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Hybrid MCDM Model for Location of Logistics Hub: A Case in China Under the Belt and Road Initiative

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ABSTRACT The location of logistics nodes that facilitate the China Railway Express (CRexpress) and rail-sea intermodal transportation has received increasing attention in China under the Belt and Road initiative. This paper selects 38 cities as candidate Chinese international container intermodal hubs (CICIHs) through qualitative screening by considering the current operations of the CRexpress/rail-sea intermodal transportation and government planning strategies. Subsequently, five connectivity indexes are proposed to reflect the node performance considering the multiple modes and stages of transportation in a logistics chain. In view of the shortcomings of the grey relational analysis-technique for order preference by similarity to ideal solution (GRA-TOPSIS) method, a hybrid multi-criteria decision making (MCDM) model is proposed to comprehensively evaluate the hub location. The model is based on the grey area relational analysis-technique for order preference by similarity to ideal solution (GARA-TOPSIS) in combination with analytic hierarchy process, entropy method and game theory. Tianjin, Harbin, Zhengzhou, Wuhan, Chongqing, Xi'an, Urumqi, Guangzhou, Shanghai and Nanning are selected as the final CICIHs, considering the geographical location, economic development and national policy pertaining to the Belt and Road initiative. A sensitivity analysis of the index weight and preference coefficient and a comparative analysis of different MCDM methods are performed. The robustness and stability of the proposed model are verified. This study can support the location selection of CICIHs and expand the methods and applications in the decision-making field.

INDEX TERMS China Railway Express, intermodal transportation, location selection, multi-criteria decision making, node connectivity.

I. INTRODUCTION

The container multimodal networks have been constantly reshaped based on the massive trade along the Sino-European routes under the Belt and Road Initiative (BRI) in recent years. As the key node in the logistics chain and freight network, logistic hubs enable to consolidate freight flows coming from different origins, to sort them by their next destination and to prepare their transshipment using unimodal or multimodal transportation resources. Previous studies have shown that the rationality of the location and layout of logistics facilities not only reduces costs through delivering an economy of scale but also maximizes transportation efficiency and service quality by planning efficient multimodal networks. To improve the efficiency of international trade transportation, the Chinese government launched the BRI in 2013, with the formal document issued in 2015 (Vision and Actions on Jointly Building Silk Road Economic Belt and 21st Century Maritime Silk Road), which highlights the importance of two logistics routes for mainland China, namely, the China Railway Express (CRexpress) and international rail-sea intermodal corridors.

At the end of 2019, international trains were operating from more than 150 Chinese cities, with more than 60 and 130 cities being served by CRexpress trains and rail-sea intermodal transportation (certain cities were served by both

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types of trains), thereby enhancing the diversity and connectivity of the international logistics network and improving the level of foreign trade. However, due to the lack of holistic planning and management for the cities at the national level, the increasing number of cities served by the international trains resulted in many problems, such as disorderly competition, insufficient cargo supply, low load factor and low overall coordination. To address these problems through systemic coordination and organization, it is necessary for China to select certain key consolidation centers from among these cities to act as hubs. In this context, considering the increasingly prominent trend of containerization of cargo transportation, this work was aimed at examining the problem of selecting a container consolidation center, defined as the Chinese international container intermodal hub (CICIH).

The CICIHs are expected to connect not only the hinterland cities in China through multiple modes of transportation, but also foreign destinations (European cities in this work) through CRexpress and rail-sea intermodal transportation. In a many-to-many logistics system, the CICIHs can attract freight by fully utilizing their capabilities to realize cargo accumulation and the transshipment and connection of various transportation modes. Therefore, the location of the CICIHs is key to enhance the efficiency of the international container land and maritime transportation services and refine China's freight intermodal network.

In addition, the connectivity is recognized as a key factor affecting the location of the logistics hub in a freight network, as it represents the advantage of the hub in terms of its geographical location and degree of convenience of transportation [1]. Therefore, in this work, according to the actual situation of China's foreign trade transportation framework, multiple connectivity indicators corresponding to multiple modes and stages of transportation in a logistics chain are proposed, and a multi-criteria decision making (MCDM) method is enhanced to comprehensively evaluate and rank the various connectivity aspects of a candidate CICIH (c-CICIH). Many methods have been proposed to solve the MCDM problem. The Grey Relational Analysis-Technique for Order Preference by Similarity to Ideal Solution (GRA-TOPSIS) method integrates the advantages of GRA and TOPSIS approaches, adopts Euclidean distance and grey correlation degree to reflect the proximity between the alternative and the ideal solutions from the similarity in position and shape respectively, and is a very extensive MCDM method. Moreover, considering the limitations of the GRA-TOPSIS, this study proposed a Grey Area Relational Analysis-Technique for Order Preference by Similarity to Ideal Solution (GARA-TOPSIS) using the relational area between two curves to calculate the grey relational coefficient and relational degree. We adopt the game theory method to integrate the subjective weight determined by AHP method and the objective weight determined by entropy method to obtain the comprehensive weight of the index. Therefore, a hybrid MCDM model is proposed to comprehensively evaluate the location of CICIHs.

This research has a threefold contribution to the literature. (1) A hybrid MCDM model is proposed to comprehensively evaluate the hub location, which is based on the GARA-TOPSIS in combination with analytic hierarchy process (AHP), entropy method and game theory. This model adopts the relational area between two curves to calculate the grey relational coefficient and relational degree, thereby enriching the methodology to solve the location decision problem with multiple attributes. (2) This study proposes an all-around method for measuring the connectivity of multimodal hubs in the transportation chain by considering multiple transport segments (domestic and international transportation) and modes (expressway, national road, railway, CRexpress and rail-sea intermodal transportation). This approach contributes to the methodology for evaluating the connectivity of logistics facilities in other regions. (3) This study provides a new research perspective pertaining to the location of the logistics hub, considering both the CRexpress and rail-sea intermodal transportation models according to the actual operation of China's foreign trade transportation framework. Moreover, the integration of the qualitative screening of the government planning/policy and quantitative calculation of the MCDM method is a relatively novel research aspect. It can efficiently reduce the complexity of the problem. Therefore, the aim of this paper is to provide decision-makers (DMs) with a practical and reasonable approach for location decision of multimodal hubs.

The remaining paper is organized as follows: Section II provides a review of the relevant literatures. Section III describes the screening process of the c-CICIHs, and Section IV describes the methods to measure the hub connectivity and evaluate the location. Section V elaborates upon the comprehensive evaluation of the location, including the calculation of the connectivity and weight, evaluation process and selection of the optimal CICIHs. The sensitivity and comparative analyses of the proposed method are discussed in Section VI, and the conclusions are presented in Section VII.

II. LITERATURE REVIEW

A. HUB LOCATION UNDER THE BRI

The hub location problem involves locating the hubs and determining the routing flows of the origin-destination pairs that pass through the hubs [2]. The hub location has been extensively examined in the logistics and transportation domain [3], [4], in the context of selecting the locations of sites such as distribution centers [5] and passengers [6]. In most cases, the location of the logistics facilities is selected strategically, and the generated solutions/decisions have a long-term impact. Multiple evaluation methods [7] and optimization algorithms [8] have been adopted to solve this problem.

Since the BRI was announced in 2013, it has triggered extensive research involving not only the qualitative analysis of the economic and political implications and motivations [9] but also the quantitative aspects pertaining to the network planning [10], logistics distribution flow [11] and consolidation centers [12]. However, the location problem of a comprehensive transportation hub has not been examined in-depth. The review of the literature indicates that most of the existing studies focused on individual aspects of the BRI. For instance, Zeng *et al.* [13] and Peng *et al.* [14] analyzed the hub port selection along the 21st-Century Maritime Silk Road, based on the gravity model and big data. Jiang *et al.* [15] examined the cargo consolidation centers for the China-Europe railway freight under the BRI. Even though these researchers studied the hub location from different perspectives, they focused on a single aspect of the BRI and did not consider the actual situation of China's foreign trade transportation network at the national scale to comprehensively study the location of a logistics hub.

B. NODE CONNECTIVITY

The connectivity is usually examined to accurately reflect the node connectivity for the entire logistics and transportation chain and to identify cost-efficient strategies to facilitate international trade [16]. The node connectivity can be defined as the ability (in terms of the transportation quality and cost as well as the number of routes required) of linking the nodes in a network by using various modes of transportation [17]. A broader definition for the connectivity emphasizes the influence of the availability and capacity of the transport services within the framework of the complex systems theory [18]. With the increasing interest in this domain, the connectivity aspects have been applied to other research fields, specifically, the transportation field, including airports and seaports [16], [19]. The measurement methods can be divided into 3 categories according to their properties: (1) Methods to calculate the connectivity from the perspective of the transportation network, based on the complex network theory [20], and to simulate the effect of the node failure on the connectivity [21]. Such methods are the most widely used and the most mature. The indicators with the node attributes, such as the degree, centrality and clustering coefficient, are usually adopted in such methods. (2) Building connectivity models based on the transportation attributes (handling/transshipment capacity and time) of the hub. However, such methods can be applied only in certain domains, and the connectivity model is established for specific cases. Langen and Sharypova [17] constructed an intermodal connectivity model among inland terminals, rail, barges and deep-sea ports, based on the connectivity of the modes, and noted that a larger freight volume can be handled by improving the internodal connectivity. (3) Methods to measure the connectivity from a geospatial perspective, based on the GIS [22] and big data [23]. With the development of geostatistics and data mining, such methods are being increasingly applied. Farooq *et al.* [24] adopted the GIS to analyze the road traffic flow between Beijing and Xiong'an and used the multicriteria method to select the influencing factors to design a traffic network, with the aim of improving the connectivity between the two hubs. In particular, many studies have considered the attractiveness, geographical location and accessibility of a hub as key indicators of the connectivity [25]. Nevertheless, with the rapidly emerging transport networks involving multiple transportation modes, the choice of a transportation chain, rather than that of a transit node, becomes more critical for logistics integrators. Therefore, the limited emphasis on a certain stage of transportation in a complete transportation system may lead to a deviation in the results or underestimation of the node potential when evaluating the comprehensive connectivity of the nodes.

C. COMPREHENSIVE EVALUATION TO THE LOCATION

In general, the location is selected by comprehensively considering the transportation convenience, geographical location, layout rationality, and the process involves analyzing several prospective alternative locations with respect to a range of criteria (the use of a single index to evaluate the objects cannot capture the complexity of the actual situation). Therefore, the location selection problem can be regarded as an MCDM problem, involving the comprehensive evaluation and ranking of multiple objects through multiple indicators. The MCDM has been demonstrated to be effective and feasible [26]–[28] for use with multi-index systems and to realize multi-alternative evaluations in the location decision problem. The main characteristics of the various MCDM methods are summarized in Table 1. Among such methods, the TOPSIS approach and its combination with other methods have been successfully applied in the domain of location selection, such as for multimodal freight terminals [21], warehouse locations [29] and grain distribution centers [30]. The GRA-TOPSIS, which integrates the advantages of the GRA and TOPSIS approaches [31], has attracted increasing attention since it was first proposed by Chen and Tzeng [32]. Liu *et al.* [33] adopted the GRA-TOPSIS to evaluate the resilience of an agricultural water/soil resource system for 15 farms in Heilongjiang Province, China, and verified the rationality and reliability of the evaluation results. The characteristics of this method render it a promising alternative for use in the location selection problem.

Furthermore, determining the weights is critical to rank the alternatives, and both subjective and objective weights must be considered [41]. Therefore, using combinative weighting, which ensures a balance between the subjective and objective aspects, is more suitable to determine the evaluation criteria for the location decision [42]. This strategy not only expresses the expert preference but also considers the intrinsic information of the index. Therefore, in this work, a highly useful and practical approach, that is, the analytic hierarchy process and the entropy concept [43] were used to calculate the subjective and objective weights, respectively, and the weights were integrated based on the game theory.

Although many studies have focused on the hub location under the BRI, the literature review indicates that a systematic analysis according to the current operation of China's freight trade transportation framework has not been

TABLE 1. MCDM methods.

Method	Advantages	Limitations
AHP [34]	Can establish a hierarchy and calculate the subjective weights.	Does not consider the correlation among the indicators.
TOPSIS [35]	Can reflect the overall similarity between the alternative and ideal schemes.	Cannot reflect the difference between the change trend of the indexes within the programme.
GRA [36]	Can measure the similarity degree of the curve shapes between the sequences.	Certain defects exist in the overall evaluation of the system scheme.
VIKOR [37]	Simple and logical computation procedure, which considers the closeness to ideal solutions.	The evaluation of the uncertainty factors is unsatisfactory.
ELECTRE [38]	Many parameters need to be defined.	The calculation process is complicated.
PROMETHEE [39]	The index does not need to be standardized, and loss of information can be avoided.	The psychology of the DMs is not considered.
TODIM [40]	The evasion of the losses and risks of the DMs can be reflected.	The value of the recession coefficient is not clearly defined.

Note: AHP (analytic hierarchy process), VIKOR (Vlsekriterijumska Optimizacija I Kompromisno Resenje), ELECTRE (Elimination et Choix Traduisant la Realite), PROMETHEE (preference ranking organization method for enrichment evaluations), TODIM (an acronym in Portuguese of interactive and MCDM).

conducted. In particular, the location and layout of an intermodal hub have not been examined at the national scale, to ensure the stable operation of the CRexpress and rail-sea intermodal transport modes. Although the node connectivity has been examined and applied in many fields, a case study of the hub location, based on comprehensive connectivity, from the perspective of the logistics chain, has not been performed. This paper is aimed at addressing these gaps. Given that the node connectivity is a key performance indicator in the transportation network, we develop a comprehensive connectivity measure considering multiple connectivity indexes to capture the aggregated connectivity of multiple modes of transportation (expressway, national road, railway, CRexpress and rail-sea intermodal transportation) and multiple stages (domestic and international transportation), based on the logistics chain, to evaluate the performance of c-CICIHs under the BRI. Considering the interaction of different c-CICIHs and different connectivity indexes in a c-CICIH subsystem, an improved GARA-TOPSIS method is proposed by analyzing the relationship between the selected scheme and ideal solution to evaluate the performance of all the alternatives to optimize the solution of the location of the c-CICIHs.

III. SCREENING OF C-CICIHS

Owing to the large geographical area of China, it is difficult to analyze all the theoretically possible locations; therefore, the research scope must be narrowed by reducing the number of candidate cities before the comprehensive evaluation. With the construction of the BRI, an increasing number of cities are being served by CRexpress and rail-sea intermodal trains. Moreover, the state has issued a series of documents related to the logistics hub planning, which provides references for the screening of the c-CICIHs.

A. SCREENING PRINCIPLES

The cities in Hainan and Taiwan are excluded from the potential c-CICIHs. In particular, as an island province without road/railway connections to the mainland, Hainan is an unsuitable option. For political reasons, Taiwan, which is another island province, is also an unsuitable option. All the remaining cities in mainland China are considered for the potential c-CICIHs. The specific principles are as follows:

Principle 1: The cities that are already served by stably operating international trains (including the CRexpress and rail-sea intermodal train) through the road-rail intermodal transportation are included in set $N1$.

Principle 2: The cities in which the CRexpress or rail-sea intermodal trains are consolidated or change with the function of the rail-rail or rail-sea intermodal transportation (e.g., land exit-ports and seaports) are included in set $N2$.

Principle 3: The national node cities that have been designated in the national strategic policy, through documents including the Allocation and Planning of China Logistics Hubs (*APLH*), Layout Planning of China Logistics Node Cities (2015-2020) (*LPLN*), Action Plan for Promoting the Construction of Logistics Corridor (2016-2020) (*APLC*), Development Planning for the China-Europe Train (2016-2020) (*DPCT*) are included in set $N3$.

According to the aforementioned three principles, the set of the c-CICIHs is selected by performing a union operation followed by an intersection operation: $N = (N1 \cup N2) \cap N3$.

B. SCREENING PROCESS

The specific screening process based on the principles is as follows:

Step 1: Based on Principle 1, 36 cities are selected: Chongqing, Chengdu, Zhengzhou, Xi'an, Yiwu/Jinhua, Suzhou, Wuhan, Changsha, Hefei, Xuzhou, Lanzhou, Changchun, Harbin, Jinan, Nanjing, Hangzhou, Ganzhou, Nanchang, Kunming, Guiyang, Shijiazhuang, Taiyuan, Linfen, Nanning, Huaihua, Bengbu, Xiangyang, Luzhou, Zibo, Xinxiang, Handan, Fŭzhou, Zhuzhou, Jining, Weifang, and Yichang.

Step 2: Based on Principle 2, 18 cities are selected (after eliminating the cities screened in step 1): Urumqi, Alashankou, Khorgas, Manzhouli, Erenhot, Suifenhe, Shanghai, Ningbo, Shenzhen, Guangzhou, Tianjin, Qingdao, Dalian, Xiamen, Yingkou, Fúzhou, Lianyungang, and Beibuwan.

Step 3: According to the formula of the selection mechanism, 39 designated cities that appear in at least two documents specified in Principle 3 are selected: Chongqing, Chengdu, Zhengzhou, Xi'an, Yiwu/Jinhua, Suzhou, Wuhan, Changsha, Hefei, Lanzhou, Changchun, Harbin, Jinan, Nanjing, Hangzhou, Nanchang, Kunming, Guiyang, Shijiazhuang, Taiyuan, Nanning, Urumqi, Alashankou, Khorgas, Manzhouli, Erenhot, Suifenhe, Shanghai, Ningbo, Shenzhen, Guangzhou, Tianjin, Qingdao, Dalian, Xiamen, Yingkou, Fúzhou, Lianyungang, and Beibuwan. Excluding the border cities with a single function and only a few local goods sources, which are mainly used for transshipment of CRexpress.

Special case: the national logistics hubs identified in the Notice on the Construction of National Logistics Hub in 2019 (NCNLH), but not included in the screening correspond to Ganzhou, Ulanqab, Linyi, and Yichang.

Finally, we screened 38 c-CICIHs: Tianjin, Harbin, Jinan, Nanjing, Hangzhou, Zhengzhou, Hefei, Wuhan, Changsha, Chongqing, Chengdu, Xi'an, Lanzhou, Urumqi, Dalian, Qingdao, Ningbo, Xiamen, Guangzhou, Shenzhen, Shanghai, Suzhou, Nanning, Kunming, Taiyuan, Shijiazhuang, Changchun, Fúzhou, Nanchang, Guiyang, Ulanqab, Yingkou, Yiwu/Jinhua, Ganzhou, Linyi, Yichang, Lianyungang, and Beibuwan.

IV. MATERIALS AND METHODS

A. STUDY AREA

This paper selects 38 c-CICIHs as the research objects for comprehensive location evaluation. A total of 333 cities in mainland China (excluding Hong Kong, Macao, Taiwan and Hainan province) serve as hinterlands/origins. As the containers from China to Europe are mainly transported by land (CRexpress, including three corridors/exit-ports: Alashankou, Erenhot and Manzhouli) and rail-sea intermodal transport (domestic railway transport to the top 10 container seaports, including Shanghai, Ningbo-Zhoushan, Shenzhen, Guangzhou, Qingdao, Tianjin, Xiamen, Dalian, Yingkou and Lianyungang, whose foreign trade container throughputs exceeds 90% of the national total, followed by shipping to Europe) under the BRI, the study area included Europe and multiple land and rail-sea transportation paths between China and Europe (Fig. 1).

According to the Highway Network Planning 2013-2030 (National Development and Reform Commission, 2013), China highway website (www.chinahighway.org), Medium and Long-term Railway Network Plan 2016-2025 and China Railway Corporation website (www.12306.cn), the transportation networks (including expressways, national roads and freight railways) in mainland China between the nodes (c-CICIHs, hinterlands/origins, land exit-ports and seaports) can be established considering three fragment based on the topological points in the ArcGIS software. The base maps

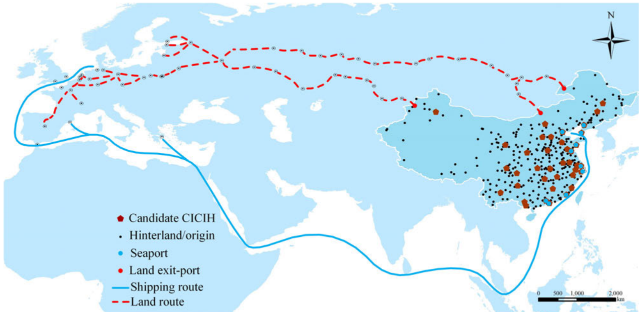


FIGURE 1. Study area.

can be derived from the National Catalogue Service for Geographic Information (www.webmap.cn).

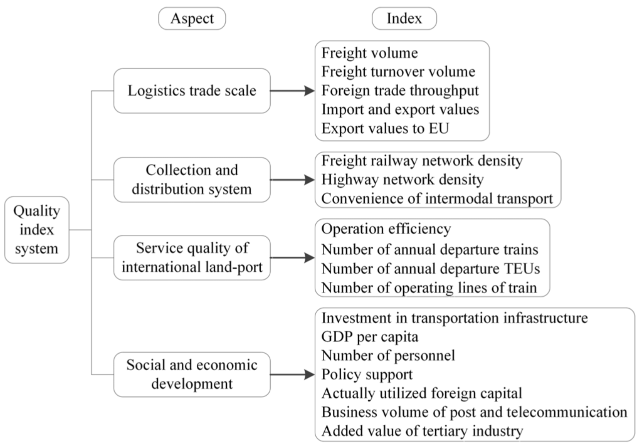
B. METHODS

Given the disputed measures of node connectivity [16], we established a comprehensive connectivity index from the perspective of a logistics chain consisted of two aspects: domestic connectivity (connecting domestic cities) and international connectivity (connecting European cities). In this work, the China export to Europe was considered as an example. Subsequently, a GARA-TOPSIS method was formulated to integrate the evaluation indexes to fully reflect the comprehensive connectivity of a city and provide the basis for the unbiased CICIH location.

1) CONNECTIVITY INDEX

For the domestic connectivity, considering that the containers are mainly transported by road and railway, we constructed three indicators pertaining to the expressway, national road and railway connectivity (*EC* & *NC* & *RC*). For the international connectivity, at present, mainland China and Europe mainly transport containers through the CRexpress and rail-sea intermodal trains; therefore, we constructed two indicators of the CRexpress and rail-sea intermodal connectivity (*CC* & *IC*).

The connectivity index A_i of c-CICIH i is expressed by the average market share of the cargo transported through c-CICIH i (For the domestic connectivity, A_i represents the average market share of the cargo transported from all hinterlands j through i. For the international connectivity, A_i represents the average market share of the cargo transported to all destinations j through i, where i and j indicate the c-CICIH and the hinterland or destination, respectively). Specifically, $A_i = \sum_{j=1}^{n} P_{ij} \Big/ n$, where P_{ij} is the market share of c-CICIH i in the total trade volume of node j; $P_{ij} = F_{ij} \Big/ \sum_{i=1}^{m} F_{ij}$, where F_{ij} represents the spatial interaction intensity between c-CICIH i and node j. A higher intensity corresponds to a larger interactional possibility. We adopted the gravity model, which is commonly used to measure the spatial connection in the hub location. Herein, $F_{ij} = GM_iM_jC_{ij}^{-\theta}$, where M_i is the comprehensive quality of c-CICIH i based on the multi-index system; C_{ij} is the spatial damping between i and j, which is



Note: The convenience of intermodal transport refers to the transfer capacity of various transport modes, including highway, railway, waterway and aviation. If the city has n(n=1,2,3,4) modes, then the value is n. Policy support refers to the frequency of a hub appearing in four documents in Section III. If the hub does not appear in any document, then the value is 0. If it appears in n(n=1,2,3,4) documents, then the value is n.

FIGURE 2. Quality index system.

expressed as the generalised transportation cost considering the sum of the monetary and time costs. In general, the gravitational constant $G = 1$, and the damping parameter $\theta = 2$. Therefore, the connectivity index can be expressed as $A_i = \frac{1}{n}\sum_{j=1}^{n}\frac{M_iC_{ij}^{-2}}{\sum_{i=1}^{m}M_iC_{ij}^{-2}}$.

The comprehensive quality of c-CICIH i can be calculated by building a multi-index system. According to the scientific aspects, purpose and operability, along with the characteristics of the c-CICIHs as key nodes of the freight network [4], [19], the index system is constructed considering 4 aspects (Fig. 2): The logistics trade scale reflects a city's logistics trade and transshipment capacity of the international goods. The collection and distribution system define the degree of convenience of the cargo transportation and operation. The service quality of the international land-port defines the handling level of international container trains at the hub station/park. The social and economic development aspects provide the basic support for the hub construction.

a: EC

According to the calculation formula of the connectivity index, EC can be defined as follows:

$$A_i^{EC} = \frac{1}{n}\sum_{j=1}^{n}\frac{M_iC_{ij}^{EC-2}}{\sum_{i=1}^{m}M_iC_{ij}^{EC-2}} \tag{1}$$

with

$$C_{ij}^{EC} = \eta_{EC}D_{ij}^{EC} + \tau D_{ij}^{EC}\Big/V_{EC} \tag{2}$$

where $i = 1, 2, \cdots, 38$ represents the c-CICIH; $j = 1, 2, \cdots, 333$ represents the hinterland city; η_{EC} is the unit transport cost of one TEU according to the expressway; D_{ij}^{EC} is the shortest expressway distance between i and j; τ is the value of the time; and V_{EC} is the average expressway running speed.

b: NC AND RC

The NC and RC were calculated similar to the EC.

c: CC

At the end of 2019, the CRexpress was serving more than 50 cities in Europe, making it challenging to study all the cities as destinations. We chose Hamburg (both the largest distribution and logistics centre of the CRexpress and second-largest container seaport in Europe), which connects land and sea transportation, as the destination city of the CRexpress and rail-sea intermodal transport. Therefore, $j = n = 1$, and the CC can be defined as follows:

$$A_i^{CC} = \frac{M_iC_{ij}^{CC-2}}{\sum_{i=1}^{m}M_iC_{ij}^{CC-2}} \tag{3}$$

Primarily, three corridors (west/centre/east corridors, $l = 1, 2, 3$, respectively) exist in the c-CICIH transporting containers to Europe through the CRexpress. The utility of each corridor determines its probability P_{ijl}^{CC} of being selected, which is calculated according to the method specified by Guo and Yang [44]. Specifically, C_{ij}^{CC} can be defined as follows:

$$C_{ij}^{CC} = \sum_{l=1}^{3}P_{ijl}^{CC}C_{ijl}^{CC} \tag{4}$$

According to the transportation process of the CRexpress, the framework can be divided into three stages (domestic, land exit-port and international stages). The generalised transportation cost of each corridor C_{ijl}^{CC} is

$$C_{ijl}^{CC} = \eta_{in}D_{ijl}^{in} + \tau D_{ijl}^{in}\Big/V_{in} + C_l^h + \tau T_l^h + \eta_{out}D_{ijl}^{out} + \tau D_{ijl}^{out}\Big/V_{out} \tag{5}$$

where η_{in}, η_{out} denote the unit transport cost of one TEU by the CRexpress in the domestic and international regions, respectively; $D_{ijl}^{in}, D_{ijl}^{out}$ denote the CRexpress distance through path l in the domestic and international regions, respectively; V_{in}, V_{out} denote the average CRexpress running speed in the domestic and international regions, respectively; and C_l^h, T_l^h denote the unit handling cost and time in the land exit-port in path l, respectively.

d: IC

The mechanism of calculating the IC is the same as that of calculating the CC. We chose Hamburg as the only destination city, and the corresponding IC could be defined as follows:

$$A_i^{IC} = \frac{M_iC_{ij}^{IC-2}}{\sum_{i=1}^{m}M_iC_{ij}^{IC-2}} \tag{6}$$

The difference is that primarily ten Chinese seaports/paths (Shanghai, Ningbo-Zhoushan, Shenzhen, Guangzhou, Tianjin, Qingdao, Dalian, Xiamen, Yingkou, and Lianyungang,

$l = 1, 2, \cdots, 10$, respectively) exist for the c-CICIH transporting containers to Europe. Therefore, the C_{ij}^{IC} can be defined as follows:

$$C_{ij}^{IC} = \sum\nolimits_{l=1}^{10} P_{ijl}^{IC} C_{ijl}^{IC} \tag{7}$$

The generalised transportation cost of each path C_{ijl}^{IC} consists of three elements, pertaining to the domestic railway C_{ijl}^{rail}, seaport C_{ijl}^{port} and shipping C_{ijl}^{ship}.

$$C_{ijl}^{IC} = C_{ijl}^{rail} + C_{ijl}^{port} + C_{ijl}^{ship} \tag{8}$$

Domestic railway stage: The calculation method and symbolic meaning of this case are the same as those of *RC*.

$$C_{ijl}^{rail} = \eta_{rail} D_{ijl}^{rail} + \tau D_{ijl}^{rail} \Big/ V_{rail} \tag{9}$$

Seaport stage: The port charges $C_l^{h,port}$ include the container storage and handling fee, and the waiting time T_l^{port} is determined by the frequency of the ship calls and scale of the port's shipping network.

$$C_{ijl}^{port} = C_l^{h,port} + \tau T_l^{port} \tag{10}$$

Shipping stage: The shipping cost is determined according to the price of the shipping lines, and the shipping time is determined according to the running time and number of shipping lines.

$$C_{ijl}^{ship} = \overline{\eta_l^{ship}} + \tau \overline{T_l^{ship}} \tag{11}$$

where $\overline{\eta_l^{ship}}$, $\overline{T_l^{ship}}$ denote the average shipping price and time from seaport l to Hamburg, respectively.

2) GARA-TOPSIS METHOD

The TOPSIS method, as one of the most popular MCDM approaches, can sort through the closeness of a limited number of evaluation objects and idealised goals, allowing it to analyse the relative merits of the evaluation objects. However, TOPSIS can only use the perspective of distance to reflect the closeness of the samples and cannot adapt to the complex diversification of an evaluation index system. More and more attention has been paid to the combination of fuzzy theory and TOPSIS [45], [46]. GRA, is a method used to measure the degree of similarity of curve shapes between sequences, can intuitively present the nonlinear relationship between sequences. GRA has significant advantages in addressing complex decision-making problems marked by vague, incomplete and inaccurate information [47]. Thus, it can make up for the deficiency of the TOPSIS method. Therefore, the GRA-TOPSIS method (combination of TOPSIS and GRA) has been adopted in multiple decision-making fields. In the GRA-TOPSIS approach, the grey relational degree is calculated considering only the proximity of the distance between the indexes (absolute difference and slope of the curves [48]). However, the relationship between the adjacent indexes must be considered in the MCDM process, especially for the continuous indexes, as the indexes considerably influence one another. Thus, the traditional calculation method of the grey relational degree involves certain limitations in the case of the MCDM model. For example, when two sequences are parallel in Fig. 3, even though the distance between them is very large/small, the relational degree is 1, that is, there is a good consistency between the two sequences, but this is inconsistent with the actual situation.

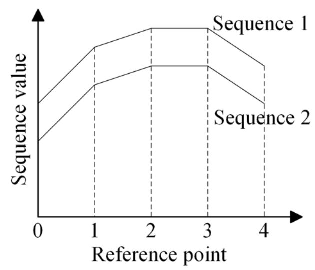


FIGURE 3. Parallel sequence.

The analysis of the relationship between the selected scheme and ideal solution (including the positive and negative ideal solutions) indicates that the polygonal area between the adjacent points in the curves, which represents the relational coefficient, can comprehensively reflect the interaction between the indexes, the proximity in terms of the distance and the similarity in the geometric shapes of the curves. Therefore, this paper uses the relational area between two curves to calculate the grey relational coefficient and relational degree and proposes a GARA-TOPSIS method by incorporating the aforementioned concept with the TOPSIS method. The specific steps are as follows.

Step 1: Standardise the decision matrix $A = (a_{ij})_{m\times n}$ to obtain a standardised matrix $B = (b_{ij})_{m\times n}$ by using the extreme value method:

$$b_{ij} = \begin{cases} \dfrac{a_{ij} - \min_{1\le j\le n} a_{ij}}{\max_{1\le j\le n} a_{ij} - \min_{1\le j\le n} a_{ij}} j \in J^+ \\ \dfrac{\max_{1\le j\le n} a_{ij} - a_{ij}}{\max_{1\le j\le n} a_{ij} - \min_{1\le j\le n} a_{ij}} j \in J^- \end{cases} \tag{12}$$

where a_{ij} is the original data of the i object and j index; J^+, J^- denote the set of the profit and cost indicators, respectively.

Step 2: Calculate the weighted decision matrix $R = (r_{ij})_{m\times n}$ by multiplying the matrix B with the combination weight w (where $r_{ij} = b_{ij} w_j$).

Step 3: Determine the positive ideal solutions (PIS) and negative ideal solutions (NIS), R_0^+, R_0^-, respectively.

$$\begin{aligned} R_0^+ &= \{r_{01}^+, r_{02}^+, \cdots, r_{0n}^+\} \\ &= \{\max_{1\le i\le m} r_{ij} \big| j \in J^+, \min_{1\le i\le m} r_{ij} \big| j \in J^-\} \\ R_0^- &= \{r_{01}^-, r_{02}^-, \cdots, r_{0n}^-\} \\ &= \{\min_{1\le i\le m} r_{ij} \big| j \in J^+, \max_{1\le i\le m} r_{ij} \big| j \in J^-\} \end{aligned} \tag{13}$$

Step 4: Calculate the weighted distances d_i^+, d_i^- from the evaluation scheme to the PIS and NIS, respectively.

$$d_i^+ = \sqrt{\sum\nolimits_{j=1}^{n} (r_{ij} - r_{0j}^+)^2}$$
$$d_i^- = \sqrt{\sum\nolimits_{j=1}^{n} (r_{ij} - r_{0j}^-)^2} \tag{14}$$

Step 5: Calculate the grey relational coefficients q_{ij}^+, q_{ij}^- and grey relational degrees q_i^+, q_i^- based on the polygonal area from the evaluation scheme to the PIS and NIS, respectively.

Step 5.1: Calculate the grey relational coefficient between r_{ij}^+ and r_{0j}^+: $q_{ij}^+ = \frac{\min_i \min_j \Delta(r_{ij}^+, r_{0j}^+) + \xi \max_i \max_j \Delta(r_{ij}^+, r_{0j}^+)}{\Delta(r_{ij}^+, r_{0j}^+) + \xi \max_i \max_j \Delta(r_{ij}^+, r_{0j}^+)}$, where $\xi \in [0, 1]$ is the distinguishing coefficient. In general, $\xi = 0.5$ is usually applied following the rule of least information. $\Delta(r_{ij}^+, r_{0j}^+)$ represents the polygonal area between adjacent points in the curves.

Theorem 1: $\Delta(r_{ij}^+, r_{0j}^+)$ is the polygonal area between the adjacent points in the selected scheme curve $R_i^+ = \{r_{i1}^+, r_{i2}^+, \cdots, r_{in}^+\}$ and positive ideal solution curve $R_0^+ = \{r_{01}^+, r_{02}^+, \cdots, r_{0n}^+\}$.

$$\Delta(r_{ij}^+, r_{0j}^+) = \int_j^{j+1} \left|R_{0t}^+ - R_{it}^+\right| dt = \begin{cases} \frac{\left|r_{0(j+1)}^+ - r_{i(j+1)}^+\right|}{2} or \frac{\left|r_{0j}^+ - r_{ij}^+\right|}{2}, \text{ if the shape is a triangle} \\ \frac{\left|r_{0j}^+ + r_{ij}^+ - r_{0(j+1)}^+ - r_{i(j+1)}^+\right|}{2} - \frac{\left|r_{ij}^+ - r_{0j}^+\right| \cdot \left|r_{0(j+1)}^+ - r_{i(j+1)}^+\right|}{\left|r_{0(j+1)}^+ + r_{ij}^+ - r_{0j}^+ - r_{i(j+1)}^+\right|}, \\ \text{if the shape is a double triangle} \\ \frac{\left|r_{i(j+1)}^+ + r_{ij}^+ - r_{0(j+1)}^+ - r_{0j}^+\right|}{2}, \text{ if the shape is a trapezoid} \end{cases}$$

Proof 1: Appendix A.

Theorem 2: The grey correlation degree method based on the relational area satisfies the four axioms of the grey relation.

Proof 2: Appendix B.

Similarly, the grey relational coefficient between r_{ij}^- and r_{0j}^- can be calculated as $q_{ij}^- = \frac{\min_i \min_j \Delta(r_{ij}^-, r_{0j}^-) + \xi \max_i \max_j \Delta(r_{ij}^-, r_{0j}^-)}{\Delta(r_{ij}^-, r_{0j}^-) + \xi \max_i \max_j \Delta(r_{ij}^-, r_{0j}^-)}$, with the calculation process of $\Delta(r_{ij}^-, r_{0j}^-)$ being the same as that for $\Delta(r_{ij}^+, r_{0j}^+)$.

Step 5.2: Calculate the grey relational degree q_i^+, q_i^-:

$$q_i^+ = \left(\sum\nolimits_{j=1}^{n} q_{ij}^+\right) \Big/ n$$
$$q_i^- = \left(\sum\nolimits_{j=1}^{n} q_{ij}^-\right) \Big/ n \tag{15}$$

Step 6: The weighted distances d_i^+, d_i^- and grey relational degrees q_i^+, q_i^- are non-dimensionalized as:

$$D_i^+ = d_i^+ \Big/ \left(\max_i d_i^+\right)$$
$$D_i^- = d_i^- \Big/ \left(\max_i d_i^-\right)$$

TABLE 2. Cost and speed under different modes of transportation (RMB/TEU·km, km/h).

Parameter	Expressway	National road	Railway	Domestic-CRexpress	Abroad-CRexpress
Cost	8	6	2	4	6
Speed	90	60	70	100	80

$$Q_i^+ = q_i^+ \Big/ \left(\max_i q_i^+\right)$$
$$Q_i^- = q_i^- \Big/ \left(\max_i q_i^-\right) \tag{16}$$

Step 7: Integrate the results of the dimensionless distance and grey relational degrees:

$$S_i^+ = \alpha D_i^- + (1-\alpha) Q_i^+$$
$$S_i^- = \alpha D_i^+ + (1-\alpha) Q_i^- \tag{17}$$

where α and $1-\alpha$ represent the evaluator's preference for the curve position and shape, respectively, with $\alpha \in [0, 1]$.

Step 8: Calculate the relative closeness.

$$C_i = S_i^+ / (S_i^+ + S_i^-) \tag{18}$$

C_i reflects the differences in the location and shape similarity. A larger or smaller relative closeness corresponds to a superior or inferior evaluation object.

V. LOCATION EVALUATION

A. DATA PREPARATION

The comprehensive quality index data for the c-CICIHs were extracted from the Statistics Bulletin of the National Economic and Social Development, Statistical Yearbook of Chinese Cities and the Government Work Report.

The transportation cost and speed for the expressway, national road and freight railway were obtained from the Container Road Transport Fee Rules, Technical Standard of Highway Engineering, Railway Freight Rate Rules and Code for Design of Railway Line. The transportation distance, speed and cost of the CRexpress to Hamburg were derived from the statistics published by the top 10 international land-port companies (Chongqing, Chengdu, Xi'an, Zhengzhou, Wuhan, Suzhou, Yiwu, Hefei, Changsha and Harbin, for which the annual number of operating CRexpress trains exceeds 80% of the national total) (Table 2). The distance among the nodes was obtained considering the transportation networks. The handling cost and time at the exit-port corresponded to the exit-port customs district (Table 3). Usually, the values for the cargo transported by the CRexpress are higher and lower than those pertaining to the shipping and air modes. The value of time was set as 29.5 RMB/h, based on the cargo value per TEU and bank lending rates.

The operation cost and time at the seaport were obtained from the port authority and JC TRANS (http://bj.jc56.com/). The number and average shipping time of the lines from China's ten seaports to Europe/Hamburg were extracted

TABLE 3. Handling cost and time at the land exit-ports (RMB/TEU and h, respectively).

Parameter	Alashankou	Erenhot	Manzhouli
Cost	980	1050	1120
Time	4.5	3	3.5

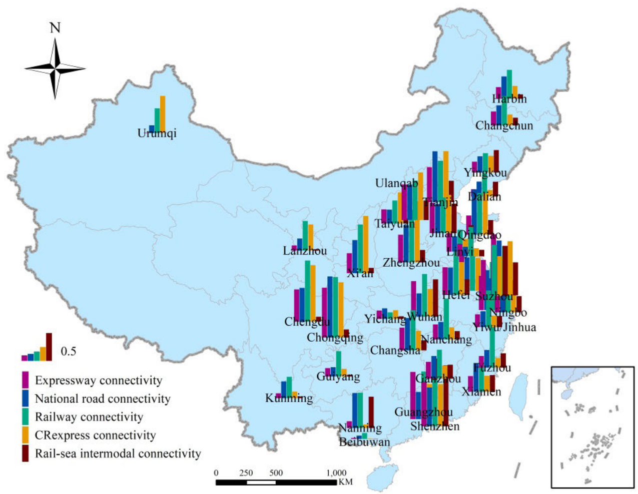


FIGURE 4. Map of five kinds of connectivity for each c-CICIH.

from the official website of the world top 10 liner companies (Maersk Line, MSC, COSCO, CMA CGM, Hapag-Lloyd, ONE, Evergreen, Yang Ming Marine, PIL, and Hyundai M.M.); the average price was derived from the SHIPPING CHINA website (http://en.shippingchina.com/) (Table 4).

B. CONNECTIVITY CALCULATION

The quality index values were standardized and tested using the KMO and Bartlett approach, and the results indicated that these values can be used for the factor analysis. According to the eigenvalue method, the common factors were extracted, and the comprehensive score of each c-CICIH was calculated. The score was transformed to [0,1] to obtain the comprehensive quality of the c-CICIH. Subsequently, the five connectivity indexes for each c-CICIH were calculated (Table 5). Fig. 4 shows the distribution of the five connectivity values for each c-CICIH, based on the standardized results.

C. INDEX WEIGHT

Since the five indexes represent different characteristics of the nodes in the transportation network, it is necessary to balance the indices by assigning them weights that reflect their importance. The subjective weight (SW) and objective weight (OW) of the index were calculated using the AHP and entropy methods, respectively, and the combination weight (CW) was obtained by integrating the values, based on the game theory.

1) AHP TO CALCULATE THE SW

First, a three-scale method (with values of 0, 1, and 2) for the AHP was used to formulate a comparison matrix for the five indexes, as follows.

$$A = (a_{ij})_{5\times 5} = \begin{cases} 0, & \text{index } i \text{ is more important than index } j \\ 1, & \text{index } i \text{ is as important as index } j \\ 2, & \text{index } i \text{ is less important than index } j \end{cases}$$

Here, using the 1–3 scales method instead of 1–9 scales is to make it easier for the experts to judge and to avoid the inconsistency problem. $A = (a_{ij}) = \{0, 1, 2\}$ is the judgment scale set, in which $a_{ij} = 0$ means that index i is less important than index j, $a_{ij} = 1$ means that index i is as important as index j, and $a_{ij} = 2$ means that index i is more important than index j. After pairwise comparison of all elements through a three-scale method, we build a comparison matrix to calculate the element rank.

We invited 15 experts (5 transport researchers, 5 logistics integrators and 5 planning bureau officials) to evaluate the pairwise importance of the five indexes through face to face interviews and email. Table 6 summarizes the comparison results.

Subsequently, we constructed the judgement matrix C by using the range method: (19), as shown at the bottom of page 11.

where

$$M_i = \prod_{j=1}^{5} c_{ij}$$
$$W_i = \sqrt[5]{M_i}, \sum_{i=1}^{5} W_i = 6.6426$$
$$\overline{W_i} = W_i \Big/ \sum_{i=1}^{5} W_i \tag{20}$$

In this case, $OW = \overline{W_i}^T = \{0.1505, 0.0869, 0.0501, 0.2608, 0.4516\}$.

Finally, assuming D as a partial matrix of C, containing the first 5 columns of C, $R = (r_i)_{5\times 1} = D \times \overline{W_i} = (0.7524, 0.4344, 0.2508, 1.3033, 2.2573)$, with the largest eigenvalue of $\lambda_{\max} = \sum_{i=1}^{n} \left(r_i / \overline{W_i}\right) / n = 5$. Consequently, $P_{CI} = (\lambda_{\max} - 5)/(5 - 1) = 0 \le \varepsilon$ $(\varepsilon = 0.001)$, which satisfies the consistency test.

2) ENTROPY METHOD TO CALCULATE THE OW

On the basis of data processing, the entropy and OW of the evaluation index determined using the entropy method can be obtained.

3) GAME THEORY TO CALCULATE THE CW

As discussed previously, there are certain limitations to consider a single weighting method under many situations. The SW is heavily influenced by expert experiences resulting in high subjectivity. On the contrary, the OW neglects the DM's knowledge and actual situation. Therefore, the comprehensive weight, combining the SW and OW with an effective algorithm, is more reasonable in the decision-making process. The CW based on the game theory was

TABLE 4. Port charges (RMB/TEU) and price/time/number of shipping lines (RMB/TEU, h).

Port	Shanghai	Ningbo-Zhoushan	Shenzhen	Guangzhou	Qingdao	Tianjin	Xiamen	Dalian	Yingkou	Lianyungang
Charges	640	690	890	860	750	610	710	590	600	640
Price/Time/Number	920/780/31	890/730/27	850/700/29	900/710/8	1080/840/15	1150/870/12	950/720/9	1050/910/7	1100/930/3	1150/820/2

TABLE 5. Quality and connectivity index of the c-CICIHs.

Node	Quality	*EC*	*NC*	*RC*	*CC*	*IC*
Tianjin	0.6654	0.0426	0.0475	0.0346	0.0482	0.0341
Harbin	0.3895	0.0143	0.0209	0.0242	0.0121	0.0072
Jinan	0.4992	0.0372	0.0273	0.0299	0.0363	0.0473
Nanjing	0.5397	0.0456	0.0314	0.0346	0.0311	0.0344
Hangzhou	0.6023	0.0418	0.0373	0.0402	0.0375	0.0185
Zhengzhou	0.5338	0.0338	0.0349	0.0441	0.0577	0.0199
Hefei	0.4915	0.0338	0.0255	0.0381	0.0310	0.0250
Wuhan	0.6344	0.0434	0.0217	0.0358	0.0263	0.0599
Changsha	0.5527	0.0277	0.0302	0.0335	0.0184	0.0161
Chongqing	0.7756	0.0608	0.0571	0.0507	0.0523	0.0131
Chengdu	0.6320	0.0393	0.0316	0.0511	0.0533	0.0078
Xi'an	0.4242	0.0244	0.0308	0.0407	0.0540	0.0086
Lanzhou	0.2992	0.0063	0.0112	0.0247	0.0247	0.0021
Urumqi	0.2246	0.0006	0.0073	0.0208	0.0351	0.0004
Dalian	0.4689	0.0091	0.0140	0.0196	0.0062	0.0238
Qingdao	0.5507	0.0235	0.0423	0.0349	0.0391	0.0234
Ningbo	0.5615	0.0331	0.0323	0.0337	0.0304	0.0260
Xiamen	0.4019	0.0191	0.0266	0.0251	0.0150	0.0266
Guangzhou	0.7702	0.0576	0.0253	0.0398	0.0331	0.0970
Shenzhen	0.8645	0.0541	0.0362	0.0388	0.0398	0.0978
Shanghai	1.0000	0.0745	0.0513	0.0413	0.0510	0.0529
Suzhou	0.7187	0.0442	0.0167	0.0429	0.0378	0.0806
Nanning	0.2327	0.0082	0.0327	0.0295	0.0033	0.0500
Kunming	0.3870	0.0059	0.0157	0.0178	0.0061	0.0028
Taiyuan	0.2445	0.0174	0.0130	0.0193	0.0294	0.0083
Shijiazhuang	0.3888	0.0434	0.0331	0.0329	0.0449	0.0313
Changchun	0.4904	0.0171	0.0188	0.0245	0.0104	0.0125
Fúzhou	0.4974	0.0141	0.0164	0.0364	0.0089	0.0230
Nanchang	0.4410	0.0185	0.0164	0.0343	0.0115	0.0135
Guiyang	0.2807	0.0103	0.0088	0.0212	0.0073	0.0029
Ulanqab	0	0	0	0	0	0
Yingkou	0.2393	0.0132	0.0152	0.0162	0.0157	0.0359
Yiwu/Jinhua	0.2728	0.0157	0.0149	0.0307	0.0108	0.0178
Ganzhou	0.3503	0.0205	0.0211	0.0242	0.0124	0.0223
Linyi	0.1647	0.0222	0.0144	0.0183	0.0122	0.0423
Yichang	0.1706	0.0101	0.0098	0.0055	0.0081	0.0042
Lianyungang	0.1145	0.0153	0.0090	0.0246	0.0078	0.0105
Beibuwan	0.0185	0.0012	0.0031	0.0049	0.0005	0.0003

integrated with the SW and OW and the weight coefficients $\rho = (0.6453, 0.3547)$. All the weight types are shown in Table 7 and Fig. 5.

As shown in Fig. 5, the curves for the SW and OW are not consistent, although they exhibit certain similarities, and the CW corresponds to the optimum equilibrium values. In

TABLE 6. Index comparison matrix.

i \ j	EC	NC	RC	CC	IC
EC	1	2	2	0	0
NC	0	1	2	0	0
RC	0	0	1	0	0
CC	2	2	2	1	0
IC	2	2	2	2	1

TABLE 7. Index weights.

Weight	EC	NC	RC	CC	IC
SW	0.1505	0.0869	0.0501	0.2608	0.4516
OW	0.2237	0.1432	0.0250	0.2533	0.3548
CW	0.1765	0.1069	0.0412	0.2581	0.4173

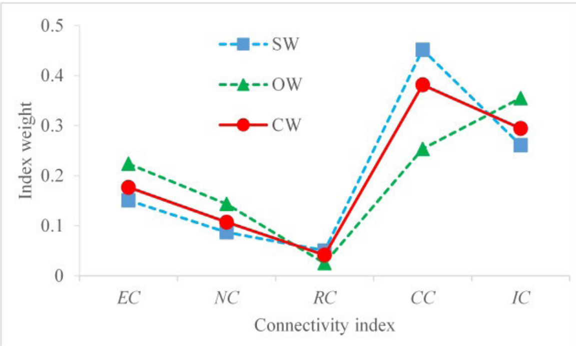


FIGURE 5. Calculation method of the weights.

general, the weight coefficient reaching the Nash equilibrium defines the proportion of the SW and OW. Therefore, the CW can overcome the bias of a single weight, and it can thus be reasonably used to determine the weights of the indexes in the evaluation process.

D. COMPREHENSIVE EVALUATION OF C-CICIHS

Considering the 5 connectivity indexes as the original evaluation indicators, the proposed GARA-TOPSIS method was used to perform the comprehensive evaluation. The key steps included standardising the index matrix and calculating the distance and grey correlation degree of the alternatives from the PIS and NIS as well as the relative closeness (Table 8).

According to the comprehensive sorting results, a higher ranking of a c-CICIH indicates a greater capacity of container consolidation, handling and distribution, rendering the city more suitable to serve as an intermodal hub. According to the relevant planning strategies of national logistics nodes, considering the construction and overall layout of hubs, as well as the agglomeration and scale effect of resources, this paper selects 10 cities as the final CICIHs. Table 8 indicates that the top 10 c-CICIHs are Shenzhen, Guangzhou, Shanghai, Suzhou, Wuhan, Tianjin, Chongqing, Zhengzhou, Chengdu, and Xi'an. The following section discusses the final CICIH selection process based on specific situations.

E. DETERMINATION OF FINAL LOCATION

Fig. 6 shows the location and distribution of the top 10 c-CICIHs, among which, Chongqing and Chengdu in the southwest region, Zhengzhou and Wuhan in the central region, and Xi'an in northwest region, are the Chinese cities with the largest container volumes carried by the CRexpress and intermodal transportation modes (in the corresponding regions) and a convenient geography enabling a connection with the other regions in China. Shenzhen, Guangzhou, Shanghai and Tianjin, distributed in the coastal areas of China, are the port cities with the largest container throughput and exhibit an advanced handling ability for the rail-sea transportation. Suzhou is the core city of the Yangtze River Delta, with a developed economy and large aggregation of goods. However, at the national scale, these c-CICIHs are mainly distributed in the relatively developed areas in the eastern coast and central China, which is not in line with the overall spatial planning and layout. This imbalance corresponds to two key phenomena: First, the location of the adjacent CICIHs is extremely centralised in certain areas (Pearl River Delta, Yangtze River Delta and the Chengdu-Chongqing City Group), and second, certain regions involve a CICIH layout (Northeast, Northwest and Southwest) that is not conducive for cargo consolidation from all parts of China and distribution to other regions. The in-depth analysis is as follows.

The geographic location of the c-CICIHs is extremely close, including Shenzhen and Guangzhou in the Pearl River Delta, Shanghai and Suzhou in the Yangtze River Delta, and Chongqing and Chengdu in the twin-city economic circle. Only one c-CICIH should be built in each of these areas to avoid a wastage of resources, redundant construction and overlapping functionalities. Compared with Shenzhen, Guangzhou, as the capital of Guangdong Province, has a large number of populations, industries and freight market, well-developed infrastructure and integrated transportation network (railway, highway, waterways and aviation), and thus, Guangzhou can more conveniently connect the domestic

$$C = (c_{ij}) = \begin{bmatrix} c & EC & NC & RC & CC & IC & M_i & W_i & \overline{W_i} \\ EC & 1 & 1.7321 & 3.0000 & 0.5774 & 0.3333 & 1.0000 & 1.0000 & 0.1505 \\ NC & 0.5774 & 1 & 1.7321 & 0.3333 & 0.1925 & 0.0642 & 0.5774 & 0.0869 \\ RC & 0.3333 & 0.5774 & 1 & 0.1925 & 0.1111 & 0.0041 & 0.3331 & 0.0501 \\ CC & 1.7321 & 3.0000 & 5.1962 & 1 & 0.5774 & 15.5904 & 1.7321 & 0.2608 \\ IC & 3.0000 & 5.1962 & 9.0000 & 1.7321 & 1 & 243.0091 & 3.0000 & 0.4516 \end{bmatrix} \tag{19}$$

TABLE 8. Comprehensive evaluation results.

Node	D_i^+	D_i^-	Q_i^+	Q_i^-	C_i	Ranking
Tianjin	0.5359	0.6164	0.8913	0.6676	0.5561	6
Harbin	0.8713	0.3840	0.7183	0.8565	0.3895	22
Jinan	0.6714	0.4387	0.7926	0.6946	0.4741	14
Nanjing	0.7536	0.5442	0.8517	0.7490	0.4816	11
Hangzhou	0.6753	0.4691	0.8122	0.7144	0.4797	12
Zhengzhou	0.6535	0.6134	0.8951	0.6995	0.5272	8
Hefei	0.6587	0.4204	0.7973	0.7340	0.4665	17
Wuhan	0.4430	0.6359	0.8319	0.6949	0.5633	5
Changsha	0.7661	0.2946	0.7648	0.7803	0.4066	21
Chongqing	0.6810	0.6341	0.9525	0.6698	0.5401	7
Chengdu	0.7423	0.5617	0.8762	0.7269	0.4946	9
Xi'an	0.6981	0.4997	0.8262	0.7015	0.4865	10
Lanzhou	0.8836	0.2420	0.7165	0.8735	0.3529	31
Urumqi	0.8847	0.3317	0.7244	0.8843	0.3738	26
Dalian	0.8034	0.2339	0.7064	0.8560	0.3617	29
Qingdao	0.6575	0.4299	0.8240	0.7231	0.4759	13
Ningbo	0.6509	0.4260	0.8015	0.7290	0.4708	15
Xiamen	0.7243	0.3135	0.7475	0.7888	0.4122	20
Guangzhou	0.2464	0.9716	0.9729	0.6412	0.6866	2
Shenzhen	0.1908	1.0000	1.0000	0.6234	0.7107	1
Shanghai	0.3638	0.7967	0.9952	0.6093	0.6481	3
Suzhou	0.2916	0.8377	0.8976	0.6646	0.6447	4
Nanning	0.6697	0.4706	0.7576	0.8028	0.4548	18
Kunming	0.9378	0.0973	0.6908	0.9158	0.2983	36
Taiyuan	0.8115	0.3041	0.7363	0.8260	0.3885	24
Shijiazhuang	0.7536	0.4209	0.8554	0.6894	0.4693	16
Changchun	0.8401	0.1910	0.7199	0.8439	0.3510	32
Fúzhou	0.7853	0.2494	0.7287	0.8260	0.3777	25
Nanchang	0.8287	0.2051	0.7278	0.8335	0.3595	30
Guiyang	0.9305	0.1022	0.6911	0.9111	0.3011	34
Ulanqab	1.0000	0.0000	0.6507	1.0000	0.2455	38
Yingkou	0.6832	0.1556	0.7309	0.8030	0.3736	27
Yiwu/Jinhua	0.8084	0.2189	0.7228	0.8337	0.3644	28
Ganzhou	0.7638	0.2684	0.7346	0.8088	0.3894	23
Linyi	0.6487	0.4153	0.7417	0.7895	0.4458	19
Yichang	0.9201	0.1060	0.6829	0.9138	0.3008	35
Lianyungang	0.8722	0.1512	0.7032	0.8741	0.3285	33
Beibuwan	0.9916	0.0168	0.6583	0.9848	0.2546	37

and overseas regions. Thus, Guangzhou can replace Shenzhen as the CICIH of South China. As Shanghai has an extremely high comprehensive strength (advanced infrastructure, ability to handle intermodal transportation, large cargo throughputs and efficient business services), it can replace Suzhou. Suzhou can be regarded as a sub-hub of Shanghai. Considering that Chongqing has more integrated functionalities and superior geographical location (i.e., it can connect the Silk Road Economic Belt through the CRexpress to the north, 21st-Century Maritime Silk Road and New Western Land-Sea Corridor through the multimodal transportation to the south, and the Yangtze River Economic Belt through shipping to the east), it can replace Chengdu.

Furthermore, due to the geographical distribution and overall planning, certain cities after the 10th sorting should also be considered. These cities are located in the southwest, northeast, and northwest regions with a relatively backward economy and weak traffic infrastructure, albeit with a vast territory and geographical location with significant traffic. As a key gateway connecting the One Belt and One Road and a key node of the South logistics corridor, Nanning is more suitable as the CICIH of the southwest region than Guiyang, Kunming and Beibuwan. In the northeast region, compared

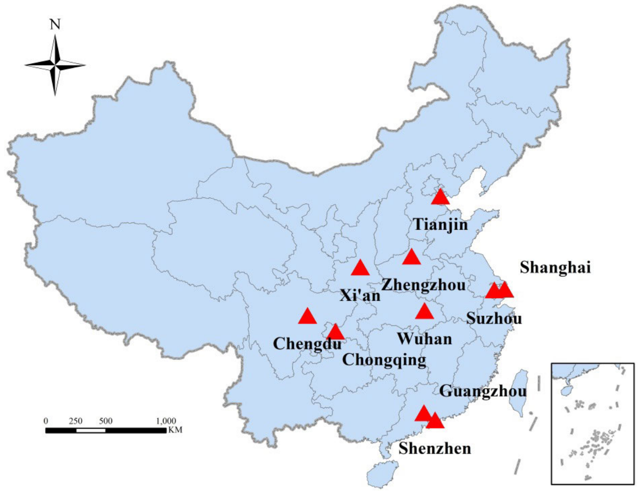


FIGURE 6. Distribution of the top 10 c-CICIHs.

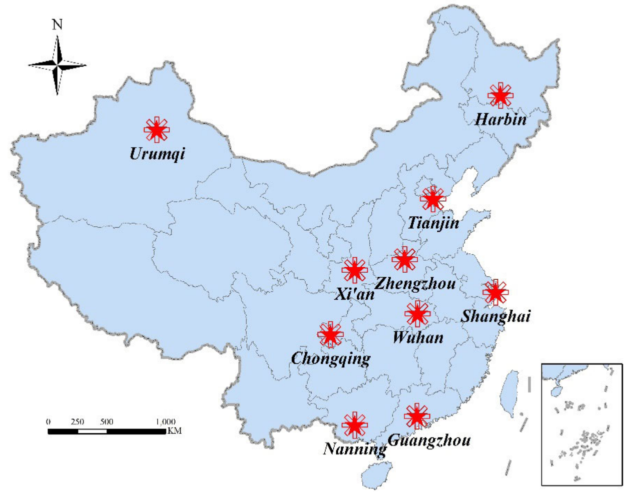


FIGURE 7. Results for the location selection of CICIHs.

with Yingkou, Dalian and Changchun, Harbin, as the capital of Heilongjiang Province, is located in the centre of the northeast region, and thus, it is suitable to be the CICIH of this region. In the screening, only Urumqi and Lanzhou are selected in the vast northwest and western regions. As the consolidation centre of the CRexpress western corridor and China's frontline in the westward opening, Urumqi is fit to be the CICIH of this region.

Based on the aforementioned considerations, Tianjin, Harbin, Zhengzhou, Wuhan, Chongqing, Xi'an, Urumqi, Guangzhou, Shanghai and Nanning are recommended as CICIHs (Fig. 7). To support this recommendation, the national policy supports, environmental conditions, transportation infrastructure construction and overall spatial layout of the CICIHs must be examined. We recommend that the CICIHs should fully exploit their geographical advantages, improve their centrality in the comprehensive transportation network (railway, highway, waterway and aviation), and fully utilise their functionalities for cargo accumulation and transhipment and as a hub connecting various modes of transportation organically in the domestic network. In the international framework, the CICIHs should enhance their export-oriented freight capabilities and efficiencies of the integrated cross-border logistics network in handling the import and export goods.

VI. DISCUSSION

A. SCREENING OF HUBS

The screening of hubs has a certain impact on the location evaluation of multimodal hubs. Different screening principles generate different numbers of hubs. If the number is too large, then the importance of individual nodes will be weakened, which does not conform to the agglomeration and scale effect of resources. Meanwhile, if too few hubs are generated, then the goods from all regions will be transhipped through these hubs, thereby increasing the total delivery cost/distance/time.

Screening such hubs has strong subjectivity. Different researchers may screen out various sets of hubs. Moreover, additional factors (e.g. geographical location, transport convenience, infrastructure and environment) should be considered in future screenings.

B. SENSITIVITY ANALYSIS

Ten cities were selected as the CICIHs by screening and comprehensive evaluation based on the GARA-TOPSIS. To examine the robustness and stability of the proposed framework and evaluation results, a sensitivity analysis was conducted for the parameters, including the index weights, share of the subjective weights and preference coefficient.

1) ADJUSTING THE INDEX WEIGHTS

A sensitivity analysis was performed to determine whether the results changed qualitatively when the index weights fluctuated. According to the criteria, the five indicators were divided into two groups, corresponding to the domestic and international connectivity. The weights were fluctuated by $\pm 10\%$, $\pm 20\%$ and $\pm 30\%$.

Fig. 8 shows that the final ranking results of the ten alternatives are basic stable, especially for the *RC*. Overall, the curve is relatively smooth, indicating that the results are stable. As the index *EC* is assigned a higher importance, the ranking scores of Shanghai and Chongqing increase slightly, while those of Nanning and Urumqi decrease compared to the initial data; however, no change occurs in the ranking results of all the alternative sites. However, in the *NC* criteria, only Shanghai and Chongqing exhibit a slight rising trend, while the values for all the other alternative sites remain stable as the weight increases. Thus, the *EC* is a more sensitive factor than the *NC* in this case. For the *RC*, the sorting results do not change; Guangzhou and Shanghai always remain in the first group, while Harbin and Urumqi exhibit the lowest suitability. Therefore, the *RC* is not a sensitive factor.

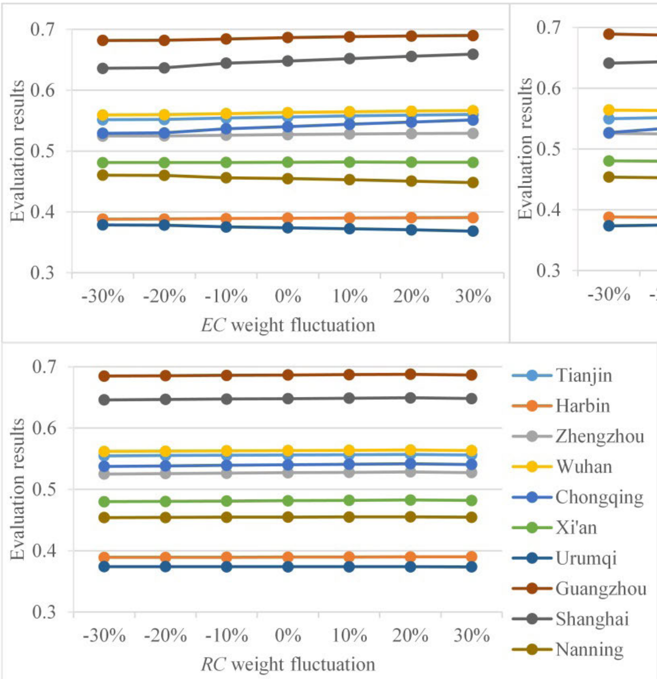


FIGURE 8. Sensitivity analysis of the domestic connectivity index weights.

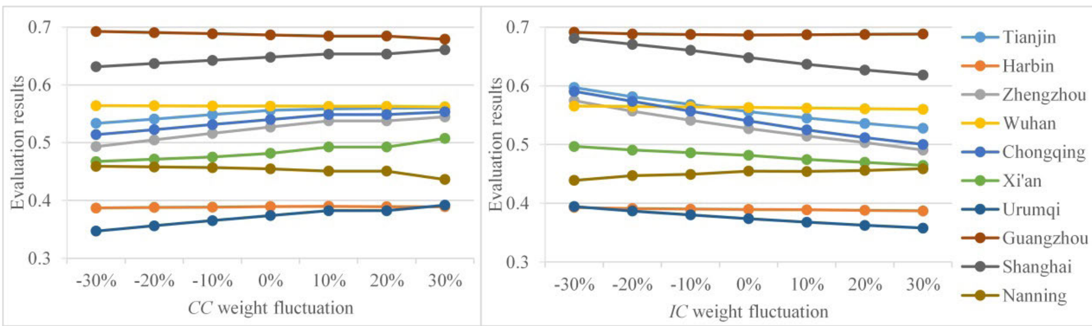


FIGURE 9. Sensitivity analysis of the international connectivity index weights.

The cases corresponding to the international connectivity are shown in Fig. 9. It can be noted that the score variations due to the *CC* and *IC* are more notable than those of the other indexes, although the ranking results remain constant, except for the case of Wuhan in terms of the *IC*. In other words, the *CC* and *IC* are sensitive indexes, and they dramatically affect the CICIH selection results. The scores of Shanghai, Tianjin, Chongqing, Zhengzhou, Xi'an and Urumqi increase while those of Guangzhou and Nanning decrease when the index *CC* increases, although the ranking results do not change. As the weight increases in the *IC* case, the score varies with a trend opposite to that of the *CC*, indicating that the two criteria have contrasting effects on the selection results.

This analysis indicates that regardless of the change in the index weights, the ranking results of the alternatives remain similar, and the proposed method exhibits a high stability and applicability.

2) ADJUSTING THE PROPORTION OF SUBJECTIVE WEIGHT

When determining the subjective weight of the indexes, different experts may have different opinions according to their own experience, which may considerably influence the ranking results. To explore the influence of the subjective weight change on the score, the share of the subjective weight was set as 0.1, 0.3, 0.5, 0.7, 0.9. The results are shown in Fig. 10.

Fig. 10 shows that with the increase in the proportion of the subjective weight, the ranking results of the alternatives change, mainly for the top sites (Guangzhou, Shanghai, Wuhan, Tianjin). This change shows that the proportion of the subjective weight influences the ranking results, and its impact on the decision criteria can change the final ranking results to a certain extent.

3) ADJUSTING THE PREFERENCE COEFFICIENT

In the existing studies, the coefficient $\alpha = 0.5$ was mostly used, indicating that the DMs exhibit the same sensitivity to

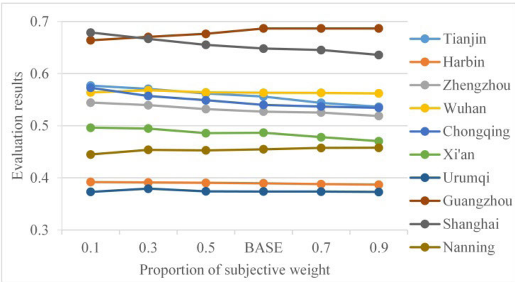


FIGURE 10. Sensitivity analysis of the subjective weight.

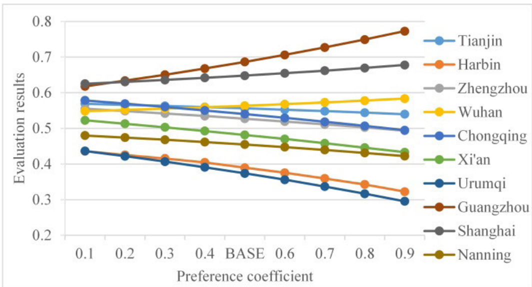


FIGURE 11. Sensitivity analysis of the preference coefficient.

the curve position and shape to calculate the relative closeness in the GARA-TOPSIS. However, this setting does not correspond to the actual situation, in which different DMs have different preferences. Therefore, in this work, $\alpha = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ was set to explore the changes in the final results (Fig. 11).

Fig. 11 indicates that the ranking results change significantly compared to the original settings. A smaller α corresponds to a larger change in the ranking. As α increases, the gap between the schemes is enlarged, although the sorting results are not affected. Overall, Guangzhou and Shanghai are always the optimal sites. The correctness and robustness of the proposed method in determining the optimal location from multiple alternatives are thus demonstrated. The DM's psychology should be considered when making the decisions.

C. COMPARATIVE ANALYSIS

The applicability and rationality of the employed methods must be demonstrated through a comparison with certain mature and stable methods commonly used in the existing studies. The GRA-TOPSIS method is the core part used in the MCDM formulated in this work. The TOPSIS and GRA are mature methodologies, and the basic MCDM methods is often used to solve the location decision problem. The GARA is a unique case of the proposed method ($\alpha = 0$). The specific calculation process is shown in Appendix C. Moreover, these methods still use the comprehensive weight during the calculation process. The results for the comparison are summarized in Table 9. When solving MCDM problems, the relationship between GARA-TOPSIS and other methods (GRA, TOPSIS, GRA-TOPSIS and GARA) is shown in Fig. 12. It can be

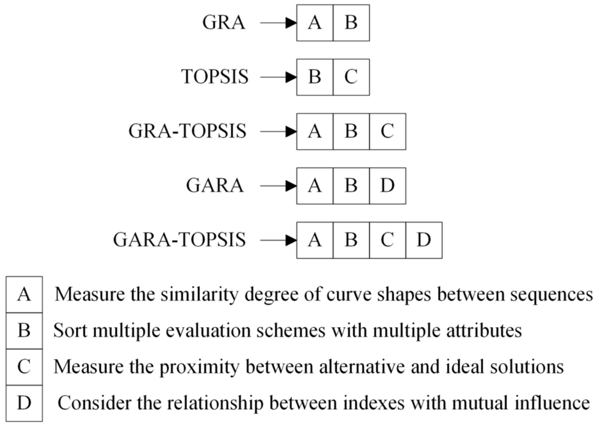


FIGURE 12. Logical flow of the evaluation methods.

seen that this combined GARA-TOPSIS method can solve complex problems.

Table 9 indicates that the final ranking results of the five methods are not equivalent. Guangzhou and Shanghai are always the optimal alternatives for the layout. However, the rankings for Chongqing, Zhengzhou and Wuhan change considerably. The ranking of the other alternatives is nearly the same. Proximity refers to the consistency rate between the ranking results of various methods and reasonable ranking. These results imply that the GARA-TOPSIS approach has the highest proximity, followed by that of the GRA-TOPSIS and TOPSIS, and the proximity of the GRA approach is the lowest. This phenomenon occurs because all these methods are based on different core ideas: The TOPSIS places a higher emphasis on the distance between the alternative and optimal reference scenarios, while the GRA focuses on the connection between the criteria but ignores the distance between the alternatives. The GRA-TOPSIS considers both the distance between the alternatives and the connections between the criteria, and thus, its closeness is more in line with the actual situation. Overall, the comparative results explain the rationality of the proposed method and demonstrate that the proposed method can comprehensively reflect the location capability.

Additionally, the discrimination [33] approach was applied to further verify and assess the reliability of the proposed method. The reliability of evaluation methods refers to the ability of the methods to distinguish the actual level of the evaluation schemes. For measures with discrimination, a larger discrimination corresponds to a higher reliability of the evaluation method. The discrimination of the five methods is shown in Table 10. The evaluation scores and rank scatter plots obtained after the standardisation of each method are shown in Fig. 13.

As shown in Table 10, the TOPSIS exhibits the highest discrimination. However, the curve shows that with the exception of the distance between the two points in the upper-left corner and the other points, the distances between most of the points are small. Consequently, the discrimination is a

TABLE 9. Comparison of five kinds of evaluation techniques.

	GARA-TOPSIS		GRA-TOPSIS		GARA		TOPSIS		GRA		Reasonable ranking
	value	ranking	value	ranking	value	ranking	value	ranking	value	ranking	
Tianjin	0.5561	4	0.5633	4	0.5718	4	0.5350	4	0.5857	4	3
Harbin	0.3895	9	0.3411	10	0.4561	9	0.3059	9	0.4288	10	9
Zhengzhou	0.5272	6	0.5213	6	0.5613	5	0.4842	5	0.5545	5	6
Wuhan	0.5633	3	0.5687	3	0.5449	6	0.5894	3	0.5530	6	4
Chongqing	0.5401	5	0.5468	5	0.5871	3	0.4822	6	0.6022	3	5
Xi'an	0.4865	7	0.4708	7	0.5321	7	0.4193	7	0.5180	7	7
Urumqi	0.3738	10	0.3786	9	0.4503	10	0.2727	10	0.4598	9	10
Guangzhou	0.6866	1	0.6965	1	0.6027	2	0.7977	1	0.6160	2	1
Shanghai	0.6481	2	0.6673	2	0.6203	1	0.6865	2	0.6527	1	2
Nanning	0.4548	8	0.4452	8	0.4855	8	0.4127	8	0.4816	8	8
Proximity%	80%		60%		40%		60%		20%		

Note: The reasonable ranking is obtained by ranking the sum of the ranking results obtained using the five evaluation methods.

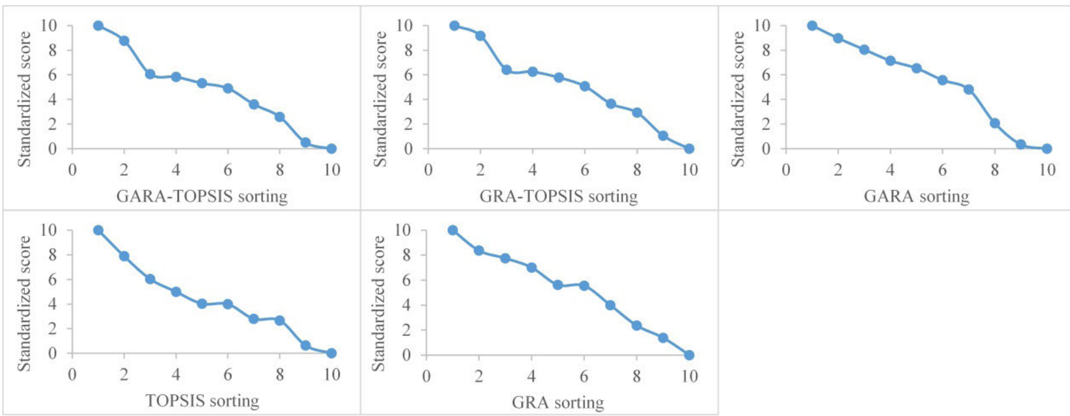


FIGURE 13. Ranking scatter plots for each evaluation method.

TABLE 10. Differentiation among the evaluation methods.

Evaluation method	GARA-TOPSIS	GRA-TOPSIS	GARA	TOPSIS	GRA
Discrimination	1.0558	1.0507	1.0354	1.0625	1.0350

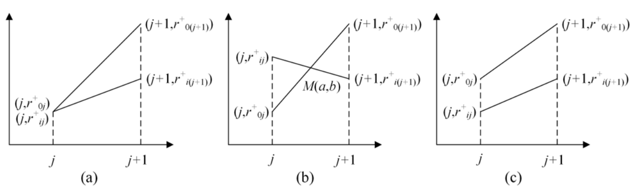


FIGURE 14. Distribution of the two sequence curves.

result of the large distance between the two cities that are the most suitable as the CICIHs and the other cities. Nevertheless, this result does not indicate that the TOPSIS is the most reliable approach. On the basis of the discrimination capability, the ranking results of the reliability is GARA-TOPSIS > GRA-TOPSIS > GARA > GRA. As shown in Fig. 13, the dot pitch between the upper-left corner and lower-right corner in all the cases is relatively large, which indicates that the superior and inferior c-CICIHs can be easily distinguished.

VII. CONCLUSION

This paper analyses the location of the CICIHs based on the actual situation of China's foreign trade transportation framework under the BRI to facilitate the overall planning and layout selection at the national level, to reduce the disorderly competition of the goods sources, and to improve the operational efficiency of the transportation routes in the China-Europe trade framework. We first selected 38 c-CICIHs through qualitative screening based on the current operations of the CRexpress and rail-sea intermodal transportation, as well as the government planning/policy related to the national logistics nodes under the BRI. Next, five connectivity indexes were proposed considering the multiple segments and modes of transportation in the logistics chain as the basis for the location selection. Furthermore, we proposed a hybrid MCDM model to evaluate the comprehensive connectivity of the c-CICIHs and rank them. The model is based on the GARA-TOPSIS in combination with analytic hierarchy process, entropy method and game theory. According to the ranking results, combined with the geographical location, economic development and national strategic planning considerations under the BRI, Tianjin, Harbin, Zhengzhou, Wuhan, Chongqing, Xi'an, Urumqi, Guangzhou, Shanghai and Nanning were determined as the final CICIHs. Considering the relatively balanced geographical distribution of the CICIHs, it can be noted that these cities cover most areas of China and can serve most of the cargo origin cities in China. Finally, a sensitivity analysis was conducted by adjusting the index weights, subjective weights and preference coefficient, and it was noted that the proposed evaluation method exhibited a high robustness and stability. By comparing the GARA-TOPSIS with the GRA-TOPSIS, GARA, TOPSIS and GRA methodologies, the GARA-TOPSIS was noted to have a high applicability and rationality.

This study provides a practical framework combining qualitative screening, intermodal connectivity and MCDM evaluation to determine the locations of the CICIHs, and the findings provide a theoretical reference to realize planning and layout determination of national logistics hubs. To enhance the functioning of the CICIHs, policy measures and supportive actions should be implemented. The government should provide policy support in establishing coordinating mechanisms to fully utilise the functions for cargo accumulation and transhipment and to connect multiple modes of transportation. Moreover, the government should provide operational support to improve the export-oriented freight capabilities of the integrated cross-border logistics network in serving the import and export goods. All these government efforts can improve the operational efficiency of the CICIHs and transportation routes and help realise the full potential of the logistics system, thereby providing support to construct the BRI.

Despite some contributions have been made, there are still some limitations in this paper. For the qualitative evaluation index, we will combine fuzzy theory with GARA-TOPSIS to build a more accurate evaluation method in the future. Further research is also expected to consider the logistics transportation network in China-Europe (including the CRexpress network and rail-sea intermodal transportation network) to establish a model to optimise the location and layout of the hubs.

APPENDIX

A. PROOF 1: CALCULATION OF THE RELATIONAL AREA IN THE THREE CASES

1) CASE 1

When the line consisting of points (j, r_{0j}^{+}) and $(j+1, r_{0(j+1)}^{+})$ and line consisting of points (j, r_{ij}^{+}) and $(j+1, r_{i(j+1)}^{+})$ intersect at the end (Fig. 14(a)), (j, r_{0j}^{+}) and (j, r_{ij}^{+}) coincide or $(j+1, r_{0(j+1)}^{+})$ and $(j+1, r_{i(j+1)}^{+})$ coincide to form a triangle. According to the formula of the triangle area, $\Delta(r_{ij}^{+}, r_{0j}^{+}) = \int_{j}^{j+1} \left| r_{0t}^{+} - r_{it}^{+} \right| dt = \left| r_{0(j+1)}^{+} - r_{i(j+1)}^{+} \right| \Big/ 2 \; or \left| r_{0j}^{+} - r_{ij}^{+} \right| \Big/ 2.$

2) CASE 2

When the line consisting of points (j, r_{0j}^{+}) and $(j+1, r_{0(j+1)}^{+})$ and line consisting of point (j, r_{ij}^{+}) and $(j+1, r_{i(j+1)}^{+})$ intersect (except the end points, Fig. 14(b)), the intersection is defined as $M(a, b)$, forming two diagonal triangles. The linear equation pertaining to points (j, r_{0j}^{+}) and $(j+1, r_{0(j+1)}^{+})$ is $b = r_{0j}^{+} + (r_{0(j+1)}^{+} - r_{0j}^{+})(a-j)$, and that pertaining to points (j, r_{ij}^{+}) and $(j+1, r_{i(j+1)}^{+})$ is $b = r_{ij}^{+} + (r_{i(j+1)}^{+} - r_{ij}^{+})(a-j)$. The coordinates of $M(a, b)$ can be obtained by solving two equations simultaneously: $\begin{cases} a = \frac{r_{ij}^{+} - r_{0j}^{+} + j(r_{ij}^{+} + r_{0(j+1)}^{+} - r_{0j}^{+} - r_{i(j+1)}^{+})}{r_{ij}^{+} + r_{0(j+1)}^{+} - r_{0j}^{+} - r_{i(j+1)}^{+}} \\ b = \frac{r_{ij}^{+} \cdot r_{0(j+1)}^{+} - r_{0j}^{+} \cdot r_{i(j+1)}^{+}}{r_{ij}^{+} + r_{0(j+1)}^{+} - r_{0j}^{+} - r_{i(j+1)}^{+}} \end{cases}.$ Thus, the sum of the areas of the two triangles is $\Delta(r_{ij}^{+}, r_{0j}^{+}) = \int_{j}^{j+1} \left| r_{0t}^{+} - r_{it}^{+} \right| dt = \frac{\left| r_{0j}^{+} + r_{ij}^{+} - r_{0(j+1)}^{+} - r_{i(j+1)}^{+} \right|}{2} - \frac{\left| r_{ij}^{+} - r_{0j}^{+} \right| \cdot \left| r_{0(j+1)}^{+} - r_{i(j+1)}^{+} \right|}{\left| r_{0(j+1)}^{+} + r_{ij}^{+} - r_{0j}^{+} - r_{i(j+1)}^{+} \right|}.$

3) CASE 3

When the line consisting of points (j, r_{0j}^{+}) and $(j+1, r_{0(j+1)}^{+})$ and line consisting of points (j, r_{ij}^{+}) and $(j+1, r_{i(j+1)}^{+})$ do not intersect (Fig. 14(c)), the four points form a trapezoid. According to the trapezoid area formula, $\Delta(r_{ij}^{+}, r_{0j}^{+}) = \int_{j}^{j+1} \left| r_{0t}^{+} - r_{it}^{+} \right| dt = \left| r_{i(j+1)}^{+} + r_{ij}^{+} - r_{0(j+1)}^{+} - r_{0j}^{+} \right| \Big/ 2.$

B. PROOF 2: PROOF OF THE FOUR AXIOMS IN THE GREY SYSTEM

1) NORMATIVE

If $\Delta(r_{ij}^{+}, r_{0j}^{+}) = \min_i \min_j \Delta(r_{ij}^{+}, r_{0j}^{+})$, $\delta_{ij}^{+} = 1$; if $\Delta(r_{ij}^{+}, r_{0j}^{+}) \neq \min_i \min_j \Delta(r_{ij}^{+}, r_{0j}^{+})$, $\Delta(r_{ij}^{+}, r_{0j}^{+}) > \min_i \min_j \Delta(r_{ij}^{+}, r_{0j}^{+})$ and $\min_i \min_j \Delta(r_{ij}^{+}, r_{0j}^{+}) + \xi \max_i \max_j \Delta(r_{ij}^{+}, r_{0j}^{+}) < \Delta(r_{ij}^{+}, r_{0j}^{+}) + \xi \max_i \max_j \Delta(r_{ij}^{+}, r_{0j}^{+})$. Consequently, $\delta_{ij}^{+} < 1$; For any j, $\delta_{ij}^{+} > 0$, $\delta_{ij}^{+} \in (0, 1]$; thus, the normative aspect is proved.

2) INTEGRITY

If $r = \{r_s \,|\, s = 0, 1, \cdots, m; m \geq 2\}$, for $\forall r_{s1}, r_{s2} \in r$, $r_{s1} \neq r_{s2}$, generally, $\max_i \max_j \Delta(r_{0j}^{+}, r_{s1j}^{+}) \neq \max_i \max_j \Delta(r_{0j}^{+}, r_{s2j}^{+})$; thus, the integrity aspect is proved.

3) EVEN SYMMETRY

If $r = \{r_0, r_1\}$, $\Delta(r_{0j}^{+}, r_{1j}^{+}) = \Delta(r_{1j}^{+}, r_{0j}^{+})$, and $\max_i \max_j \Delta(r_{s1j}^{+}, r_{ij}^{+}) \neq \max_i \max_j \Delta(r_{ij}^{+}, r_{s2j}^{+})$. Consequently, $\delta_{01}^{+} = \delta_{10}^{+}$, and the even symmetry is proved.

4) PROXIMITY

If the difference information $\Delta(r_{ij}^{+}, r_{0j}^{+})$ is small, δ_{ij}^{+} is large, based on the formula of the grey relational coefficient;

correspondingly, R_0^+ and R_i^+ are close, and the proximity aspect is proved.

C. GARA METHOD

The specific steps of GARA method are as follows.

Step 1: Standardise the decision matrix $A = (a_{ij})_{m\times n}$ to obtain a standardised matrix $B = (b_{ij})_{m\times n}$ by using the extreme value method:

$$b_{ij} = \begin{cases} \dfrac{a_{ij} - \min_{1\le j\le n} a_{ij}}{\max_{1\le j\le n} a_{ij} - \min_{1\le j\le n} a_{ij}} & j \in J^+ \\ \dfrac{\max_{1\le j\le n} a_{ij} - a_{ij}}{\max_{1\le j\le n} a_{ij} - \min_{1\le j\le n} a_{ij}} & j \in J^- \end{cases} \tag{C1}$$

where a_{ij} is the original data of the i object and j index; J^+, J^- denote the set of the profit and cost indicators, respectively.

Step 2: Calculate the weighted decision matrix $R = (r_{ij})_{m\times n}$ by multiplying the matrix B with the combination weight w (where $r_{ij} = b_{ij}w_j$).

Step 3: Determine the positive ideal solutions (PIS) and negative ideal solutions (NIS), R_0^+, R_0^-, respectively.

$$\begin{aligned} R_0^+ &= \{r_{01}^+, r_{02}^+, \cdots, r_{0n}^+\} \\ &= \{\max_{1\le i\le m} r_{ij} \,|\, j \in J^+, \min_{1\le i\le m} r_{ij} \,|\, j \in J^-\} \\ R_0^- &= \{r_{01}^-, r_{02}^-, \cdots, r_{0n}^-\} \\ &= \{\min_{1\le i\le m} r_{ij} \,|\, j \in J^+, \max_{1\le i\le m} r_{ij} \,|\, j \in J^-\} \end{aligned} \tag{C2}$$

Step 4: Calculate the grey area relational coefficients q_{ij}^+, q_{ij}^- and grey area relational degrees q_i^+, q_i^- based on the polygonal area from the evaluation scheme to the PIS and NIS, respectively.

Step 4.1: Calculate the grey area relational coefficient between r_{ij}^+ and r_{0j}^+: $q_{ij}^+ = \frac{\min_i \min_j \Delta(r_{ij}^+, r_{0j}^+) + \xi \max_i \max_j \Delta(r_{ij}^+, r_{0j}^+)}{\Delta(r_{ij}^+, r_{0j}^+) + \xi \max_i \max_j \Delta(r_{ij}^+, r_{0j}^+)}$, where $\xi \in [0, 1]$ is the distinguishing coefficient. In general, $\xi = 0.5$ is usually applied following the rule of least information. $\Delta(r_{ij}^+, r_{0j}^+)$ represents the polygonal area between adjacent points in the curves.

Similarly, the grey area relational coefficient between r_{ij}^- and r_{0j}^- can be calculated as $q_{ij}^- = \frac{\min_i \min_j \Delta(r_{ij}^-, r_{0j}^-) + \xi \max_i \max_j \Delta(r_{ij}^-, r_{0j}^-)}{\Delta(r_{ij}^-, r_{0j}^-) + \xi \max_i \max_j \Delta(r_{ij}^-, r_{0j}^-)}$, with the calculation process of $\Delta(r_{ij}^-, r_{0j}^-)$ being the same as that for $\Delta(r_{ij}^+, r_{0j}^+)$.

Step 4.2: Calculate the grey area relational degree q_i^+, q_i^-:

$$\begin{aligned} q_i^+ &= \left(\sum_{j=1}^n q_{ij}^+\right) \Big/ n \\ q_i^- &= \left(\sum_{j=1}^n q_{ij}^-\right) \Big/ n \end{aligned} \tag{C3}$$

Step 5: The grey area relational degrees q_i^+, q_i^- are non-dimensionalized as:

$$S_i^+ = q_i^+ \Big/ \left(\max_i q_i^+\right)$$

$$S_i^- = q_i^- \Big/ \left(\max_i q_i^-\right) \tag{C4}$$

Step 6: Calculate the relative closeness.

$$C_i = S_i^+ / (S_i^+ + S_i^-) \tag{C5}$$

C_i reflects the differences in the location and shape similarity. A larger or smaller relative closeness corresponds to a superior or inferior evaluation object.

REFERENCES

[1] S. Mishra, T. F. Welch, and M. K. Jha, "Performance indicators for public transit connectivity in multi-modal transportation networks," *Transp. Res. A, Policy Pract.*, vol. 46, no. 7, pp. 1066–1085, Aug. 2012.

[2] C.-C. Lin and S.-W. Lin, "Two-stage approach to the intermodal terminal location problem," *Comput. Oper. Res.*, vol. 67, pp. 113–119, Mar. 2016.

[3] A. Ghaderi and R. L. Burdett, "An integrated location and routing approach for transporting hazardous materials in a bi-modal transportation network," *Transp. Res. E, Logistics Transp. Rev.*, vol. 127, pp. 49–65, Jul. 2019.

[4] T. Sakai, A. Beziat, and A. Heitz, "Location factors for logistics facilities: Location choice modeling considering activity categories," *J. Transp. Geography*, vol. 85, May 2020, Art. no. 102710, doi: 10.1016/j.jtrangeo.2020.102710.

[5] G. Musolino, C. Rindone, A. Polimeni, and A. Vitetta, "Planning urban distribution center location with variable restocking demand scenarios: General methodology and testing in a medium-size town," *Transp. Policy*, vol. 80, pp. 157–166, Aug. 2019.

[6] B. Fan, Y. Yang, and L. Li, "Integrated optimization of urban agglomeration passenger transport hub location and network design," *EURASIP J. Wireless Commun. Netw.*, vol. 2018, no. 1, pp. 1–7, Jul. 2018.

[7] C.-C. Chou, "Application of FMCDM model to selecting the hub location in the marine transportation: A case study in southeastern Asia," *Math. Comput. Model.*, vol. 51, nos. 5–6, pp. 791–801, Mar. 2010.

[8] S. Limbourg and B. Jourquin, "Optimal rail-road container terminal locations on the European network," *Transp. Res. E, Logistics Transp. Rev.*, vol. 45, no. 4, pp. 551–563, Jul. 2009.

[9] X. Wen, H.-L. Ma, T.-M. Choi, and J.-B. Sheu, "Impacts of the belt and road initiative on the China-Europe trading route selections," *Transp. Res. E, Logistics Transp. Rev.*, vol. 122, pp. 581–604, Feb. 2019.

[10] D. Yang, K. Pan, and S. Wang, "On service network improvement for shipping lines under the one belt one road initiative of China," *Transp. Res. E, Logistics Transp. Rev.*, vol. 117, pp. 82–95, Sep. 2018.

[11] J. B. Sheu and T. Kundu, "Forecasting time-varying logistics distribution flows in the one belt-one road strategic context," *Transp. Res. E, Logistics Transp. Rev.*, vol. 117, pp. 5–22, Sep. 2018.

[12] L. Zhao, Y. Zhao, Q. Hu, H. Li, and J. Stoeter, "Evaluation of consolidation center cargo capacity and loctions for China railway express," *Transp. Res. E, Logistics Transp. Rev.*, vol. 117, pp. 58–81, Sep. 2018.

[13] Q. Zeng, G. Wang, C. Qu, and K. Li, "Impact of the Carat Canal on the evolution of hub ports under China's belt and road initiative," *Transp. Res. E, Logistics Transp. Rev.*, vol. 117, pp. 96–107, Sep. 2018.

[14] P. Peng, Y. Yang, F. Lu, S. Cheng, N. Mou, and R. Yang, "Modelling the competitiveness of the ports along the maritime silk road with big data," *Transp. Res. A, Policy Pract.*, vol. 118, pp. 852–867, Dec. 2018.

[15] X. Jiang, X. Wang, and D. Zhu, "Research on the problem of site selection of logistics infrastructure under the 'one belt one road' development strategy," *Shanghai Manage. Sci.*, vol. 37, no. 5, pp. 1–6, Oct. 2015.

[16] G. W. Y. Wang, Q. Zeng, K. Li, and J. Yang, "Port connectivity in a logistic network: The case of Bohai bay, China," *Transp. Res. E, Logistics Transp. Rev.*, vol. 95, pp. 341–354, Nov. 2016.

[17] P. W. de Langen and K. Sharypova, "Intermodal connectivity as a port performance indicator," *Res. Transp. Bus. Manage.*, vol. 8, pp. 97–102, Oct. 2013.

[18] R. Redondi, P. Malighetti, and S. Paleari, "Hub competition and travel times in the world-wide airport network," *J. Transp. Geography*, vol. 19, no. 6, pp. 1260–1271, Nov. 2011.

[19] Z. Zhu, A. Zhang, Y. Zhang, Z. Huang, and S. Xu, "Measuring air connectivity between China and Australia," *J. Transp. Geography*, vol. 74, pp. 359–370, Jan. 2019.

[20] Z. Zhu, A. Zhang, and Y. Zhang, "Connectivity of intercity passenger transportation in China: A multi-modal and network approach," *J. Transp. Geography*, vol. 71, pp. 263–276, Jul. 2018.

[21] K. Kanwar, H. Kumar, and S. Kaushal, "Complex network based comparative analysis of Delhi metro network and its extension," *Phys. A, Stat. Mech. Appl.*, vol. 526, Jul. 2019, Art. no. 120991, doi: 10.1016/j.physa.2019.04.227.

[22] G. D'Orso and M. Migliore, "A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments," *J. Transp. Geography*, vol. 82, Jan. 2020, Art. no. 102555, doi: 10.1016/j.jtrangeo.2019.102555.

[23] T. Suwanwong, A. Sopadang, S. Hanaoka, and T. Rodbundith, "Evaluation of air cargo connectivity and policy in thailand," *Transp. Policy*, vol. 72, pp. 24–33, Dec. 2018.

[24] A. Farooq, M. Xie, S. Stoilova, F. Ahmad, M. Guo, E. J. Williams, V. K. Gahlot, D. Yan, and A. M. Issa, "Transportation planning through GIS and multicriteria analysis: Case study of Beijing and XiongAn," *J. Adv. Transp.*, vol. 2018, Oct. 2018, Art. no. 2696037.

[25] W. Xu, J. Zhou, L. Yang, and L. Li, "The implications of high-speed rail for Chinese cities: Connectivity and accessibility," *Transp. Res. A, Policy Pract.*, vol. 116, pp. 308–326, Oct. 2018.

[26] R. F. M. Ameen and M. Mourshed, "Urban sustainability assessment framework development: The ranking and weighting of sustainability indicators using analytic hierarchy process," *Sustain. Cities Soc.*, vol. 44, pp. 356–366, Jan. 2019.

[27] S. Zeng, S.-M. Chen, and K.-Y. Fan, "Interval-valued intuitionistic fuzzy multiple attribute decision making based on nonlinear programming methodology and TOPSIS method," *Inf. Sci.*, vol. 506, pp. 424–442, Jan. 2020.

[28] S. Zeng and Y. Xiao, "A method based on topsis and distance measures for hesitant fuzzy multiple attribute decision making," *Technol. Econ. Develop. Economy*, vol. 24, no. 3, pp. 969–983, May 2018.

[29] T. Özcan, N. Çelebi, and Ş. Esnaf, "Comparative analysis of multi-criteria decision making methodologies and implementation of a warehouse location selection problem," *Expert Syst. Appl.*, vol. 38, no. 8, pp. 9773–9779, Aug. 2011.

[30] D. Li, L. Zhao, C. Wang, W. Sun, and J. Xue, "Selection of China's imported grain distribution centers in the context of the belt and road initiative," *Transp. Res. E, Logistics Transp. Rev.*, vol. 120, pp. 16–34, Dec. 2018.

[31] S. Zeng, D. Luo, C. Zhang, and X. Li, "A correlation-based TOPSIS method for multiple attribute decision making with single-valued neutrosophic information," *Int. J. Inf. Technol. Decis. Making*, vol. 19, no. 1, pp. 343–358, Feb. 2020.

[32] M.-F. Chen and G.-H. Tzeng, "Combining grey relation and TOPSIS concepts for selecting an expatriate host country," *Math. Comput. Model.*, vol. 40, no. 13, pp. 1473–1490, Dec. 2004.

[33] D. Liu, X. Qi, Q. Fu, M. Li, W. Zhu, L. Zhang, M. A. Faiz, M. I. Khan, T. Li, and S. Cui, "A resilience evaluation method for a combined regional agricultural water and soil resource system based on weighted Mahalanobis distance and a gray-TOPSIS model," *J. Cleaner Prod.*, vol. 229, pp. 667–679, Aug. 2019.

[34] A. K. Pandey, A. I. Khan, Y. B. Abushark, M. M. Alam, A. Agrawal, R. Kumar, and R. A. Khan, "Key issues in healthcare data integrity: Analysis and recommendations," *IEEE Access*, vol. 8, pp. 40612–40628, Feb. 2020.

[35] F. Lei, G. Wei, H. Gao, J. Wu, and C. Wei, "TOPSIS method for developing supplier selection with probabilistic linguistic information," *Int. J. Fuzzy Syst.*, vol. 22, no. 3, pp. 749–759, Mar. 2020.

[36] F. Lei, G. Wei, J. Lu, J. Wu, and C. Wei, "GRA method for probabilistic linguistic multiple attribute group decision making with incomplete weight information and its application to waste incineration plants location problem," *Int. J. Comput. Intell. Syst.*, vol. 12, no. 1, pp. 1547–1556, Dec. 2019.

[37] P. Shojaei, S. A. S. Haeri, and S. Mohammadi, "Airports evaluation and ranking model using Taguchi loss function, best-worst method and VIKOR technique," *J. Air Transp. Manage.*, vol. 68, pp. 4–13, May 2018.

[38] B. Ka, "Application of fuzzy AHP and ELECTRE to China dry port location selection," *Asian J. Shipping Logistics*, vol. 27, no. 2, pp. 331–353, Aug. 2011.

[39] G. Kabir and R. S. Sumi, "Power substation location selection using fuzzy analytic hierarchy process and PROMETHEE: A case study from Bangladesh," *Energy*, vol. 72, pp. 717–730, Aug. 2014.

[40] J. Yuan, X. Li, C. Xu, C. Zhao, and Y. Liu, "Investment risk assessment of coal-fired power plants in countries along the belt and road initiative based on ANP-entropy-TODIM method," *Energy*, vol. 176, pp. 623–640, Jun. 2019.

[41] H. Quan, S. Li, H. Wei, and J. Hu, "Personalized product evaluation based on GRA-TOPSIS and Kansei engineering," *Symmetry*, vol. 11, no. 7, p. 867, Jul. 2019.

[42] J. Zhou, Y. Wu, C. Wu, F. He, B. Zhang, and F. Liu, "A geographical information system based multi-criteria decision-making approach for location analysis and evaluation of urban photovoltaic charging station: A case study in Beijing," *Energy Convers. Manage.*, vol. 205, Feb. 2020, Art. no. 112340, doi: 10.1016/j.enconman.2019.112340.

[43] J. Lu, C. Wei, J. Wu, and G. Wei, "TOPSIS method for probabilistic linguistic MAGDM with entropy weight and its application to supplier selection of new agricultural machinery products," *Entropy*, vol. 21, no. 10, p. 953, Sep. 2019.

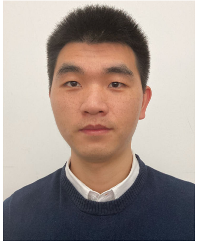
[44] L. Guo and Z. Yang, "Evaluation of foreign trade transport accessibility for mainland China," *Maritime Policy Manage.*, vol. 45, no. 1, pp. 34–52, Jan. 2018.

[45] A. Agrawal, A. K. Pandey, A. Baz, H. Alhakami, W. Alhakami, R. Kumar, and R. A. Khan, "Evaluating the security impact of healthcare Web applications through fuzzy based hybrid approach of multi-criteria decision-making analysis," *IEEE Access*, vol. 8, pp. 135770–135783, Jul. 2020.

[46] M. Zarour, M. T. J. Ansari, M. Alenezi, A. K. Sarkar, M. Faizan, A. Agrawal, R. Kumar, and R. A. Khan, "Evaluating the impact of blockchain models for secure and trustworthy electronic healthcare records," *IEEE Access*, vol. 8, pp. 157959–157973, Aug. 2020.

[47] G. Wei, J. Lu, C. Wei, and J. Wu, "Probabilistic linguistic GRA method for multiple attribute group decision making," *J. Intell. Fuzzy Syst.*, vol. 38, no. 4, pp. 4721–4732, Apr. 2020.

[48] S. Liu, *Grey System Theory and Its Application*. Beijing, China: Science Press, 2010.



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