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The Interconnectivity and Spatio-Temporal Evolution of Rail Transit Network Based on Multi-Element Flows: A Case Study of Beijing-Tianjin-Hebei Urban Agglomeration, China

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Abstract: For intercity transportation within urban agglomerations, rail transit interconnectivity not only stimulates city-to-city interactions but also facilitates the networking of urban spaces. Crucially, comprehending the spatial network of urban agglomerations needs a focus on rail transit interconnectivity. Drawing on the space of flows theory, this study establishes a framework to evaluate rail transit interconnectivity and the spatial structure of urban agglomerations, utilizing the Beijing-Tianjin-Hebei urban agglomeration as a case study. The objective of this study is to explore the impact of rail transit interconnectivity on the spatial structure in the urban agglomeration. Firstly, it establishes a coupled concept of urban quality and line quality to elucidate the interaction between rail transits and urban development. Secondly, it employs the AHP-CRITIC-TOPSIS and modified gravity model to evaluate the interconnectivity degree of rail transits and visualize the network. Thirdly, based on the multi-element flows facilitated by rail transit interconnectivity, the evolution of the spatial structure within the urban agglomeration is quantified using social network analysis. The study findings are as follows: (1) From 2010 to 2021, the interconnectivity degree of rail transit in the Beijing-Tianjin-Hebei urban agglomeration experienced substantial growth, emphasizing the correlation between interconnectivity and the city hierarchy within the urban agglomeration. (2) The interconnectivity degree of the Beijing-Tianjin-Hebei urban agglomeration shows an uneven pattern of "three cores and numerous weak links," characterized by spatial polarization. (3) Rail transit interconnectivity contributes to shaping the spatial structure of urban agglomerations in terms of interconnectivity, polycentricity, and integration, although the enhancement of polycentricity is limited. The framework developed in this study can be extensively employed to investigate the interplay between rail transit interconnectivity and the spatial structure of urban agglomerations, thereby promoting the sustainability of regional planning.

Keywords: rail transit; urban agglomeration; transport interconnectivity; urban spatial structure; spatio-temporal evolution

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1. Introduction

With the accelerated process of urbanization and globalization, urban agglomerations have become a crucial strategy for national development and competition [1]. The increasing demand for enhanced interconnectivity and cooperation among cities in urban agglomerations continues to grow [2]. However, challenges persist within the intercity transportation system, including insufficient interconnectivity, inefficient transportation, and transport pollution [3]. The incoherence between the transportation subsystem and other urban subsystems has become a significant factor hindering the development of urban agglomerations. In this condition, regional rail transits are regarded as the preferred mode of green transportation for addressing these challenges of intercity transportation, with the advantages of large capacity, high punctuality, fast speed, and low pollution [4,5]. The five megacities, including New York, London, Tokyo, Paris, and the North American Great Lakes region, all alleviated a significant portion of their passenger traffic by developing advanced intercity rail transit systems, which are integrated and coordinated with other modes of transportation [6]. Hence, constructing an interconnected rail transit system that aligns with social needs and urban planning is crucial for promoting the sustainable development of urban agglomerations.

Rail transit not only functions as a carrier for intercity transportation but also plays a guiding role in the spatial structures of urban agglomerations through its interconnectivity [7]. As a transport carrier, rail transits facilitate the physical interconnectivity of urban agglomerations. Cities can foster the exchange, cooperation, and shared utilization of flows, including people, goods, information, energy, and financial resources. The space of flows theory indicates that the high-speed characteristics of multi-element flows enhance the convenience and efficiency of spatial circulation, significantly reducing distances among cities and propelling the networking of the urban spatial structure [8]. At present, the spatial structure of regional systems has been established on the logical foundation of networks, flows, and nodes. As a key aspect of the space of flows theory, the multi-element flows generated by rail transit interconnectivity can reflect variations among cities in terms of connection density, connection strength, and urban hierarchical structure [9]. Therefore, the specific objective of this study is to explore the interaction between rail transit interconnectivity and the spatial structure of the urban agglomeration to guide the networking of spatial structure and optimize spatial order in urban agglomerations.

More existing studies have focused on the interaction between transportation systems and spatial planning at the urban scale, investigating the accessibility of air traffic, railways, and highways, and their impact on urban space [9,10]. The research methodologies evolved from qualitative analysis to quantitative indicator evaluations, and later incorporated techniques such as data mining and Geographic Information Systems (GIS) [11,12], currently being in a phase of integrated development across multiple disciplines. However, regional spatial development is moving towards integration and networking, which can accelerate the movement of elements among cities unrestricted by administrative boundaries. Hence, this study agrees that there is a need to enrich the studies at the urban agglomerations scale, considering the complexity of the spatial planning and formulation of refined policies. For modern intercity transportation systems, interconnectivity is no longer confined to the physical single dimension, presenting a limitation in many existing studies. This study regards it as representing dimensional interactions on the virtual space with multi-element flows. Furthermore, existing studies almost evaluate the rail transit interconnectivity with indicators in terms of line and network attributes and overlook the interaction between rail transit and urban development. Therefore, establishing a scientific evaluation model remains an effective approach to address the current issues of one-sided and singular evaluation indicators that fail to reflect the actual development situation.

Against this background, this study aims to establish a comprehensive framework for evaluating rail transit interconnectivity and examining its role in shaping the spatial structure network at the urban agglomeration scale. The novelty and originality of the evaluation framework can be highlighted as follows. Drawing on the space of flows theory, this study concentrates on the intricate spatial network system of urban agglomerations. It introduces the concept of coupling urban quality with line quality, revealing the interaction mechanisms between rail transit and urban development. Interconnectivity is defined here as the interaction of multi-element flows. Building on this foundation, we first evaluate rail transit interconnectivity and then delve into the spatio-temporal evolution of its network's spatial structure within the urban agglomeration, which can systematically investigate the evolutionary structure, spatial attributes, and specific characteristics of the network. The evaluation framework streamlines the effective integration of multi-element flows resulting from rail transit interconnectivity within an urban agglomeration. This study enhances the theoretical aspects of rail transit interconnectivity, broadens the utilization of the space of flows theory in urban agglomeration development, and complements research on the coordinated development of rail transit systems and spatial planning.

To fulfill the study objective, we take the Beijing-Tianjin-Hebei (BTH) urban agglomeration as a case study and describe how we combined the AHP-CRITIC-TOPSIS method with the gravity model and social network analysis (SNA) method to create an evaluating framework that leverages the advantages of all models. First, an evaluation indicator system is developed, rooted in the frameworks of urban quality and line quality. Second, we employ the AHP-CRITIC-TOPSIS method to calculate the indicator system, deriving the urban integrated quality, which serves as the basis for modifying the gravity model. Third, this study refines the parameters of the gravity model to evaluate the interconnectivity degree of rail transits. Finally, the SNA method is employed to analyze the spatio-temporal evolution of the BTH rail transit network (BTHRTN), revealing the impact of rail transit interconnectivity on the spatial structure of the BTH urban agglomeration. The study results may help reveal the underlying mechanisms governing the development and evolution of rail transit interconnectivity networks, playing a crucial role in optimizing and establishing a rational urban spatial network plan dominated by rail transit.

2. Literature Review

2.1. Rail Transit and Urban Spatial Networking

With the globalization trend, cities no longer function as independent entities; instead, they engage in the exchange of materials and energy with the external environment. In this dynamic process, intercity relations become integral components within the network space of the urban agglomeration. Many scholars consider that the pattern of urban growth and form is characterized by a strong link with the interaction of multi-flows in urban networks [13]. Guided by the space of flows theory, urban studies based on flow data has evolved into a novel research paradigm in urban network science [14]. The studies utilize geographic methods such as spatial interaction models and accessibility models to conduct research related to the spatial pattern and interconnectivity of urban networks [15,16]. Transportation serves as the physical foundation of the regional connection, and its interconnectivity offers a method to evaluate the regional spatial interaction. The interaction between transport interconnectivity and the urban spatial structure has become a hot topic [17].

Rail transit serves a foundational role in intercity operations, making flows central elements for characterizing regional connections [18]. Most studies concentrate on the urban or national scale, exploring the interaction between regional spatial networking and rail transit systems in terms of evolution and optimization [19]. The results have found that the primary impact of rail transit on the regional spatial planning lies in accessibility and polycentricity [9]. However, few studies have explored the urban agglomeration space from a network perspective based on flows developed by rail transit interconnectivity. Exploring spatial interaction is an important path to study regional relations, regional connection, and regional spatial structure. By evaluating the interconnectivity degree of the rail transit in the urban agglomeration, we can deeply understand its role in shaping the spatial structure network.

Regarding data sources and methods, analysts frequently examined pertinent data (e.g., GDP, population, passenger and freight volume) [20,21] using approaches such as the gravity model, field strength model, breaking point analysis, exploratory spatial data analysis (ESDA), and SNA to gauge relative advantages or connections among cities in the regional spatial network [22,23]. Due to coordinated development, the exchange of flows among cities has become more diverse and interactive, an aspect not fully considered in previous research on sustainable regional development. The DPSIR framework can tackle this challenge by enabling users to model feedback processes and identify the parameters driving them. It provides a holistic perspective on the effects of changes within the rail transit system and the system's response to many changes [24]. However, when using DPSIR in research, it does not comprehensively depict the system's structure and functionality. Thus, combining DPSIR with other models for enhancing its utility is necessary [25].

Considering the comprehensive use of methods, we discovered that traditional approaches such as ESDA and spatial econometrics have limitations because they depend on measuring proximity or distance relationships among geographical regions. This limitation makes it challenging to dynamically grasp the structural characteristics of spatial associations in the overall context of rail transit interconnectivity. As inter-regional flow and interconnectivity trends become more prominent in the rail transit system, spatial associations demonstrate a multi-threaded and complex network structure [26]. The SNA method provides a breakthrough in overcoming the limitations of analyzing attribute data, focusing on effectively analyzing the network characteristics of relationship data [27]. In conclusion, this study emphasizes the necessity of exploring the spatial networking of urban agglomerations, particularly focusing on element flows generated by rail transit interconnectivity using the SNA method and similar approaches.

2.2. The Evaluation of Rail Transit Interconnectivity

At present, the top priority for urban agglomeration development is still the issue of interconnectivity [28]. Measuring the intensity and structure of network interconnectivity and determining a city's status in the regional network can significantly support the development of regional spatial planning [29]. Reasonable evaluation of interconnectivity is the basis for making scientific policies to promote sustainable urban development [10].

In terms of the selection of evaluation indicators, existing studies focus on selecting a smaller quantity of representative indicators in the aspects of the economy, population, and physical indicators of lines and networks, such as line length, number of nodes, network density, and toll costs [30,31]. In the context of modernization and informatization, the element flows carried by rail transit interconnectivity are diverse, including people, goods, information, funds, energy, and more. A limited number of indicators cannot fully capture the complexity of the element flow. Furthermore, there exists a complex interaction relationship between rail transits and urban development. A very substantial amount of research effort has already been devoted to analyzing the interaction between rail transit (i.e., accessibility, station, and passenger capacity) and urban form (i.e., land use, spatial distribution, and accessibility) [7,9]. However, existing studies evaluating rail transit interconnectivity fail to reflect that the capacity of a rail transit service in urban agglomerations not only depends on its own construction but also is impacted by the multi-urban agglomeration attributes [32]. Therefore, this study constructs a framework for coupling urban quality and line quality, which can reveal the interaction between rail transits and regional development.

In terms of evaluation methods, the entropy weight method, TOPSIS method [11], gravity model [23], and informatization methods such as GIS [12] have been used in conjunction. Among them, the traditional gravity model is widely employed in the domains of geographic distance attenuation and spatial interaction [33]. It takes into account both the size and attributes of the study area, especially showing the direction of material flows within networks. However, existing gravity models often use a limited set of indicators, such as GDP and population, to explain complex network systems. In fact, rail transit networks are complex and influenced by multiple factors, including social, economic, cultural, and geographical aspects. Hence, in this study, the model parameters were modified to better reflect the urban spatial interactions affected by rail transit interconnectivity.

In summary, existing literature about rail transit interconnectivity in the regional spatial space focuses more on the urban scale and less on the networking of the spatial structure in urban agglomerations based on the space of flows theory. In the evaluation of interconnectivity, the selection of evaluation indicators mostly focuses on the rail transit attributes and neglects the flow interaction between rail transit and urban development. The DPSRI model can systematically translate the interaction of multi-element flows, and when combined with SNA, it can compensate for its inability to explore the structure of network systems. Evaluation methods are diverse; among them, the gravity model can capture interactions between cities and also visualize the directional interconnectivity network. However, the modified gravity model is constrained by limitations in indicator selection. Therefore, academics are still at the stage of exploring the indicator selection and the evaluation methods and lack a comprehensive framework to evaluate rail transit interconnectivity and its impact on regional spatial planning.

3. Materials and Methods

3.1. Study Area

The BTH urban agglomeration is situated at the nexus connecting three major regions: North China, Northeast China, and East China, as shown in Figure 1. Covering an expansive 216,800 km^2, it includes 16 cities, comprising the municipalities of Beijing and Tianjin, and 13 cities within Hebei Province: Zhangjiakou, Chengde, Qinhuangdao, Tangshan, Cangzhou, Hengshui, Langfang, Baoding, Shijiazhuang, Xingtai, Handan, Dingzhou, Xinji, and Anyang in Henan Province. As of 2021, the BTH urban agglomeration had a population of 113 million and a gross domestic product (GDP) of 96,356 million yuan, marking a 2.2-fold increase from 2014. However, cities within the BTH urban agglomeration exhibit significant spatial disparities in socioeconomic development levels [9]. Specifically, a notable economic gap existed between Beijing and Hebei in 2021, with Beijing's GDP per capita soaring to 183,980 yuan, in stark contrast to Hebei's meager 54,172 yuan.

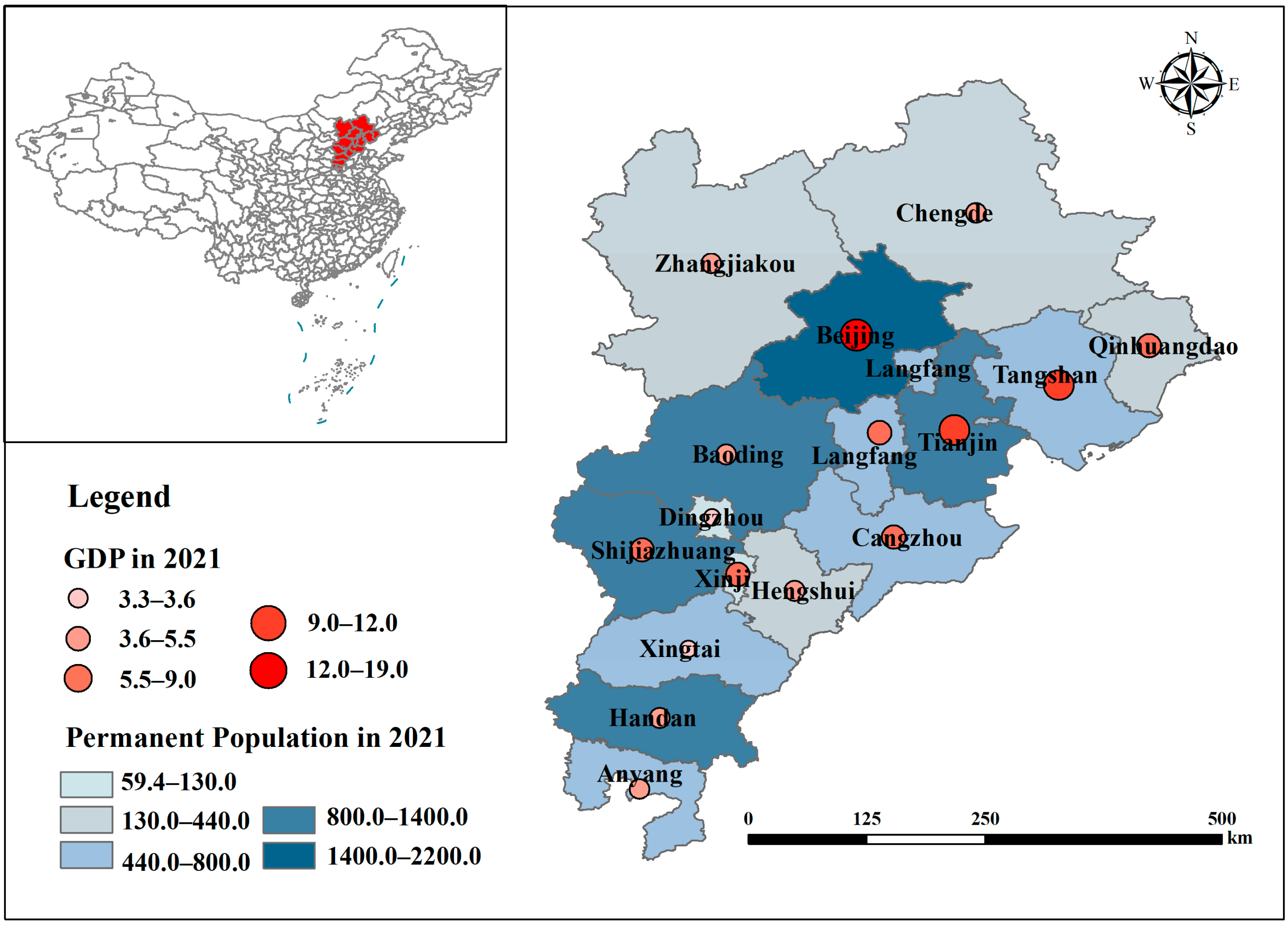

Figure 1. The location of the BTH urban agglomeration in China.

China initiated the strategy of coordinating the development of the national capital of Beijing and the neighboring Tianjin Municipality and Hebei Province in early 2014. Intercity transportation forms the cornerstone for enhancing connections and mitigating regional disparities. In 2015, China introduced the concept of constructing "BTH on the track" for coordinated development, with plans to realize this vision by 2025. Driven by continuous policies and social demands in China, the BTHRTN has expanded rapidly, and a myriad of transportation problems are receiving much attention from multi-disciplinary researchers, including the over-concentration of transport functions in the capital and an uneven regional transport layout [27]. Urgent measures are necessary to revamp the intercity transport network, striving for a networked spatial pattern in regional spatial planning [34]. Accordingly, the BTH urban agglomeration serves as a valuable case study, probing the impact of the rail transit network's interconnectivity on shaping the networked spatial structure within the urban agglomeration. A pressing concern is the definition of the interconnectivity degree of the BTHRTN and the analysis of the evolution characteristics of its spatial structure.

3.2. Data Source

This study utilizes the panel data of the BTH urban agglomeration from 2010 to 2021 as the main data source for analysis. And the years 2010, 2014, 2018, and 2021 are selected as the cross-sectional data sources in the social network analysis. The study data are mainly obtained from the following sources: (1) To guarantee the scientific and accuracy of the data, most of the raw data come from the China Statistical Yearbook, China Urban Statistical Yearbook, China Transportation Statistical Yearbook, China Environmental Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Statistical Yearbook, and Henan Statistical Yearbook for the years 2010–2021. (2) The map of the study area comes from the 1:1 million topographic databases of the National Geographic Information Resource Catalog Service System (NGIRCS). (3) Rail transit network data come from the Open Street Map. (4) Per capita carbon emission data come from the MEIC database. (5) The data on rail transit travel time and costs are primarily sourced from the China Railway Network: https://www.12306.cn/index/ (accessed on 21 October 2022) and other research collections. For the missing data, this study uses the linear interpolation method to supplement. The standardization of positive and negative indicators is selected to address the disparity in the nature and scale of indicators.

3.3. Research Framework

This study constructs a research framework that mainly includes the following aspects (Figure 2). First, clarifying the relationship among rail transit, interconnectivity, and urban agglomeration is the foundation to evaluate the interconnectivity of rail transit in the urban agglomeration. Second, establishing the indicator system in the aspects of urban quality and line quality to obtain the urban integrated quality, can reveal the complex mechanism of rail transit systems. Third, the gravity model is modified to evaluate the interconnectivity degree of rail transits in the urban agglomeration, demonstrating the urban attributes and visualizing the directional network. Fourth, the gravity matrix is used as the basic data for social network analysis to investigate the spatio-temporal impact of rail transit networks on the spatial structure in the urban agglomeration. Finally, based on the above, a case study of the BTH urban agglomeration is conducted and options proposed to improve the interconnectivity, polyneutrality, and tailored policies in the urban agglomeration development based on the evaluation results.

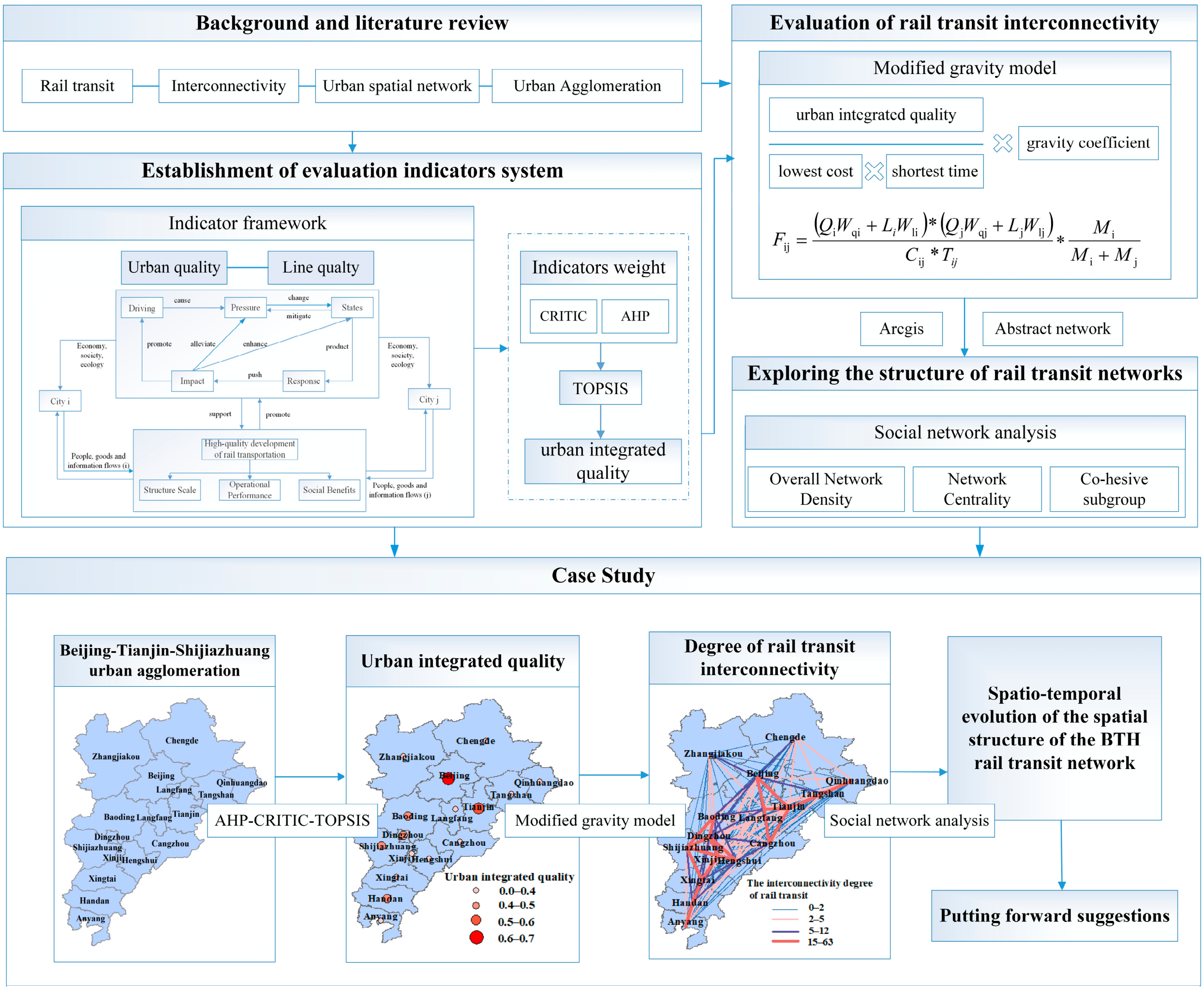

Figure 2. Research framework.

3.4. Establishment of Evaluation Indicator System

3.4.1. Indicator System Framework

The development of rail transit interconnectivity can enhance accessibility, alleviate traffic congestion, optimize spatial utilization efficiency, foster regional integration, and then prompt the urban spatial structures. Its interconnectivity degree can indicate the spatial interaction in the urban agglomeration, which offer a path for exploring the regional spatial structure. The top priority for evaluating the interconnectivity degree is to establish a scientific evaluation indicator system. Considering the intricate and interactive relationship between rail transit and urban development, this study establishes an indicator system within the framework of coupling urban quality and line quality. Urban quality indicators gauge the extent of urban functionality, encompassing evaluations of economic, social, and ecological operations. Line quality indicators pertain to the physical attributes of rail transit that influence its interconnectivity. Urban quality influences the demand for multi-element flows within the urban agglomeration, whereas line quality determines the efficiency of multi-element flows transmission.

Urban development is a multi-level open system, covering dynamic flows on economy, society, and ecology. In particular, sustainability and livability are often acknowledged as the main final objectives of urban development. Against this, the DPSIR framework is a conceptual model for understanding complex interactions between social, economic, and ecological systems [35]. In the DPSIR framework (Figure 3), human and natural drivers exert pressure on the urban systems, leading to state changes and a series of impacts that may require a policy response. The human response can simultaneously produce feedback to the drivers, reduce pressures, improve states, and reduce negative impacts, thus creating a feedback loop of Driver-Pressure-State-Impact-Response [36]. For effective management towards sustainable urban agglomerations, integrating the DPSIR framework into urban development can conceptualize the interaction of energy and material flows between humans and environmental systems. The literature shows that natural, economic, and social factors are the basic elements of urban ecosystems. So, the principal indicators of sustainable urban development in this day are derived from these factors.

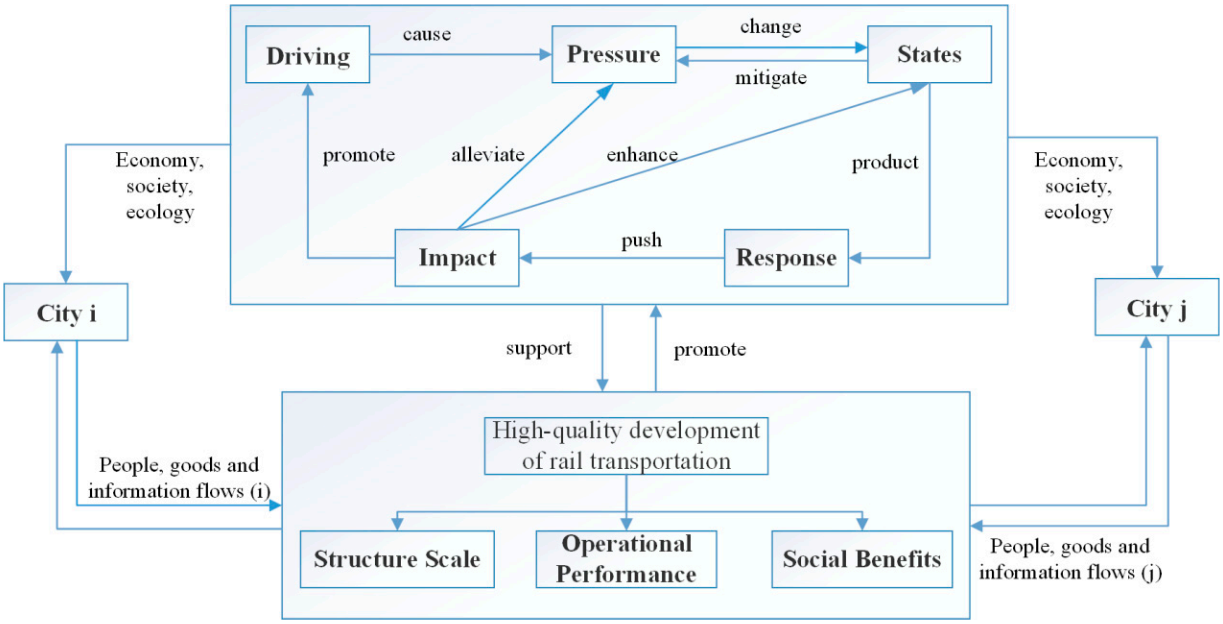

Figure 3. The indicator system framework of urban quality–line quality.

The primary objective of urban rail transit systems is to deliver high-quality services [37]. Rail transits facilitate the swift exchange and utilization of people, logistics, and information flow within urban agglomerations. This enhances accessibility, reduces time-space distances for residents traveling within urban agglomerations, fosters regional synergy, and bolsters overall competitiveness [38]. To achieve these goals, the line quality evaluation indicator system is constructed, considering aspects like line network structure and scale, operational performance, and social benefits.

The framework of the urban quality–line quality evaluation system is shown in Figure 3.

3.4.2. Evaluation Indicator System Construction

In Section 3.4.1, the study establishes the urban quality–line quality framework. Adhering to the principles of independence, scientific rigor, and operational feasibility, the research ultimately chooses 25 indicators (refer to Tables 1 and 2) to evaluate the interconnectivity degree of rail transits within the urban agglomeration.

(1) The selection of urban quality indicators

In the evaluation indicators of urban quality, the overall indicators need to form a logically closed loop under the DPSIR, reflecting the intrinsic mechanism of sustainable urban development oriented by rail transit [39]. The indicators of DPSIR are defined as follows:

"Driving force" is the fundamental and potential power of urban development. A high per capita GDP reflects strong economic capacity, enabling urban areas to invest in and strengthen rail transit networks. The increasing urbanization rate concentrates populations in cities, leading to more frequent movements within and between urban agglomerations, thus boosting the demand for rail transits. With growing awareness of sustainable development and environmental concerns, urban areas allocate budget resources to enhance energy conservation and environmental protection, supporting rail transit development.

"Pressure" is the load of accelerated urban development developed by the driving force. GDP growth year-on-year reflects economic expansion, driving increased transportation needs. Population density indicates a concentrated population, leading to heightened transit demands. Energy efficiency of GDP growth emphasizes the importance of energy-efficient transit solutions for sustainable development.

"State" is the comprehensive performance of urban development. With urbanization and rail transit development, the city and transportation demonstrate stability. Disposable income influences individual transportation choices. Road area underscores the need for efficient alternatives like rail transit systems. Carbon emissions highlight environmental impact, emphasizing sustainable modes such as rail transit.

"Impact" refers to the impact of the state of the system in economic, social, and ecological aspects. The robust growth of urban areas and transportation systems will influence the proportion of the tertiary sector. This reflects the city's economic structure, and modifications may affect the demand and scale of rail transport. The extensive advancement of rail transits can impact the adjustment of the average noise level of transportation arteries, thereby enhancing the residents' quality of life index. Additionally, the implementation of green transportation in urban areas will decrease the average annual concentration of PM2.5, thus improving the overall environmental quality of the city.

"Response" indicates the countermeasures taken by human beings to stabilize and maintain the state of the urban systems. The share of science and technology expenditure reflects the investment level in technological innovation resulting from urban and transportation development. An increasing proportion indicates the adoption of more advanced technologies, fostering industrial upgrading and economic innovation. With the expansion of the transportation industry, employment opportunities increase, contributing to the enhancement of urban economic vitality and social development. Additionally, the urban greening coverage rate mirrors the urban ecological environmental condition. Increasing urban greening coverage can improve air quality, mitigate the urban heat island effect, and promote ecological balance and sustainable development.

(2) The selection of line quality indicators

In the evaluation indicators of line quality, they are influenced not only by the number of lines and network density, but also by the capacity for people, logistics, and information flow [40].

The number of lines, line density, and number of connected cities serve as representative indicators reflecting the scale of the rail transit structure. The number of lines offers an intuitive demonstration of the rail transit system's scale, depicting the scope of public transportation infrastructure expansion. Line density evaluates the concentration of rail transit lines within a specific geographical area, with higher density typically correlating with increased interconnectivity and accessibility. The number of connected cities indicates the quantity of urban centers served by the rail transit system, highlighting its role in geographical coverage and regional integration.

Total passenger transportation, cargo turnover, and operating mileage serve as representative indicators reflecting the operational performance of the rail transit system. The total passenger transportation metric reveals fluctuations in passenger demand, playing a crucial role in assessing the system's busyness and efficiency. Cargo turnover measures the system's contribution to urban and regional freight transport, providing insights into its capacity and involvement in commercial activities. Operating mileage represents the distance covered by the system, and an increase in this metric typically signals an expanded service range, which is crucial for evaluating geographical coverage and interconnectivity.

The rate of growth in passenger numbers and smart payment system utilization rate are representative indicators of the social benefits associated with urban agglomeration interconnectivity. The growth in passenger numbers within the urban agglomeration rail transit system brings about positive impacts, including reduced traffic congestion, improved traffic safety, and decreased air pollution, leading to societal benefits. The increasing passenger numbers indicate a rising preference for sustainable rail transit, diminishing the demand for individual cars and contributing to the enhancement of urban traffic conditions. Concurrently, the widespread use of smart payment systems enhances payment efficiency, mitigates the impact of cash transactions on system operations, and improves the overall travel experience.

Based on the above, this study constructs the urban quality and line quality evaluation indicator systems as shown in Tables 1 and 2.

Table 1. Evaluation indicators of urban quality.

Aspect	Dimension	Indicators	Supporting References	AHP Weights	CRITIC Weights	Indicator Weights
Driving	Economic Driving	GDP per capita	Wang et al. (2022) [20]	9.01	4.79	6.90
	Social Driving	Urbanization rate	Mu et al. (2022) [41]	13.28	6.60	9.94
	Ecology Driving	Energy saving and environmental protection budget expenditure	Chen et al. (2021) [42]	3.55	4.09	3.82
Pressure	Economic Pressure	GDP growth year-on-year	Liu et al. (2020) [43]	3.51	8.73	6.12
	Social Pressure	Population Density	Zhao et al. (2021) [36]	4.32	7.72	6.02
	Ecology Pressure	Energy consumption per unit of GDP growth rate	Li et al. (2020) [44]	7.32	5.42	6.37
States	Economic States	Disposable income per capita	Chen and Whalley (2012) [3]	3.25	4.56	3.91
	Social States	Road area per capita	Sun et al. (2016) [45]	2.60	9.37	5.99
	Ecology States	Carbon emissions per capita	Lugaric and Krajcar(2016) [46]	11.00	7.12	9.06
Impact	Economic Impact	Share of tertiary industry	Chan et al. (2002) [47]	5.89	5.56	5.73
	Social Impact	Average noise value of transportation arteries	Peng et al. (2021) [48]	3.08	8.50	5.79
	Ecology Impact	Average annual concentration of PM2.5	Qiu et al. (2020) [49]	4.74	7.21	5.98
Response	Economic Response	Share of science and technology expenditure	Handy and Susan (2005) [50]	8.97	6.02	7.50
	Social Response	Number of employed persons in the transportation industry	Zhang et al. (2019) [51]	9.43	6.50	7.97
	Ecology Response	Urban greening coverage rate	Tirachini et al. (2013) [52]	10.05	7.82	8.94

Table 2. Evaluation indicators of line quality.

Aspect	Dimension	Indicators	Supporting References	AHP Weights	CRITIC Weights	Combined Weights
High-quality development of rail transit	Structure Scale	Number of lines	Chen et al. (2014) [53]	15.18	11.43	13.31
		Line density	Sekar et al. (2016) [54]	19.23	11.64	15.44
		Number of connected cities	Experts' suggestion	15.02	11.43	13.23
	Operational Performance	Total passenger transportation	Pan et al. (2017) [21]	9.29	9.40	9.34
		Cargo turnover	Gao et al. (2020) [55]	8.26	11.17	9.72
		Operating mileage	Hu et al. (2017) [56]	10.13	10.16	10.14
	Social Benefits	Rate of growth in passenger numbers	Chalumuri et al. (2017) [57]	7.40	18.86	13.13
		Smart payment system utilization rate	Experts' suggestion	15.49	15.91	15.70

3.4.3. Indicators Weight

The rationality of indicator weights plays a pivotal role in directly influencing the reliability and validity of evaluation results. Indicator weights can be determined using three categories of calculating methods: subjective weighting, objective weighting, and a combination of subjective–objective weighting [58]. To enhance the accuracy of indicator weights, this study employs the combined assignment method (AHP-modified CRITIC) [59]. The AHP-CRITIC method provides numerous advantages. The comprehensiveness of the assessment is bolstered by considering various factors, including expert judgments and overall system consistency. By effectively balancing subjective judgments with system objectivity, the method mitigates subjectivity and adeptly handles uncertainty. Furthermore, employing CRITIC to address potential inconsistencies in AHP results in reduced errors, improved consistency, and reliability of the entire assessment system. This demonstrates enhanced stability and trustworthiness in complex decision environments.

The steps of the hierarchical analysis method are shown below: (1) establish a hierarchical model, and decompose the relevant factors into multiple levels from top to bottom according to different attributes; (2) construct a judgment matrix, and score it using Santy's 1–9 scale method; (3) solve the matrix eigenvectors, and calculate the approximation value of the matrix eigenvectors by the square-root method; (4) test the consistency of the judgment matrix, and in this study, CR = CI/RI = 0.044 < 0.1, passing the one-time test.

The CRITIC method integrates the strengths of the evaluation indicators and conflicts between indicators to provide a comprehensive measure of objective indicator weights [60]. The steps for its determination are shown below: (1) Using the normalized data, the first step is to carry out the calculation of indicator variability, which is expressed in the form of standard deviation, and S_j represents the standard deviation of the jth indicator, as shown in Equation (3). (2) The second step is calculating the ability of indicators' conflict, expressed in the form of the correlation coefficient, R_j denotes the correlation coefficient between evaluation indicators i and j, as shown in Equation (3). (3) The third step is to calculate the amount of information, as shown in Equation (4), the larger the C_j is, the greater the role of the jth evaluation indicator in the indicator system, and the higher the weight of the indicator. Based on the above, the objective weight w_j of the jth indicator is determined, as shown in Equation (5).

$$\overline{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \tag{1}$$

$$\mathrm{S_j} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(x_{ij} - \overline{x}_j\right)^2}{n-1}} \tag{2}$$

$$R_{\mathrm{j}} = \sum_{\mathrm{i}=1}^{\mathrm{p}}\left(1 - \mathrm{r_{ij}}\right) \tag{3}$$

$$C_{\mathrm{j}} = S_{\mathrm{j}}\sum_{\mathrm{i}=1}^{\mathrm{p}}\left(1 - \mathrm{r_{ij}}\right) = S_{\mathrm{j}} \times R_{\mathrm{j}} \tag{4}$$

$$w_{\mathrm{j}} = \frac{C_{\mathrm{j}}}{\sum_{\mathrm{j}=1}^{\mathrm{p}} C_{\mathrm{j}}} \tag{5}$$

Integrated weighting method: the subjective and objective weights are $W_1 = \left(w_1^{\alpha}, w_2^{\alpha}, \cdots w_m^{\alpha}\right)^T$ and $W_1 = \left(w_1^{\beta}, w_2^{\beta}, \cdots w_m^{\beta}\right)^T$ respectively, then the linear weightings are derived from the combined indicator weight $W = (w_1, w_2, \cdots, w_m)^T$, and the combined weight of the jth indicator $W_{\mathrm{j}} = \alpha w_j^{\alpha} + \beta w_j^{\beta}$,where $j = 1, 2, \cdots, n; \alpha + \beta = 1$, and this study takes $\alpha = \beta = 0.5$, from which the combined weight of each indicator can be calculated.

3.4.4. Calculation of the Values of Urban Quality and Line Quality

Based on indicator weights determined by the AHP-CRITIC method, this study selects the TOPSIS method to score the urban quality and line quality separately to obtain the Q_{i} and L_{i} values, which is the foundation of evaluating the interconnectivity degree of the rail transis. The TOPSIS is a technique for ranking a finite set of evaluation objects based on their proximity to an idealized target [61]. It serves as a method for assessing the relative merits and demerits among existing alternatives by considering the degree of closeness between the evaluated objects and an idealized goal [62]. The key computational steps are as follows: (1) Create the evaluation matrix D, as shown in Equation (6) below; (2) Multiply the decision matrix D obtained above by each indicator weight w_j derived in the previous context to obtain the weighted decision matrix D_2, as shown in Equation (8) below; (3) Obtain the positive and negative ideal solutions by incorporating the aforementioned into the weighted decision matrix, i.e., identify the maximum and minimum values for each matrix column. Here, t_j^+ denotes the optimal solution for the j-th indicator, and t_j^- denotes the worst solution for the j-th indicator, as shown in Equations (9) and (10) below; (4) Compute the euclidean distance between each indicator and the optimal/worst solutions, as shown in Equations (11) and (12) below; (5) Combine the distances from optimal and worst points for each evaluation indicator, calculate the final scores, thus obtaining values for both urban quality Q_i and line quality L_i.as shown in Equations (13) and (14) below

$$D = \begin{bmatrix} \mathrm{r}_{11} & \cdots & \mathrm{r}_{1\mathrm{n}} \\ \cdots & \cdots & \cdots \\ \mathrm{r}_{\mathrm{m}1} & \cdots & \mathrm{r}_{\mathrm{mn}} \end{bmatrix} \tag{6}$$

$$t_{\mathrm{ij}} = w_{\mathrm{j}} \cdot \mathrm{r}_{\mathrm{ij}} \tag{7}$$

$$D_2 = \begin{bmatrix} w_1\mathrm{r}_{11} & \cdots & w_1\mathrm{r}_{1\mathrm{n}} \\ \cdots & \cdots & \cdots \\ w_{\mathrm{m}}\mathrm{r}_{\mathrm{m}1} & \cdots & w_{\mathrm{m}}\mathrm{r}_{\mathrm{mn}} \end{bmatrix} \tag{8}$$

$$\mathrm{t}_{\mathrm{j}}^{+} = \max\left\{w_{\mathrm{j}}r_{1\mathrm{j}}, \ldots w_j r_{mj}\right\} \tag{9}$$

$$\mathrm{t}_{\mathrm{j}}^{-} = \min\left\{w_{\mathrm{j}}r_{1\mathrm{j}}, \ldots w_j r_{mj}\right\} \tag{10}$$

$$S_{\mathrm{i}}^{+} = \sqrt{\sum_{\mathrm{j}=1}^{\mathrm{n}}\left(\mathrm{t}_{\mathrm{ij}} - \mathrm{t}_{\mathrm{j}}^{+}\right)^2} \tag{11}$$

$$S_{\mathrm{i}}^{-} = \sqrt{\sum_{\mathrm{j}=1}^{\mathrm{n}}\left(\mathrm{t}_{\mathrm{ij}} - \mathrm{t}_{\mathrm{j}}^{-}\right)^2} \tag{12}$$

$$Q_{\mathrm{i}} = \frac{s_i^-}{s_i^+ + s_i^-} \tag{13}$$

$$L_{\mathrm{i}} = \frac{s_i^-}{s_i^+ + s_i^-} \tag{14}$$

3.5. Evaluation of the Interconnectivity Degree of Rail Transits

In this study, the gravity model is modified guided by the space of flow theory and used to evaluate the interconnectivity degree of rail transits. The traditional quality is adjusted to the urban integrated quality M_i [3]. It refers to the capacity of individual cities to implement rail transit interconnectivity and is determined by the the combination of urban quality and line quality, as shown in Equation (15) below.

$$M_{\mathrm{i}} = Q_{\mathrm{i}} W_{\mathrm{qi}} * L_{\mathrm{i}} W_{\mathrm{li}} \tag{15}$$

The transportation distance R_{ij} is adjusted to the geometric mean of the shortest time T_{ij} and lowest cost C_{ij} of rail transit, as shown in Equation (16) below:

$$R_{\mathrm{ij}} = \sqrt{C_{\mathrm{ij}} \times T_{\mathrm{ij}}} \tag{16}$$

The spatial attractiveness and interconnections between districts are directional, and districts with a high comprehensive quality tend to be more attractive. This study adjusts the gravity coefficient by the urban integrated quality, as shown in Equation (17) below:

$$G_{\mathrm{i}} = \frac{M_{\mathrm{i}}}{M_{\mathrm{i}} + M_{\mathrm{j}}} \tag{17}$$

In summary, the modified gravity model is shown in Equation (18) below:

$$F_{\mathrm{ij}} = \frac{\left(Q_{\mathrm{i}} W_{\mathrm{qi}} + L_i W_{\mathrm{li}}\right) \times \left(Q_{\mathrm{j}} W_{\mathrm{qj}} + L_{\mathrm{j}} W_{\mathrm{lj}}\right)}{C_{\mathrm{ij}} \times T_{ij}} \times \frac{M_{\mathrm{i}}}{M_{\mathrm{i}} + M_{\mathrm{j}}} \tag{18}$$

In Equation (18), F_{ij} is the interconnectivity degree of rail transit between city i and city j; M_{i} is the the urban integrated quality of city i; Q_{i} is the urban quality of city i; L_{i} is the line quality of city i; W_{qi} and W_{li} are the weights of the city's urban quality and line quality, which are 0.6 and 0.4; C_{ij} and T_{ij} is the lowest cost and time of traveling between cities i and j. between city i and city j.

3.6. Exploration of the Spatial Structure of the Rail Transit Network

The SNA method is an important research method for exploring the formation of multiple relationships between cities. It views the relationships between nodes as the basic unit of analysis and the structure as the pattern of relationships between cities. The SNA can be divided into two analytical frameworks: egocentric networks and holistic networks, which can reflect both the individual's position in the network structure and also reveal the overall network structure characteristics of the whole network. Therefore, the study utilizes the SNA method and Ucinet 6.5 software to explore the spatial structure of the urban agglomeration, which is oriented by the element flows in the process of rail transit interconnectivity. It is measured in terms of density, centrality, and cohesive subgroups.

3.6.1. Overall Network Density

Network density is a fundamental concept in social network analysis, indicating the degree of correlation between nodes in the network, i.e., the probability of connection between nodes. The overall network density can take account of the interconnectivity degree within BTHRTN. The higher the BTHRTN density, the greater interconnectivity and cooperation. Its calculation formula is as follows:

$$D = \frac{\mathrm{m}}{\mathrm{n}(\mathrm{n}-1)} \tag{19}$$

In Equation (19), D represents the network density, m represents the total number of actual interconnections between cities, and n represents the total number of city nodes in the network.

3.6.2. Network Centrality

Centrality analysis aims to explore the urban status and rights in the network. The measurements include three aspects: degree centrality, betweenness centrality, and closeness centrality.

Degree centrality. It is a measure of the nodes' significance in the network, as shown in Equation (20). A higher centrality value indicates that the node city occupies a more central position within BTHRTN.

$$C_D(c_i) = \frac{ID(c_i) + OD(c_i)}{2(\mathrm{n} - 1)} \tag{20}$$

In Equation (19), $ID(c_i)$ represents the indegree of city I, $OD(c_i)$ represents the outdegree of city i.

Closeness centrality. Closeness centrality, also known as overall centrality, refers to the degree of closeness between cities within BTHRTN, and determines the city's control capacity over other members within BTHRTN, as shown in Equation (20).

$$C_C(c_i) = \frac{\sum_{\mathrm{j<k}} g_{jk}(c_j)/\mathrm{g_{jk}}}{(\mathrm{n} - 1)(\mathrm{n} - 2)} \tag{21}$$

In Equation (21), $g_{jk}(c_j)$ represents the ability of city i to control city j.

Betweenness centrality. It is the number of times a node acts as an intermediary between two other nodes within BTHRTN, as shown in Equation (21). A higher betweenness centrality value indicates a closer interconnectivity degree between the core city and non-core cities within BTHRTN.

$$C_{\mathrm{B}}(c_i) = \frac{(\mathrm{n} - 1)}{\sum_{\mathrm{j=1}}^{\mathrm{n}} \mathrm{d_i}(c_i, c_j)} \tag{22}$$

In Equation (22), $d_i(c_i, c_j)$ represents the number of lines involved in the connection between city i and city j.

3.6.3. Cohesive Subgroup

Cohesive subgroups refer to the actors in a network that have direct, frequent, strong, and active links or communications. Cohesive subgroup analysis can identify relative groups among cities, i.e., cities with relatively dense relationships and strong ties. Cohesive subgroups in the networks are essential for delineating the internal structure of the urban agglomerations. Based on this method, we can determine the number of these subgroups and their specific members, as well as analyze the relationship and interaction patterns among them. These provide valuable insights into the development dynamics of urban agglomeration networking from a holistic perspective.

4. Results and Analysis

Rail transit, as a key component of the transportation network, has greatly facilitated the integration of transportation within urban agglomerations. It facilitates the unrestricted movement of diverse production factors across urban agglomerations, directing them towards advantageous areas and thereby improving resource allocation efficiency. Given this context, the rapid construction of a rail transit interconnectivity system, aligned with societal demands and regional spatial planning, is vital for promoting the sustainable development of urban agglomerations. To fulfill the research objectives, this study takes the BTH urban agglomeration as a case study and analyzes the spatio-temporal evolution of rail transit interconnectivity in the BTH urban agglomeration in terms of node cities, rail transit lines, and the rail transit network. The results and analysis are shown as follows.

4.1. Node Cities Characteristics within BTHRTN

Utilizing Equation (15), this study computes the urban integrated quality values for the years 2010 to 2021 within the BTH urban agglomeration, as shown in Table 3. This analysis illustrates the distinctive characteristics of these pivotal urban nodes, which play a foundational role in understanding the cities' roles and influence in the BTHRTN.

Table 3. The values of the urban integrated quality.

Region	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
Beijing	0.59	0.58	0.61	0.64	0.69	0.71	0.71	0.74	0.76	0.77	0.71	0.73	0.687
Tianjin	0.47	0.49	0.50	0.50	0.50	0.53	0.53	0.55	0.60	0.63	0.60	0.60	0.542
Shijiazhuang	0.41	0.43	0.41	0.41	0.44	0.49	0.53	0.56	0.52	0.54	0.55	0.58	0.489
Zhangjiakou	0.26	0.26	0.27	0.28	0.30	0.32	0.33	0.35	0.41	0.44	0.43	0.44	0.341
Chengde	0.28	0.28	0.29	0.29	0.32	0.32	0.34	0.36	0.39	0.41	0.42	0.43	0.345
Qinhuangdao	0.37	0.36	0.32	0.39	0.40	0.38	0.40	0.41	0.46	0.46	0.44	0.48	0.406
Tangshan	0.37	0.35	0.37	0.37	0.39	0.38	0.41	0.42	0.47	0.46	0.44	0.50	0.412
Cangzhou	0.31	0.29	0.31	0.32	0.34	0.34	0.35	0.37	0.42	0.43	0.44	0.45	0.364
Hengshui	0.32	0.32	0.32	0.35	0.37	0.38	0.39	0.40	0.42	0.42	0.44	0.46	0.381
Langfang	0.35	0.35	0.37	0.37	0.38	0.39	0.42	0.45	0.49	0.50	0.50	0.52	0.424
Baoding	0.40	0.39	0.38	0.40	0.42	0.43	0.43	0.47	0.48	0.49	0.51	0.54	0.445
Xingtai	0.35	0.35	0.35	0.35	0.39	0.39	0.39	0.43	0.47	0.47	0.46	0.48	0.407
Handan	0.41	0.43	0.43	0.43	0.50	0.45	0.45	0.46	0.50	0.50	0.49	0.52	0.463
Dingzhou	0.38	0.37	0.37	0.44	0.46	0.47	0.40	0.41	0.47	0.46	0.46	0.50	0.432
Xinji	0.30	0.29	0.29	0.31	0.33	0.33	0.36	0.37	0.41	0.43	0.42	0.46	0.360
Anyang	0.34	0.33	0.36	0.36	0.37	0.38	0.39	0.43	0.44	0.44	0.45	0.47	0.397
Mean	0.369	0.369	0.372	0.388	0.412	0.417	0.427	0.450	0.481	0.490	0.485	0.511	

From an aggregate viewpoint of the BTH urban agglomeration, the mean values of overall urban integrated quality exhibit a noticeable upward trend, with values of 0.369 (2010), 0.412 (2014), 0.481 (2018), and 0.511 (2021). The largest change in sequential growth rate appeared in 2014 and 2016. This phenomenon may be attributed to the formal proposal of the BTH coordinated development strategy in 2014 and the initial proposal of constructing the "BTH on the track" in December 2015. The mean values for 2018 and 2020 decreased compared to the previous year, corresponding to the global financial crisis in 2018 and the outbreak of the pandemic in December 2019. From the individual perspective of the 16 node cities, the mean values across the period from 2010 to 2021 exhibit notable distinctions. Beijing claims the top position with a mean of 0.69, doubling the value of the last-ranked city, Zhangjiakou (0.341). Tianjin and Shijiazhuang closely trail Beijing and surpass most other cities significantly. This suggests that Beijing, Tianjin, and Shijiazhuang lead as top cities with elevated urban integrated quality in the BTH urban agglomeration, demonstrating enhanced capabilities and attractiveness for interconnection with other cities. In Hebei Province, Qinhuangdao, Tangshan, Langfang, Baoding, Handan, Xingtai, and Dingzhou closely resemble each other with high mean values of urban integrated quality. Particularly noteworthy is Handan's fourth position, leveraging evident geographical advantages as a national railway hub. Positioned strategically within the BTH urban agglomeration and surrounded by the three major economic circles in China, Handan holds a key status across four provinces, manifesting substantial overall influence.

In summary, the figures for BTH urban integrated quality vary at the spatial level but increase at the temporal level. It is characterized by the gradual evolution of the "Beijing-Tianjin double-core" pattern to the "Beijing-Tianjin-Shijiazhuang (weak) triple-core" pattern.

4.2. Interconnectivity Degree of BTHRTN

Utilizing Equation (18), this study calculates the interconnectivity degree of rail transits in the BTH urban agglomeration and constructs gravity matrices for the years 2010 to 2021. The results are uniformly processed. If the processed rail transit interconnectivity values remain below one, it indicates a weak connection, and these values are recorded as zero. Due to space limitations, the calculation results for 2010, 2014, 2018, and 2021 are presented in the supplementary materials. The spatio-temporal change trend of the interconnectivity degree among the 16 node cities within BTHRN from 2010 to 2021 is illustrated in Figure 4.

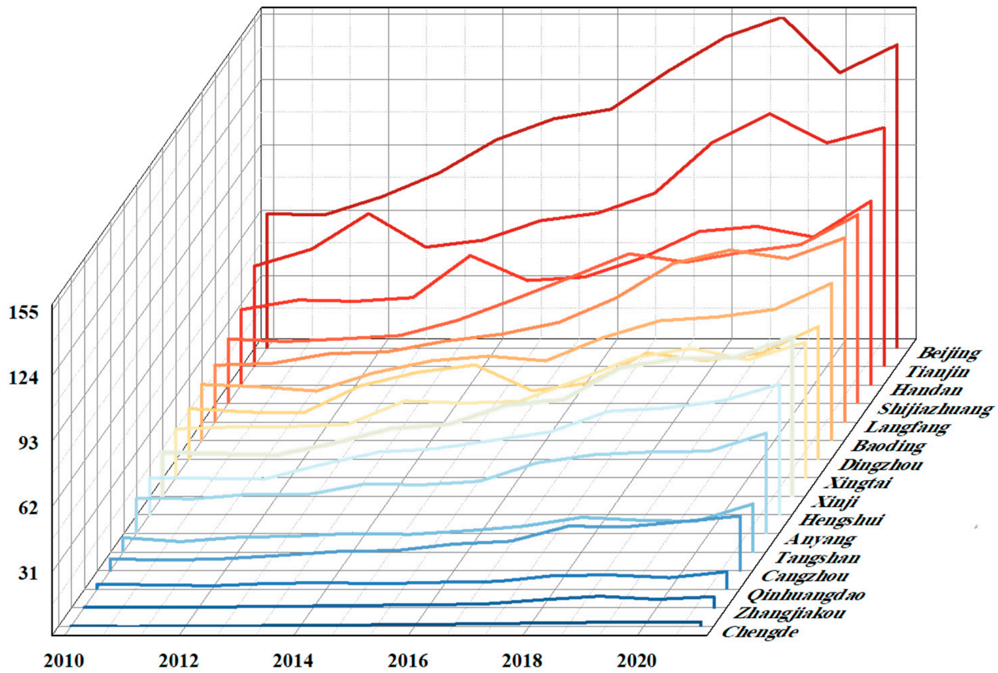

Figure 4. The total values of the interconnectivity degree of 16 cities from 2010 to 2021.

To further evaluate rail transit interconnectivity, this study employs the natural breakpoint method in ArcGIS to categorize the results from 2010 to 2021 into four levels (0–5, 6–15, 16–30, 30–72); the urban integrated quality of node cities is categorized into four degrees (0–0.4, 0.4–0.5, 0.5–0.6, and 0.6–0.7). Furthermore, the XY to Line tool in ArcGIS is employed to visually represent the BTHRTN based on the gravity matrix data, as depicted in Figure 5.

The spatio-temporal characteristics of BTHRTN interconnectivity degree are summarized through a combined analysis of Table 4, Figures 3 and 4:

(1) Between 2010 and 2021, the interconnectivity degree of the BTHRTN displays an uneven pattern characterized by spatial polarization. Figure 4 depicts significant regional discrepancies in the interconnectivity degree within the BTHRTN. Development imbalance continues among Beijing, Tianjin, Shijiazhuang, and other non-core cities, indicating a spatial pattern of "three cores and weak overall" in the BTH urban agglomeration. Using 2021 as an example and referring to Table 4, Beijing occupies an absolute core position in the BTH urban agglomeration. Its mean interconnectivity degree is twice the overall average degree of the BTH agglomeration and 19 times higher than Zhangjiakou, the city with the lowest degree. It is apparent from Figure 5 that the high interconnectivity degrees exist between cities with high urban integrated quality and their neighboring cities. Cities with lower urban integrated quality, such as Zhangjiakou, Chengde, Qinhuangdao, and Hengshui, fail to make strong connections with cities beyond the core cities. Consequently, in the evolution of interconnectivity within the BTHRTN, a small number of node cities bear the majority of the transmission pressure.

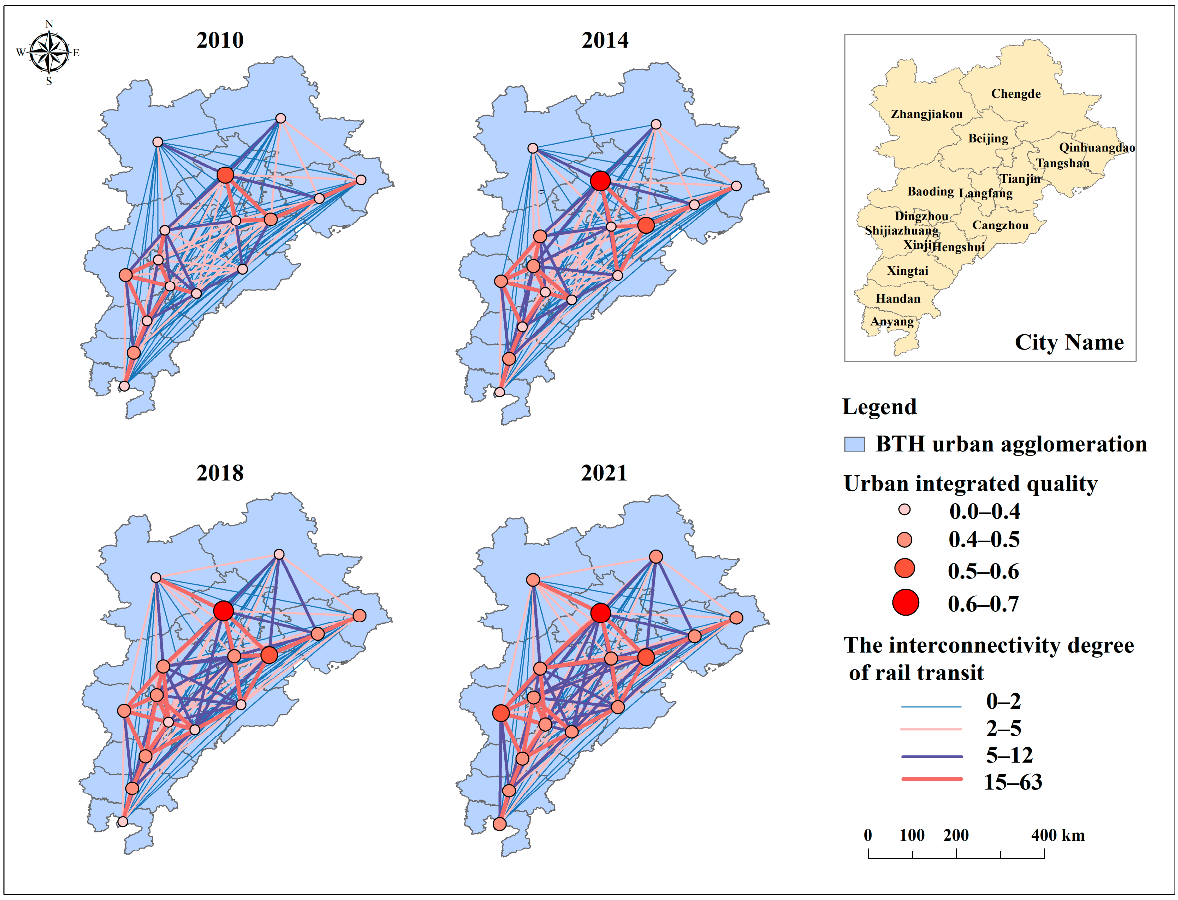

Figure 5. The interconnectivity degree of rail transit in the BTH urban agglomeration.

(2) Since 2010, the overall interconnectivity degree of the BTHRTN has been increasing, and the growth rates of individual cities are coordinated. Figure 4 provides detailed data on the total values of interconnectivity degree within the BTHRTN over the study period. In the temporal perspective, the overall degree in 2010 is 1.7 times higher than that in 2021, which demonstrates that the interconnectivity degree of the BTHRTN has significantly improved. The five years 2014, 2017, 2018, and 2021 are the fastest growing years with a high growth of 15%. This phenomenon is similar to the evolution of urban integrated quality, which indicates the coordinated development between rail transit and cities. In the spatial perspective, 12 cities have a year-on-year growth rate higher than the average degree of the BTH urban agglomeration. This indicates that the improvement in interconnectivity degree among most cities in the BTH urban agglomeration is a result of collaborative efforts. Beyond that, as shown in Figure 4, all 16 cities experienced varying degrees of fluctuations from 2010 to 2021. Langfang and Chengde are the two cities with the least fluctuations and low interconnectivity degree.

(3) As of 2021, the foundational spatial structure of the "BTH on the track" has consolidated, with Beijing, Tianjin, and Shijiazhuang functioning as the three core hubs. Figure 5 illustrates the establishment of a rail transit interconnectivity network around these core cities throughout the study period. The changes in node size and line thickness in Figure 5 depict the central role of Beijing, Tianjin, and Shijiazhuang, radiating outward and fostering the interconnectivity of neighboring cities. The interconnectivity degree of Beijing, Zhangjiakou, Chengde, and Tangshan has significantly improved. Likewise, the southern region, centered around Shijiazhuang, has consistently improved in interconnectivity, a change more pronounced than in the region with Beijing and Tianjin at its cores. This change emphasizes the marginal influence

of rail transit conduction. The most intriguing aspect in Figure 5 is the relationship between the advancement of rail transit interconnectivity and the integrated quality of urban areas. When examined in conjunction with the results in Section 4.1, it becomes clear that the advancement in urban integrated quality and the augmentation of rail transit interconnectivity mutually reinforce each other. Essentially, the BTH urban agglomeration exemplifies a pattern of integrated development. This phenomenon emphasizes the importance of researching the coordinated development between transportation and cities, suggesting a fertile area for further exploration.

Table 4. Network density.

	2010	**2014**	**2018**	**2021**
Study area	0.322	0.408	0.523	0.617

4.3. Spatial Structure Evolution of BTHRTN

Based on the gravity matrix data calculated by the modified gravity model, this study selects four-year panel data (2010, 2014, 2018, and 2021), and uses SNA and Ucinet 6.5 software to explore the spatial structure of the BTHRTN in terms of network density, centrality, and cohesive subgroups.

4.3.1. Centrality Analysis

In Table 4, the density of the BTHRTN demonstrates an overall increase trend, which shows that the interconnectivity degree of the BTHRTN generally improves, and its spatial structure becomes closer.

4.3.2. Centrality Analysis

Given that the BTHRTN is directional, the urban centrality is divided into indegree and outdegree for analysis. The indegree indicates how much the city is influenced by other cities, and the outdegree indicates the city's capability to influence other cities.

(1) Degree centrality

The calculation results of degree centrality are shown in Table 5. From the temporal perspective, both the indegree and outdegree show improvement, particularly from 2014 to 2018. When comparing the urban outdegree, Beijing's outdegree surpasses the average value, which indicates Beijing's absolute core position within the BTHRTN. Beijing can make it the primary driving force for overall rail transit interconnectivity. The urban outdegree has increased on average by a factor of 2.02, indicating the growing significance and influence of each city, and their interconnectivity degree has significantly enhanced. In particular, the degree of six cities, namely, Zhangjiakou, Chengde, Cangzhou, Hengshui, Langfang, and Xinji are much higher than the average degree of the BTH urban agglomeration, and their disparities with other cities in the BTHRTN are narrowing. When comparing the urban indegree, cities with high outdegree tend to also possess high indegree (Figure 6). The indegree of Tianjin and Langfang is higher than other cities. The two cities can make full use of the spillover effect from Beijing and are more frequently interconnected with other cities. It is worth noting that Shijiazhuang, the provincial capital of Hebei Province, shows a rising trend year by year. However, it still lags behind Baoding and Handan. This phenomenon indicates its hub position within the BTHRTN has been weakened. When comparing the indegree and outdegree, the outdegree of the five cities, namely Beijing, Tianjin, Shijiazhuang, Langfang, and Handan, is always greater than their indegree (Figure 6). This evidences that the five cities have an obvious diffusion effect, and their influence on other cities surpasses those cities' influence on themselves. The other cities in Hebei Province and Anyang consistently exhibit a phenomenon where the outdegree is lower than the indegree (Figure 6). These cities are more dependent on the interconnectivity radiation from the five cities centered on Beijing and Tianjin.

Table 5. The values of the degree centrality in the BTH agglomeration.

City	2010		2014		2018		2021	
	Indegree	Outdegree	Indegree	Outdegree	Indegree	Outdegree	Indegree	Outdegree
Beijing	41.57	64.65	58.95	99.81	96.93	148.46	104.63	144.78
Tianjin	43.73	48.60	59.07	60.98	97.69	107.27	105.80	114.33
Shijiazhuang	27.57	31.73	37.78	40.50	59.91	68.14	76.27	90.65
Zhangjiakou	2.87	1.27	4.56	2.01	9.45	4.87	9.74	6.37
Chengde	2.27	1.01	3.46	1.60	5.16	2.63	7.20	3.18
Qinhuangdao	3.71	3.30	5.65	4.12	9.06	5.68	10.11	9.45
Tangshan	8.76	7.88	12.21	9.90	21.08	17.54	26.65	24.00
Cangzhou	10.52	6.66	14.62	10.26	29.13	20.63	34.49	26.99
Hengshui	19.38	18.70	32.44	30.89	55.38	48.50	66.90	63.12
Langfang	41.33	28.11	58.26	39.45	99.12	76.27	105.85	88.45
Baoding	28.74	27.84	44.37	38.86	61.57	58.00	75.86	75.81
Xingtai	27.43	24.28	45.08	37.51	61.85	56.17	72.32	65.41
Handan	32.07	36.80	48.31	62.47	70.56	73.92	82.78	88.40
Dingzhou	27.31	25.17	40.36	42.33	56.12	51.58	70.49	64.03
Xinji	28.15	21.99	41.36	33.34	69.58	62.18	88.19	76.80
Anyang	20.35	17.71	32.17	24.55	44.78	38.56	53.15	48.65
Mean	22.86	22.86	33.67	33.66	52.53	52.53	61.90	61.90
Network Centralization (Indegree)	7.07		5.67		6.65		6.46	
Network Centralization (Outdegree)	14.15		14.77		13.75		12.183	

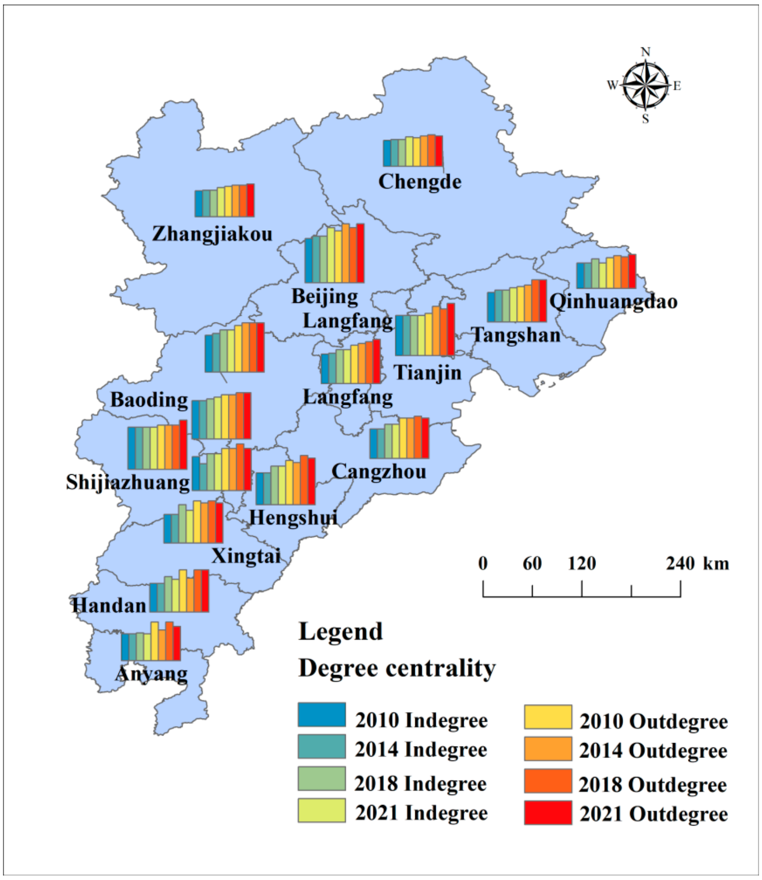

Figure 6. Degree centrality map.

Network centralization refers to the overall centrality of the network. The closer the value is to 100%, the more centralized the network becomes. In Table 5, the overall central potential of indegree and outdegree demonstrates a decreasing trend, indicating that there are imbalances and asymmetries of interconnectivity within the BTHRTN. In summary, Beijing, Tianjin, and Langfang occupy the central positions of the BTHRTN, along with obvious regional differences.

(2) Closeness centrality

The calculation results of closeness centrality are shown in Table 6. The higher values represent the closer connections between cities within the BTHRTN, and the less possibility to be controlled by other cities in the interconnectivity process. From Table 6, the mean values of both incloseness and outcloseness demonstrate an overall increase trend, which indicates that the interconnectivity degree of the BTHRTN is getting higher and the flow of people, logistics, and information is rapidly accelerating. From the node cities' perspective (Figure 7), the discrimination between incloseness and outcloseness of each city demonstrates an overall decrease trend, indicating that the distribution of closeness centrality between cities tends to be balanced over time, and the overall interconnectivity degree within the BTHRTN is gradually increasing. Before 2014, Beijing, Tianjin, and Shijiazhuang consistently wielded substantial influence over other cities. After 2014, the interconnectivity degree of Hengshui, Langfang, Baoding, Xingtai, and Handan has experienced a notable increase. On the other hand, Zhangjiakou, Chengde, and Qinhuangdao are always in the stage of lower connection and are easily controlled by the core cities.

Table 6. The values of the closeness centrality.

City	2010		2014		2018		2021	
	Incloseness	**Outcloseness**	**Incloseness**	**Outcloseness**	**Incloseness**	**Outcloseness**	**Incloseness**	**Outcloseness**
Beijing	75.00	78.95	78.95	93.75	88.24	100.00	93.75	100.00
Tianjin	68.18	68.18	68.18	68.18	71.43	83.33	78.95	88.24
Shijiazhuang	71.43	71.43	71.43	71.43	75.00	75.00	75.00	83.33
Zhangjiakou	44.12	45.46	45.46	50.00	51.72	53.57	53.57	55.56
Chengde	44.12	45.46	45.46	50.00	48.39	51.72	53.57	51.72
Qinhuangdao	42.86	42.86	50.00	42.86	51.72	55.56	53.57	57.69
Tangshan	50.00	53.57	53.57	57.69	60.00	62.50	71.43	71.43
Cangzhou	50.00	50.00	57.69	57.69	68.18	68.18	71.43	68.18
Hengshui	53.57	53.57	65.22	65.22	75.00	71.43	83.33	78.95
Langfang	50.00	51.72	57.69	57.69	65.22	68.18	71.43	75.00
Baoding	62.50	65.22	71.43	71.43	78.95	83.33	83.33	83.33
Xingtai	48.39	48.39	65.22	55.56	71.43	68.18	71.43	68.18
Handan	48.39	48.39	60.00	55.56	71.43	57.69	71.43	71.43
Dingzhou	65.22	65.22	68.18	71.43	75.00	75.00	78.95	78.95
Xinji	57.69	45.46	62.50	62.50	71.43	71.43	78.95	71.43
Anyang	45.46	45.46	46.88	45.46	65.22	51.72	65.23	57.69
Mean	54.81	54.96	60.49	61.03	68.02	68.55	72.21	72.57
Network in-Centralization	44.62		40.78		44.66		47.60	
Network out-Centralization	53.01		72.30		69.48		60.61	

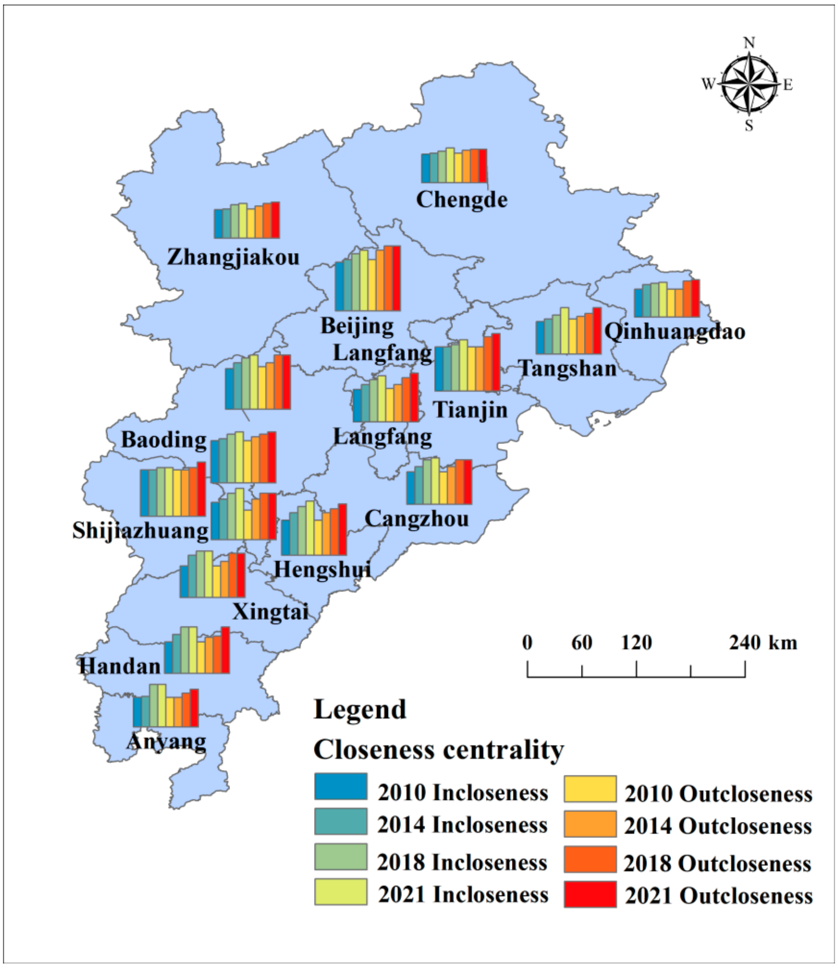

Figure 7. Closeness centrality map.

To summarize, by 2021, Beijing, Tianjin, Shijiazhuang, and Baoding together form a core circle with close ties and are radiating the others' urban development while also promoting the connection between other cities.

(3) Betweenness centrality

Table 7 displays the results of betweenness centrality. A high value signifies increased control over interconnectivity and a more pivotal position within the BTHRTN. From Table 7 and Figure 8, first, there is a significant disparity in betweenness centrality values among cities in the BTH agglomeration. Second, the overall betweenness centrality values show a decreasing trend throughout the study period. These observations suggest a gradual reduction in the role of intermediary cities in the network, allowing cities to engage in direct interconnectivity more effectively. Beijing, Tianjin, Shijiazhuang, Baoding, and Dingzhou function as prominent hubs, enhancing the interconnectivity of the BTHRTN and serving as crucial bridges to other cities. In contrast, Zhangjiakou, Chengde, Qinhuangdao, and Anyang consistently maintain a betweenness centrality value of zero, indicating their marginalization and isolation.

Table 7. The values of the betweenness centrality.

City	2010	2014	2018	2021
Beijing	87.62	82.61	62.14	43.50
Tianjin	40.16	21.12	14.00	17.89
Shijiazhuang	44.98	17.47	5.86	4.64

Table 7. *Cont.*

City	2010	2014	2018	2021
Zhangjiakou	0.00	0.00	0.00	0.00
Chengde	0.00	0.00	0.00	0.00
Qinhuangdao	0.00	0.00	0.00	0.00
Tangshan	5.37	4.05	2.09	4.02
Cangzhou	0.00	2.55	3.07	2.28
Hengshui	1.60	8.12	3.26	5.03
Langfang	0.33	1.37	5.70	7.35
Baoding	11.78	12.51	10.95	6.09
Xingtai	1.33	4.39	2.29	0.74
Handan	1.33	3.21	0.91	1.43
Dingzhou	16.48	8.94	7.85	4.64
Xinji	1.00	1.65	3.89	3.38
Anyang	0.00	0.00	0.00	0.00

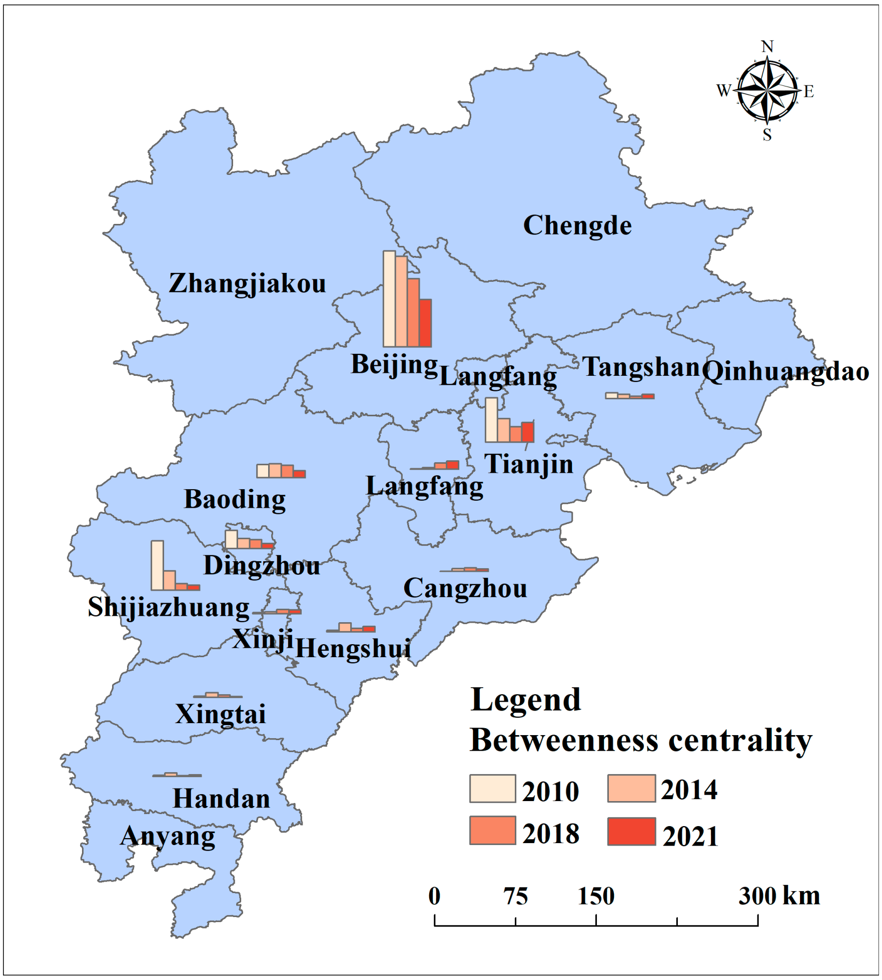

Figure 8. Betweenness centrality map.

4.3.3. Cohesive subgroup analysis

This study employs the Convergence of Iterative Correlations (CONCOR) method in Ucinet 6.5 software to examine the correlations among cities within the BTHRTN. The analysis is conducted with a maximum cut depth of three, achieving an R-squared value of 0.7 or higher. Figures 8 and 9 illustrate the division of the BTH urban agglomeration into four secondary cohesive subgroups and eight tertiary cohesive subgroups.

Some secondary cohesive subgroups have experienced significant changes in membership from 2010 to 2021. The original subgroups shifted from a single-core subgroup centered around Beijing to a dual-core subgroup involving both Beijing and Tianjin. This evolution results in progressively closer connections among the cities surrounding Beijing, including Zhangjiakou, Chengde, and Langfang. Changes in the first subgroup also influence the second subgroup, enhancing interconnectivity in the eastern part of the BTH urban agglomeration. Conversely, the third and fourth subgroups remained stable throughout the same period. In summary, Figure 9 clearly shows that the spatio-temporal evolution of the BTHRTN exhibits characteristics of integration and stability.

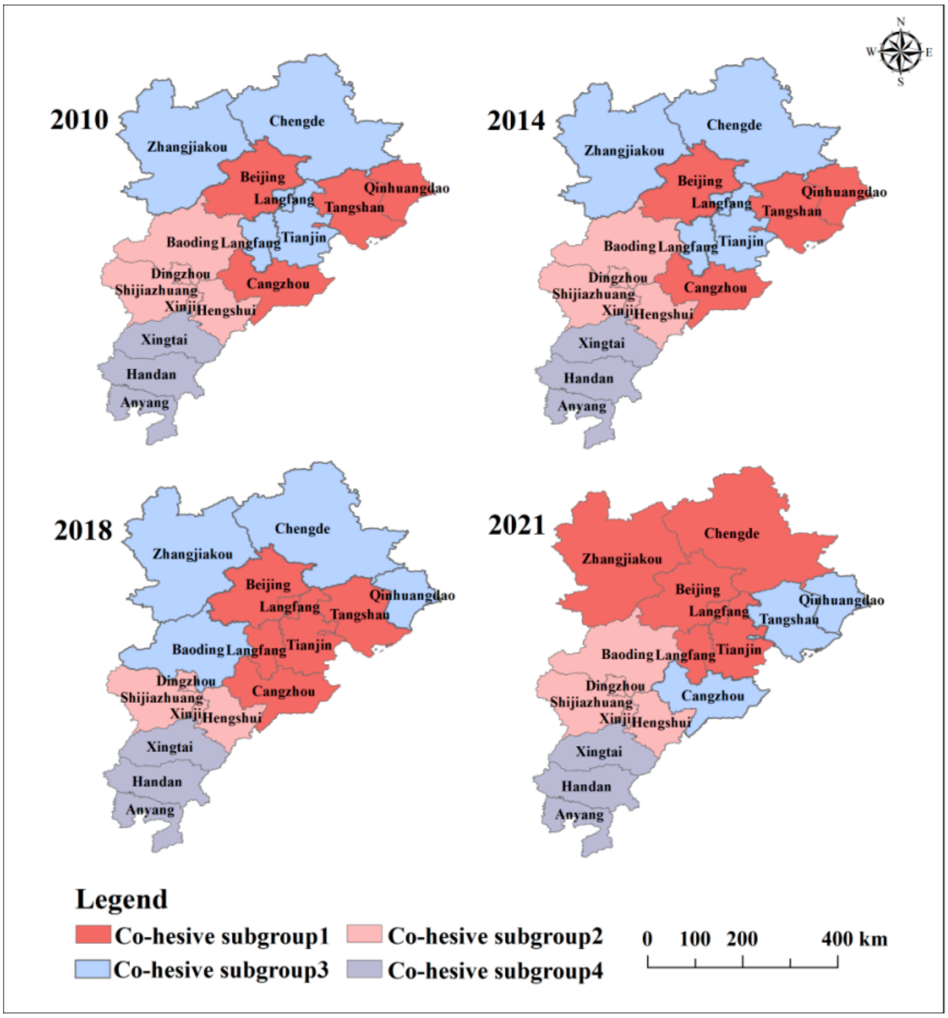

Figure 9. The secondary cohesive subgroups members.

Within the tertiary cohesive subgroups, the number of stable relationship pairs increased from 2010 to 2014. However, only one cohesive subgroup formed among Shijiazhuang, Hengshui, and Xinji. In 2018, a subgroup emerged comprising Beijing, Tianjin, Langfang, and Cangzhou. In 2021, a subgroup consisting of Beijing, Tianjin, and Langfang was formed, building upon the configuration established in 2018. In summary, Figure 10 reveals relatively stable interaction patterns among cities, characterized by a high number of relationship pairs but a limited number of stable cohesive subgroups. There is a need to enhance collaborative development.

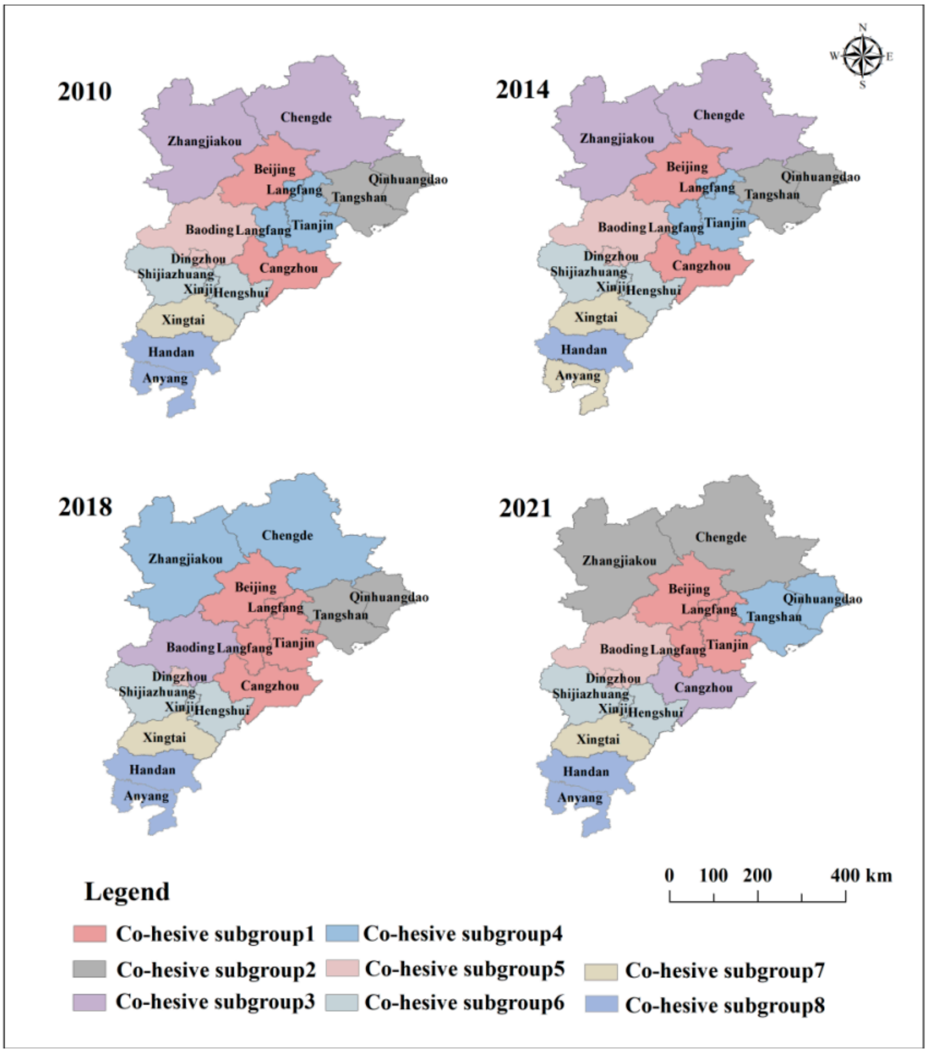

Figure 10. The tertiary cohesive subgroups members.

5. Discussion

5.1. Discussion

This study takes the BTH urban agglomeration as a case study and constructs a framework to evaluate rail transit interconnectivity and explore the network's spatial structure of the BTH urban agglomerations. This framework is designed to integrate three methods: multi-attribute decision-making, improved gravity models, and social network analysis. In the enhancement of the gravity model, the AHP-CRITIC method is employed in this study to determine indicator weights, and the TOPSIS method is utilized to calculate model parameter values. Through the process of this framework, a more comprehensive investigation into the rail transit interconnectivity of urban agglomerations can be conducted, with a focus on the characteristics of node cities, the degree of rail transit interconnectivity, and the spatial structure of the BTHRTN. This facilitates a more thorough analysis of the spatio-temporal evolution characteristics of rail transit interconnectivity in urban agglomerations, providing a more robust basis for spatial planning. The above analysis reveals the complex evolutionary characteristics of rail transit in the BTH agglomeration. These insights are crucial for advancing research in regional rail transit construction and the spatial planning of urban agglomerations. Furthermore, the discussion of our priority findings is shown as follows:

(1) The uneven pattern and spatial disparities in the interconnectivity degree of rail transits. One significant importance of urban agglomeration development is to pro-

mote regional integration, address the issue of imbalanced regional development, and leverage the development of core cities to better drive the development of peripheral cities. However, in this study, we uncovered significant inequalities in rail transit interconnectivity across the BTHRTN. Core cities such as Beijing, Tianjin, and Shijiazhuang play central roles, while non-core cities demonstrate lower rail transit interconnectivity. Imbalances and asymmetries persisted throughout the study period within the BTHRTN. The spatial configuration, characterized by "three hubs and numerous weak links," indicates that rail transit burdens are concentrated in a few core cities. This emphasizes the urgent need to optimize resource allocation to address these disparities. This finding is consistent with existing research, as most studies suggest that the current urban agglomeration is in a three-core stage, although some argue that it may still be in a two-core stage [15]. Nevertheless, regardless of the stage, the status of Shijiazhuang within the urban agglomeration needs further enhancement. Initiatives aimed at enhancing the interconnectivity of non-core cities should be informed by this critical insight. Strategically allocating resources and investments can effectively foster the development of a more balanced and integrated rail transit network within the BTHRTN.

(2) The evolution of the relationship between rail transit interconnectivity and urban development. Data analysis uncovers a correlation between cities with high interconnectivity degrees and superior urban integrated quality. Cities with lower urban integrated qualities, such as Zhangjiakou, Chengde, Qinhuangdao, and Hengshui, show relatively weaker interconnectivity with non-core cities. This connection emphasizes the importance of simultaneously considering both transportation and urban development in urban planning and rail transit construction. These findings mirror those of Fang et al. [2], who also observed a positive correlation between network spatial connectivity and the hierarchy of cities in the urban agglomeration. In the future, delving deeper into the mechanisms of this mutual relationship and exploring ways to better integrate them will be essential.

(3) The role of rail transit interconnectivity in shaping the spatial structure of urban agglomerations. Despite the uneven development and significant disparities in rail transit interconnectivity, interestingly, exploration of the BTHRTN structure evolution guided by the space of flows theory suggests that rail transit construction enhances the interconnectivity, integration, and stability of the spatial structure in the urban agglomeration. Additionally, this study highlights a specific challenge: limited improvement in polycentricity, indicating a potential area for further exploration and targeted interventions. This finding aligns with other studies linking rail transit with urban spatial structure [63]. This could be attributed to various factors, including the incomplete nature of the railway network, insufficient investments, and competition from other modes of transportation. Nevertheless, rail transit interconnectivity is considered a potential mechanism driving the polycentric development of urban agglomerations. Therefore, future research should focus on enhancing rail transit interconnectivity to foster a more balanced and sustainable polycentric development within urban agglomerations.

5.2. Suggestion

Through a detailed analysis of the BTHRTN's interconnectivity and spatial structure, customized recommendations are proposed to address issues with rail transit interconnectivity and facilitate the development of spatial integration in urban agglomerations.

(1) Focusing on spatial disparities in the interconnectivity degree of rail transits at the urban agglomeration scale. This disparity arises from varying urban capacities to attract and radiate the exchange of element flows with other cities. The key to alleviating this situation lies in addressing the disequilibrium in the urban integrated quality. It is necessary to implement national-level policies that foster a balanced allocation of traffic resources. Moreover, it is necessary to promote coordination

between northern and southern BTH regions, leverage the advantages of the north, especially Beijing's capital and policies, and recognize its leadership role. Additionally, it is recommended to concentrate on increasing the network density of rail transits and expanding the length of rail transit lines as well as the overall network scale.

(2) Enhancing polycentric development in the rail transit network to elevate the status of non-core cities. The existing BTHRTN comprises three core cities: Beijing, Tianjin, and Shijiazhuang. Although these three cities exert a growing influence on nearby cities through their radiation effects, the overall interconnectivity degree remains relatively weak. Therefore, the urban planning sector must promote the trend toward a polycentric development pattern and enhance the interconnectivity of non-core cities. To achieve this goal, it is necessary to elevate the status and transportation hubs of Tianjin and Shijiazhuang. The construction of a "1 h functional circle" in Hebei Province can enhance the interconnectivity degree of non-core cities. Moreover, the BTH urban agglomeration should draw valuable insights and best practices from both domestic and international urban agglomerations, particularly in areas related to legal protection, urban planning and construction, and route coordination [64].

(3) Developing tailored policies for rail transit interconnectivity based on different city statuses. Cities occupy various geographic locations in rail transit networks and perform distinct functions. Therefore, it is imperative to implement more accurate and differentiated policies that suit local circumstances. Cities acting as communication hubs and less susceptible to the influence of nearby cities must fully leverage their intermediary roles. This entails strengthening the bidirectional spillover effects across regions and enhancing urban interconnectivity frequencies. Furthermore, policymakers should prioritize enhancing intelligent services and resilience in key nodal cities to improve the overall robustness of rail transit networks within urban agglomerations, thus promoting sustainability.

6. Conclusions

With rapid urbanization and expansion, researchers and policymakers are increasingly interested in the spatial relationship between rail transport development and regional spatial planning. In this study, an initial objective of the project is to determine the impact of the rail transit interconnectivity on the regional spatial structure in urban agglomerations to optimize the spatial planning for sustainable urban agglomeration development. This study innovatively employs a framework combining AHP-CRITIC, TOPSIS method, gravity model, ArcGIS, and SNA method to evaluate rail transit interconnectivity and explore the network's spatial structure at the urban agglomeration scale, considering multi-element flows. The contribution of this study can inform policy development for rail transit interconnectivity and spatial optimization in urban agglomerations. Additionally, the study draws the following conclusions:

(1) The interconnectivity degree of rail transit in the BTH urban agglomeration exhibits an uneven pattern known as "three cores and numerous weak links," characterized by spatial polarization. Over the study period, the figures for the interconnectivity degree of rail transits reveal persistent regional disparities between core and non-core cities. Beijing, Tianjin, and Shijiazhuang firmly occupy the core positions in the BTHRTN, while non-core cities like Zhangjiakou, Chengde, and Qinhuangdao have limited connections with cities beyond the cores. Analysis of BTHRTN characteristics indicates a decreasing trend in centralization, emphasizing imbalances and asymmetries in rail transit interconnectivity within the BTH urban agglomeration.

(2) From 2010 to 2021, the interconnectivity degree of rail transit in the BTH urban agglomeration experiences significant growth and shows a coordinated development trend. The total interconnectivity degree of the BTH urban agglomeration has risen by 82% from 2010 to 2021. The network density of the BTHRTN has consistently grown over the study period. Figures for incloseness and outcloseness are on the rise, while their disparity is decreasing. These findings suggest an overall increase in

the interconnectivity degree of the BTHRTN, accompanied by a narrowing disparity between cities. The central region, led by Beijing, and the southern region, with Shijiazhuang as the focal point, are actively fostering synergy in the BTH urban agglomeration through two high-degree interconnectivity corridors: "Beijing-Tianjin-Longfang" and "Beijing-Baoding-Shijiazhuang". These corridors will strengthen overall interconnectivity and promote coordinated development between the two regions. The emerging pattern of BTH-coordinated development is starting to manifest tangible results.

(3) The BTH urban agglomeration exhibits a polycentric development trend driven by core cities, yet the influence of rail transit interconnectivity on this polycentric pattern is comparatively feeble. The foundational framework of "BTH on the track" has solidified and clarified, designating Beijing, Tianjin, and Shijiazhuang as the three core cities. While the three core cities radiate and guide the development of the BTHRTN, they remain somewhat isolated. Additionally, Shijiazhuang, the capital of Hebei province, holds the third-highest interconnectivity degree. However, it is noteworthy that its rankings in betweenness centrality and closeness centrality are gradually decreasing, indicating a weakening hub position. Simultaneously, the positions of Baoding and Langfang within the BTHRTN are rising. As a result, the full emergence of the third pole in the world-class urban agglomeration centered on Shijiazhuang is yet to be realized. Moving forward, emphasis should be placed on enhancing the impact of rail transit interconnectivity on the polycentric development pattern.

(4) Rail transit interconnectivity generates multi-element flows that impact the spatial structure networking in urban agglomerations. The SNA method unveils the crucial role of rail transit in enhancing interconnectivity and integration among cities through the analysis of the spatial evolution of the BTHRTN. Both the network density and the degree of centrality show an increasing trend. Furthermore, applying the CONCOR method to evaluate city correlations within the BTHRTN indicates an integrating spatial pattern, while the interaction relationships among cities remain stable. Going forward, emphasis must be placed on fostering coordinated development among cities within the urban agglomerations.

While this study has uncovered significant findings, it is not without limitations. Firstly, the indicator system in this study incompletely captures the dynamics of an intelligent rail transit system due to factors such as data accessibility. Future research can enhance this by utilizing multi-source big data for the integrated analysis of intelligent transportation systems. Secondly, although the study explores the network structure's evolution characteristics over four key years (2010, 2014, 2018, and 2021), it fails to explore the impact of changes in the interconnectivity degree on the dynamic optimization of spatial structures in the BTH urban agglomeration at different time stages. Future research can explore employing machine learning methods and multi-source big data for continuous simulation of rail transit interconnectivity. Comparing and analyzing these simulations with real-world situations could offer practical insights for the sustainable development of rail transit interconnectivity in urban agglomerations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13020249/s1.

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