

Spatial Structure of China's E-commerce Express Logistics Network Based on Space of Flows

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Abstract: The intermediate link compression characteristics of e-commerce express logistics networks influence the traditional mode of circulation of goods and economic organization, and alter the city spatial pattern. Based on the theory of space of flows, this study adopts China Smart Logistics Network relational data to build China's e-commerce express logistics network and explore its spatial structure characteristics through social network analysis (SNA), the PageRank technique, and geospatial methods. The results are as follows: the network density is 0.9270, which is close to 1; hence, indicating that e-commerce express logistics lines between Chinese cities are nearly complete and they form a typical network structure, thereby eliminating fragmented spaces. Moreover, the average minimum number of edges is 1.1375, which indicates that the network has a small world effect and thus has a high flow efficiency of logistics elements. A significant hierarchical diffusion effect was observed in dominant flows with the highest edge weights. A diamond-structured network was formed with Shanghai, Guangzhou, Chongqing, and Beijing as the four core nodes. Other node cities with a large logistics scale and importance in the network are mainly located in the 19 city agglomerations of China, revealing the fact that the development of city agglomerations is essential for promoting the separation of experience space and changing the urban spatial pattern. This study enriches the theory of urban networks, reveals the flow laws of modern logistics elements, and encourages coordinated development of urban logistics.

Keywords: space of flows; e-commerce express logistics; urban logistics network; logistics big data

Citation: LI Yuanjun, WU Qitao, ZHANG Yuling, HUANG Guangqing, ZHANG Hongou, 2023. Spatial Structure of China's E-commerce Express Logistics Network Based on Space of Flows. *Chinese Geographical Science*, 33(1): 36–50. <https://doi.org/10.1007/s11769-022-1322-0>

1 Introduction

The internet, as a new infrastructure, has prompted changes in the traditional retail and service industry business models. The e-commerce industry has increasingly prospered (Gibreel et al., 2018) and continues to expand into the fields of production and life, developing new industrial structures and allocating resource elements (Jaller and Pahwa, 2020; Kumar et al., 2021). Express logistics is an important link in the e-commerce

chain, characterized by fast and flexible circulation (Chen et al., 2013), thus effectively connecting offline production and online consumption. Compared with traditional logistics, e-commerce express logistics combines advanced information technology and various innovative elements, integrates transportation and warehousing resources on larger platforms, and achieves higher logistics efficiency and sustainability (Rotem-Mindali and Weltevreden, 2013). Therefore, it is a pioneering industry that promotes the transformation of cir-

Received date: 2022-05-11; accepted date: 2022-09-09

Foundation item: Under the auspices of National Natural Science Foundation of China (No. 42071165, 41801144), GDAS' Project of Science and Technology Development (No. 2023GDASZH-2023010101, 2021GDASYL-20210103004)

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culatation, stimulates consumption upgrading, encourages the development of urban informatization and intelligence, and enhances urban service capacities from multiple dimensions.

An e-commerce express logistics network is the result of the development of logistics productivity up to a certain stage (Wang et al., 2016). It was established to meet the market demand for express industrial integration and systematic development, reflecting the orderly trend in modern logistics development. Furthermore, this ordering is expressed in mesoscale urban logistics networks with cities as nodes (Russo and Comi, 2010; Akhavan et al., 2020). Existing studies on logistics networks, especially e-commerce express logistics networks, mostly focus on mesoscale urban networks for the following reasons. First, cities are the centers of social and economic activities, and their logistics development plans are comparatively consistent (Fossheim and Andersen, 2017). Therefore, it is reasonable to unify a city's internal logistics resources and aggregate them as network nodes. A horizontal comparison of cities helps to analyze the cross-regional allocation patterns of information and capital (Akhavan et al., 2020). Second, e-commerce express logistics has a small volume, a wide variety, a high efficiency, and miniaturized transportation vehicles (Dai et al., 2020). Its main transportation paths are concentrated on roads and air transportation between cities (Wu, 2014; De Giovanni et al., 2019; Dai et al., 2020); thus, using inter-city logistics links as network edges is comparatively suitable for determining real flow characteristics. The integration of e-commerce and China's substantive economy has accelerated in recent years (Loo and Wang, 2018), contributing to the rapid development of the express logistics industry. In this circulation link, the e-commerce economy drives direct links between upstream and downstream enterprises. Infrastructures such as own- and third-party logistics warehouses have been established nationwide (He et al., 2020), simplifying or eliminating some of traditional logistics' wholesale and retail links and reducing of logistics costs (Seghezzi and Mangiaracina, 2022). More cities are increasingly benefitting from intermediate link compression and expanding their market scope to join the e-commerce express logistics network from point to surface, continuously promoting the construction of a modern logistics network. With this continuous improvement of the network, the flow

efficiency of production and consumption materials in the e-commerce supply chain as well as their flow range in the urban network is gradually expanding. The e-commerce express logistics network has profoundly altered the urban spatial pattern, as well as the traditional circulation of goods and the mode of economic organization (Zhou et al., 2021). However, only a few studies have focused on these changes.

Existing studies on urban logistics networks have focused primarily on logistics enterprise networks (Akhavan et al., 2020; Tang and Ma, 2020), urban hub-and-spoke networks (Liu and Wang, 2014; Ghaffari-Nasab et al., 2016), and urban gravity networks (Davydenko and Tavasszy, 2013; Kashiwagi et al., 2020). However, studies on these types of logistics networks have been conducted from static and physical perspectives (Xiu et al., 2013). They focus on the organizational structure of logistics networks and the level of urban logistics development without considering the network's dynamic mobility characteristics and the shaping of urban spaces. Manuel Castells proposed the concept of space of flows in the 1990s, arguing that space is generated around flow elements, such as capital, information, and traffic flows (Castells, 1999). These flows induce a timeless time and space of flows, compressing temporal sequences and spatial distances and allowing humans to reconstruct their social and productive connections in a broad spatial and temporal context (Yan, 2019). For network studies, the space of flows theory generates new spatial mechanisms and dynamic analysis perspectives. Many scholars have explored the tourism flow network formed by inter-city tourism flows (Zeng, 2018), the information flow network formed by flows of information (Doran and Fox, 2016), and the knowledge flow network formed by scientific research cooperation (Matthiessen et al., 2010), among others, revealing the laws of agglomeration and diffusion of various types of flows and expanding the meaning and extension of traditional network research from multiple dimensions, such as network construction and analysis and urban space interactions. However, due to the difficulty of obtaining flow data as well as other objective reasons, research on logistics networks from the perspective of space of flows is relatively scarce.

From the perspective of the space of flows, this study explores the urban spatial pattern and the regularity of logistics flows under the influence of an e-commerce

express logistics network. The following are this study's contributions in terms of methodology, theory, and practice. First, it builds an e-commerce express logistics network based on China Smart Logistics Network (CSN) data, and conducts beneficial explorations in spatial big data mining and application. Second, it analyzes the networks' spatial characteristics from the perspectives of nodes, edges, and overall structure, and it goes on to discuss the shaping of urban space by logistics flows based on network logic to enrich the space of flows theory. Finally, relevant policy recommendations are made to encourage the coordinated development of the e-commerce express logistics industry.

2 Literature Review

2.1 Progress in the study of urban networks from the perspective of space of flows

Scholars have attempted to explore the shaping of urban spatial structures, connections, and functions using various flows as the subject of movement in the space of flows. Previous studies have mostly focused on physical flows with high measurability, such as tourism flows (Rogerson and Visser, 2006; Yang et al., 2007), traffic flows (Derudder and Witlox, 2008; Mahutga et al., 2010), and population flows (Zhang et al., 2009; Kraler and Reichel, 2011). Spatial transmission is not limited to physical elements in the context of the Internet (Castells, 1996), as big data has led to a deeper exploration of virtual flow elements. Scholars have begun to analyze capital flows using enterprise correlation data (Jin et al., 2018), information flows using mobile phone communication data or network indices (Sobolevsky et al., 2013; Doran and Fox, 2016), and knowledge flows using thesis co-authorship data (Matthiessen et al., 2010), thus entering the field of virtual flow research.

Previous studies have paid little attention to shaping the urban spatial structure through logistics from the perspective of space of flows. The logistics industry is a composite service industry that integrates transportation, warehousing, and information industries; moreover, it is an essential industry that supports the development of the national economy (Liedtke and Friedrich, 2012). In addition, relevant flow data can be used as an important parameter to characterize the pattern of inter-city linkages and reflect material exchange among cities (Liedtke and Friedrich, 2012). Compared to virtual flows, such as

capital and information flows, logistics flows include the physical flows of materials, revealing a more realistic industrial connection and social division of work among cities. Compared to physical flows, such as population and traffic flows, logistics flows are more sensitive to changes in market supply and demand and are more deeply related to economic development, because they are directly involved in the operation of industrial chains and constitute important links in enterprise production and sales (Hesse and Rodrigue, 2006). Therefore, exploring the shaping of urban spaces by logistics flows based on the logistics networks is an important direction in urban network research.

2.2 Progress in research on urban logistics networks

As mentioned in the introduction, the studies on urban logistics networks primarily focus on three areas: logistics enterprise networks, urban hub-and-spoke networks, and urban gravity networks. Table 1 summarizes the meanings, construction methods, and research objectives of the three networks.

When comparing the three types of logistics networks mentioned above, the logistics enterprise network is especially important for studying the enterprise organization structure and the work division pattern in urban industries (Akhavan et al., 2020; Tang and Ma, 2020). However, this network focuses on the nodes and analyzes their edges only superficially. In addition, broken edges and edges without weights make it difficult to show the network structure and analyze the logistics link strengths between cities comprehensively. Because data on inter-city logistics flows is difficult to obtain, the urban hub-and-spoke and gravity networks reflect the structural characteristics of the logistics network and the strengths of these connections between cities to a certain extent (Liu and Wang, 2014; Ghaffari-Nasab et al., 2016; Kashiwagi et al., 2020); however, they are simulated models that cannot truly show the structural characteristics of the network and the law of logistics flows. Constructing an urban network based on real and dynamic relational data of inter-city flows, using the concept of space of flows, has become the frontier of logistics network research in the era of big data.

E-commerce express logistics has certain links and differences with traditional logistics in terms of indicating the spatial connection of cities. The links are mainly

Table 1 Main forms of urban logistics networks

Logistics network	Meaning	Construction method	Research objective
Logistics enterprise network	Network is constructed using organizational links and geographical locations of corporate headquarters and branches (Zong et al., 2015; Ye and Duan, 2016)	The organizational links and spatial locations between enterprise headquarters and branches form the basis for measuring inter-city logistics links and hierarchical relationships, from which logistics enterprise networks can be constructed (Zong et al., 2015; Ye and Duan, 2016)	To analyze business development patterns and inter-city logistics links, formulate business development strategies, among others
Urban hub-and-spoke network	The network is constructed using mathematical modeling. It consists of nodes (hub nodes, common nodes) and channels (trunk channels, branch channels) (O'Kelly and Bryan, 1998; O'Kelly, 1998)	Construct an index assessment system and quantify the levels of logistics development of urban nodes, classify them into hierarchies, and identify hub nodes and common nodes. Finally, connect nodes at different levels to form channels, thus building an urban hub-and-spoke network	To reasonably deploy the logistics infrastructure, use the advantages of economies of scale to reduce logistics costs, realize the efficient connection of urban nodes, and promote coordinated logistics development (Horner and O'Kelly, 2001; Matsubayashi et al., 2005)
Urban gravity network	The network is constructed based on the gravity model. The gravity values between cities are the edge weights	Similar to the concept of gravity in physics, the gravity of logistics between two cities is proportional to the mass of the cities and is inversely proportional to their distance. The mass is the comprehensive logistics strength of the city, calculated using the index assessment system; the distance is the spatial or temporal distance between cities (Reilly, 1929; Shen et al., 2018)	To analyze urban spatial interactions, construct urban hierarchy systems, and promote coordinated logistics development

manifested in the form of physical flows that provide point-to-point transportation for materials production and consumption while also changing their spatial location. Thus, e-commerce express logistics shares the basic characteristics of traditional logistics. However, the former mainly serves online transactions, and drives the direct link between upstream and downstream enterprises through information technology and time-efficient logistics systems to achieve intermediate link compression (Chen et al., 2013; Rotem-Mindali and Weltevreden, 2013; Seghezzi and Mangiaracina, 2022). In addition, the manifestation of e-commerce express logistics is the physical flow of intercity traffic and essentially controlled by the guidance of information flow. It combines the virtual flow of information and physical flow of traffic, which is a typical representative of the virtual and real dual property of space of flows. This study adopts the relational data of the CSN to construct an e-commerce express logistics network, which has a complete network structure. The direction and weight of the network edges are comparatively intuitive and known. This network can demonstrate the characteristics of intercity logistics connections as well as the regularity of logistics flows. It also explains how modern logistics flows impact the spatial structures of cities.

3 Data and Methodology

3.1 Study region

For 345 study units, the study region included prefecture-level cities, municipalities, special administrative regions and Taiwan Province in China (Fig. 1). In 2018, the number of global online shoppers reached 1.5 billion (<https://unctad.org>), accounting for 20% of the global population, with China ranking first with 0.6 billion online shoppers. Global e-commerce sales and cross-border purchases have increased by 8% year-on-year to reach US\$ 25.6 trillion, accounting for 30% of total GDP. The e-commerce industry has immensely contributed to global economic development. In terms of e-commerce sales, the United States, China, and the United Kingdom ranked among the top three in 2018, with China recording the highest e-tailing transaction value. According to the data (<http://dzsws.mofcom.gov.cn>), China's e-commerce transactions reached US\$5.4 trillion in 2019, which included US\$ 1.7 trillion in online retail sales. China's level of economic development has gradually increased in recent years. In addition, China has a large population base with a lot of Internet users and labor, with 51.3 million people working in e-commerce. This creates favorable conditions for devel-



Fig. 1 Sketch map of the study area

oping the e-commerce industry, resulting in increased demand for express logistics. The national express business volume in 2019 was 63.5 billion pieces (<https://www.spb.gov.cn>), representing an increase of 25.3% yearly. As a region with leading e-commerce development and frequent express logistics, China is central to express logistics networks research.

3.2 Data sources

The relational data used to construct the e-commerce express logistics network in this study came from the China Smart Logistics Network (CSN) official website (<https://56.1688.com>). The CSN was initiated by the Alibaba Group and created in collaboration with major Chinese third-party express logistics companies, such as Shunfeng Express, Shentong Logistics, Yuantong Express, Zhongtong Express, and Yunda Express, which have become the most prominent social express logistics platforms in China's e-commerce industry. The CSN network connects cities through logistics transport lines. The lines include details such as carrier companies, origin and destination cities, and the number of such lines. Additionally, they are a source of relational data that aid

in accurately characterizing inter-city e-commerce express logistics links. The number of directed logistics lines between cities was obtained from CSN. To avoid chance effects due to the periodic changes in the lines, five batches of data were collected between July 5 and July 9, 2020, and the average values were taken. The removal of lines with duplicate origins and destinations, such as lines from Beijing to Beijing (Beijing-Beijing), was part of the redundant data processing. Following this, 114 366 origin-destination (O-D) pairs between 345 cities were obtained, totaling 21 430 731 directed lines. The GDP, population, and other statistics were obtained from the China Statistical Yearbook issued by the National Bureau of Statistics (<http://www.stats.gov.cn/tjsj>).

3.3 Methodology

3.3.1 Network construction

A directionally weighted e-commerce express logistics network was constructed using the graph theory principle. In this network, Chinese cities constitute the nodes, inter-city directed e-commerce express logistics lines are the edges, and the number of lines form the

weights. The formula used is as follows:

$$N = \begin{bmatrix} 0 & N_{12} & \dots & N_{1(i-1)} & N_{1i} \\ N_{21} & 0 & \dots & N_{2(i-1)} & N_{2i} \\ \dots & \dots & \dots & \dots & \dots \\ N_{(i-1)1} & N_{(i-1)2} & \dots & 0 & N_{(i-1)i} \\ N_{i1} & N_{i2} & \dots & N_{i(i-1)} & 0 \end{bmatrix} \quad (1)$$

where N is the directional weighted e-commerce express logistics network, N_{1i} is the number of express logistics lines starting from the first city to the i th city, N_{i1} is the number of express logistics lines starting from the i th city to the first city. The entire network reflects the flow direction of e-commerce express logistics and includes the weight characteristics of flow lines.

3.3.2 Network analysis

An analysis of the overall network characteristics, nodes, and edges is included in the network analysis. This study selected the network density index to analyze the degree of network completeness. The closer the calculated network density value is to 1 after binarizing the e-commerce express logistics network, the more complete the network. The small-world effect index was selected to analyze the network flow efficiency. This study selected the node degree (including out-degree and in-degree) for the nodes (cities) to quantify the scale of urban express logistics. The out-degree, in-degree, and node degree represent the node's outward radiation capacity, the node's receiving and storage capacity, and the comprehensive capacity, respectively. The betweenness centrality index is selected to explore the nodes with intermediary or transit functions in the network. The PageRank algorithm analyzes the importance of nodes, indicating their degree of participation in the network. The spatial distribution differences of the directed edges were explored using GIS spatial analysis. The network density index, node degree, and betweenness centrality index are standard methods in social network analysis and have been explained in precious studies with relevant formulas (Dang-Pham et al., 2017; Lopez Rodriguez et al., 2021).

Small-world network effect: a small-world network is a topological network that exists between a completely regular and a completely random network. This is also known as the six degrees of separation, that is, any two nodes in the network can be connected by a few edges, but not more than six. In a logistics network with a small-world effect, the flow of logistics elements between cities is more efficient, and the network system is better

connected. The small-world network effect is measured using the average minimum number of edges of all connected nodes in the network as shown below:

$$S = \text{sum}(e_{ij}) / \text{sum}(E) \quad (2)$$

where e_{ij} refers to the minimum number of edges when nodes i and j are connected and $\text{sum}(E)$ is the number of edges in the existing connection state between nodes. The smaller the S , the closer the connection between nodes, and the higher the network flow efficiency. When $S < 6$ or S grows logarithmically with the number of nodes n , the network exhibits a small-world effect.

PageRank algorithm: the nodes are ranked in order of importance using the PageRank algorithm principle in machine learning as follows: the cities are treated as nodes, the inter-city e-commerce express logistics lines are treated as directed edges, and the number of lines from city nodes B to A is used as an importance vote of B to A . The more times A is voted for and the more important the city node that votes for A , the more important the city node A . The PageRank for city node A is calculated as follows:

$$\text{PageRank}(A) = \alpha \frac{1}{N} + (1 - \alpha) \sum_{P_i \Rightarrow A} \frac{\text{PageRank}(P_i)}{K_{\text{out}}(P_i)} \quad (3)$$

where N is the total number of city nodes in the network, α is the damping factor, $K_{\text{out}}(P_i)$ is the number of lines flowing from city P_i to other cities. The larger the PageRank of node A , the higher is its importance and participation in the network.

4 Results

4.1 Network node analysis

4.1.1 Node characteristic value analysis

The node characteristic value analysis shows that the difference in the out-degree is more pronounced. The city with the highest out-degree was Shanghai, with a value of 566 600, followed by Guangzhou and Beijing, with 531 017 and 505 479, respectively. These are important goods supply areas for e-commerce express logistics and have a tremendous outward radiation capacity. The places with the smallest out-degree were Taiwan Province and Macao Special Administrative Region (SAR), each with a value of zero, indicating that the express logistics channel opened by the CSN in Taiwan Province and Macao SAR is unidirectional. Currently only e-commerce express logistics routes ex-

ist from other regions to Taiwan and Macao SAR. The city with the highest in-degree was Chongqing, with a value of 279 744. As the main destination of express logistics delivery, Chongqing has obvious logistics agglomeration characteristics and a robust logistics capacity. The city with the smallest in-degree of 2799 is Sansha, Hainan Province. Compared with the out-degree, the numerical difference in the in-degree was relatively small. Shanghai has the highest node degree at 693 185 and has the strongest comprehensive logistics distribution capacity, followed by Chongqing and Guangzhou with 628 856 and 628 498, respectively. The Hong Kong SAR had the highest betweenness centrality at 15.95, indicating that it serves as an important express

transit station in the network. The node with the smallest betweenness centrality was Sansha City at 1.003.

The out-degree, in-degree, node degree, and betweenness centrality values of all nodes were classified into five levels according to the Jenks natural break method and visualized to analyze their spatial distribution patterns. Levels A-E represent the highest, higher, medium, lower, and lowest values, respectively. As shown in Fig. 2, the spatial distribution similarity in the node characteristic values is because the Heihe-Tengchong Line is the boundary, and its two sides differ significantly. The A- and B-level nodes are mainly distributed in the south-east of the boundary and the D- and E-level nodes in the northwest. The Heihe-Tengchong Line depicts the spa-

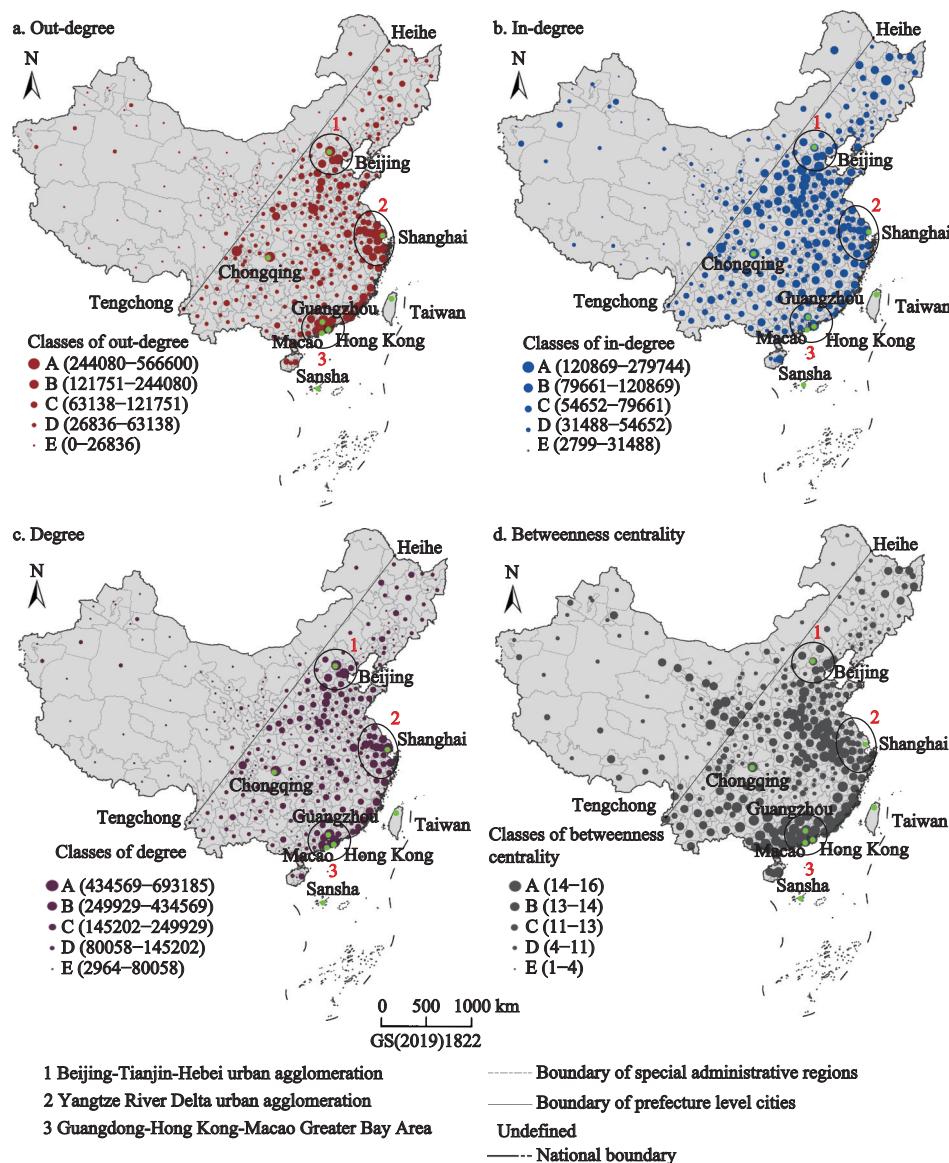


Fig. 2 Distribution pattern of node characteristic values of Chinese cities in 2020

tial variability of population density distribution and economic and social development levels in China. The southeastern boundary is more densely populated, with higher levels of urbanization, transportation infrastructure construction, and economic development. The northwestern region is the polar opposite. The spatial distribution of all node characteristic values remains ineffective in breaking the phenomenon that China's economic and social development pattern is locked by the Heihe-Tengchong Line. In addition, the spatial distribution of the node characteristic values varied. There was significant spatial unevenness in the distribution of out-degrees. The A- and B-level nodes are mainly concentrated in the three major urban agglomerations in China's coastal regions, namely, the Beijing-Tianjin-Hebei urban agglomeration, Yangtze River Delta urban agglomeration, and Guangdong-Hong Kong-Macao Greater Bay Area. The level E nodes in other regions are relatively low, especially in northwestern China. In the Heihe-Tengchong Line boundary, the in-degrees are relatively evenly distributed and have high values in the southeast of the boundary; however, they are generally low in the northwest. The spatial pattern of the node degree distribution highly matched that of the out-degree distribution. The betweenness centrality has a spatial distribution pattern different from the above characteristic values, with A and B level nodes mainly concentrated in the Yangtze River Delta urban agglomeration in the east, and the Guangdong-Hong Kong-Macao Greater Bay Area in the south.

4.1.2 Analysis of the importance of nodes

According to the PageRank results, Shanghai was the top most important node in the network, with a PageRank value of 2.5375. It was followed by Guangzhou and Beijing with 2.4073 and 2.3264, respectively. Sansha City in Hainan Province was ranked at the bottom, with a PageRank value of 0.0007, which is approximately 3600 times lower than that of the top city.

According to the Jenks natural breaks method for hierarchical visualization, the PageRank value, GDP, and total population of each city were also divided into five levels (A–E). As shown in Fig. 3, the spatial non-equilibrium characteristic of city PageRank values is significant, because the distribution areas of level A and B cities overlap significantly with the locations of the 19 urban agglomerations (Fig. 1) classified in China, and the Heihe-Tengchong Line bounds the distribution of cities at all levels. Level A cities are concentrated in

southeastern coastal cities, municipalities, or provincial capitals, such as Beijing, Chongqing, Wuhan in Hubei Province, Zhengzhou in Henan Province, Qingdao in Shandong Province, Suzhou in Jiangsu Province, and Ningbo in Zhejiang Province. Level B cities have prominent territoriality and are mainly concentrated in coastal provinces such as Guangdong, Zhejiang, Jiangsu, Shandong, and Hebei provinces, relying on level A cities as the axis and forming concentrated and contiguous express logistics belts along the eastern coast of China. Levels C and D are widely distributed, whereas level E cities are concentrated northwest of the Heihe-Tengchong Line.

In addition, there are some correlations between the spatial distribution pattern of city importance based on the PageRank value, city population, and GDP. The spatial distribution by city importance and GDP distribution patterns are nearly identical, with the exception of the Hohhot-Baotou-Ordos-Yulin urban agglomeration in the Inner Mongolia Autonomous Region, the middle Yangtze River urban agglomeration, and Taiwan Province. The spatial distribution of city importance and population are identical because the Heihe-Tengchong Line bounds both, and the numerical value levels on both sides of the line differ significantly; the difference occurs because cities with large populations are concentrated in the central, northern, and southwestern regions of China, whereas cities with high importance are concentrated in the coastal regions. As shown in Fig. 3, linear regression was performed with city GDP and population as independent variables and the PageRank value as the dependent variable. The PageRank value was positively correlated with GDP and population, where the R^2 of the fit function of the PageRank value with GDP was 0.5869 and the R^2 of its fit function with population was 0.2789. This indicates a correlation between the PageRank value and GDP, and that the importance of cities in the e-commerce express logistics network is related to economic development.

4.2 Analysis of network edges and network structure characteristics

4.2.1 Quantitative analysis of directed edge weights

The weights of the directed edges were divided into 10 levels using the Jenks natural breaks method. The edge weights of each level were quantified and analyzed,

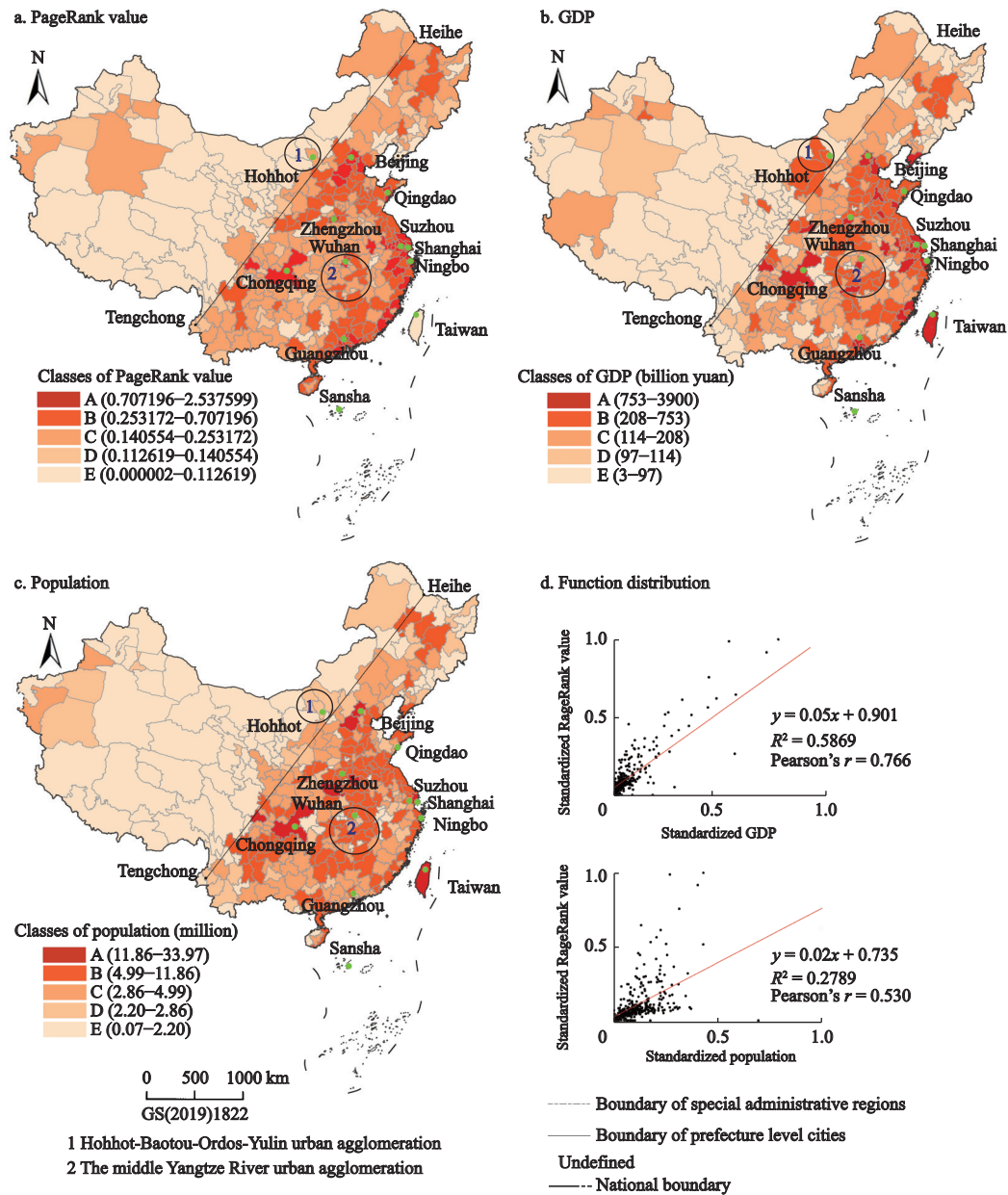


Fig. 3 Spatial distribution patterns of PageRank values, GDP and population of Chinese cities in 2020 (a–c); correlation analysis between PageRank values and GDP and population, respectively (d)

with levels 1–10 representing the lowest to highest levels (Table 2). The differences in the directed edge weights of the e-commerce express logistics network are significant and concentrated in low-level. The directed edges in the first two low levels exceeded 60%, with 38 077 (34.19%) directed edges in the 1st level (1–77) and 36 863 (33.10%) directed edges in the 2nd level (77–170). The number of directed edges at level 10 (3490–7092) was the lowest, with 29 (0.03%) edges.

4.2.2 Analysis of the overall network structure

The network density is 0.9270, which represents high

network density, and that the inter-city express logistics lines are generally complete, forming a typical network-type spatial structure. From the perspective of output direction, the Hong Kong SAR is the only city fully connected to all cities in China, while the Macao SAR and Taiwan Province have no express logistics lines outward. All Chinese cities have opened receiving lines for express logistics, and only a few cities lack direct express logistics links with each other. Based on the small-world network effect measurement results, the average minimum number of connected edges in the en-

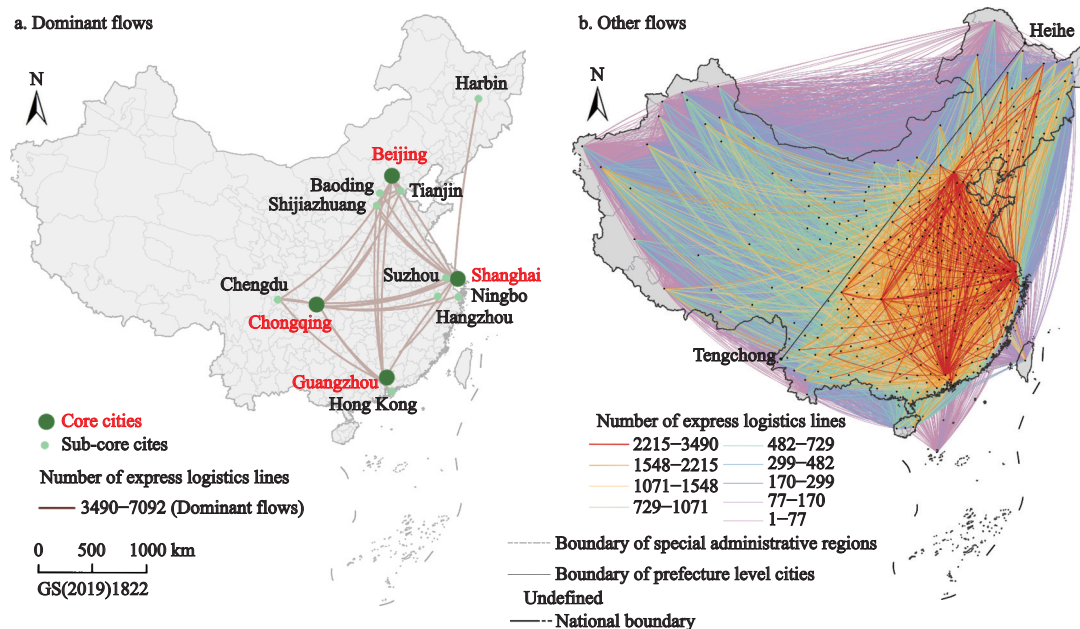
Table 2 Hierarchical list of directed edge weights in the China's e-commerce express logistics network in 2020

Weight hierarchy	Weights	Number of directed edges	Proportion / %
Level 10	3490–7092	29	0.03
Level 9	2215–3490	226	0.20
Level 8	1548–2215	619	0.56
Level 7	1071–1548	1286	1.15
Level 6	729–1071	2512	2.26
Level 5	482–729	4809	4.32
Level 4	299–482	8691	7.80
Level 3	170–299	18254	16.39
Level 2	77–170	36863	33.10
Level 1	1–77	38077	34.19

tire network was 1.1375, which was significantly lower than 6. Hence, less than two intermediary cities need to pass over to be connected to any city, in accordance with the six degrees of separation theory. Therefore, the e-commerce express logistics network has a small-world network effect, and the intercity express logistics flows are comparatively efficient.

All hierarchical lines were visualized, and the network's spatial structure was analyzed (Fig. 4). The overall characteristics are as follows. 1) E-commerce express logistics lines are widely distributed and have a high degree of network coverage. Express logistics lines have also been established in Sansha City in the South China Sea, Taiwan Province, which is across the sea

from Fujian Province, and in the Tibet Autonomous Region on the western border, which is located on a plateau and has harsh environmental conditions. 2) The dominant flows in the e-commerce express logistics network have a clear diamond-like structure. The directed edges in the 10th level (3490–7092), which show dominant flows with the highest weights, are concentrated in a few major cities such as Shanghai, Guangzhou, Chongqing, and Beijing, forming a diamond structure. The core cities are surrounded by 1–3 sub-core cities, forming an urban agglomeration based on express logistics services, with a spatial scope that corresponds to the layout of China's major urban agglomerations, such as the Yangtze River Delta urban agglomeration with Shanghai as the core and Ningbo, Hangzhou, and Suzhou as sub-cores, and the Beijing-Tianjin-Hebei urban agglomeration with Beijing as the core and Baoding, Tianjin, and Shijiazhuang as sub-cores. In addition, the dominant flows showed noticeable hierarchical diffusion effects. Dominant flows connect cities with large economic and population scales, beginning and ending in cities with similar levels but with a broader spatial scope than those with neighboring geospatial distances. 3) The spatial structure of China's e-commerce express logistics network is still locked by the Heihe-Tengchong Line. The directed edges in the southeast of the Heihe-Tengchong boundary line have higher weights and levels, more logistics express lines, and frequent inter-

**Fig. 4** Spatial structure of China's e-commerce express logistics network in 2020

city traffic. Furthermore, the spatial polarization of the southeast region is evident, showing strong logistics dispersion and aggregation. The opposite is true northwest of the boundary.

In terms of levels, the directed edges of level 9 have an extension to connect nodes in eastern, northeastern, and southwestern China based on those in level 10, forming the region with dense lines in the Shanghai-North China, Shanghai-South China, Guangzhou-North China, and Guangzhou-Northeast China regions. Levels 8 and 7 have an extremely wide distribution of directed edges, with lines connecting most of China's provincial capitals and major regional cities, such as Wuhan City in Hubei Province, Zhengzhou City in Henan Province, and Urumqi City and Kashgar regions in Xinjiang. The majority of the lines below level 7 show no obvious regional directivity or spatial variability and are widely distributed throughout China, with the lines of lowest weights distributed between Chinese border cities, such as Heilongjiang and Xinjiang, and between cities on islands and inland cities, such as cities between Taiwan and Fujian.

5 Discussion

Manuel Castells's theory of space of flows describes a new space form based on network logic within neoliberalism (Castells, 1999). Along with the birth of new space forms, the spatial structure and social order are continuously adjusted and reshaped around network logic. According to Castells, the new economy, which has existed since the 1980s and is characterized by informatization, globalization, and networking, also adheres to the theory of space of flows to form a general social order (Castells, 1996; 1999). Information technology unleashes capital vitality while also stimulating labor potential. The ability to handle and apply information has become a critical to the competitiveness of economic participants. Globalization emphasizes a wide range of global economic activities, from distribution to consumption and even production. Networking emphasizes multi-directional organization and multiple connections of economic activities, and it uses network logic to create a new economic structure. In the space of flows theory, information technology infinitely shortens time and organizes all types of transactions on a large scale to overcome the barriers of time and space, to achieve

the immediacy of global economic activities and integrate all trading partners into the global network. This economic activity culminates in a networked global economy that bypasses the local economy (Yan, 2019). Now we can use Castells' network logic, which is based on globalized and localized development, to understand how e-commerce express logistics flows shape China's urban space.

Generally, the process of forming a space of flows based on network logic can be divided into four stages (Fig. 5) (Yan, 2019). Stage 1: within the experience space that matches people's intuitive perception of space, that is, in the physical space where people live-spatial mobility is hindered by distance, and people's main social actions are fixed in local places with specific administrative boundaries. The main social structure of the experience space is predominantly vertical, with a clear hierarchical division between cities. Stage 2: the continuous development of information technology, with its time for space characteristics, reduces the spatial distance obstacle and releases the potential of spatial mobility. The flow of information, capital, and other elements begin to dominate interaction and changes in experience space. The original continuous and integral experience space is gradually separated and produces a dual structure. Stage 3: the spatial locations in the original experience space that follow a standard

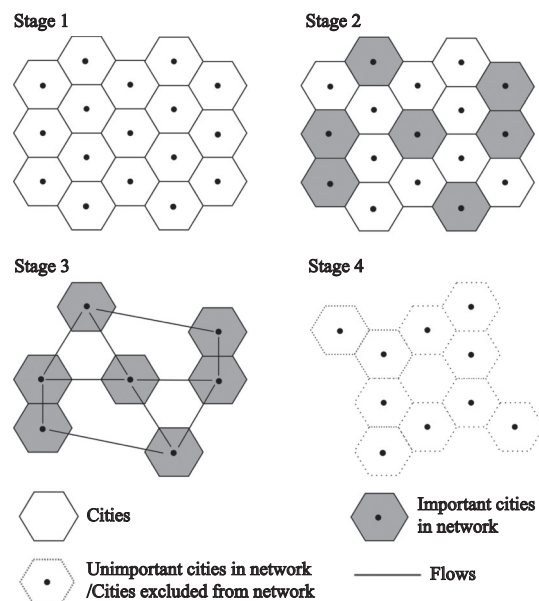


Fig. 5 Schematic diagram of the process of forming a space of flows based on network logic

code of conduct and share the same practice behavior are strung together by flow elements, and are combined with capital or power to form a network structure and a new spatial association, thus the space of flows is born. Stage 4: the remaining spatial locations in the original experience space exhibit fragmented characteristics and are excluded from the network.

The above analysis of nodes, edges, and overall network structure reveals the structural characteristics of China's e-commerce express logistics network as well as the pattern of urban space from the perspective of space of flows. The modern flow element, e-commerce express logistics, in reshaping the urban space follows the above-mentioned network logic proposed by Castells; however, it is subject to restrictions in the flow element's characteristics, demonstrating a unique form of the space of flows organization. This uniqueness is reflected in the fact that the e-commerce express logistics flows between cities are deeply affected by economic and demographic factors while being less affected by distance.

First, the space of flows shaped by e-commerce express logistics is dependent on the development of economically prosperous and densely populated urban agglomerations, which correspond to Stage 2. The development of urban agglomerations can be viewed as an important force in promoting the separation of the experience space. With economic globalization and regional integration, urban agglomerations have become critical units for national participation in global competition and international division of work, and they will determine the new pattern of world politics and economy. The development of urban agglomerations is valued globally. The core urban agglomerations in China, such as the Guangdong-Hong Kong-Macao Bay Area, the Yangtze River Delta, Beijing-Tianjin-Hebei, and Chengdu-Chongqing regions, derive their central competitiveness from the information and service industries, as opposed to the manufacturing industry. The service industry, as represented by modern logistics, has the advantage of penetrating other industries and has emerged as a new economic growth engine in urban agglomerations. In contrast, as a flow field where multiple flow elements such as capital, information, and traffic flows converge, urban agglomerations have certain advantages in terms of market information feedback, diffusion of innovation elements, and online-offline synergistic

development. Urban agglomerations have unquestionably tremendous development potential for the e-commerce express logistics industry, which pursues information technology, automation, and intellectualization. The main nodes in the diamond structure formed by the dominant flows in the e-commerce express logistics network are all located in the above-mentioned core urban agglomerations, such as Beijing in the Beijing-Tianjin-Hebei urban agglomeration and Guangzhou in the Guangdong-Hong Kong-Macao Greater Bay Area. In the spatial distribution of PageRank values, which characterize the importance and network participation of cities (Fig. 4), the radiating and driving effects of urban agglomerations are clearly demonstrated. Cities with high network participation and logistics importance are located in the urban agglomerations.

Second, the diffusion of e-commerce express logistics flows mainly follows the mechanism of hierarchical diffusion and is less dependent on distance, which is also in accordance with the characteristics of flow elements that tend to be combined with capital or power in stage 3. In recent years, exploring the spatial structural characteristics of China's urban network around various flows has become an important topic. Integrating existing studies on traffic and economic flows shows that the dominant flow of China's urban economy, road transport, and population networks has evident characteristics of proximity connections. The diffusion of flows mainly follows the proximity diffusion mechanism (Leng et al., 2011; Wang et al., 2021). In contrast, the dominant flow of China's e-commerce express logistics network tends to connect provincial capital cities at the same development level and regional economic or population center cities rather than neighboring areas, and the flow diffusion mainly follows the hierarchical diffusion mechanism. Spatial structure based on distance has always been an important expression of space of flows. The concentration and diffusion of inter-city flows are subject to distance, which maintains a certain stickiness with traditional physical space. This stickiness is closely related to the characteristics of the flow elements. The theory of space of flows is proposed against the background of the information era and is typified by information flow, which is characterized by significant co-temporality and can cover a wide spatial area in a comparatively short time, truly realizing time for space and promoting the continuous compression of space and the in-

finite reduction of the obstruction due to distance. In the above-mentioned types of networks, the concentration and distribution of population flows depend on traffic flows (especially road and railway flows), which are mainly dependent on road networks in the physical space, such as roads and tracks, with a strong dependence on distance. Therefore, the population and traffic flows mainly follow the proximity diffusion mechanism. However, e-commerce express logistics combine information, traffic, and other flow elements. The efficient operation of information flow achieves the instant sharing of commodity information across the country. Neighboring cities have fewer advantages in developing the e-commerce market compared to distant cities. In recent years, China's courier speed has continued to increase, and in general, most regions in China, except Xinjiang, Tibet, Qinghai, and other remote areas, can achieve 1–2 days of delivery within the province and 3–4 days of delivery outside the province. The impact of distance on express logistics delivery time was weak. With a marginal difference in delivery time, consumers are more inclined to seek a wide variety of goods at reasonable prices in a wider space and market range; thus, cities with advantages in information dissemination and e-commerce industry development are often areas where e-commerce express logistics flow frequently.

Finally, corresponding to Stage 4, the coverage of China's e-commerce express logistics network is comparatively wide, and the participation rate of cities in the network is comparatively high. Thus, an absolutely fragmented space does not appear, and there are comparatively more relatively fragmented spaces. According to network logic, the fragmented space under the dual structure is the space outside the network. This can be interpreted in two ways: first, it is completely excluded from the network and never exists as a network node, which can be called an absolutely fragmented space; second, it exists as a network node but has a lower degree of participation in the network compared to the surrounding areas, which is manifested in a smaller number of connected cities and a weaker connection strength, which can be called a relatively fragmented space. China's e-commerce express logistics network is comparatively complete, with Sansha City in Hainan Province, at a remote location in the South China Sea, and the Ali region, located on the Qinghai-Tibet Plateau, all participating in the network. There was no absolutely frag-

mented space. Relatively fragmented spaces appear in areas such as central and southwestern China. These relatively fragmented spaces with low characteristic values are mostly located at provincial border junctions. In recent years, residents' standard of living and e-commerce consumption demand have gradually improved. The government has introduced several policies to accelerate the construction of modern logistics infrastructure facilities and promote the development of the express logistics industry to meet consumer demands. Thus, the coverage of e-commerce express logistics networks has been expanding, and all cities have become network nodes, eliminating the existence of absolutely fragmented spaces. Concurrently, there are relatively fragmented spaces at the junctions of provinces and between urban agglomerations. When the proximity diffusion mechanism fails and hierarchical diffusion is evident, these cities do not fully enjoy the dividends released by the economic development of urban agglomerations. In addition, because the development level of e-commerce, manufacturing, modern logistics, and other industries is not high in these cities and their degree of integration with the core structure of the flow network is low, they form express logistics basins.

As a result, these basins should be given special consideration for the future development of China's e-commerce express logistics industry. The provinces of Hubei and Guangxi are used as examples. Hubei is located in central of China and known as the 'Thoroughfare to Nine Provinces'. Because of this, Hubei should use its location to deploy large-scale logistics hubs in core cities (such as Wuhan) to promote gradient diffusion of logistics elements and improve network integrity. Moreover, the entry threshold for the e-commerce industry is relatively low, which means that Guangxi can foster talented professionals and build logistics infrastructure, integrate the agricultural product processing industry with e-commerce, and promote the development of impoverished areas, and rural revitalization while improving the logistics industry.

6 Conclusions

This study explores the spatial structural characteristics of China's e-commerce express logistics network using the theory of space of flows. It analyses the unique role of e-commerce express logistics flows in shaping urban

spaces in the context of the network logic. The main conclusions are as follows.

E-commerce express logistics lines between Chinese cities are almost complete, forming a typical network structure and eliminating absolutely fragmented urban spaces with their small world effect. The efficiency of e-commerce express logistics flow elements is high. From the perspective of outbound direction, the Hong Kong SAR is the only region that is directly connected to all other cities with express logistics lines. From an inbound direction perspective, all cities in China have opened express logistics receiving lines, and only a few cities lack direct express logistics links.

The dominant flows with the highest edge weight level have a significant hierarchical diffusion effect, with Shanghai, Guangzhou, Chongqing, and Beijing as the core nodes forming a diamond structure. The directed edges with the lowest weight levels are distributed between border cities in China or between cities on islands and inland areas. Based on the characteristics of the nodes, Shanghai has the highest out-degree and node degree; it has the largest outward radiation capacity and the strongest comprehensive logistics capacity in China. Chongqing has the highest in-degree and outstanding express logistics accommodation capacities. The Hong Kong SAR has the highest betweenness centrality, strong transfer capacity in the network. Most of the nodes in the network with large logistics scale and outstanding importance are distributed within the 19 urban agglomerations existing at this stage in China, indicating that the development of urban agglomerations is an important force to promote the separation of experience space and urban spatial pattern changes.

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