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Performance Evaluation and Strategic Analysis of Logistics Development for China Railway Express: A Spatial Connectivity Perspective

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Abstract: Amid global challenges like COVID-19 and trade wars, resilient logistics networks are crucial. The China Railway Express (CRE) offers a sustainable alternative to sea and air transport, supporting China's national logistics strategy and strengthening links between China and Europe. This study applies a three-stage Social Network Analysis (SNA) to CRE using a "point–line–network" approach. It evaluates city logistics with the entropy weight method, modifies the gravity model to assess intercity logistical gravity, and constructs a weighted network to analyze centrality evolution through SNA. The results show that cities such as Zhengzhou, Wuhan, and Chongqing have emerged as central logistics hubs, benefiting from strategic investments in infrastructure and multimodal systems. However, regional disparities persist, with cities like Harbin, Lanzhou, and Urumqi facing challenges in integration due to infrastructure deficits and geographic constraints. Furthermore, inefficiencies in border logistics, inconsistent customs procedures, and limited multimodal integration hinder the CRE's potential. Addressing these challenges through infrastructure investment, unified customs standards, multimodal hub development, and advanced technologies like IoT and blockchain is crucial for enhancing connectivity and competitiveness. The findings offer actionable recommendations for policymakers, logistics firms, and researchers, contributing to the sustainable optimization of the CRE within global supply chains.

Keywords: China Railway Express; logistics performance evaluation; spatial network analysis; sustainable logistics development

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1. Introduction

China Railway Express (CRE) is a block train transportation service offering fixed-schedule, non-stop container shipments that connect China with Central Asia and Europe [1]. In 2015, China's National Development and Reform Commission, the Ministry of Foreign Affairs, and the Ministry of Commerce jointly issued the "Vision and Actions on Jointly Building the Silk Road Economic Belt and 21st Century Maritime Silk Road" document, underscoring the importance of CRE in establishing an international land cargo route under the Belt and Road Initiative (BRI) policy [2]. In October 2016, the "CRE Construction and Development Plan (2016–2020)" [3] was introduced. As the first top-level design for CRE development, this plan outlined specific targets for the next five years. With the gradual implementation of these initiatives, trade volume between China and countries along the Silk Road, particularly European nations, has steadily increased [4].

Since 2011, the number of CRE trains has grown significantly, rising from 17 trains in that year to 16,562 trains in 2022. In the realm of international railway multimodal transport, CRE has undergone substantial transformation, achieving an average annual growth rate of 58% since the inception of China's "13th Five-Year Plan". In 2022 alone, CRE transported 1.614 million TEUs, marking a 9% year-on-year increase. Despite external challenges such as the Russia–Ukraine conflict, the scheduled CRE transport corridor has maintained both safety and efficiency, endeavoring to mitigate the conflict's impact and resume its rapid growth trajectory (Figure 1) [5].

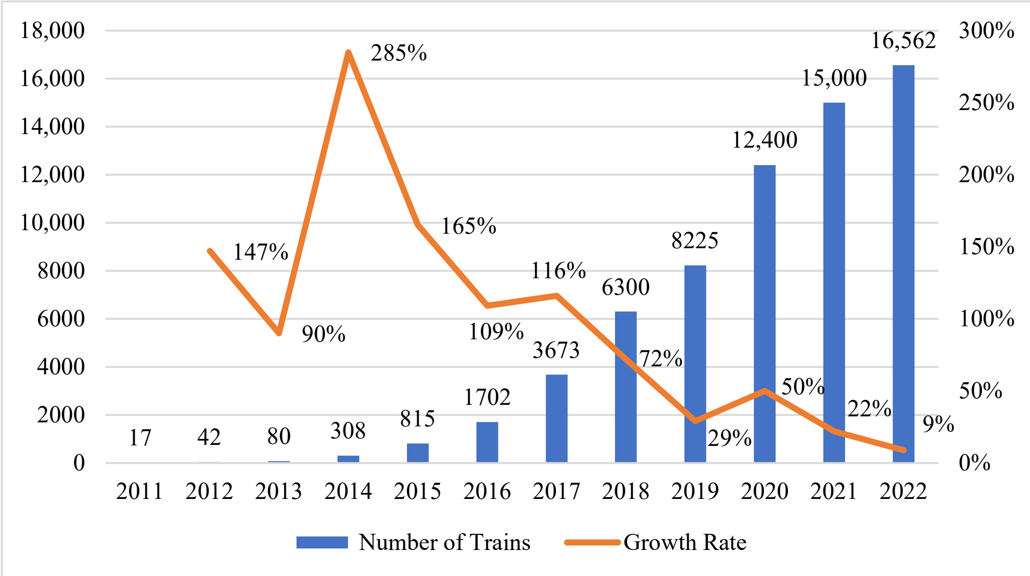

Figure 1. The number of CRE trains and growth rate. Source: China Container Industry Association (2023).

Meanwhile, the one-way travel time of CRE decreased from 20 days to 12–14 days, and the freight rate for a full trip dropped by approximately 40%. CRE offers significant advantages, saving time compared to traditional sea freight and being far less expensive than air freight while maintaining shorter delivery times [6]. Recently, CRE, with its strong transportation competitiveness, has played a pivotal role in strengthening trade partnerships between China and Europe [7].

On the other hand, amidst the volatility of international geopolitics and the disruptions caused by natural calamities, the CRE has emerged as a vital and reliable transportation alternative. The COVID-19 pandemic significantly impacted global logistics, with air travel being severely curtailed and maritime cargo facing numerous port blockages due to security concerns. This scenario necessitated a shift towards land-based transportation. Given the weight restrictions imposed on trucks, rail transport became the most feasible option. Despite the challenges faced by the railway sector, it demonstrated remarkable resilience, maintaining a steady level of operations and even witnessing an increase in cargo volume in certain regions during the pandemic. This was attributed to the escalating costs of empty freight, the prolonged delivery times of trucking due to border protocols, and the frequent blank sailings in ocean freight. Rail transport offers several advantages: it is less susceptible to weather-related disruptions compared to air and sea freight, making it a safer option. It is also more cost-effective than air transport and faster than sea transport. Importantly, rail freight is more environmentally sustainable than air freight, with only marginally higher CO_2 emissions than sea freight. As both China and Europe prioritize environmental sustainability, rail transport is poised to play a pivotal role in their bilateral relations. Moreover, the 2021 Suez Canal blockage underscored the increasing significance of CRE as a robust alternative to conventional maritime routes [8]. In essence, CRE's competitive edge is not solely based on its cost and time efficiencies but also on its capacity to bolster the stability of the global supply chain and its substantial social benefits.

Over the past decade, the CRE has demonstrated strong performance in establishing transport links between China and Europe. As key nodes in the CRE network, relevant cities have made significant efforts to support the integrated logistics system, greatly contributing to the success of CRE. However, to ensure the sustainable growth of CRE in the rapidly evolving global supply chain, the logistics development of CRE's cities must be approached from both horizontal and vertical network perspectives rather than a limited, node-specific view [9]. While previous studies mostly have focused on assessing CRE's competitiveness from a static perspective [7,10,11] or analyzing the CRE network at a single point in time [1,2,12], there has been little emphasis on conducting integrated horizontal (all objects at the same time) and vertical (the subject's changes over time) analyses of the CRE network.

This study aims to offer valuable insights to support the sustainable development of CRE. By employing spatial network analysis to evaluate the logistics capabilities of various nodes within China and the interconnectivity between them from both horizontal and vertical perspectives, the study proposes a three-stage analysis method grounded in SNA. The analysis follows a "point–line–network" sequence. Based on the results, actionable development strategies for the future of CRE will be proposed. Furthermore, spatial network analysis can identify key nodes within the network, enabling operators to enhance the reliability of CRE in response to major international events and minimize the risk of complete network failure.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature on the CRE. In Section 3, a three-stage analysis method based on SNA is proposed. Section 4 presents the results. Section 5 discusses the results and offers recommendations. Finally, Section 6 summarizes the conclusions of the paper and suggests directions for future research.

2. Literature Review

Based on the research motivation and gap described in the Introduction, this section reviews studies on the CRE from three main aspects: (1) economic competitiveness and market integration, (2) network configuration and node optimization, and (3) sustainable development.

2.1. Economic Competitiveness and Market Integration of CRE

The economic competitiveness of CRE stems from its ability to balance cost efficiency and timeliness, addressing the critical demands of Eurasian trade. This dual advantage positions CRE as a preferred alternative to maritime transport, especially in time-sensitive supply chains. By integrating speed and reliability, CRE enhances trade facilitation and logistics connectivity, reinforcing its role as a catalyst for economic integration between Asia and Europe [7,10,13]. Li et al. [7] underscored the time-saving and cost-effective advantages of CRE compared to sea and air transport, demonstrating that its market competitiveness is primarily driven by faster delivery times and lower costs, particularly for time-sensitive goods. Their study employed a multi-logit model to quantify CRE's competitive edge and highlighted its increasing significance in China–Europe trade, with speed and service frequency emerging as key factors. Similarly, Feng et al. [10] examined the competitive dynamics between CRE and maritime transport, arguing that CRE is particularly advantageous for transporting high-value, time-sensitive goods due to its superior speed and reliability, whereas maritime transport remains more cost-effective for bulkier, less-time-sensitive products. Lastly, Liu and Meng [13] explored the role of CRE in enhancing economic vitality along the Belt and Road routes, emphasizing that its operational benefits substantially contribute to the economic dynamism of the cities it serves. Their findings indicate that CRE's convenience and reliability generate significant regional spillover effects, further reinforcing its competitiveness and pivotal role in fostering trade and economic connectivity between China and Europe.

The literature consistently highlights government subsidies as crucial for stabilizing and expanding CRE's market position. Targeted subsidies not only mitigate operational risks but also incentivize service optimization. For example, financial interventions enable CRE to remain competitive against established modes of transportation, particularly in markets with fluctuating demand [14,15].

For instance, Xing et al. [14] examined the optimization of empty container repositioning within CRE, demonstrating how government subsidies can mitigate operational costs. By developing a multi-period model to optimize the repositioning of empty containers in sea–land intermodal transportation, the study illustrated that subsidies can enhance CRE's service levels and cost-efficiency. The findings further indicated that financial support for service innovations, such as the adoption of foldable containers, can significantly reduce the total costs associated with container repositioning. Such investments contribute to the sustainability of CRE by addressing logistical challenges more effectively, ensuring its competitiveness with alternative transport modes, particularly during periods of high demand and market fluctuations. Similarly, Ma et al. [15] highlighted the role of government subsidies in shaping competitive pricing strategies for CRE. Using a non-cooperative game model, the study explored how subsidies influence pricing decisions among competing CRE operators. The findings revealed that government subsidies play a crucial role in determining operators' pricing and service frequency decisions, directly impacting market share and profitability. The study suggested that targeted financial support enables operators to make strategic decisions that not only strengthen CRE's competitive position but also foster regional cooperation and market integration between China and Europe. Furthermore, the research underscored that granting operators greater flexibility in determining service frequency can promote both profitability and social welfare. This analysis illustrated how financial interventions help align policy frameworks with operational efficiency, reinforcing the strategic foundations necessary for CRE's sustainable growth.

Another significant factor contributing to CRE's competitiveness is its ability to meet diverse customer expectations through superior service quality. The integration of reliability, site optimization, and backhaul management creates a customer-oriented service ecosystem, ensuring adaptability to dynamic market conditions [16–18]. This comprehensive approach reinforces CRE's ability to serve as a reliable logistics backbone in cross-continental trade. Li et al. [16] examined customer preferences for rail freight services, emphasizing their critical role in delivering superior service quality. Utilizing a multi-criteria decision analysis (MCDA) method, specifically the Best–Worst Method (BWM), the study assessed customer preferences for various service attributes, with reliability emerging as the most influential factor in freight transport decisions. The findings suggest that by identifying these preferences, CRE operators can optimize their services and tailor them to meet the diverse needs of different customer segments. The study further demonstrated that service reliability is directly linked to customer satisfaction and competitive advantage, reinforcing its centrality to the service quality that underpins CRE's success.

Similarly, Huang et al. [17] addressed site optimization as a crucial factor in enhancing CRE's service quality. By establishing a set of planning indicators for selecting railway express freight service sites, the study ensured that CRE's logistics infrastructure aligns with both market demand and policy strategies. The research underscored the importance of strategic site selection in high-demand areas such as Beijing, Chongqing, and Wuhan to optimize resource distribution and enhance service efficiency. This approach enables CRE to expand its service reach, reduce transit times, and improve overall logistics reliability, all of which contribute to a more customer-centric service model. Site optimization is, therefore, essential for ensuring that CRE can efficiently meet evolving customer demands in a dynamic logistics environment. Furthermore, Du et al. [18] investigated backhaul management, a key component of CRE's operational efficiency and service optimization. The study proposed an innovative passenger service-like (PSL) model to improve empty backhaul operations, addressing a long-standing inefficiency in the CRE network. By optimizing the utilization of empty container space, the research demonstrated how CRE can reduce wasted capacity and economic losses. Using a programming model to optimize routes and cargo handling, the study suggested that CRE can significantly enhance the sustainability of its operations while improving service quality through more reliable and cost-effective solutions. This approach to backhaul capacity management ensures that CRE remains competitive by maximizing its logistical resources, thereby improving both service levels and cost-efficiency.

2.2. Network Configuration and Node Optimization of CRE

The effectiveness of CRE's network configuration lies in its capacity to integrate strategic nodes and optimize intermodal connectivity. The spatial arrangement of key hubs ensures seamless transitions between transportation modes, minimizing costs and maximizing network utility [2,4,19]. These studies collectively highlight the importance of combining technical methodologies, such as mixed-integer programming and genetic algorithms, with practical insights into hub location dynamics. Zhao et al. [2] focused on optimizing consolidation routes and identifying strategic hubs within the CRE network. Employing complex network evolution principles, the study analyzed the historical development of the network to determine the most suitable consolidation centers. By applying optimization techniques to routes leading to these hubs, the findings suggest that cities such as Chongqing, Xi'an, Chengdu, and Zhengzhou could serve as key consolidation centers, thereby enhancing the network's efficiency and cost-effectiveness. This approach underscores the strategic importance of hub placement in facilitating cargo consolidation, improving intermodal connectivity, and reducing operational inefficiencies. Wu et al. [4] examined the implementation of the hub-and-spoke transportation model as a means to reduce CRE's operational costs and enhance network efficiency. The study developed a hub location model based on genetic algorithms (GAs) to identify optimal consolidation centers. It designated cities such as Chengdu, Yingkou, and Zhengzhou as central hubs, while others, including Urumqi and Xining, were assigned to direct transport routes. The research highlighted the significance of an optimized hub system capable of managing differentiated cargo volumes effectively. Moreover, it demonstrated how advanced computational methodologies, such as genetic algorithms, can refine hub selection processes, ensuring seamless transportation transitions across the network. Ma et al. [19] introduced a hierarchical multimodal hub location model with time constraints to enhance cargo flow balance and transport efficiency within CRE. Using mixed-integer programming (MIP), the study determined the optimal number and locations of hubs across China, proposing a network configuration that prioritizes central and western regions. The findings indicate that cities such as Zhengzhou, Xi'an, Chongqing, and Chengdu should be prioritized for regional connectivity, with Wulanchabu identified as having the largest hinterland coverage. This analysis underscores the importance of selecting hubs that facilitate extensive regional coverage, optimize cargo distribution, and reduce transit times across various transport modes.

Node optimization remains central to CRE's operational success. The prioritization of hubs based on multi-attribute evaluation models reflects a growing emphasis on network adaptability and resilience. For example, studies emphasize the dual importance of infrastructure quality and strategic location in facilitating logistics flows, enabling CRE to efficiently handle increasing freight volumes [1,20,21]. This alignment of quantitative rigor and spatial planning demonstrates CRE's capacity to evolve with market demands. Zhang et al. [1] proposed a multi-attribute evaluation model to rank the significance of logistics nodes within the CRE network from the perspective of China's Belt and Road Initiative. By incorporating the theory of structural holes and Multiple Attribute Decision-Making (MADM) methods, the study identified key nodes across both inland and seaport areas, thereby optimizing CRE's network structure. The research highlighted the dual importance of infrastructure quality and strategic location in strengthening CRE's network stability and capacity to accommodate increasing freight volumes. The study's practical contribution lies in identifying critical nodes essential for network optimization, further enhancing CRE's adaptability in responding to market demands and facilitating smoother logistics flows. Zhao et al. [20] examined the selection of optimal hub locations in Europe for CRE, emphasizing the importance of strategic node positioning in improving network efficiency. Using a hierarchical spatial aggregation process and centrality measures, the study identified 87 origin nodes and ranked them using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) model. The findings indicated that hub locations such as Berlin, Budapest, and Duisburg were selected based on their centrality within the European rail, road, and waterway networks. By integrating infrastructure quality with strategic positioning, the study demonstrated that carefully selected hubs can optimize intermodal connectivity, reduce operational costs, and enhance the overall resilience of the CRE network, particularly in response to increasing freight demand. Sun et al. [21] focused on the selection of consolidation centers within China, employing the TOPSIS method to rank cities based on their suitability as consolidation hubs. The study utilized cluster analysis and correspondence analysis to identify key consolidation cities, including Tianjin, Guangzhou, and Chongqing. It underscored the significance of strategic location and infrastructure in ensuring that consolidation centers can efficiently manage freight flows, thereby supporting CRE's capacity to handle rising cargo volumes. Additionally, the research explored the role of the hub-and-spoke system in optimizing network efficiency, demonstrating that well-positioned consolidation centers are crucial for maintaining network resilience and enhancing CRE's overall logistics performance.

Moreover, the incorporation of hub-and-spoke organizational strategies illustrates CRE's commitment to operational refinement. By optimizing logistics coordination and transport models, CRE enhances not only route efficiency but also cost-effectiveness, laying the groundwork for scalable network expansion [22,23]. These findings suggest that CRE's success is contingent on its ability to integrate innovative organizational frameworks with robust network planning. Tang et al. [22] examined the transition from a point-to-point direct-transportation model to a more efficient hub-and-spoke network. The study proposed a dual-objective planning model that considers both cost and time, addressing key challenges faced by CRE, such as high operational costs and inefficiencies in logistics coordination. By focusing on hub-port allocation and employing a Lagrange relaxation heuristic algorithm, the research demonstrated how CRE can optimize its transportation network. The findings underscored the significance of strategically configured hub-and-spoke systems, in which key hubs function as central nodes, enhancing logistics coordination and reducing operational expenses. This study aligns with the broader argument that CRE's ability to refine its operational structure through optimized transportation models and hub placement is essential for network expansion and long-term sustainability. Similarly, Guo et al. [23] investigated the integration of maritime and railway terminals within the CRE network, with a particular focus on the intermodal container terminal system that facilitates connectivity between these transport modes. The study analyzed two container accumulation approaches—fixed-length and fixed-time—while assessing how cooperation between terminals can accelerate container accumulation. By modeling the system as a two-echelon dual-channel supply chain, the research highlighted the critical role of coordination between maritime and railway terminal systems in enhancing operational efficiency. The findings demonstrated that effective collaboration between these terminals can improve container flow, reduce transportation delays, and enhance overall cost-effectiveness and route efficiency. This integration of maritime and rail logistics supports CRE's broader objective of strengthening network resilience and scalability.

2.3. Sustainable Development for CRE Expansion

Sustainability has become a cornerstone of CRE's long-term development strategy, particularly through its focus on reducing environmental impact while maintaining economic viability. CRE's role as a green logistics enabler is evidenced by its contributions to emission reductions and the promotion of eco-innovation across connected industries [24,25]. This dual focus on environmental stewardship and economic efficiency positions CRE as a model for sustainable freight systems. For instance, Zou and Feng [24] emphasized that the establishment of the CRE has led to a significant increase in green patent applications among enterprises located near key CRE nodes. This suggests that the CRE network not only enhances logistics efficiency but also serves as a driver of green innovation. Their study further demonstrated that the presence of the CRE has positively influenced regional economic development, alleviated corporate financing constraints, and reduced logistics costs, all of which contribute to sustainable industrial practices. Additionally, the findings indicate that the expansion of the CRE has particularly fostered green innovation within the secondary and tertiary industries, reinforcing its role as a catalyst for eco-innovation in the region. Similarly, Hu et al. [25] found that the CRE has substantially improved environmental efficiency in Chinese cities by facilitating technological innovation and reducing dependence on environmentally harmful foreign investments. Their research highlights the CRE's contribution to greener and more sustainable logistics operations by enhancing environmental performance and promoting knowledge spillovers across cities. These findings collectively underscore the CRE's positive impact on environmental efficiency, further aligning with its green logistics strategy.

Government subsidies are integral to fostering CRE's sustainable growth. By balancing social benefits and operator profitability, subsidy mechanisms encourage long-term investments in green technologies and logistics innovation [26,27]. Such policies not only support the operational resilience of CRE but also align its development trajectory with broader sustainability goals. Feng et al. [26] examined the critical role of government subsidies in the early stages of CRE development, highlighting their importance in mitigating the higher operational costs associated with rail transport compared to sea freight. Their study proposes a subsidy model that aligns the interests of local governments and CRE operators, ensuring that financial support is directed toward sustainable development objectives. By incentivizing CRE operators to prioritize long-term efficiency improvements and adopt greener technologies, these subsidies play a crucial role in enhancing the environmental sustainability of the CRE. Furthermore, Feng et al. [27] employed evolutionary game theory and Activity-Based Costing (ABC) to analyze the interplay between government subsidies and CRE sustainability. Their findings underscore that optimal subsidy levels not only facilitate CRE's market presence but also encourage the adoption of more rational and strategic operational approaches. Well-designed subsidy policies that balance the objectives of both governments and CRE operators are essential for ensuring the economic viability of the CRE while advancing its green logistics agenda.

Additionally, digitalization and logistical coordination have emerged as key enablers of CRE's sustainability. The integration of hybrid cloud models and collaborative alliances facilitates real-time decision-making and operational efficiency, enhancing CRE's adaptability to market fluctuations [28,29]. These technological advancements ensure that CRE remains competitive in an increasingly complex logistics landscape while adhering to sustainable practices. Wei and Lee [28] proposed a coordinated horizontal alliance system for inland ports within CRE's network, using an improved entropy-weighted TOPSIS method to optimize logistics capability and demand-matching. By integrating inland ports into CRE's intermodal system, the study shows how these alliances help streamline logistics operations, improve network coordination, and reduce overall carbon emissions. Such technological coordination enhances CRE's ability to adapt to market changes and reduce environmental impact, making it a sustainable logistics solution for cross-border trade. Finally, Huang et al. [29] discussed the development of a cloud-based logistics platform (CLICP) to improve cross-border shipping within CRE's network. By using a hybrid cloud model, the CLICP optimizes real-time freight information, carrier management, and operational decision-making. This platform facilitates better logistics coordination, increasing supply chain efficiency and reducing the carbon footprint of CRE operations. The integration of digital solutions ensures that CRE remains a sustainable and resilient logistics system while meeting the growing demands of international trade.

2.4. Summary

Overall, existing research has made significant contributions to understanding CRE's economic competitiveness, network configuration, and sustainable development. However, several gaps remain. First, there is a lack of integrated horizontal and vertical analyses of the CRE network, which limits comprehensive insights into its interconnectivity. Second, many studies focus on static models, overlooking the dynamic evolution of the network over time. Third, there has been limited exploration of city-level logistics capabilities and their roles in CRE's long-term development. To address these gaps, this study employs spatial network analysis to assess CRE's logistics capabilities and interconnectivity from both horizontal and vertical perspectives, providing actionable insights for improving network efficiency, enhancing resilience against global disruptions, and supporting strategic planning for CRE's sustainable growth.

3. Methodology

In order to apply spatial network analysis to CRE both horizontally and vertically, this study proposes a three-stage analysis method grounded in SNA. The analysis follows a "point–line–network" sequence. First, this study employs the entropy weight method to objectively evaluate the overall logistics development levels of cities in the CRE. Commonly used in logistics research, this method evaluates supply chain nodes, including cities, businesses, and logistics systems [30,31]. In the second stage, the gravity model is modified to reflect current conditions, using the composite score of a city's logistics development level as a weight to calculate the logistical gravity between cities, as shown in Figure 2. In the final stage, the gravity values between cities are used to construct a weighted network in the third stage. Subsequently, the evolution of network centrality is analyzed through SNA. The combination of the entropy weight method, gravity model, and SNA was chosen for this study due to its ability to provide a comprehensive and dynamic evaluation of the CRE network. The entropy weight method ensures an objective assessment of cities' logistics development, while the gravity model captures the logistical flows based on economic size and proximity, reflecting real-world trade patterns. SNA offers insights into the evolution of network centrality, helping to assess the resilience and connectivity of the CRE network over time. This multi-stage, multi-method approach allows for a holistic understanding of CRE's performance, addressing both structural and dynamic aspects, and provides a more nuanced analysis compared to single-method approaches.

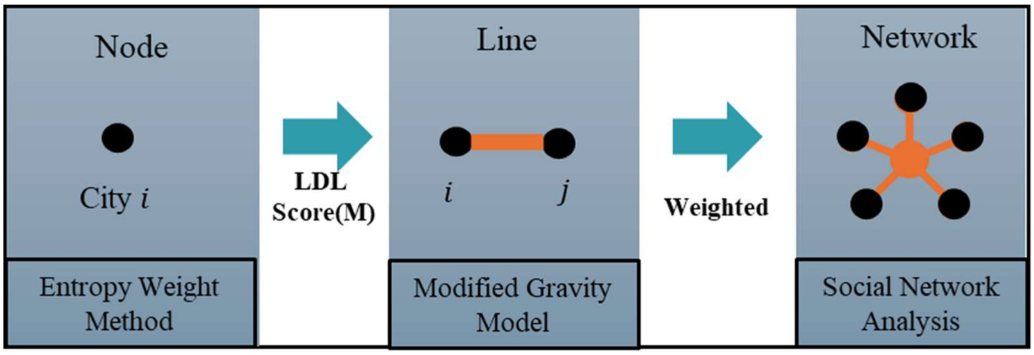

Figure 2. Three-stage analysis diagram.

3.1. Entropy Weight Method

The entropy weight method was initially developed in thermodynamics and later adopted in information theory, serving as an effective tool for quantifying and synthesizing indicator data. It objectively assigns weights based on the inherent variability of indicators, thereby simplifying the evaluation process and providing a clear representation of scores across various layers. Moreover, by minimizing subjective biases, the entropy weight method enhances the objectivity and accuracy of the results, making it a valuable approach for comprehensive data-driven analysis.

The calculation process is as follows:

Normalize the collected data matrix X_{ij}, $X_{ij}' = \frac{X_{ij}}{X_{ij}max*}$ and thus the normalized matrix of data $Y_{ij} = (Y_{ij})m*n$.

$$Y_{ij} = X_{ij} / \sum_{i=1}^{m} X_{ij} \tag{1}$$

Calculate the entropy value of the j^{th} indicator ej. Where $k = 1/\ln n$, y_{ij} is the normalization matrix.

$$ej = -k\sum_{i=1}^{m} y_{ij}\ln\ y_{ij} \tag{2}$$

Calculate the deviation of the j^{th} index d_j, where e_{ij} is the entropy value.

$$d_j = 1 - e_{ij} \tag{3}$$

Calculate the weight wj of the jth indicator, where d_j is the deviation degree.

$$wj = \frac{d_j}{\sum_{i=1}^{n} d_{ij}} \tag{4}$$

The composite score U is calculated.

$$U = \sum_{i=1}^{n} y_{ij}\ w_j \tag{5}$$

3.2. Modified Gravity Model

The modified gravity model is based on the principles of gravitational force and spatial distance decay. First introduced by Zipf [32] for analyzing urban interactions, it has since been widely applied to spatial interaction studies, serving as a crucial tool for examining logistics, trade flows, and economic performance. In economic research, the modified gravity model plays a key role in assessing distance decay effects and spatial relationships. Its fundamental formulation is as follows:

$$G_{ij} = k\frac{M_i M_j}{D_{ij}^b} \quad (6)$$

where

G_{ij} is the spatial gravity between cities *i* and *j*;
M_i and M_j denote the "mass" of cities *i* and *j*;
d_{ij} denotes the distance between cities *i* and *j*.

The economic connection between two cities is observed to be inversely proportional to the square of their distance, with b set to 2 and k representing the gravitational adjustment coefficient [33]. Traditionally, scholars have used a single index to measure "mass" and "distance"; however, this approach often fails to fully capture the complexities of these concepts. With the growing emphasis on timeliness and cost-effectiveness in logistics, spatial distance alone is insufficient to reflect the evolving characteristics of the industry. Enhancing the model parameters can thus improve the accuracy of spatial logistics analysis among cities.

In this study, the spatial logistics connectivity of CRE node cities is examined, with "mass" represented by the logistics industry's development level, assessed using the entropy weight method. This replaces the mass variable M in Equation (6). Additionally, this study incorporates relevant research findings on the evaluation index system for urban logistics development [34].

City distances are evaluated across three dimensions: time, physical distance, and cost. These factors are integrated into the distance calculation, as outlined in Equation (7). Given the relatively low transport volumes of air, pipeline, and waterway modes among CRE node cities, this study focuses on rail and road transportation.

$$D_{ij} = \sqrt[3]{d_{ij} t_{ij} c_{ij}} \quad (7)$$

where

d_{ij} denotes the spatial distance between city *i* and *j*, calculated as the geometric mean of their respective road and rail distances;

t_{ij} denotes the time distance between city *i* and *j*, determined as the geometric mean of their road and rail transportation times;

c_{ij} denotes the unit transportation rate between city *i* and *j*. The rate is calculated as the geometric mean of road and rail transportation rates between cities *i* and *j*. Based on the results of existing studies, the road transportation rate is 1.5, while the rail transportation rate is 1 [34].

The modified gravity model is calculated as Equation (8):

$$G_{ij} = \frac{M_{\mathrm{i}} M_j}{\left(\sqrt[3]{d_{ij} t_{ij} c_{ij}}\right)^2} \quad (8)$$

3.3. SNA

Social Network Analysis (SNA) is a relatively recent methodological approach that has gained significant interest among researchers due to its potential applications [35]. It examines social networks—groups of individuals connected by specific relationships—by applying techniques to analyze, modify, and quantify network structures and characteristics. These relationships are then scientifically interpreted and visually mapped to provide meaningful insights [20].

3.3.1. Degree Centrality

Degree centrality is measured as the percentage of a node's actual connections relative to the maximum possible connections within a network. It reflects the extent of a node's connectivity and influence. The concept is based on the premise that nodes with more connections possess greater autonomy, dominance, and opportunities within the network [36]. A highly connected city can assume a strategic position, potentially evolving into a central hub that facilitates access to other cities. In essence, degree centrality quantifies the extent to which a node is linked to others in the network, serving as a key indicator of its influence and accessibility [37].

$$C_D(N_i) = \frac{\sum_{j=1}^{g} x_{ij}}{g-1},\ i \neq j \tag{9}$$

$C_D(N_i)$: the degree centrality of node i;
$\sum_{j=1}^{g} x_{ij}$: the number of connections node i has with $(g-1)$ other nodes;
x_{ij} = 0 or 1, g: the number node.

3.3.2. Closeness Centrality

Closeness centrality measures how efficiently a node can reach all other nodes in a network by evaluating the shortest path distances. A node with a lower total distance to others has higher closeness centrality, indicating a more favorable position within the network. Nodes with higher closeness centrality are typically located near the network's core, facilitating efficient connectivity. Generally, a greater number of direct connections enhance a node's overall proximity to the network. Closeness centrality measures a node's proximity to others by calculating the shortest path distance to all other nodes [37].

$$C_c(N_i) = (g-1)\left[\sum_{j=1}^{g} d(N_i,\ N_j)\right]^{-1},\ i \neq j \tag{10}$$

$C_c(N_i)$: the closeness centrality of node i;
$\sum_{j=1}^{g} d(N_i,\ N_j)$: the total of all shortest path distances between node i and node j;
g: the number node.

3.3.3. Betweenness Centrality

Betweenness centrality measures how effectively a node serves as an intermediary among other nodes in the network, indicating its influence over indirect connections. It measures a node's ability to control or relay interactions between nodes that are not directly connected. This metric considers the entire network, excluding immediate neighbors, making the node's position within the overall structure crucial in determining its centrality. Essentially, betweenness centrality reflects a node's involvement in the shortest paths within the network and serves as an indicator of its potential role as a broker or control point. Its calculation is presented in Equation (11).

$$C_B(N_i) = \frac{\left[\sum_{j<k} \frac{g_{jk}(N_i)}{g_{jk}}\right]}{(g-1)(g-2)},\ i \neq j \neq k \tag{11}$$

$C_B(N_i)$: the betweenness centrality of node i;
g_{jk}: the number of shortest paths from j to k;
$g_{jk}(N_i)$: the number of paths including i among the shortest paths between j and k.

4. Empirical Analysis

This section outlines the empirical approach employed to assess the logistics performance of the CRE network. Building on the methodology established in the preceding sections, the analysis emphasizes both node capabilities and centrality to provide a comprehensive evaluation of CRE's operational efficiency and connectivity.

4.1. Establishment of Logistics Capability Evaluation Index

4.1.1. Selection of Evaluation Index

Urban logistics development is a complex, multi-faceted process influenced by interrelated factors. Beyond freight volume and turnover, comprehensive logistics research also considers a city's economic environment, infrastructure, and technological advancements. A review of prior studies identified "urban logistics" and "evaluation" as the most frequently cited keywords, forming the basis for establishing a preliminary set of evaluation indices (Table 1). Drawing on previous work, frequently cited indicators were categorized into five dimensions: economic level, logistics infrastructure, consumer-related factors, population, and informatization. Ayadi et al. [38], Bartuška et al. [39], and Mei et al. [40] included all five dimensions above. Furthermore, Mo et al. [41] and Feliú [42] presented logistics infrastructure indicators (e.g., freight volume and facility scale) for logistics development evaluation. Patier and Browne [43] and Andruetto et al. [44] created frameworks for sustainable urban freight and urban logistics performance, especially considering environmental factors. Sun et al. [45] analyzed the measurement of logistics capability and presented "urban economic strength", "urban investment and construction capacity", and "urban external circulation capacity"; in particular, the importance of economic factors was emphasized.

Table 1. Pre-selection indicators of urban logistics capability evaluation.

Main Indicator	Re-Selection Indicator
Regional economic level	Gross Regional Domestic Product (GRDP)
	Gross Regional Product (GDP) per capita
	GDP growth rate
Logistics infrastructure level	Disposable income per capita
	Total investment in fixed assets
	Total import and export
	The ratio of primary industry to GDP
	The ratio of secondary industry to GDP
	The ratio of the tertiary industry to GDP
Logistics infrastructure level	Railway transport mileage
	Road transport mileage
	Waterway transport mileage
	Total regional freight
	Regional freight turnover
	Total regional passenger transport
	Regional passenger turnover
Consumer indicators	Total social consumer goods
	Total postal business

Table 1. *Cont.*

Main Indicator	Re-Selection Indicator
Population	Total population
	The population density
	Logistics employment-population
	Number of college students
Informatization level	Internet penetration rate
	Population using mobile phones

Source: by authors.

Subsequently, a citation frequency-based approach was employed to ensure that each selected indicator had achieved adequate academic consensus within the reviewed literature. Specifically, only indicators cited five or more times across the surveyed publications were retained (Table 2). The decision to use the "≥5 citations" threshold was based on two primary considerations. Firstly, indicators appearing at least five times tend to reflect a broader scholarly consensus and relevance to urban logistics evaluation. Fewer than five mentions, such as four or fewer, may indicate less frequently tested metrics or context-specific measures that lack broader applicability. Secondly, a higher threshold, such as "≥6 citations", risks excluding well-recognized indicators that fall just below that frequency. Conversely, lowering the threshold to four or fewer would inflate the total indicator list, complicate data collection, and dilute the focus on widely accepted metrics.

Table 2. Logistics capability evaluation index system of CRE's node cities.

Main Indicator	Sub-Indicator
Regional economic level	GRDP
	Total retail sales of consumer goods
	Total import and export value
Logistics infrastructure level	Mileage of highway and railway
	Freight volume of highway and railway
	Freight turnover of highway and railway
	Employment in transportation, storage, and post
	Investment in transportation, storage, and post
Informatization level	Internet penetration

Source: by authors.

This study focuses on CRE node cities, with railway and road freight capacity as well as foreign trade volume as key evaluation targets. By integrating previous research findings with the study's objectives, a logistics capability evaluation index system for CRE node cities is developed. Indicators cited more than five times in the literature were selected. Table 2 presents the detailed index system.

(1) The economic development index reflects a city's overall economic strength, with its structure and scale influencing urban logistics growth and indicating potential for further development. Key performance indicators include GRDP, total retail sales of consumer goods, and total import and export value.
(2) The logistics infrastructure index evaluates a city's transportation network and investment levels, offering a comprehensive view of the logistics sector's current status. It primarily considers factors such as regional traffic mileage, freight volume, turnover, fixed-asset investment in logistics, and employment within the logistics industry.

(3) The rapid adoption of internet and digital technologies has significantly enhanced logistics efficiency. Advanced solutions, such as unmanned aerial vehicles and autonomous robots, leverage digitalization to optimize logistics operations, reflecting the growing sophistication of urban logistics. Cities with higher levels of informatization contribute to structural improvements and overall industry growth. Indicators such as internet penetration and mobile-phone usage are included.

4.1.2. Data Collection

To assess the logistics capability and network structure of CRE node cities, this study considers logistics source cities and transportation hubs outlined in the CRE Construction and Development Plan (2016–2020). The 19 domestic node cities analyzed include Shenyang, Yingkou, Tianjin, Qingdao, Lianyungang, Suzhou, Yiwu, Dongguan, Jinan, Hefei, Wuhan, Changsha, Zhengzhou, Chongqing, Chengdu, Xi'an, Lanzhou, and Urumqi. Ulaanchab, located in the Xinjiang Autonomous Region, was excluded due to data collection challenges associated with its lower development level; however, a literature review confirmed that this omission does not affect the selection of collection centers [46].

For comparative analysis of policy implementation, the years 2016, 2019, and 2022 were selected. Data were obtained from statistical yearbooks of the target provinces and cities, national economic and social development bulletins, and additional sources such as local statistical bureaus, the China Railway Administration, and the 12306.com website. The evaluation indicators are detailed in Table 3.

Table 3. The logistics capability scores of 2016, 2019, and 2022.

Region	City	2016	Rank	2019	Rank	2022	Rank	2016–2022
Eastern	Shenyang	0.030	13	0.030	16	0.031	15	↓3
	Harbin	0.028	14	0.031	15	0.028	16	↓2
Central	Beijing	0.085	4	0.080	3	0.090	2	↑2
	Tianjin	0.166	1	0.080	4	0.079	5	↓4
Mideastern	Suzhou	0.099	3	0.084	2	0.060	8	↓5
	Jinan	0.037	10	0.043	11	0.032	14	↓4
	Nanjing	0.081	5	0.065	6	0.073	7	↓2
	Yiwu	0.010	18	0.011	19	0.010	19	↓1
	Hangzhou	0.047	8	0.051	9	0.049	10	↓2
Western	Xi'an	0.033	11	0.037	12	0.038	12	↓1
	Urumuqi	0.012	17	0.015	17	0.017	17	→0
	Chongqing	0.123	2	0.166	1	0.110	1	↑1
	Lanzhou	0.010	19	0.014	18	0.015	18	↑1
	Chengdu	0.044	9	0.051	8	0.083	4	↑5
Midwestern	Changsha	0.022	16	0.035	13	0.040	11	↑5
	Zhengzhou	0.032	12	0.045	10	0.076	6	↑6
	Wuhan	0.063	6	0.073	5	0.085	3	↑3
	Hefei	0.028	15	0.033	14	0.035	13	↑2
	Dongguan	0.052	7	0.056	7	0.049	9	↓2
Geometric Mean		0.039		0.043		0.044		

Source: by authors.

4.2. Logistics Capability Evaluation of CRE's Node Cities

The entropy weighting method, an objective assignment technique, determines indicator weights based on original evaluation data and is widely used for comprehensive multi-indicator assessments. Using Equation (8), the logistics development levels of 19 cities were analyzed from 2016 to 2022, revealing an overall increase from 0.039 to 0.044. However, regional disparities persist, with logistics capabilities declining in the eastern and central-eastern regions, while central and midwestern cities have shown significant improvement in recent years.

In 2016, key logistics hubs such as Beijing, Tianjin, Suzhou, Nanjing, and Chongqing played a pivotal role in the pre-development of the CRE, representing three core areas. By 2022, Wuhan, situated in the central corridor, experienced notable growth, and the rapid expansion of Zhengzhou and Wuhan disrupted the original core patterns, leading to a more integrated and balanced logistics network. These trends are illustrated in Figure 3.

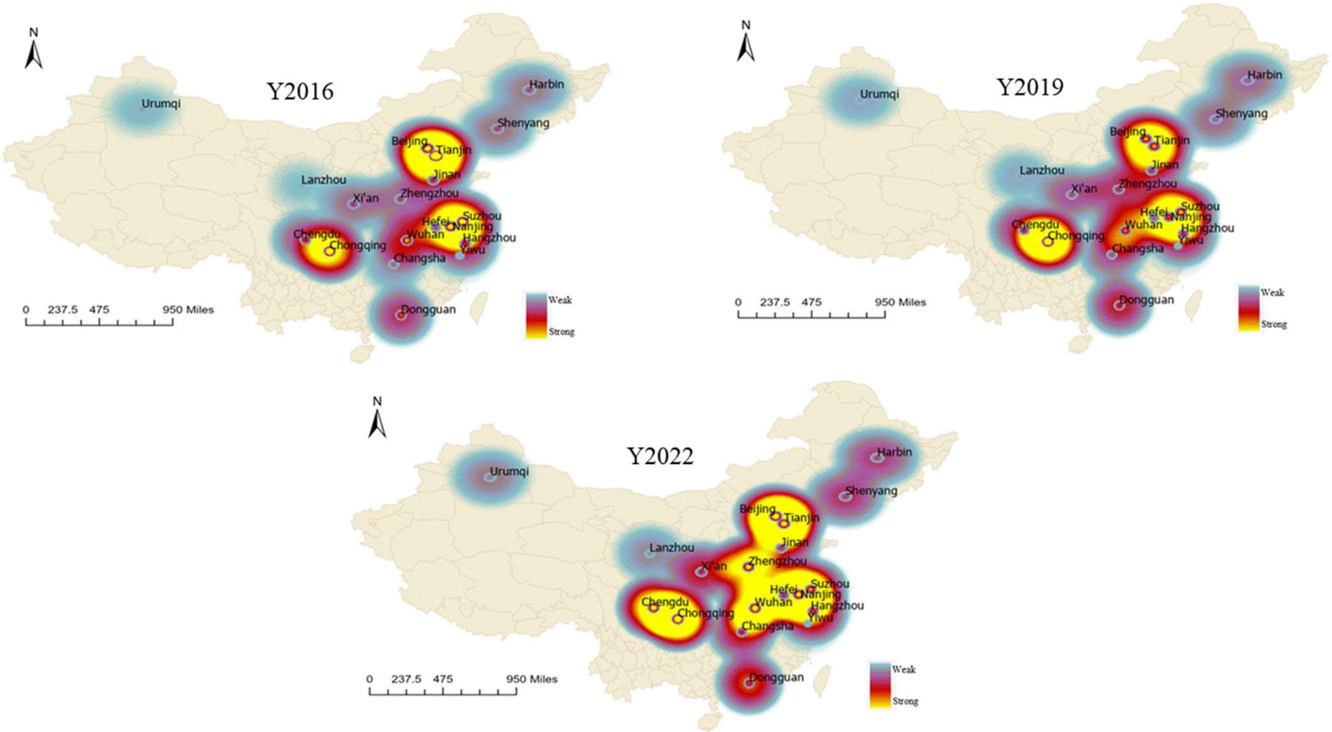

Figure 3. Logistics capability level of 2016, 2019, and 2022.

Zhengzhou has experienced significant growth in logistics from 2016 to 2022, driven by its robust economic performance and strategic location in Central China. Its GRDP has consistently surpassed the national average, ensuring steady financial support for infrastructure development. As a result, the city has evolved into a major distribution hub, offering efficient transit connections across mainland China. In recent years, Zhengzhou's market-driven initiatives have further accelerated its logistics expansion. By October 2021, the city had facilitated 5,000 CRE train operations, connecting 23 European countries and handling over 50,000 types of commodities. These efforts have strengthened Zhengzhou's position as a crucial hub within the CRE network.

In 2022, Chengdu and Changsha advanced five positions in the rankings, with Beijing and Wuhan securing second and third place, respectively. In contrast, Tianjin fell from first place in 2019 to fifth in 2022, while Suzhou dropped to seventh, declining five positions. Jinan experienced a notable decline to 14th place, and cities such as Shenyang, Harbin, Hangzhou, Nanjing, and Dongguan also saw a downward trend. Yiwu, part of Jinhua City, ranked last due to its relatively modest economy compared to other cities in the group. Meanwhile, Urumqi and Lanzhou consistently lagged behind other cities from 2016 to 2022, reflecting sluggish logistics growth and insufficient infrastructure development.

4.3. Evaluation of Logistics Gravity in CRE's Node Cities

From a linear perspective, the modified gravity model was applied to analyze the logistics gravity between two nodes. The computation results are visualized using the ArcGIS Pro 3.2.2, as illustrated in Figure 4.

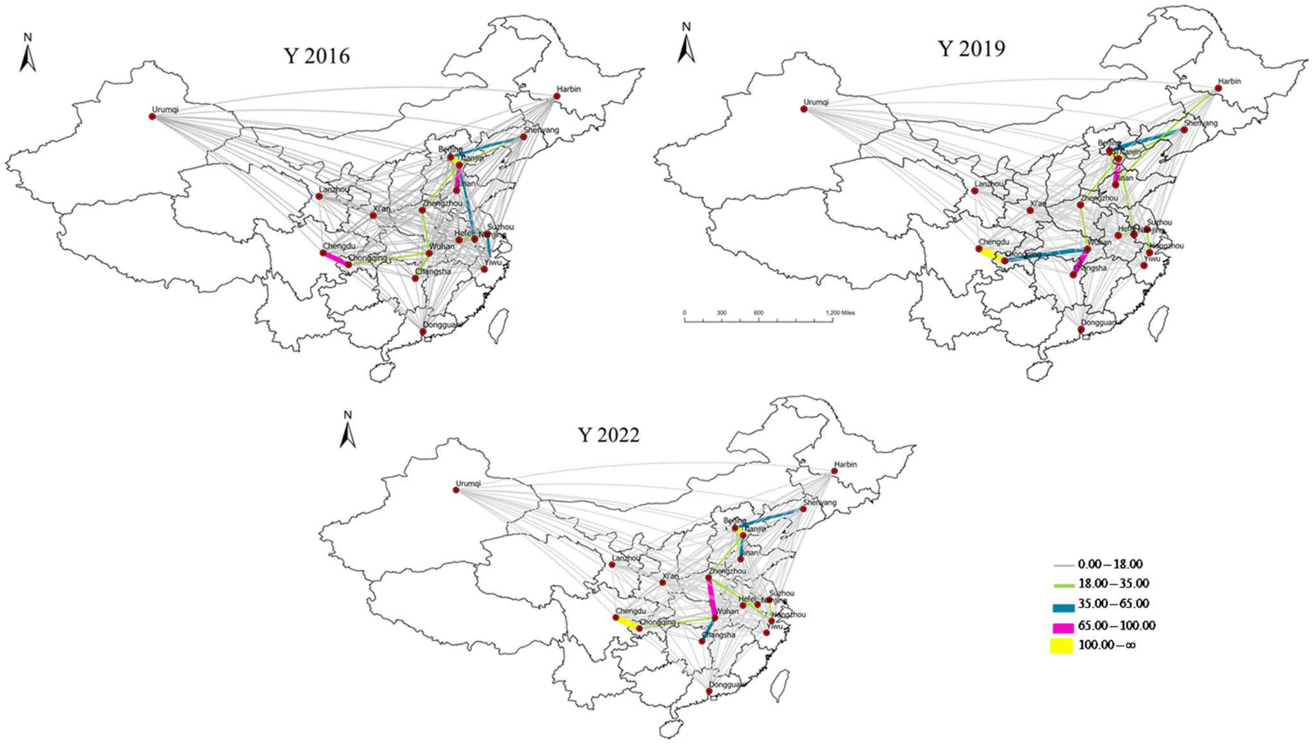

Figure 4. Logistics gravity in CRE's node cities of 2016, 2019, and 2022.

The natural breakpoint method was applied to categorize gravity values into five intervals. Beijing and Tianjin consistently ranked in the first interval from 2016 to 2022, with Tianjin hosting northern China's largest port and serving as a critical logistics hub connecting the country's north and south. As China's capital, Beijing boasts high commercial activity and population density, with both cities benefiting from excellent railway and road connectivity. The Tianjin–Jinan and Chengdu–Chongqing corridors ranked in the second interval, while the Eastern Corridor cities, such as Suzhou and Hangzhou, demonstrated strong logistics appeal in the third interval. Chengdu's emergence as a major electronics manufacturing hub in southern China propelled the Chengdu–Chongqing corridor to the first interval in 2019, facilitating 400 trains to Europe and supporting Chongqing's logistics expansion. Notable increases in logistics gravity were observed in the Jinan–Tianjin corridor in the north and the Wuhan–Changsha corridor in the south. The Changsha CRE, operational since 2015, expanded to 30–35 trains per week, becoming a crucial international logistics route during the pandemic. Following the implementation of the CRE Construction and Development Plan in 2019, Zhengzhou and Wuhan experienced rapid growth, positioning them in the second interval and reinforcing connectivity between northern and southern China.

4.4. Social Network Analysis of CRE's Node Cities

Network centrality is commonly employed to assess the significance and influence of nodes within a network, as well as to evaluate the overall degree of centralization. Nodes positioned at the center of the network possess greater resources, authority, and decision-making power compared to peripheral nodes [47]. In Section 4.3, the gravitational interactions among the 19 inland node cities of the CRE are analyzed. To ensure a more accurate representation of the centrality within the complex network, the threshold value was adjusted to 1 for cases where the calculated value between certain nodes was less than 1. Logistics gravity values below 1 are assigned a value of 0, while values of 1 or higher remain unchanged. Social network centrality analysis in this study was conducted using Gephi 0.10 software. Appendix A presents the results, showing that while higher network density strengthens logistics connections between node cities, excessive density may hinder network expansion. Maintaining an optimal level of network density is a key objective in network development. The calculated network density values over three years (0.41, 0.45, and 0.48) indicate a growing trend, reflecting the strengthening connectivity among node cities following the implementation of the CRE Construction and Development Plan (2016–2020).

4.4.1. Degree Centrality

In general, a higher degree of centrality indicates stronger connectivity between a node city and other network nodes, reflecting its logistical influence and distribution capacity. Table 4 presents the degree centrality results for CRE node cities, highlighting Wuhan, Nanjing, Tianjin, and Chongqing as the top-ranked cities in 2016, demonstrating their strong connectivity within the logistics network. These cities maintained leading positions in 2019, while Lanzhou and Urumqi continued to lag despite China's western development initiatives, though potential for growth remains.

Table 4. Results of degree centrality analysis of 2016, 2019, and 2022.

City	Rank	D.C-2016	Rank	D.C-2019	Rank	D.C-2022
Zhengzhou	5	21	4	22	1	30
Wuhan	1	28	1	28	2	28
Nanjing	3	22	6	21	3	26
Tianjin	2	27	3	24	4	22
Chongqing	3	22	2	25	4	22
Suzhou	5	21	4	22	6	21
Beijing	8	17	7	18	7	19
Hangzhou	7	18	7	18	8	18
Changsha	12	10	11	13	9	17
Jinan	8	17	9	17	10	16
Hefei	10	15	10	16	10	16
Xi'an	11	14	11	13	10	16
Chengdu	16	5	15	5	13	13
Shenyang	14	6	15	5	14	8
Dongguan	13	9	13	9	14	8
Harbin	16	5	15	5	16	7
Yiwu	14	6	14	7	16	7
Lanzhou	18	1	18	2	18	4
Urumqi	19	0	19	0	19	0

Source: by authors.

Notably, Nanjing fell from third to sixth place in 2019 without significant changes in its centrality value, while other cities experienced considerable growth. By 2022, Zhengzhou emerged as the network's core, rising from fifth place in 2016 to the top position, showcasing its increasing logistical vitality. Wuhan, Nanjing, and Tianjin closely followed in rank.

In-degree and out-degree centrality indicators reflect a node's capacity to absorb and distribute cargo within the network. Figure 5 illustrates Chongqing's strong in-degree centrality from 2016 to 2022, reinforcing its role as a key transportation hub in western China. Its well-developed infrastructure, abundant labor force, sufficient capital investment in the tertiary sector, and comprehensive logistics capabilities contribute to its strength, as discussed in Section 4.2. Conversely, Tianjin's in-degree centrality declined in 2019, largely due to the lingering impact of the 2015 port explosion, which led to a sustained drop in cargo turnover through 2022. Meanwhile, Zhengzhou and Wuhan showed significant improvements, rising to the top two positions in both in-degree and out-degree centrality.

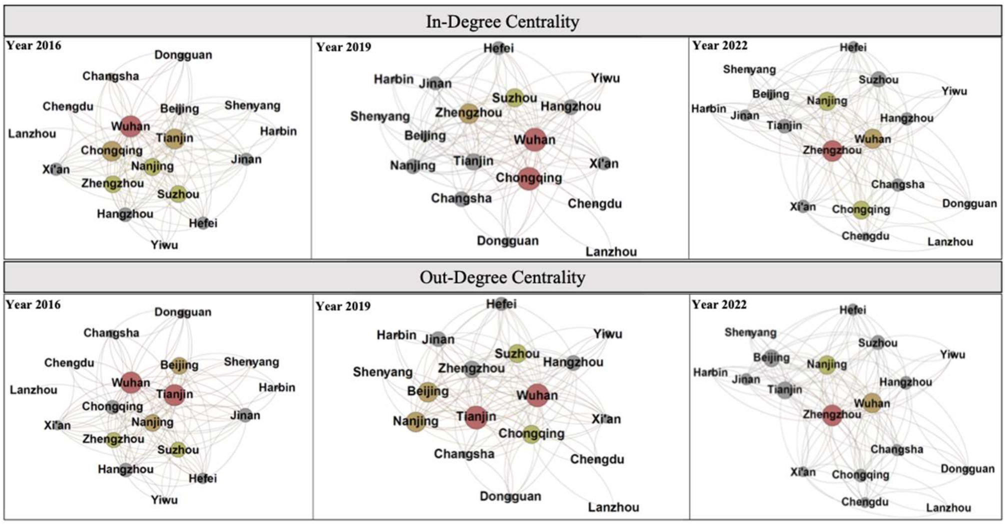

Figure 5. The in-degree and out-degree centrality of 2016, 2019, and 2022.

4.4.2. Closeness Centrality

Analysis of closeness centrality (Table 5 and Figure 6) indicates that Wuhan and Tianjin ranked first in 2016 and 2019. As major logistics hubs in southern and northern China, their well-established connections with numerous cities enabled relatively shorter distances to other nodes within the network. However, the implementation of the CRE Construction and Development Plan (2016–2020) spurred Zhengzhou's rapid development, elevating it to the top position in 2022. A key factor driving Zhengzhou's logistics expansion has been the development of cross-border e-commerce warehouses [48]. The city has become a major distribution hub, with overseas goods entering through Zhengzhou Airport for nationwide distribution, while domestic shipments are consolidated and transported to Europe via CRE. In contrast, cities such as Shenyang and Harbin in North-Xentral China, and Lanzhou and Urumqi in the northwest, remain geographically distant from core logistics centers, resulting in lower closeness centrality.

Table 5. Results of closeness centrality analysis of 2016, 2019, and 2022.

City	Rank	C.C-2016	Rank	D.C-2019	Rank	C.C-2022
Zhengzhou	5	0.727	7	0.708	1	0.895
Wuhan	1	0.889	1	0.850	2	0.850
Nanjing	3	0.762	3	0.773	3	0.810

Table 5. *Cont.*

City	Rank	C.C-2016	Rank	D.C-2019	Rank	C.C-2022
Tianjin	1	0.889	1	0.850	4	0.773
Beijing	3	0.762	3	0.773	4	0.773
Suzhou	5	0.727	5	0.739	6	0.708
Chongqing	7	0.696	5	0.739	7	0.680
Hangzhou	7	0.696	9	0.654	7	0.680
Hefei	10	0.640	9	0.654	9	0.654
Changsha	12	0.593	12	0.531	9	0.654
Jinan	7	0.696	8	0.680	11	0.630
Xi'an	11	0.615	11	0.586	11	0.630
Chengdu	14	0.516	14	0.515	11	0.630
Yiwu	14	0.516	14	0.515	14	0.548
Dongguan	12	0.593	12	0.531	15	0.531
Shenyang	14	0.516	16	0.486	15	0.531
Harbin	17	0.500	16	0.486	17	0.515
Lanzhou	18	0.425	18	0.436	18	0.436
Urumqi	19	0.000	19	0.000	19	0.000

Source: by authors.

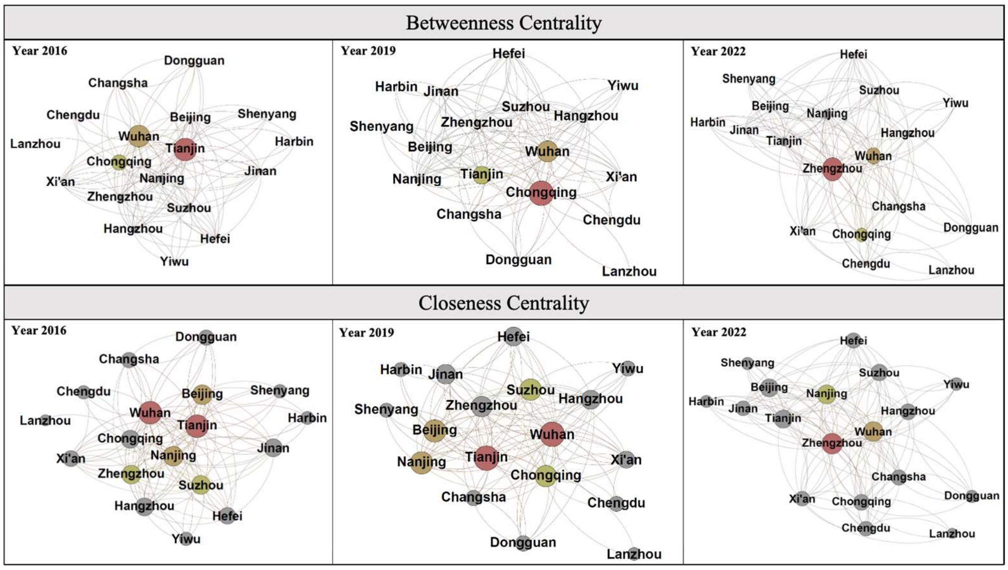

Figure 6. The closeness centrality and betweenness centrality of 2016, 2019, and 2022.

4.4.3. Betweenness Centrality

Betweenness centrality measures how frequently a node acts as an intermediary between other nodes [49]. As shown in Table 6, Tianjin, Wuhan, and Chongqing ranked as the top three cities in 2016, highlighting their critical role in China's inland logistics network. By 2022, Tianjin had fallen to third place, while Chongqing ascended to the top position, reinforcing its significance as a major transportation hub linking China's southeast coast with the western region. Cities ranked 4th to 6th, including Nanjing, Suzhou, and Hangzhou, serve as key bridging points within the southeast coastal subregion. Meanwhile, cities with a betweenness centrality value of zero primarily rely on nearby hubs to access the broader logistics network. Figure 6 illustrates the varying levels of betweenness centrality across all analyzed cities.

Table 6. Results of betweenness centrality analysis of 2016, 2019, and 2022.

City	Rank	B.C-2016	Rank	D.C-2019	Rank	B.C-2022
Zhengzhou	9	0.020	6	0.032	1	0.136
Wuhan	2	0.136	2	0.140	2	0.094
Chongqing	3	0.095	1	0.165	3	0.079
Nanjing	4	0.041	7	0.032	4	0.055
Tianjin	1	0.142	3	0.119	5	0.047
Suzhou	5	0.038	4	0.040	6	0.034
Hangzhou	6	0.030	9	0.025	7	0.028
Xi'an	10	0.006	10	0.005	8	0.027
Beijing	8	0.023	5	0.036	9	0.017
Changsha	11	0.003	11	0.004	10	0.017
Chengdu	14	0.000	14	0.000	11	0.014
Jinan	7	0.025	8	0.030	12	0.012
Hefei	12	0.002	12	0.003	13	0.004
Dongguan	13	0.001	13	0.001	14	0.000
Shenyang	15	0.000	15	0.000	15	0.000
Harbin	16	0.000	16	0.000	16	0.000
Yiwu	17	0.000	17	0.000	17	0.000
Lanzhou	18	0.000	18	0.000	18	0.000
Urumqi	19	0.000	19	0.000	19	0.000

Source: by authors.

5. Discussion

This study implemented a comprehensive spatial connectivity analysis of the CRE's logistics performance, offering critical insights into the evolution of its logistics network and areas for strategic improvement. The findings emphasize the increasing prominence of key nodes, the persistent regional disparities in logistics capabilities, and the impact of economic and strategic factors on network performance, while also proposing actionable strategies to optimize the CRE network.

Cities like Zhengzhou, Wuhan, and Chongqing have emerged as critical logistics hubs, demonstrating significant improvements in logistics capability and network centrality from 2016 to 2022. Zhengzhou, in particular, stands out due to its central location at the crossroads of China's logistics corridors, combined with substantial infrastructure investments and government support. Similarly, Wuhan effectively bridges northern and southern China, while Chongqing serves as a vital hub in the western corridor, linking inland China with Southeast Asia and Europe. These cities exemplify how strategic positioning and infrastructure development can transform regional logistics capabilities into national strengths.

However, despite the overall improvement in the CRE network, the results reveal stark disparities in regional logistics development. Historically strong eastern cities, such as Tianjin and Suzhou, have seen declines in network centrality metrics by 2022, reflecting challenges like infrastructure bottlenecks and external shocks such as the 2015 Tianjin port explosion. Meanwhile, peripheral cities such as Harbin, Lanzhou, and Urumqi consistently rank low in network analysis due to underdeveloped transportation infrastructure and geographical disadvantages. These imbalances limit the broader integration of these cities into the national logistics network.

The network performance of CRE cities is closely linked to both their economic strength and strategic location. While Beijing and Tianjin have significant economic clout, their complementary logistics functions require better coordination to enhance their collective performance. Conversely, the rise of cities like Wuhan and Zhengzhou underscores the importance of targeted investments in logistics infrastructure and multimodal transportation systems, demonstrating that economic strength alone is insufficient for high network centrality without strategic planning.

Addressing regional disparities in the CRE network requires a comprehensive and multi-faceted approach that combines infrastructure development, regional collaboration, logistical optimization, and policy support.

(1) Enhancing Infrastructure in Underperforming Regions

Investments in transportation infrastructure are critical for integrating peripheral cities such as Lanzhou, Harbin, and Urumqi into the broader logistics network. Upgrading rail and road networks, expanding multimodal transportation facilities, and developing regional logistics hubs are essential steps. For example, constructing modern logistics parks equipped with advanced warehousing and distribution technologies can attract industries and increase freight volumes in these regions. These infrastructure improvements should be supported by tailored government policies, such as subsidies or tax incentives, to stimulate private-sector involvement and ensure the long-term sustainability of these projects.

(2) Fostering Regional Collaboration and Synergies

Collaboration between adjacent cities with complementary strengths can significantly enhance their collective logistics performance. Cities like Beijing and Tianjin, or Chengdu and Chongqing, can benefit from coordinated development plans that align infrastructure investments and optimize resource allocation. For instance, joint development of shared logistics facilities, such as freight consolidation centers, can reduce redundancy and improve network efficiency. Establishing regional logistics alliances can also facilitate information sharing, streamline operations, and ensure more balanced economic growth across regions.

(3) Streamlining Border Logistics and Promoting International Cooperation

Inefficiencies at border crossings remain a major bottleneck for CRE operations. A unified customs framework is essential to reducing delays and ensuring seamless international trade. Establishing digital platforms for real-time cargo tracking and pre-clearance procedures can significantly enhance efficiency. Furthermore, expanding multilateral agreements, such as those facilitated by the CRE Transport Coordination Committee, can harmonize customs procedures and improve coordination with European trade partners. Initiatives to create standardized customs policies among Belt and Road Initiative (BRI) countries will also enhance the CRE's global competitiveness.

(4) Promoting Multimodal Transportation Integration

Developing integrated multimodal transportation systems is vital for improving the adaptability and scalability of the CRE network. Building multimodal hubs that connect rail, road, and maritime transportation can optimize cargo handling and reduce transit times. These hubs should focus on efficiently managing high-value or time-sensitive goods, creating a distinct competitive advantage for the CRE compared to sea or air freight. In addition, encouraging partnerships between rail operators and shipping companies can expand the CRE's service network, offering flexible and reliable solutions to meet diverse market demands.

(5) Encouraging Technology Adoption for Logistics Optimization

Utilizing technologies such as big data analytics, Internet of Things (IoT), and Artificial Intelligence (AI) can enhance logistics planning and decision-making. Real-time data integration can improve visibility across the supply chain, allowing operators to optimize cargo flow and minimize bottlenecks. For example, real-time tracking systems can provide updates on border wait times and congestion, enabling dynamic rerouting of shipments. Encouraging the adoption of such technologies across all node cities can level the playing field, enabling even underdeveloped regions to improve their logistics capabilities and better integrate with the broader network.

By implementing these targeted measures, the CRE can reduce regional disparities, enhance network connectivity, and ensure sustainable growth. These strategies not only address existing challenges but also position the CRE as a resilient and efficient logistics corridor, capable of meeting the demands of global trade in the 21st century.

6. Conclusions

In recent years, social challenges such as the COVID-19 pandemic and trade wars have significantly disrupted global supply chains, emphasizing the need for diversified and resilient logistics networks. The CRE, as a critical railway link between China and Europe, offers a viable alternative to traditional sea and air transportation. Its development represents a cornerstone of China's national logistics strategy, underscoring the necessity of its sustainable expansion and optimization. Meanwhile, CRE has become an essential part of the global supply chain, particularly in the context of BRI, which has reshaped the global logistics landscape. By connecting China with Europe and Central Asia, CRE plays a crucial role in enhancing trade flows between Asia and Europe. This development not only supports China's economic expansion but also facilitates cross-border trade, linking emerging economies with developed markets. CRE's ability to handle diverse cargo, including high-value and time-sensitive goods, highlights its potential to serve as a backbone for international trade. As the global economy continues to integrate, CRE's role as a strategic logistics link between Asia and Europe will only grow in significance. The expansion of CRE has also provided critical support for regional economies along the Silk Road, creating a sustainable pathway for trade and economic cooperation.

This study employed a spatial network analysis from both horizontal and vertical perspectives to evaluate the CRE's logistics performance, revealing several critical insights. Cities such as Zhengzhou, Wuhan, and Chongqing have emerged as vital logistics hubs, reflecting significant improvements in their capabilities and network centrality due to strategic geographic positioning, robust infrastructure investments, and effective multi-modal transportation systems. Zhengzhou's rise as the most central node demonstrates the success of targeted government initiatives in enhancing its logistics role. However, regional imbalances persist, with peripheral cities like Harbin, Lanzhou, and Urumqi struggling to integrate effectively into the national logistics network due to inadequate infrastructure and geographic constraints. Even historically strong hubs like Tianjin and Suzhou have experienced declines, highlighting their vulnerability to external disruptions and infrastructure bottlenecks. Furthermore, inefficiencies in border logistics, inconsistent customs procedures, and limited multimodal integration present significant challenges to the CRE's growth but also offer opportunities for improvement. Strategic measures such as investing in infrastructure for underperforming regions, streamlining customs processes through unified standards and digital platforms, developing multimodal transportation hubs, and adopting advanced technologies like IoT and blockchain are critical to addressing these challenges. These initiatives can enhance connectivity, optimize cargo flows, and strengthen the CRE's adaptability and competitiveness in global logistics.

When comparing CRE to other international rail transport systems like the Trans-Siberian Railway or European rail corridors, CRE stands out due to its strategic positioning, innovative network planning, and efficient hub-and-spoke organization. While the Trans-Siberian Railway and European corridors have their merits, their operational challenges and regulatory complexities highlight CRE's advantage in providing faster, more flexible, and environmentally friendly transport solutions. The efficiency of CRE in handling cross-border cargo and its ability to integrate various transport modes demonstrate its superiority in meeting the growing demands of global supply chains.

Furthermore, the findings from this study highlight the strategic importance of fostering collaboration among adjacent cities and integrating innovative logistics practices. Enhancing the CRE's resilience and adaptability is essential to addressing the rising demands of global trade and maintaining competitiveness in the evolving logistics sector.

In conclusion, this study provides valuable insights and practical recommendations for the sustainable development of the CRE. The findings and proposed strategies are anticipated to serve as a valuable reference for policymakers, logistics companies, and researchers, supporting efforts to optimize the CRE and ensure its role as a vital link in global supply chains. However, this study has several limitations. While it examines network changes over time through analyses at three-time points (2016, 2019, and 2022), it does not provide a fully dynamic analysis. Future research could incorporate dynamic approaches, such as agent-based simulation models, to enhance the analysis. Additionally, a comprehensive assessment of the opportunities and challenges in CRE development would benefit from an integrated methodology combining quantitative and qualitative approaches. Furthermore, in-depth investigations into the environmental benefits of CRE are needed to explore its sustainable development from an environmental science perspective. Finally, beyond relying on government subsidies, further exploration of diversified funding sources such as public–private partnerships (PPPs) and private-sector investments can offer long-term financial stability and reduce CRE's dependence on subsidies, enhancing its resilience and scalability.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Network matrix (Y2016).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.00	27.51	14.66	0.26	1.17	0.88	0.03	0.14	0.71	0.27	0.56	0.14	0.54	0.22	0.07	0.15	0.02	0.01	0.14
2	27.51	0.00	353.32	4.10	7.98	5.97	0.17	0.77	19.42	2.02	3.72	0.71	5.53	1.22	0.31	1.01	0.10	0.05	0.82
3	14.66	353.32	0.00	7.94	18.44	12.40	0.35	1.57	43.28	4.22	7.75	1.60	11.92	2.55	0.63	2.20	0.21	0.10	1.52
4	0.26	4.10	7.94	0.00	0.61	0.72	0.05	0.20	8.67	0.35	0.52	0.13	0.66	0.49	0.08	0.29	0.04	0.02	0.19
5	1.17	7.98	18.44	0.61	0.00	7.85	0.27	0.67	1.41	3.18	3.63	0.77	4.45	2.50	0.72	1.13	0.12	0.06	1.28
6	0.88	5.97	12.40	0.72	7.85	0.00	4.54	0.66	5.31	14.64	2.84	0.75	4.99	2.11	0.56	1.65	0.19	0.08	16.98
7	0.03	0.17	0.35	0.05	0.27	4.54	0.00	0.24	0.12	0.44	1.22	0.18	1.00	0.44	0.05	0.05	0.01	0.01	2.83
8	0.14	0.77	1.57	0.20	0.67	0.66	0.24	0.00	0.37	0.49	1.75	1.31	0.39	1.19	0.25	0.22	0.03	0.03	1.17
9	0.71	19.42	43.28	8.67	1.41	5.31	0.12	0.37	0.00	1.37	2.04	0.01	2.42	1.02	0.13	0.70	0.08	0.03	0.59
10	0.27	2.02	4.22	0.35	3.18	14.64	0.44	0.49	1.37	0.00	1.28	0.27	1.62	0.92	0.25	0.50	0.05	0.02	2.13
11	0.56	3.72	7.75	0.52	3.63	2.84	1.22	1.75	2.04	1.28	0.00	12.71	10.87	12.05	2.16	2.01	0.17	0.06	5.87
12	0.14	0.71	1.60	0.13	0.77	0.75	0.18	1.31	0.01	0.27	12.71	0.00	1.13	1.45	0.31	0.38	0.04	0.02	0.89
13	0.54	5.53	11.92	0.66	4.45	4.99	1.00	0.39	2.42	1.62	10.87	1.13	0.00	1.52	0.53	2.97	0.15	0.04	4.81
14	0.22	1.22	2.55	0.49	2.50	2.11	0.44	1.19	1.02	0.92	12.05	1.45	1.52	0.00	63.68	4.25	0.97	0.12	2.14
15	0.07	0.31	0.63	0.08	0.72	0.56	0.05	0.25	0.13	0.25	2.16	0.31	0.53	63.68	0.00	1.21	0.35	0.04	0.25
16	0.15	1.01	2.20	0.29	1.13	1.65	0.05	0.22	0.70	0.50	2.01	0.38	2.97	4.25	1.21	0.00	0.48	0.06	0.26
17	0.02	0.10	0.21	0.04	0.12	0.19	0.01	0.03	0.08	0.05	0.17	0.04	0.15	0.97	0.35	0.48	0.00	0.04	0.04
18	0.01	0.05	0.10	0.02	0.06	0.08	0.01	0.03	0.03	0.02	0.06	0.02	0.04	0.12	0.04	0.06	0.04	0.00	0.03
19	0.14	0.82	1.52	0.19	1.28	16.98	2.83	1.17	0.59	2.13	5.87	0.89	4.81	2.14	0.25	0.26	0.04	0.03	0.00

(Density = 0.41, threshold value = 1).

Table A2. Network matrix (Y2019).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.00	25.79	7.09	0.29	0.94	0.75	0.03	0.15	0.82	0.32	0.65	0.22	0.75	0.29	0.09	0.17	0.03	0.02	0.15
2	25.79	0.00	170.80	4.56	6.39	5.09	0.18	0.83	22.58	2.38	4.30	1.11	7.79	1.65	0.36	1.16	0.15	0.06	0.89
3	7.09	170.80	0.00	8.84	14.76	10.57	0.38	1.69	50.32	4.98	8.96	2.50	16.79	3.44	0.74	2.52	0.31	0.12	1.65
4	0.29	4.56	8.84	0.00	0.49	0.61	0.05	0.22	10.08	0.41	0.60	0.20	0.93	0.66	0.09	0.33	0.05	0.02	0.21
5	0.94	6.39	14.76	0.49	0.00	6.69	0.29	0.72	1.64	3.75	4.19	1.21	6.27	3.38	0.84	1.29	0.18	0.07	1.39
6	0.75	5.09	10.57	0.61	6.69	0.00	4.99	0.71	6.17	17.27	3.28	1.17	7.04	2.85	0.66	1.89	0.27	0.09	18.39
7	0.03	0.18	0.38	0.05	0.29	4.99	0.00	0.26	0.14	0.52	1.41	0.29	1.41	0.60	0.06	0.06	0.01	0.01	3.07
8	0.15	0.83	1.69	0.22	0.72	0.71	0.26	0.00	0.43	0.58	2.02	2.05	0.54	1.61	0.30	0.25	0.04	0.03	1.27
9	0.82	22.58	50.32	10.08	1.64	6.17	0.14	0.43	0.00	1.62	2.36	0.01	3.40	1.38	0.15	0.81	0.11	0.04	0.64
10	0.32	2.38	4.98	0.41	3.75	17.27	0.52	0.58	1.62	0.00	1.47	0.42	2.29	1.24	0.30	0.58	0.08	0.03	2.31
11	0.65	4.30	8.96	0.60	4.19	3.28	1.41	2.02	2.36	1.47	0.00	19.91	15.31	16.28	2.54	2.30	0.24	0.07	6.36
12	0.22	1.11	2.50	0.20	1.21	1.17	0.29	2.05	0.01	0.42	19.91	0.00	1.59	1.96	0.36	0.43	0.06	0.02	0.96
13	0.75	7.79	16.79	0.93	6.27	7.04	1.41	0.54	3.40	2.29	15.31	1.59	0.00	2.05	0.63	3.40	0.22	0.05	5.21
14	0.29	1.65	3.44	0.66	3.38	2.85	0.60	1.61	1.38	1.24	16.28	1.96	2.05	0.00	75.09	4.87	1.38	0.15	2.32
15	0.09	0.36	0.74	0.09	0.84	0.66	0.06	0.30	0.15	0.30	2.54	0.36	0.63	75.09	0.00	1.39	0.49	0.05	0.27
16	0.17	1.16	2.52	0.33	1.29	1.89	0.06	0.25	0.81	0.58	2.30	0.43	3.40	4.87	1.39	0.00	0.68	0.08	0.28
17	0.03	0.15	0.31	0.05	0.18	0.27	0.01	0.04	0.11	0.08	0.24	0.06	0.22	1.38	0.49	0.68	0.00	0.05	0.04
18	0.02	0.06	0.12	0.02	0.07	0.09	0.01	0.03	0.04	0.03	0.07	0.02	0.05	0.15	0.05	0.08	0.05	0.00	0.03
19	0.15	0.89	1.65	0.21	1.39	18.39	3.07	1.27	0.64	2.31	6.36	0.96	5.21	2.32	0.27	0.28	0.04	0.03	0.00

(Density = 0.45, threshold value = 1).

Table A3. Network matrix (Y2022).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.00	30.00	7.24	0.27	1.10	0.55	0.03	0.14	0.64	0.35	0.78	0.25	1.31	0.20	0.14	0.18	0.03	0.02	0.15
2	30.00	0.00	177.75	4.33	7.60	3.81	0.18	0.77	17.90	2.72	5.27	1.34	13.84	1.15	0.62	1.25	0.17	0.07	0.91
3	7.24	177.75	0.00	3.80	7.94	3.58	0.17	0.71	18.06	2.57	4.96	1.36	13.50	1.09	0.57	1.23	0.16	0.07	0.76
4	0.27	4.33	3.80	0.00	0.55	0.44	0.05	0.19	7.61	0.45	0.70	0.23	1.57	0.44	0.15	0.34	0.06	0.03	0.20
5	1.10	7.60	7.94	0.55	0.00	4.29	0.24	0.57	1.11	3.66	4.40	1.25	9.53	2.03	1.23	1.19	0.17	0.08	1.21
6	0.55	3.81	3.58	0.44	4.29	0.00	2.75	0.38	2.81	11.32	2.31	0.81	7.18	1.15	0.65	1.17	0.18	0.07	10.77
7	0.03	0.18	0.17	0.05	0.24	2.75	0.00	0.23	0.11	0.56	1.64	0.33	2.37	0.40	0.10	0.06	0.01	0.01	2.97
8	0.14	0.77	0.71	0.19	0.57	0.38	0.23	0.00	0.31	0.59	2.22	2.21	0.87	1.01	0.45	0.24	0.04	0.03	1.16
9	0.64	17.90	18.06	7.61	1.11	2.81	0.11	0.31	0.00	1.53	2.40	0.01	5.01	0.80	0.21	0.72	0.10	0.04	0.54
10	0.35	2.72	2.57	0.45	3.66	11.32	0.56	0.59	1.53	0.00	2.19	0.62	4.91	1.05	0.61	0.75	0.10	0.04	2.85
11	0.78	5.27	4.96	0.70	4.40	2.31	1.64	2.22	2.40	2.19	0.00	30.52	34.62	14.50	5.51	3.16	0.35	0.11	8.25
12	0.25	1.34	1.36	0.23	1.25	0.81	0.33	2.21	0.01	0.62	30.52	0.00	4.80	2.33	1.05	0.79	0.12	0.04	1.66
13	1.31	13.84	13.50	1.57	9.53	7.18	2.37	0.87	5.01	4.91	34.62	4.80	0.00	3.23	2.41	8.24	0.55	0.13	11.94
14	0.20	1.15	1.09	0.44	2.03	1.15	0.40	1.01	0.80	1.05	14.50	2.33	3.23	0.00	108.56	4.45	1.33	0.15	2.01
15	0.14	0.62	0.57	0.15	1.23	0.65	0.10	0.45	0.21	0.61	5.51	1.05	2.41	108.56	0.00	2.70	1.01	0.11	0.50
16	0.18	1.25	1.23	0.34	1.19	1.17	0.06	0.24	0.72	0.75	3.16	0.79	8.24	4.45	2.70	0.00	0.85	0.10	0.31
17	0.03	0.17	0.16	0.06	0.17	0.18	0.01	0.04	0.10	0.10	0.35	0.12	0.55	1.33	1.01	0.85	0.00	0.09	0.06
18	0.02	0.07	0.07	0.03	0.08	0.07	0.01	0.03	0.04	0.04	0.11	0.04	0.13	0.15	0.11	0.10	0.09	0.00	0.05
19	0.15	0.91	0.76	0.20	1.21	10.77	2.97	1.16	0.54	2.85	8.25	1.66	11.94	2.01	0.50	0.31	0.06	0.05	0.00

(Density = 0.48, threshold value = 1).

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