde{e} = (24, 34, 44)$. Moreover, based on an existing study [49], the fuzzy time parameters and normal parameters have the values shown in Table 3 and 4.

B. COMPUTATIONAL RESULTS OF AN INSTANCE

To make the calculation results clearer, we show the calculation results for a small-scale example instance-a1, as shown in Fig. 10.

TABLE 3. Values of fuzzy parameters for instances.

Fuzzy Parameter	$\widetilde{t^{uh}}$	$\widetilde{t^{lh}}$	$\widetilde{t^{lm}}$
Value	(0.1,0.2,0.3)	(0.4,0.5,0.6)	(0.3,0.5,0.7)

TABLE 4. Values of parameters for instances.

Parameter	f_t	f_l	f_d	f_i
Value	600	200	202.5	490
Parameter	o_l	o_t	s	M
Value	25	195	312.5	99999

This figure shows that three types of transportation networks constitute this transport system. The two DMSs and their train departure times are the significant nodes in the transport network, and the location selection operation is implemented. Among them, the first intercontinental train of the second DMS is not used. Multimodal transport does not occur in the cargo collection of the second intercontinental train of the first DMS. Additionally, the other two intercontinental trains are formed by road and rail multimodal transport. In addition, there are a total of 32 tractors for road transport, which are not marked in the figure.

C. SENSITIVITY ANALYSIS OF THE OBJECTIVE FUNCTION WITH THE QUANTITY OF INTERCONTINENTAL TRAINS

To verify the impact of the quantities of intercontinental trains per day on the objective function, we selected quantities of N $=$ $2, 4,$ and 6 for calculation, as shown in Fig. 11. As N increases, the total cost decreases. This shows that an improvement in the DMS's ability to send trains will improve the operating efficiency of the intercontinental multimodal transport system.

Table 5 shows the gaps between different values of N, using the value of N $=$ 6 as a benchmark. The results show that, after the quantity of intercontinental trains reaches a certain value, an increase in their number of them does not greatly improve the objective function. In this case, because the intercontinental train sending capacity of the DMS already meets the needs of the transportation system, additional intercontinental trains will not be used. In real-world transport practices, we can comprehensively determine the most appropriate quantity of intercontinental trains based on the capabilities of the DMS.

D. SENSITIVITY ANALYSIS OF THE OBJECTIVE FUNCTION WITH THE SERVICE LEVEL OF INTERCONTINENTAL TRAINS

Fig. 12 shows a sensitivity analysis of the capacity of instance-c1. From the figure, we can infer the following:

(1) With an increase in capacity, we can obtain a better transport optimization scheme;

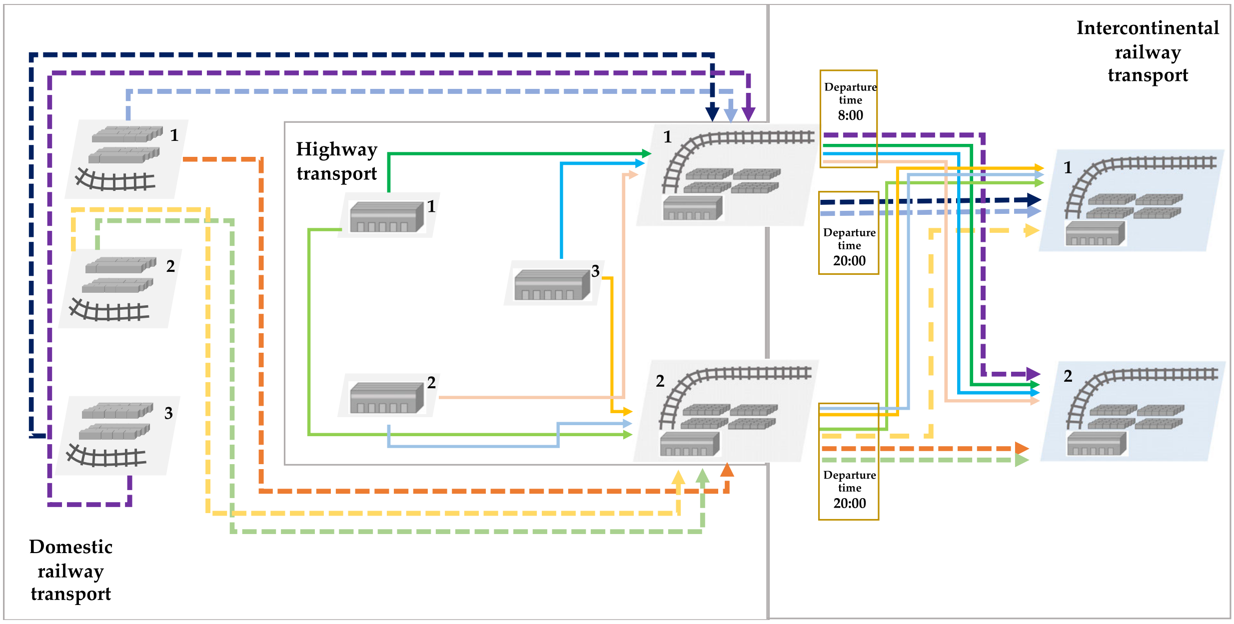

FIGURE 10. Schematic diagram of instance calculation results.

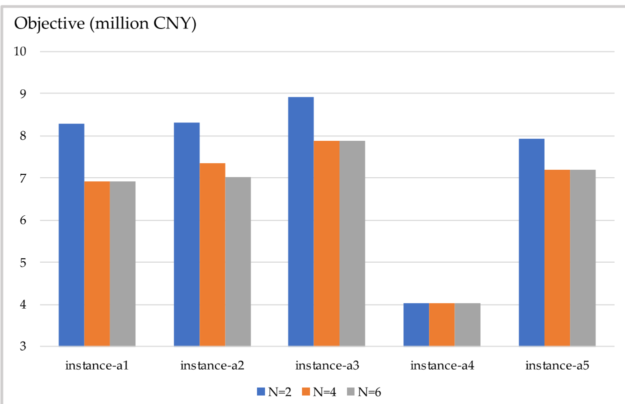

FIGURE 11. Total cost for different quantities of intercontinental trains.

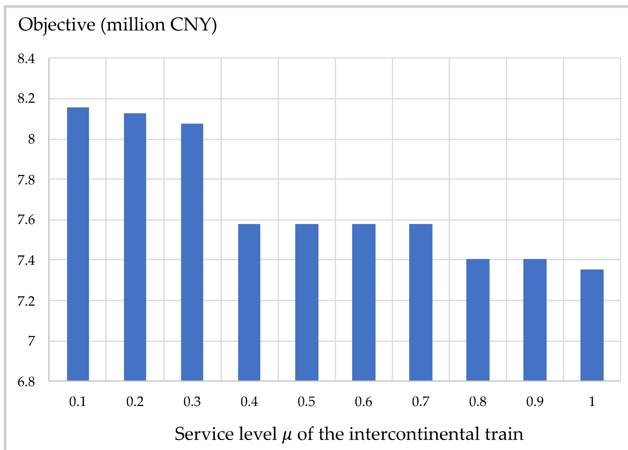

FIGURE 12. Sensitivity analysis of the service level of instance-c1.

TABLE 5. Gaps for different quantities of intercontinental trains.

	N=2	N=4
instance-b1	0.19655202	0.00002745
instance-b2	0.18600945	0.04723533
instance-b3	0.13254535	0
instance-b4	0.00003974	0
instance-b5	0.10291476	0

(2) In some intervals, the objective function does not change with capacity. However, the transport scheme may change;

(3) In different ranges, the slopes of the curve in the graph are different. This shows that when the capacity is greater than a certain value, the objective function will be considerably improved. This result provides a basis for decision-making, as we can achieve higher returns with less investment in intercontinental transportation systems.

Fig. 13 shows the calculation results for instances c2 to c5. When $\mu \geq 0.5$, a conclusion consistent with Fig. 12 can be obtained. However, when $\mu < 0.5$, many examples have no optimal solution. This is due to the differences in the distances between nodes and transport requirements in different instances. These results show that when the service level of the train is less than a certain value, it cannot meet all transportation requirements. Therefore, under this condition, we recommend that the number of containers per column of intercontinental train load cannot be less than 34.

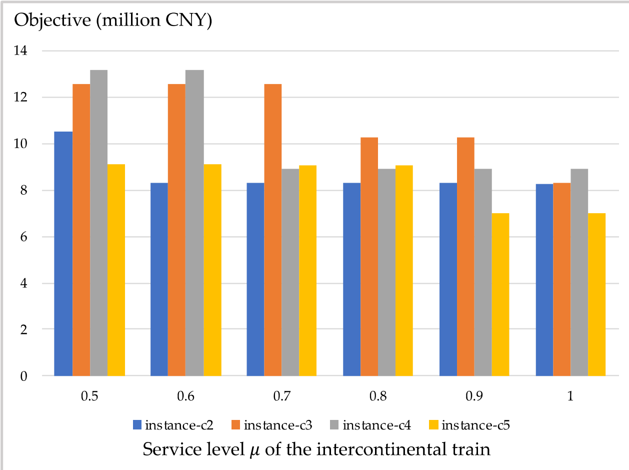

FIGURE 13. Sensitivity analysis of the service level of instances c2 to c5.

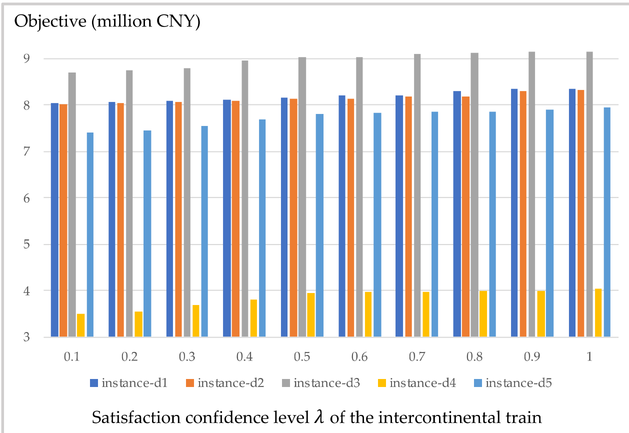

FIGURE 14. Sensitivity analysis of the satisfaction confidence level of instances d1 to d5.

E. SENSITIVITY ANALYSIS OF THE OBJECTIVE FUNCTION WITH THE TIME SATISFACTION CONFIDENCE LEVEL

When the values of the other parameters are determined, we perform a sensitivity analysis on the time satisfaction confidence level. Several calculation instances are selected for calculation, as shown in Fig. 14.

As shown in the figure, the sensitivity analysis results of the time satisfaction confidence level have the following characteristics:

(1) The effect of fuzzy time on the objective function is mainly reflected by two aspects—on the one hand, it affects the storage cost, and on the other hand, it affects the assembly process from a DHS to a DMS;

(2) In terms of influencing storage cost, since the problem is intercontinental transport, the storage cost accounts for a small proportion of the total cost, so its impact is relatively limited;

(3) For influencing the assembly process from a DHS to a DMS, the degree of influence is different for different calculation instances. For calculation instances with high transport capacity requirements, fuzzy time has a greater impact on the objective function because fuzzy time affects the assembly process of road–rail multimodal routing. For calculation instances with low transport capacity requirements, the impact of fuzzy time is relatively limited.

VII. CONCLUSION

In this paper, we propose a fuzzy intercontinental road–rail multimodal routing model with time and train capacity uncertainty and solve the fuzzy model for a series of instances. Based on the analysis results, this fuzzy model is suitable for solving the characteristics of long distances, several types of transport nodes, and fuzzy capacity and fuzzy time routing problems. In addition, the model is relatively close to real-world transport practices, such as the Euro-China Expressway. Based on the defuzzification approaches, the triangular fuzzy numbers are suitable for this fuzzy model, and therefore, the MILP model can be solved. Based on the analysis results, we summarize the following conclusions and recommendations:

(1) In this problem, the most critical optimization node is the DMS. The DMS may undertake functions as a tractor departure station, an intercontinental train departure station, and a multimodal transport organization hub. Therefore, the long-distance transport routing problem should be given more attention than the multi-echelon connection optimization problem;

(2) One of the characteristics of the transportation network in this problem is that it adds to the transport demand between DHSs. Judging from the results, considering the transport demand between DHSs in a multimodal transport network, the flexibility of the tractors and semi-trailers can be considered more. Moreover, this provides a good solution for the mixed problem of road transport and multimodal freight collection in a specific area;

(3) From the sensitivity analysis of the objective function with the quantity of intercontinental trains, the results show that $N = 4$ is a better result considering total costs and facility inputs in stations. The sensitivity analysis of the objective function with the service level of intercontinental trains shows that the cost drops from more than 8 to below 7.6 million CNY when μ increases from 0.3 to 0.4 in instance-c1. Similar trends are also shown for instance-c2 to instance-c5.

(4) According to the calculation results, during the intercontinental train assembly process, trains with sufficient carrying capacity should be arranged, which can greatly reduce the cost of the transport network. In the DMS's daily train schedule, according to the actual situation of transport demand, the appropriate number of daily trains can be determined to meet container demand. On the one hand, a smaller quantity of trains will cause a series of inefficient situations. On the other

hand, a larger quantity of trains will cause a waste of resources and increase the operating pressure of stations;

(5) It is necessary to effectively reduce the container storage time and reduce the total cost by using intelligent loading and unloading equipment. Uncertain station operation times may affect the optimization of nodes and routes in the transport network. In general, the impact of the time uncertainty of stations on an intercontinental multimodal transport network is less than the impact of the capacity uncertainty of intercontinental trains;

(6) In real-world transport practice, because the long-distance transport link of intercontinental transport needs to follow transport agreements and transport plans between countries, these problems often relatively fixed or difficult to further optimize in a short time. Therefore, it is recommended that transportation decision-makers pay more attention to the optimization of multimodal transport assembly, which will also have a greater impact on the total cost;

(7) In future research, we suggest that scholars pay more attention to the assembly of maritime and rail assembly in intercontinental multimodal systems. This makes this intercontinental transport network an important part of the land bridge. Furthermore, scholars could use different heuristic algorithms to solve the fuzzy intercontinental multimodal routing problem.

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