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Flow space reveals the urban network structure and development mode of cities in Liaoning, China

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As an important supplement to "location space", "flow space" has become an important trend in urban network research. At present, the theoretical basis and empirical research of urban network structure from the perspective of "flow space" are not completely clear. Based on the urban spatial network structure research system framework, this paper comprehensively studies the urban spatial structure, spatial network pattern and development mode of Liaoning Province in China by using multivariate data flow. The results show that: (1) Cities at all levels in Liaoning Province have different functions and roles in the urban network level, with Shenyang and Dalian as the leading cities, and Anshan and Jinzhou as "transit hubs"; (2) Liaoning Province takes Shenyang-Dalian as its main axis, the Shenyang economic circle with Shenyang as the core and the coastal economic belt with Dalian as the core and Dandong and Yingkou as the two wings intersect to form the urban spatial network pattern; (3) In the future, Liaoning Province should further form the urban development model of "core city-axis-cluster". Under the trend of globalization, it should carry out in-depth promotion in combination with "Shenyang Modern Metropolitan Circle" "Liaoning Coastal Economic Belt" and "Liaoning Northwest Strategy", and finally form a balanced, efficient and comprehensive urban network structure.

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Introduction

Compared with the rural areas, the urban area is a stable and large settlement (Li et al., 2022; Li et al., 2022), which plays a role in coordinating and promoting the flow of population, information, technology and economy in the social system (Tian et al., 2014). In today's era of rapid economic growth, the level of urban development has become an important indicator to judge the strength of a country. Central place theory and rank-size rule are the main methods of urban network research. Central place theory analyzes the distribution and relative scale of central places in a certain region from the perspective of service industry (Richard, 2020). Rank-size rule is based on city size and scale ranking to judge the city size system (Hsin-Ping, 2004). Under these two classical theories, cities are non-dynamic and relatively closed, and the competitiveness and hierarchical differentiation between cities are the focus of the study (Yang et al., 2011). With the change of times, driven by economic globalization and the development of information technology, the thinking paradigm of urban research has changed from the initial static, relatively isolated and hierarchical scale mode to the mobile, interconnected and multi-center network mode (Favero et al., 2022; Roosta et al., 2022; Zhang and Wang, 2022; Guan et al., 2021; Wang et al., 2019). Urban network links the relevant characteristics of node cities at a specific spatial scale (Zhang and Tang, 2021; Richard, 2015; Jiao et al., 2016; Luo and Chen, 2021; Wu et al., 2015). The population flow, logistics, fund flow and information flow circulate among cities, and "flow space", as an important supplement to "location space", together with it, forms a three-dimensional urban space human settlement environment (Xu et al., 2019; Wu et al., 2022).

M.Castells proposed the classical theory of "space of flows", which became a new perspective to study urban structure (Zhang et al., 2018; Zhang et al., 2020; Li et al., 2021; Li et al., 2021; Zheng et al., 2020). From this perspective, scholars have carried out many studies on urban networks (Guo and Qin, 2022; Wei and Pan, 2021; Burger et al., 2014; Wang et al., 2021). Sassen studied the formation process of global cities based on the geographical distribution characteristics of producer services; POLYNET took 8 large cities in Europe as the research area and expanded the research scale of urban network based on inter-urban traffic flow and business flow (Taylor et al., 2002); Meijers (2007) proposed to replace the central place theory with "paradigm change" and "network model"; Derudder and Taylor (2018) proposed interlocking network (central flow theory) and developed "Interlocking Network Model" (INM) to integrate a broader theoretical framework centered on "central flow theory" into urban network research.

The research on urban network based on the perspective of flow space is early in the world. The GAWC model developed by GAWC(Globalization and World Cities Research Team) was first applied to the measurement and subsequent empirical analysis of the formation of service center network in 2000 (Hanssens et al., 2011); Beaverstock et al. (2000) studied the business connectivity of global cities based on information flow by sampling the business headlines of major newspapers in American cities; Derudder et al. (2008) proposed MIDT and AEA schemes to evaluate the spatial pattern of global urban network with air population flow information; Malecki (2002) set connections and spatial aggregation of connection sites in the context of urban level of world cities based on Internet telecommunication flows; Sonn and Storper (2008) used patent citations as the basic data of knowledge flow to construct the urban innovation connection network.

In recent years, Chinese scholars have conducted a number of studies on urban networks based on the perspective of flow space. Previous studies mainly focused on analyzing the urban hierarchy and network spatial structure through the connection between

cities at the realistic level of population flow and logistics. ① In terms of population flow, Ma and Tang (2018) took more than 216 prefecture-level cities with actual high-speed railway stations as the research object, obtained the high-speed railway passenger flow data between cities, and conducted a preliminary study on the pattern of China's urban network based on passenger flow; Based on flow space theory and complex network theory; Luo et al. (2021) proposed a conceptual model of urban flow space from the perspective of complex network with the population flow as the research object, providing planning guidance for later empirical research. ② In terms of logistics, Ye and Duan (2016) analyzed the data of logistics enterprises in the Yangtze River Delta region through network, and concluded that the spatial network of the Yangtze River Delta is "one body with two wings"; Based on the data sources obtained by major domestic express logistics companies, Li et al. (2021) analyzed the spatial structure characteristics and formation mechanism of urban logistics network by taking the three major urban agglomerations of China's Yangtze River Delta, Beijing-Tianjin-Hebei and Pearl River Delta as research regions. ③ With the in-depth research of many scholars on the spatial structure of urban network, the fund flow and information flow based on network data, Baidu index and network communication have gradually become a new perspective to study the spatial structure of urban network. In terms of fund flow, scholars mostly integrate fund flow with other flow elements to study the spatial structure of urban network. Chu et al. (2022) comprehensively used economic flow, traffic flow and information flow to construct the urban connection strength model and urban spatial network in Northeast China, and studied the spatial structure of urban network in Northeast China from multiple dimensions, which is of great significance for the revitalization and development of Northeast China; Jin et al. (2018) adopted innovative ideas, combined fund flow with information flow, and analyzed the intensity difference of connection flow between core cities and provincial groups, which affected the balance of internal connection flow among provinces and cities, and the influencing factors from the provincial level. ④ In terms of information flow, Dong et al. (2014) studied the network pattern of Jilin Province from the perspective of information flow based on the call time between cities, and found that the flow space characteristic of Jilin province is Changchun city as a "single center", without prominent sub-centers; Zhao et al. (2015) explored the network structure of 34 cities in Northeast China based on the Baidu Index of inter-city search, and found that the three provinces in Northeast China are not closely connected with each other, but closely connected within the three provinces. The spatial pattern of Liaoning and Jilin provinces is "one main and one vice", and the urban network of Heilongjiang Province is "single center".

Overall, The research on urban network based on the perspective of flow space started late in China, and it is mostly based on the single element flow such as population flow and logistics to construct urban network and analyze urban spatial structure (Yang et al., 2021; Yang et al., 2020; Yang et al., 2022; Lin et al., 2022). Even with the development of information technology, information flow has gradually become a key research direction (Feng et al., 2022; An et al., 2019; Liu and Sun, 2021), but it is still limited by a single attribute (Wang et al., 2019). In the process of urban development, if the status and development level of a city in the urban network are judged according to a single flow element, it will not be conducive to the future development direction and strategy of the city.

In general, the spatial structure of urban network should vary from single element to multi-element connection (Bonaventura et al., 2021; Castells, 2020), from isolation to interconnection
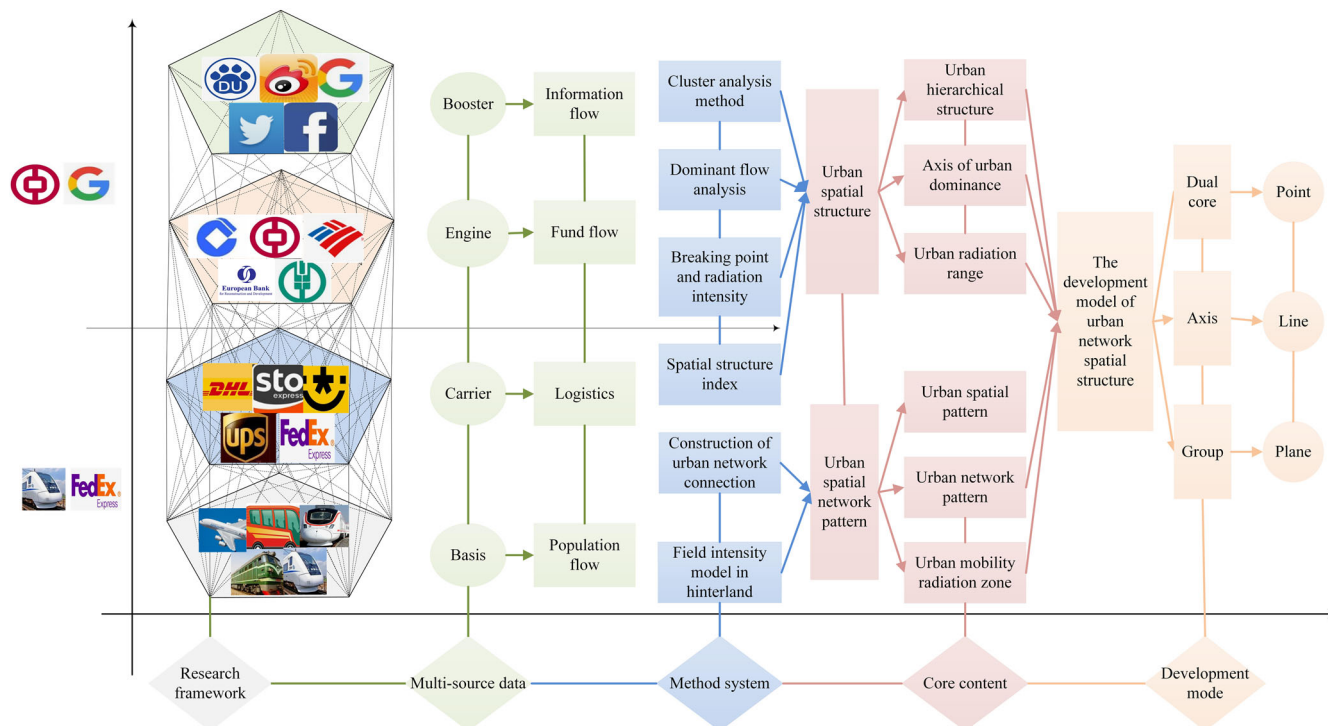
Fig. 1 Urban spatial network structure research system framework. Based on multivariate data, in which population flow is the basis, logistics is the carrier, fund flow is the engine, and information flow is the booster, this paper studies the urban spatial structure, spatial network pattern and development mode of Liaoning Province in China by using multivariate data flow and adopting the methods such as quantitative geography and geographic information science.

(Batty, 2013; Taylor et al., 2002), from static to dynamic (Taylor, 2001; Curado et al., 2021), from single center to multiple center development (Navarro-Azorín et al., 2022; Odell et al., 2022). Therefore, based on the urban spatial network structure research system framework (Fig. 1) and from the perspective of multiple flow elements, this paper comprehensively studies the spatial structure characteristics and pattern of urban network in Liaoning Province, and explores the development model of urban network spatial structure in Liaoning Province. The innovative contributions are as follows:

1. Inter-city connection develops from single element to multi-element diversification. ① Therefore, the comprehensive use of four kinds of multivariate data flow, such as population flow, logistics, fund flow and information flow, is conducive to breaking through the limitations of single flow element research. ② The connections between cities are developing from short distance to long distance. Based on the first law of geography, close cities have stronger connections than distant cities. With the development of modern logistics technology, capital and financial system, Internet and we-media, the connections between distant cities are becoming stronger and stronger.
2. The connections between cities are becoming more integrated. ① Explicit and implicit city connection. The explicit expression is that a certain element connection between two cities can be intuitively measured, such as product transportation between cities; Most of the implicit connections between cities are invisible exchanges and cooperation, such as scientific research exchange, information exchange, financial contact and trade secret contact between cities. ② Strong connection and weak connection. The connection strength of cities is divided into strong connection and weak connection, showing the strong

connection between the capital city and the provincial capital city, while the marginal city has the corresponding weak connection. The strong connection mostly forms the urban axis, urban cluster and urban agglomeration, while the weak connection is more scattered.
3. The connections between cities are becoming three-dimensional. ① The research content of this paper is logical and progressive. From the "point-line-network-area" perspective, it studies the urban hierarchical structure, urban dominance axis, urban network pattern, urban mobility radiation area and so on. ② The research has substantial contributions and social practical significance. Based on theoretical basis and empirical research, the development model of urban network spatial structure of Liaoning Province, which is "core city-axis-cluster", has been formed from the "point-line-plane" perspective, hoping to provide scientific basis for the high-quality development of Liaoning cities as the advice of senior administration.

In the face of the shift of the research paradigm of urban geography, the connections between cities constantly form the urban network spatial pattern of multi-element, multi-dimension and multi-development state from single to multiple (Derudder et al., 2010), from scattered to comprehensive (Schwartz, 2021), from plane to three-dimensional (Prieto-Curiel et al., 2022), and finally form the urban spatial network structure research system framework (Fig. 1).

Liaoning is in the border area between Northeast China and North China, which is the traffic throat of northeast China and the only coastal province in Northeast China. It plays an important economic and strategic role, and its economic development directly affects the economic situation of Northeast China, making it a province vigorously developed by the country (Liu and Chen, 2020; Li et al., 2021). However, in China's 14th

Five-Year Plan, Liaoning urban agglomeration has changed from the second echelon to the third echelon, and the rise of Liaoning province, the leader in the northeast revitalization strategy, is faced with difficulties.

Therefore, the study area of this paper covers 14 prefecture-level cities in Liaoning Province, namely Shenyang, Dalian, Anshan, Fushun, Benxi, Dandong, Jinzhou, Yingkou, Fuxin, Liaoyang, Tieling, Panjin, Chaoyang, and Huludao. On the basis of previous studies, this paper starts from the characteristics of urban comprehensive spatial structure. In order to avoid the limitation of single flow element, this paper selects the most representative flow elements among cities, namely population flow, logistics, fund flow and information flow, and studies the spatial structure characteristics and urban spatial network pattern of Liaoning Province from the perspective of multiple flow elements. It also discusses the development mode of urban network space structure in Liaoning Province. The aim is to promote the research progress of "flow space" and provide decision support for the strengthening of economic exchanges, joint development and strategic planning of Liaoning Province.

Data and methods
Data
Population flow. Population flow connection refers to the population flow between cities carried by train, passenger car, airplane, ship and so on. Population flow between cities is the basis and core of the flow of other elements and even the connections between cities at different levels (Wang et al., 2022; Wei and Wang, 2020). Population is the carrier of culture, economy, and information, and the population flow between cities builds the backbone of urban contact and promotes the agglomeration, union, diffusion and synthesis of multiple flows such as logistics, fund flow, information flow in cities (Luo et al., 2021; Michèle, 2018; Lim, 2014). There are many factors affecting the population flow between cities, so the measurement of the population flow is uncertain and difficult to measure. After comprehensive consideration, the direct measurement of the population flow is replaced by railway, highway and passenger bus frequency. Check the frequency of high-speed rail, bullet train, train and passenger car in March 2022 through 12306 China Railway Customer Service Center website and Passenger station website respectively. After comprehensive consideration of the actual situation, it is stipulated that the carrying capacity of bullet train and high-speed railway is 600, that of train is 1200, and that of passenger bus is 50. The final population flow is calculated based on the following formula, and the sum of population flow connection strength is 15458858.

$$M_{ij} = 600A_{ij} + 600B_{ij} + 1200C_{ij} + 50D_{ij} \tag{1}$$

$$R_{ij} = \frac{\left(M_{ij} + M_{ji}\right)}{2} \tag{2}$$

where, M_{ij} represents the unilateral population flow from city i to city j; R_{ij} represents the population flow connection strength between cities i and j; A_{ij}, B_{ij}, C_{ij}, and D_{ij} denote the frequency of high-speed rail, bullet train, train and passenger bus from city i to city j within a day. Calculate the intensity of population flow connection between cities and draw the urban population flow connection matrix (Table 1):

Logistics. Logistics connection refers to the logistics between cities of UPS, FedEx, China STO, SF Express logistics companies. Urban logistics connection is the key material carrier for different cities to become urban organisms and urban agglomerations (Li et al., 2023). The rapid development of regional economy and

Table 1 Connection matrix of urban population flow in Liaoning province.

	Shenyang	Dalian	Anshan	Fushun	Benxi	Dandong	Jinzhou	Yingkou	Fuxin	Liaoyang	Tieling	Panjin	Chaoyang	Huludao
Shenyang		986,464	1,102,500	52,286	352,500	314,786	676,929	275,893	360,750	842,571	537,643	567,643	433,929	602,786
Dalian			479,036	31,714	80,571	127,071	260,143	265,179	61,821	416,679	192,750	261,643	148,286	189,750
Anshan				43,393	32,143	16,821	226,821	161,893	55,393	525,857	117,000	225,000	117,429	111,429
Fushun					9750	3000	19,821	3000	2250	34,714	18,000	15,321	2250	18,429
Benxi						198,429	29,375	2036	21,536	26,250	38,679	24,107	23,357	21,000
Dandong							33,000	4929	22,714	20,893	32,143	15,750	24,000	25,393
Jinzhou								69,000	99,875	174,750	104,464	363,357	168,214	532,286
Yingkou									19,607	111,750	16,714	76,179	50,571	42,107
Fuxin										71,143	51,107	67,821	213,429	43,286
Liaoyang											96,536	200,464	107,464	142,714
Tieling												54,214	45,964	72,321
Panjin													143,786	298,286
Chaoyang														76,821
Huludao														

online shopping in today's world has promoted people's increasing demand for logistics and the continuous development of logistics between cities (Ma et al., 2022; Li et al., 2021). Under comprehensive consideration, the scope of exploration is determined to include a total of 4708 logistics branch companies: STO, SF Express, YTO, Best, Huitong, Tiantian, ZTO, Uxu, Deppon, Yunda, Anneng and Suning. Referring to Taylor's method of world urban network (Chen et al., 2021), X_{ia} represents the distribution number of logistics branch companies of logistics company a in city i, which represents its important level in the urban structure. Taking a logistics company as an example, the logistics connection strength between cities i and j is calculated by the following formula, and the total logistics connection strength is 9211755.

$$R_{ij,a} = X_{ia} \times X_{ja} \qquad (3)$$

R_{ij} represents the logistics connection strength between cities i and j:

$$R_{ij} = \sum_j R_{ij,a} \qquad (4)$$

Calculate the logistics connection strength between cities and draw the urban logistics connection matrix (Table 2):

Fund flow. Fund flow connection refers to the fund flow between cities through the European Central Bank, Bank of America, Bank of China, Industrial and Commercial Bank of China. It reflects the capital and financial connections between the urban governments and enterprises. Fund flow connection is an important development engine for a single city to become an urban agglomeration, and the close fund flow connection between cities greatly amplifies the wealth accumulation effect of high-quality development of urban agglomeration (Jin et al., 2018). Capital circulates between cities as an fund flow, capital circulates among cities, which promotes the economic development of cities and influences the spatial pattern of cities. Similar to the analysis method of logistics, the research object is determined to be a total of 4897 bank branches in 14 prefecture-level cities in Liaoning Province, including 6 banks including Bank of China, Agricultural Bank of China, Industrial and Commercial Bank of China, Bank of Communications, Construction Bank and Postal Savings Bank. V_{ib} is the score value of bank named b in city i, which represents its importance level in the urban structure. Taking bank b as an example, the fund flow link strength between cities i and j is calculated by the following formula, and the sum of fund flow link strength is 10614647.

$$R_{ij,b} = V_{ib} \times V_{jb} \qquad (5)$$

R_{ij} represents the fund flow connection strength between cities i and j:

$$R_{ij} = \sum_j R_{ij,b} \qquad (6)$$

According to the fund flow data, the following urban capital flow connection matrix can be obtained (Table 3):

Information flow. Information flow connection refers to the production, transmission and exchange of information between cities through Internet platforms such as Google, Baidu, Weibo and Facebook (Tian et al., 2021; Yu et al., 2023). The information flow connection between cities is a booster for the vigorous development of urban agglomeration in the 21st century. The increasingly enhanced information connection between cities will continue to play the radiating role of urban agglomeration in social development (Lai et al., 2019; Shi et al., 2022). With the rapid development of 3 S and other new methods and technologies in the field of geography, the intensity of communication

Table 2 Connection matrix of urban logistics in Liaoning province.

	Shenyang	Dalian	Anshan	Fushun	Benxi	Dandong	Jinzhou	Yingkou	Fuxin	Liaoyang	Tieling	Panjin	Chaoyang	Huludao
Shenyang		1,521,891	514,692	303,195	158,253	317,985	249,951	331,296	152,337	195,228	440,742	152,337	258,825	178,959
Dalian			358,092	210,945	110,103	221,235	173,901	230,496	105,987	135,828	306,642	105,987	180,075	124,509
Anshan				71,340	37,236	74,820	58,812	77,952	35,844	45,936	103,704	35,844	60,900	42,108
Fushun					21,935	44,075	34,645	45,920	21,115	27,060	61,090	21,115	35,875	24,805
Benxi						23,005	18,083	23,968	11,021	14,124	31,886		18,725	12,947
Dandong							36,335	48,160	22,145	28,380	64,070	22,145	37,625	26,015
Jinzhou								37,856	23,072	13,596	39,336	30,694	18,025	21,175
Yingkou									23,072	29,568	66,752	23,072	39,200	27,104
Fuxin										13,596	30,694	10,609	18,025	12,463
Liaoyang											39,336	13,596	23,100	15,972
Tieling												30,694	52,150	36,058
Panjin													18,025	12,463
Chaoyang														21,175
Huludao														

Table 3 Connection matrix of urban fund flow in Liaoning province.

	Shenyang	Dalian	Anshan	Fushun	Benxi	Dandong	Jinzhou	Yingkou	Fuxin	Liaoyang	Tieling	Panjin	Chaoyang	Huludao
Shenyang		711,424	359,682	250,110	165,152	221,526	235,024	235,024	115,130	184,208	204,058	204,058	175,474	196,912
Dalian			405,888	282,240	186,368	249,984	265,216	265,216	129,920	207,872	230,272	230,272	198,016	22,208
Anshan				142,695	94,224	126,387	134,088	134,088	65,685	105,096	116,421	116,421	100,113	112,344
Fushun					65,520	87,885	93,240	93,240	45,675	73,080	80,955	80,955	69,615	78,120
Benxi						58,032	61,568	61,568	30,160	48,256	53,456	53,456	45,968	51,584
Dandong							82,584	82,584	40,455	64,728	71,703	71,703	61,659	69,192
Jinzhou								87,616	42,920	68,672	76,072	76,072	65,416	73,408
Yingkou									42,920	68,672	76,072	76,072	65,416	73,408
Fuxin										33,640	37,265	37,265	32,045	35,960
Liaoyang											59,624	59,624	51,272	57,536
Tieling												66,049	56,797	63,736
Panjin													56,797	63,736
Chaoyang														54,808
Huludao														

between cities through the Internet platform has gradually become an important index to evaluate the connectivity between cities (Barnett et al., 2001; Jiang et al., 2015; Wei and Wang, 2020). In consideration of the actual situation, the Baidu Index is selected to reflect the intensity of internet information flow between cities. In the Baidu Index website page, select the option of "classification by region", name the core words of 14 prefecture-level cities in Liaoning Province respectively, and set the time span as October 2021 to March 2022 to obtain the search frequency of a city on other cities. The expression of internet information flow network connectivity between cities is as follows, and the sum of internet information flow connection strength is 1239117.

$$R_{ij} = A_b \times B_a \qquad (7)$$

where, A_b represents the frequency of searching city A by the population located in city B; A_b indicates how often the population in city B searches for city A; R_{ij} represents the connection strength of internet information flow between cities i and j. Through calculation, the inter-city internet information flow connection matrix is obtained (Table 4):

Comprehensive data processing. The population flow, logistics, fund flow and information flow are processed according to the same influencing factors (Liu and Zeng, 2011), and four types of flow data are normalized to obtain the comprehensive flow data. The calculation is as follows:

$$X = \frac{(x - \min)}{(\max - \min)} \qquad (8)$$

where, x is the initial flow data; min represents the lowest value of the associated flow strength in the matrix; max represents the highest intensity of the connection flow in the matrix; X is the comprehensive flow data. The minimum value of X is 0, indicating that the total connection between the two cities is the most distant; The maximum value of X is 1, indicating that the total connection between the two cities is the closest. Sum up the comprehensive flow of a city with 13 cities:

$$R_i = \sum_j R_{ij} \qquad (9)$$

where, R_i is the total connection degree of comprehensive flow between city i and other cities; R_{ij} represents the comprehensive flow connection strength of cities i and j.

Research structure and methods. This paper analyzes the urban spatial structure and urban spatial network pattern of Liaoning Province at the present stage, discusses the development mode of urban network spatial structure in the future, and finally draws a conclusion and puts forward relevant suggestions after the discussion. The research structure is divided into three parts. The first part analyzes the urban spatial structure of Liaoning Province, including the urban hierarchy structure, urban dominance axis and urban radiation range; The second part discusses the urban spatial network pattern of Liaoning Province, including urban spatial pattern, urban network pattern and urban mobility radiation area; The third part studies the development pattern of urban network space structure in Liaoning Province from "point-line-plane".

Cluster analysis method. The Natural breaks method in ArcGIS is used to analyze the comprehensive flow connection strength between cities, to ensure the minimum gap within each level and the maximum gap between levels. The 14 prefecture-level cities in Liaoning Province are divided into four levels. According to the results of urban hierarchy division, the position and influence

Table 4 Connection matrix of urban information flow in Liaoning province.

	Shenyang	Dalian	Anshan	Fushun	Benxi	Dandong	Jinzhou	Yingkou	Fuxin	Liaoyang	Tieling	Panjin	Chaoyang	Huludao
Shenyang		140,149	51,376	41,912	34,310	35,496	46,943	29,952	32,512	30,636	37,848	35,856	32,712	51,042
Dalian			33,532	17,097	18,753	25,619	22,304	24,764	16,692	16,560	16,256	21,330	18,212	17,936
Anshan				6016	6720	7684	8056	13,736	4738	12,544	5727	11,739	6464	5978
Fushun					4416	5032	6882	4158	3819	3456	6072	5135	6935	3933
Benxi						8084	4480	3363	2419	4891	3948	4284	3551	3087
Dandong							6916	5848	4189	4092	3675	5382	4624	5530
Jinzhou								6804	9628	5304	5530	13,334	6800	15,255
Yingkou									3504	4484	4209	11,770	4740	4332
Fuxin										2745	2898	8075	5226	4752
Liaoyang											4125	7084	4290	3304
Tieling												3976	3920	4158
Panjin													6162	7650
Chaoyang														7656
Huludao														

degree of each city in the urban network space are evaluated (Wang et al., 2017).

Dominant flow analysis. In the analysis of urban network space, Nystuen and Dacey proposed the dominant flow theory (Dong et al., 2014). The idea is to analyze the direction of the maximum element flow of a city, and then evaluate the city scale and its role in the network structure. Based on the dominant flow theory, cities are divided into three types: dominant city, secondary dominant city and subordinate city (Song et al., 2008).

This paper determines the urban dominant flow direction through quantitative analysis of comprehensive flow intensity, identifies the first, second, third and fourth dominant flow direction spatially, studies the backbone and main flow axis of cities in Liaoning Province, and discusses the basic framework and general pattern of urban spatial structure based on "data flow" in Liaoning Province.

Breaking point and radiation intensity. Based on converse breaking point formula, the operation point of flow connection between a city and other cities is determined, and the calculation is made according to the following formula:

$$D_A = \frac{D_{AB}}{1 + \sqrt{R_B/R_A}} \tag{10}$$

R_A and R_B represent the comprehensive flow intensity of city A and B, respectively; D_{AB} stands for road time between two cities; D_A represents the road time needed for city A to reach the breaking point between city A and B. Combined with the following field intensity formula, the urban radiation intensity (expressed as F_A) is studied, and then the influence area of each city is evaluated (Wang et al., 2017; Wang and Wang, 2018):

$$F_A = \frac{R_A}{D_A^2} \tag{11}$$

Spatial structure index. The spatial structure index (SSI) proposed by Hanssens is used to determine the spatial dispersion of 14 prefecture-level cities in Liaoning Province (Hanssens et al., 2013). The minimum SSI value is 0, indicating that the urban network space is individualized; The maximum value of SSI is 1, indicating that the urban network is in a diversified change situation. The calculation is carried out as follows (Wang et al., 2019):

$$SSI = \begin{cases} \left(2 - \frac{SD}{SD_{rc}}\right) \times 2^{-1}, & SD < SD_{rc} \\ SD_{rc}/2SD, & SD > SD_{rc} \end{cases} \tag{12}$$

The 14 prefecture-level cities are sequenced, and the standard deviation of corresponding numbers is SDrc; SD represents the standard deviation of the comprehensive flow of each prefecture-level city; SSI represents the spatial structure index of prefecture-level cities.

Field intensity model in hinterland. Taking city quality as the basis for evaluating urban radiation influence, the urban radiation influence decreases with the increase of the distance between cities. By calculating the hinterland of cities, the spatial structure characteristics of urban network in Liaoning Province are studied from the perspective of area. The calculation formula is as follows (Wang et al., 2019):

$$F_{ik} = \frac{Z_k}{D_{ik}} \tag{13}$$

where, F_{ik} represents the radiation influence of city k on point i; Z_k represents the quality of city k, and urban comprehensive

Table 5 Actual speed of the road type.

Lattice parameters	National highway	Provincial highway	County highway	Others
Passage time (min)	0.75	1	1.5	3
Actual speed (km/h)	80	60	40	20
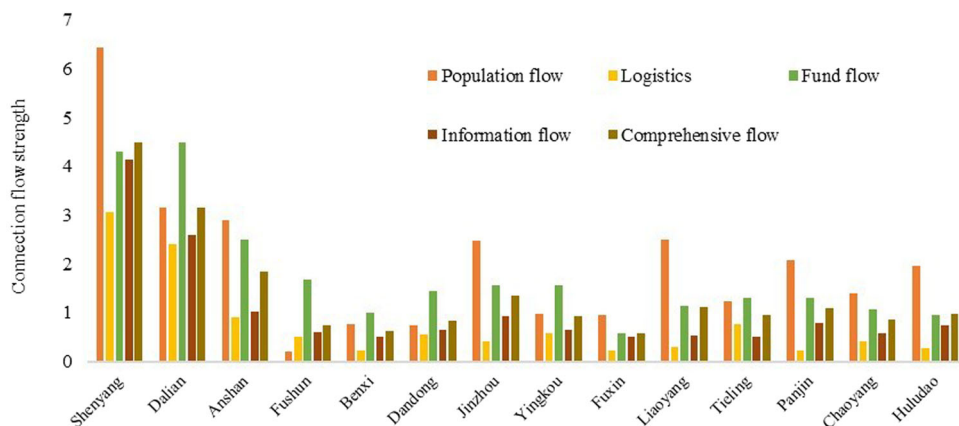
Fig. 2 Urban connection flow intensity in Liaoning Province. Take the population flow as an example. The higher the orange bar, the stronger the connection of population flow between the city and other cities. The figure was developed by the authors using Microsoft Excel Version 2023.

flow intensity is chosen to replace the city quality; D_{ik} is the distance from city k to point i.

The shortest travel time is used to represent the distance from the geographical core to a certain location. According to "Highway Engineering Technical Representation", the actual speed of national road, provincial road, county road and other roads are respectively set, and the shortest passage time is converted into grid parameters to obtain the shortest time distance (Table 5).

Results

Analysis of urban spatial structure in Liaoning Province

Urban hierarchical structure. Shenyang and Dalian rank first and second respectively in terms of connection strength with other cities in Liaoning Province, while Anshan, Jinzhou, Liaoyang and Panjin are in the middle, and there is no significant difference in other cities. There is a difference of 7.87 times between Shenyang, the city with the highest link flow intensity, and Fuxin, the city with the lowest link flow intensity (Fig. 2). The relation degree of population flow changes greatly among cities: Shenyang and Dalian have the closest relation with other cities, followed by Anshan, Jinzhou, Liaoyang and Panjin, and Fushun is the lowest. Located in the center of Liaoning Province, Anshan, Jinzhou, Liaoyang and Panjin serve as transit stations. Fushun is located in the edge of Liaoning Province, and compared with the inner cities, it has a low degree of population flow connection with other cities. To explore the urban level of Liaoning Province, Natural breaks is used to divide the cities of Liaoning Province into four levels (Table 6).

Shenyang ranks first in all the element flow connection strength; Dalian is at the first level in the connection degree of logistics, fund flow and information flow, but at the second level in the connection degree of population flow; Although the comprehensive relation degree of Anshan is lower than that of Shenyang and Dalian, the relation degree of each element flow is in the second grade, and the development of Anshan is more comprehensive and balanced (Table 6). Overall, the first tier of cities is relatively stable, Shenyang and Dalian are two core node cities; The second-tier city is Anshan, which is the connecting

point and transit station of urban network space; The third-tier cities, including Jinzhou, Yingkou, Liaoyang, Tieling, Panjin and Huludao, are the local contact centers, whose connection flow intensity is lower than that of the first-tier and second-tier cities, but they have their own unique functional advantages. For example, Jinzhou has a higher level of information flow, and Tieling has the advantage in logistics connection degree; The fourth-tier cities, including Fushun, Benxi, Dandong, Fuxin and Chaoyang, have a low intensity of flow connection.

The urban network in Liaoning Province presents a "dual-core" driven urban hierarchy, with the distribution of "2 + 1 + 6 + 5". The intensity of connection flow between different levels of cities varies greatly. Considering the geographical location of cities, it can be found that the hierarchical position of cities is affected by their spatial position in the urban network. The cities in the fourth tier are located in the peripheral area of the urban comprehensive data flow network space of Liaoning Province. In the sense of element flow, they are far away from the two core cities of Shenyang and Dalian, and receive less radiation from the two cities. Meanwhile, they are less connected with the population flow, logistics, fund flow and information flow of other cities. It can be seen that the urban connection strength from the perspective of multiple element flows can objectively map the overall spatial structure of the city, while the single element flow has certain uncertainty and inauthenticity.

Axis of urban dominance. The dominant flow method is used to comprehensively analyze the dominant flow intensity of 14 prefecture-level cities in Liaoning province, and finally the trend of urban dominant flow in Liaoning province is obtained (Fig. 3). From the analysis of spatial trend of urban dominant flow in Liaoning Province, the first dominant flow of all cities flows to Shenyang and Dalian, among which 13 cities flow to Shenyang and 1 city flows to Dalian. The second dominant flow of most cities flows to Dalian. According to the dominant flow direction, Shenyang and Dalian are the dominant cities in Liaoning Province (Wang et al., 2019; Huang et al., 2022). Shenyang, as the capital and vice-provincial city of Liaoning Province, plays a pivotal role in urban communication. Dalian, as a sub-provincial

Hierarchy	Population flow contact strength	Logistics contact strength	Fund flow contact strength	Information flow contact strength	Comprehensive flow contact strength
I	Shenyang	Shenyang Dalian	Shenyang Dalian	Shenyang Dalian	Shenyang Dalian
II	Dalian	Anshan Tieling	Anshan	Anshan Jinzhou	Anshan
	Anshan Jinzhou Liaoyang Panjin Huludao				
III	Yingkou Fuxin Chaoyang Tieling	Fushun Dandong Jinzhou Yingkou Chaoyang	Fushun Dandong Jinzhou Yingkou Tieling Panjin	Dandong Yingkou Panjin Huludao	Jinzhou Yingkou Liaoyang Tieling Panjin Huludao
IV	Fushun Benxi Dandong	Benxi Fuxin Liaoyang Panjin Huludao	Benxi Fuxin Liaoyang Chaoyang Huludao	Fushun Benxi Fuxin Liaoyang Tieling Chaoyang	Fushun Benxi Dandong Fuxin Chaoyang

Table 6 Urban hierarchy.
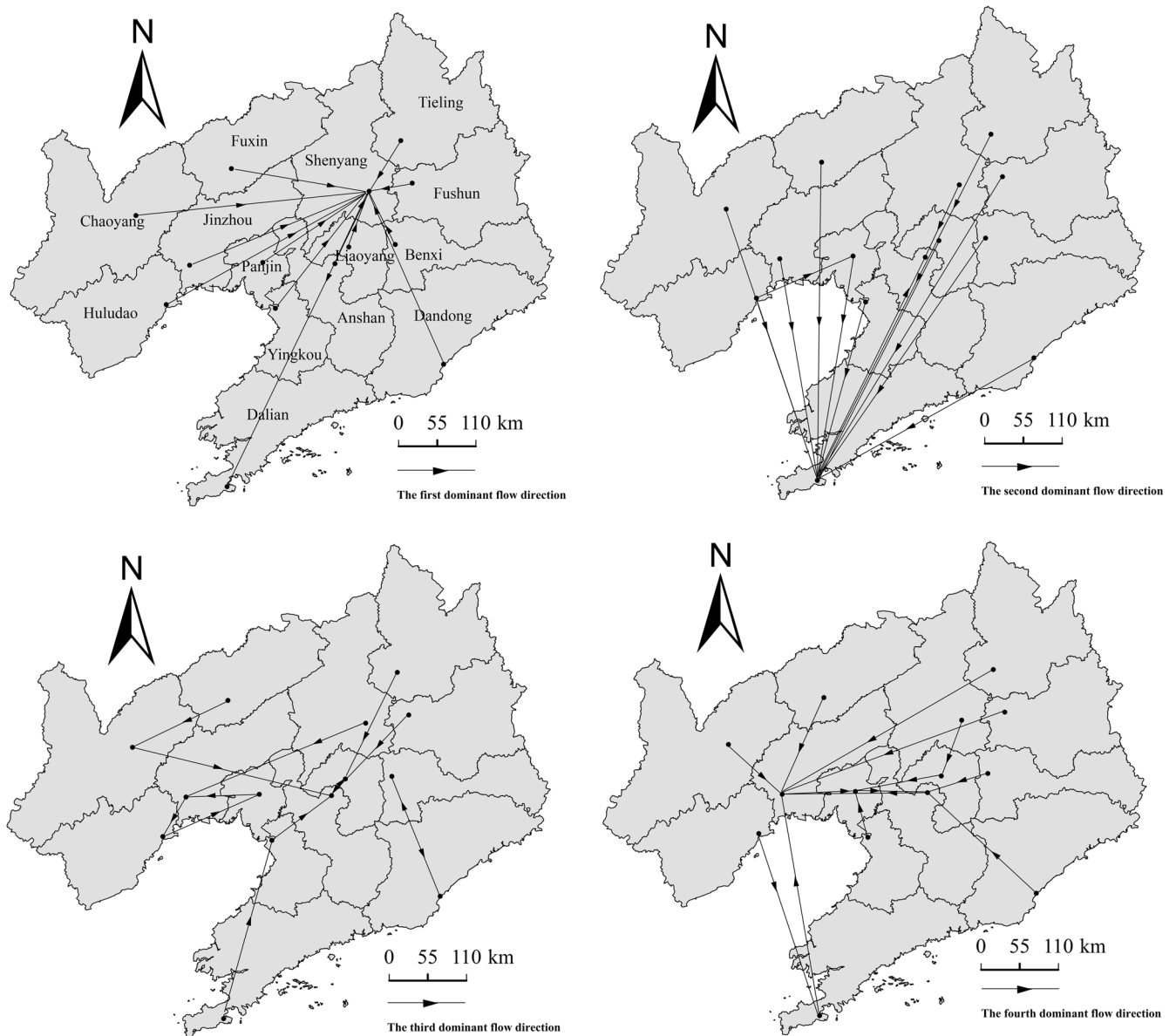
Fig. 3 Urban dominant flow in Liaoning Province. Arrow direction indicates the dominant flow direction of a city. The first dominant flow of 13 prefecture-level cities flows to Shenyang, and the second dominant flow of most cities flows to Dalian. The map was developed by the authors using ArcGIS Pro Version 3.0.3.

city and new first-tier city in Liaoning Province, promotes the economic and trade development of China's eastern coastal areas. It can be seen that comprehensive connection strength of a city is not only related to the spatial location of the city, but also closely related to the political level of the city. The strategy of "Shenyang Economic Belt" and "Liaoning Coastal Economic Belt" at the present stage is consistent with the spatial structure of Liaoning Province under the analysis of dominant flow, which to some extent explains the rationality of the strategy at the present stage.

According to the second, third and fourth dominant flow directions, Anshan and Jinzhou are the secondary dominant cities. Due to their advantages in flow spatial location and high level of development, they play the role of "transit hubs", which not only receive high-level technology and information from the dominant cities, but also carry out element flows with smaller cities. However, Benxi and Fuxin, which are located in the outer region of the urban comprehensive data flow network space in Liaoning province, can only receive the radiation of the dominant city and the secondary dominant city. They belong to the subordinate cities and have little influence factor in the urban network space.

Urban radiation range. Based on the hierarchical division of node cities, city positioning and function, and the actual situation of cities in Liaoning Province, the node cities are quantitatively divided as follows: If $R_i \geq R + 2RD$, it is a first-level node city; If $R_i \geq R + RD$, it is a second-level node city; If $R_i \geq R$, it is a third-level node city. R and RD are the mean and standard deviation of the comprehensive flow connection strength of each city respectively. After calculation and analysis, Shenyang is the first-level node city, Dalian is the second-level node city, and Anshan is the third-level node city. After the node city is established, the radiation scope of the node city is analyzed and evaluated based on ArcGIS visualization (Fig. 4).

The first-level node city Shenyang and the second-level node city Dalian have a wide range of radiation influence, and the breaking point of radiation contact with other cities is far away, and the total scope of radiation covers most of Liaoning Province. The radiation influence range of Anshan, the third-level node city, is small and has certain bias, and the main cities affected by radiation are Liaoyang, Yingkou and Benxi. It can be found that the radiation intensity of a city is closely related to the comprehensive element flow of two cities, and the radiation intensity is also related to the distance between two cities.

Analysis of urban spatial network pattern in Liaoning Province
Urban spatial pattern. The overall network space of Liaoning province shows a dual-polarization development trend with Shenyang and Dalian as the core cities, which is similar to the dual-core spatial pattern of Liaoning Province from the perspective of typical geographic theory analysis. The spatial structure index SSI of Liaoning Province is 0.114, in which SSI is comprehensively calculated by formula (12).

The comprehensive connection flow intensity of Shenyang is about 4.486, and that of Dalian is about 3.165, which together account for about 39.03% of the total connection strength of all cities in Liaoning Province, and the difference between the comprehensive flow connection strength of Dalian and the third city Anshan is about 72% (Table 7). Shenyang, as the core hub of the province, has the strongest connection with other cities in the province, while Dalian, as a leading city, drives the continuous development of foreign economic and trade relations among surrounding coastal cities. The two cities are located at a moderate distance and complement each other, which not only reduces the problems of resource shortage, population

accumulation and environmental damage, but also promotes the harmonious and balanced development of urban structure in Liaoning Province.

Urban network pattern. The connection matrices of population flow, logistics, fund flow, information flow and comprehensive flow between cities are visualized by ArcGIS respectively, and the spatial network of urban elements flow connection (Fig. 5) and comprehensive flow connection spatial network are constructed. In addition, the comprehensive flow spatial network is comprehensively compared with urban per capita GDP and GDP growth (Fig. 6), and then the characteristics of urban spatial network, its relationship with urban economic development and other influencing mechanisms of Liaoning Province are analyzed and evaluated.

The urban connection strength of Liaoning province decreases from the axis of Shenyang to Dalian to the periphery. At the same time, the northeast and central part of Liaoning Province have high connection flow strength, and the overall development is good, while the external connection of the northwest is relatively backward, and there are differences in connection flow intensity between regions. Therefore, the urban network space of Liaoning Province presents a "core-edge" structure. The inner part of the province takes Shenyang as the core to form Shenyang economic circle. The outer coastal zone of the province takes Dalian as the core and intersects with Shenyang economic circle to form the urban spatial network of Liaoning Province. At the same time, as shown in Fig. 6, network connection strength of cities in Liaoning Province is positively correlated with per capita GDP. Benxi and Fuxin, which are located in the outer region of the network space of urban comprehensive data flow in Liaoning Province and are far away from Shenyang and Dalian, also have relatively low per capita GDP. However, with the in-depth implementation of "Shenyang Economic Belt" "Liaoning Coastal Economic Belt" "Northwest Liaoning Strategy" and other plans, the economic development of fringe cities is speeding up. The GDP growth of Benxi and Fuxin in 2021 was 5.8% and 6.4% respectively, higher than Anshan's 4.5% and Panjin's 0.5%.

The spatial structure of Liaoning Province shows the coexistence of radiation and integration. On the one hand, the axis from Shenyang to Dalian radiates to the surrounding cities and promotes the development of marginal cities. On the other hand, the central and peripheral cities actively strengthen the connection with the core cities. For example, Shenyang modern metropolitan circle with Shenyang as the core has a superior spatial location, which plays a role in coordinating the transportation links in Northeast Asia, and its industrial development is constantly optimized. With Dalian as the leader and Dandong and Yingkou as the wings, Liaoning's coastal geometric economic belt will jointly benchmark free trade ports under the influence of Dalian Port and realize an efficient institutional opening to the outside world.

Urban mobility radiation zone. The mobility radiation area of 14 prefecture-level cities in Liaoning Province is calculated by using the field intensity model formula with the city comprehensive flow size instead of city quality. This paper studies the spatial structure of urban network in Liaoning Province from the perspective of plane and evaluates the competitiveness of each city.

The radiation area of Shenyang accounts for about 80.8% of the area of Liaoning Province, and its mobility radiation area accounts for more than half of Liaoning Province. The radiation area involves 13 other cities, presenting a "tiled" radiation form. The radiation area of Benxi is the smallest, accounting for only about 0.05% of the area of Liaoning Province, which is far different from that of Shenyang, the city with the highest flow radiation (Fig. 7). The mobility radiation area of Dalian accounts
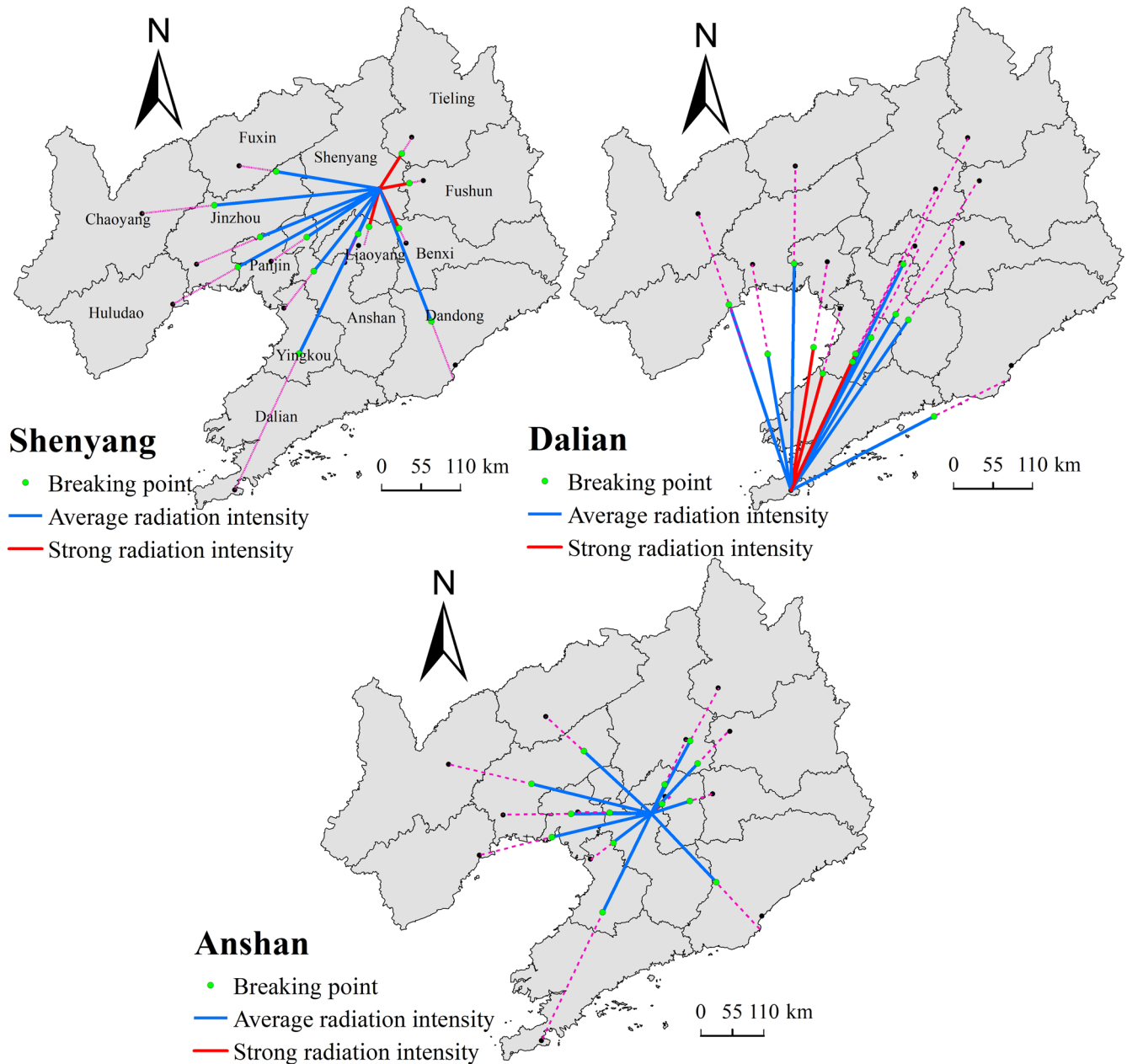
Fig. 4 Radiation range and intensity of each node city. The further the distance from the node city, the weaker the connection strength. The blue line indicates that the connection between cities is average, while the red line indicates that the connection between cities is strong. The map was developed by the authors using ArcGIS Pro Version 3.0.3.

for 8.5%, and the radiation area involves Yingkou, Anshan and Dandong. Other areas close to the city center, with its city as the center, show "clumpy" outward radiation.

Overall, Shenyang has the absolute advantage of mobility radiation. Based on the Shenyang economic circle, the mobility radiation covers all cities in Liaoning Province. In addition, the mobility radiation zones of Dalian, Anshan and Dandong infiltrate each other, which is in line with the "one axis and two wings" structure proposed by the government in the coastal economic belt of Liaoning Province with Dalian as the leader. Chaoyang and Huludao are located at the edge of Liaoning Province, which are less affected by the mobility radiation of core cities, and their own capacity is limited (Fig. 8). Therefore, they should actively integrate into the urban network space as well as carry out economic and cultural exchanges with surrounding cities and core cities, realizing industrial upgrading and policy adjustment.

The development model of urban network spatial structure in Liaoning Province

Dual-core development model. The dual-core driven urban structure model should be developed to drive the economic connection within the region, the coordinated development and common progress of coastal and hinterland, and the agglomeration space should be pulled. In the dual-core city development model, the two core cities are separated from each other by a certain distance and both have a high economic level. Shenyang is in the central part of Liaoning Province. It is the capital of Liaoning Province as well as an important industrial base in China, and forms the Shenyang Economic zone with Anshan, Fushun, Benxi, Yingkou, Fuxin, Liaoyang and Tieling. Dalian is located at the southern end of Liaoning Province and has developed tourism and high-tech industries as a port of opening to the outside world in Northeast China. Liaoning Province, with Dalian as its leader, comprises

Table 7 Urban spatial structure index (SSI) in Liaoning Province.

Sorting	City	R_i	SD_{rc}
1	Shenyang	4.486	1
2	Dalian	3.165	0.5
3	Anshan	1.837	0.333
4	Jinzhou	1.342	0.25
5	Liaoyang	1.118	0.2
6	Panjin	1.106	0.167
7	Huludao	0.986	0.143
8	Tieling	0.956	0.125
9	Yingkou	0.940	0.111
10	Chaoyang	0.869	0.1
11	Dandong	0.849	0.091
12	Fushun	0.752	0.083
13	Benxi	0.626	0.077
14	Fuxin	0.570	0.071
	Standard deviation (SD)	1.105	0.251
	SSI	0.114	

Yingkou, Jinzhou, Dandong, Panjin and Huludao to form the Liaoning Coastal economic belt (Fig. 9).

Shenyang Economic zone and Liaoning coastal economic belt are developing increasingly closely. Shenyang economic zone provides a strong economic foundation and low cost of human resources for the development of port economy and marine economy in coastal area. At the same time, the development and construction of the coastal economic belt, as the opening port of Northeast China, can promote the industrial structure and layout change of Shenyang economic circle. Strengthen the two core cities and develop their leading role in radiating radiation. Regional integration will be formed between coastal and inland areas to promote the comprehensive and stable development of Liaoning and realize the revitalization of Liaoning.

Axis development model. Based on the traffic corridor, the urban axis is constructed to strengthen the regional economic development along Liaoning Province. Considering the above analysis of the
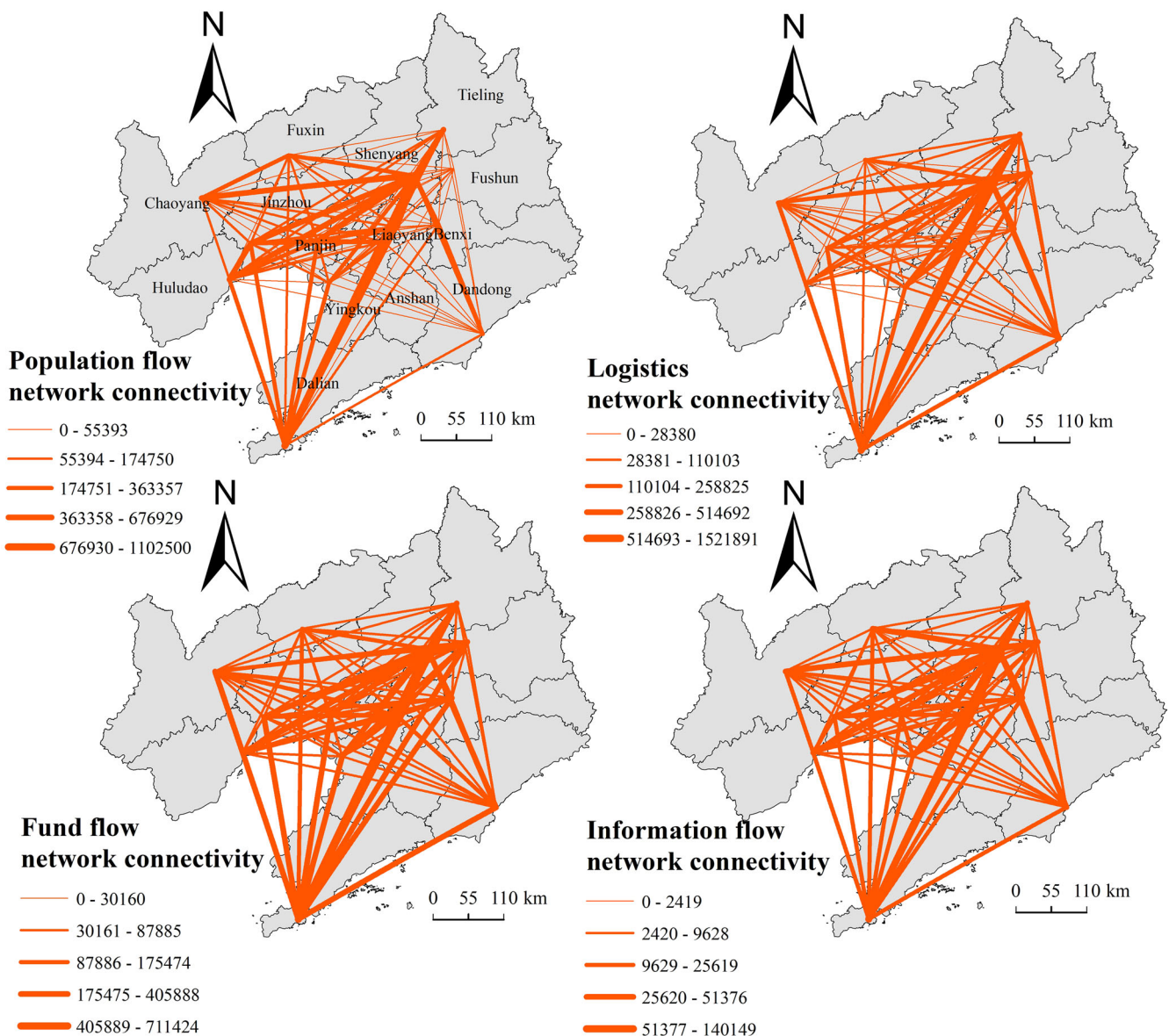
Fig. 5 Urban element flow connection network in Liaoning province. The thicker the red line in the inter-city factor flow connection network, the closer the inter-city connection. Taking population flow as an example, the urban connection intensity in Liaoning Province decreases from the core of the Shenyang-Dalian axis to the periphery. The map was developed by the authors using ArcGIS Pro Version 3.0.3.
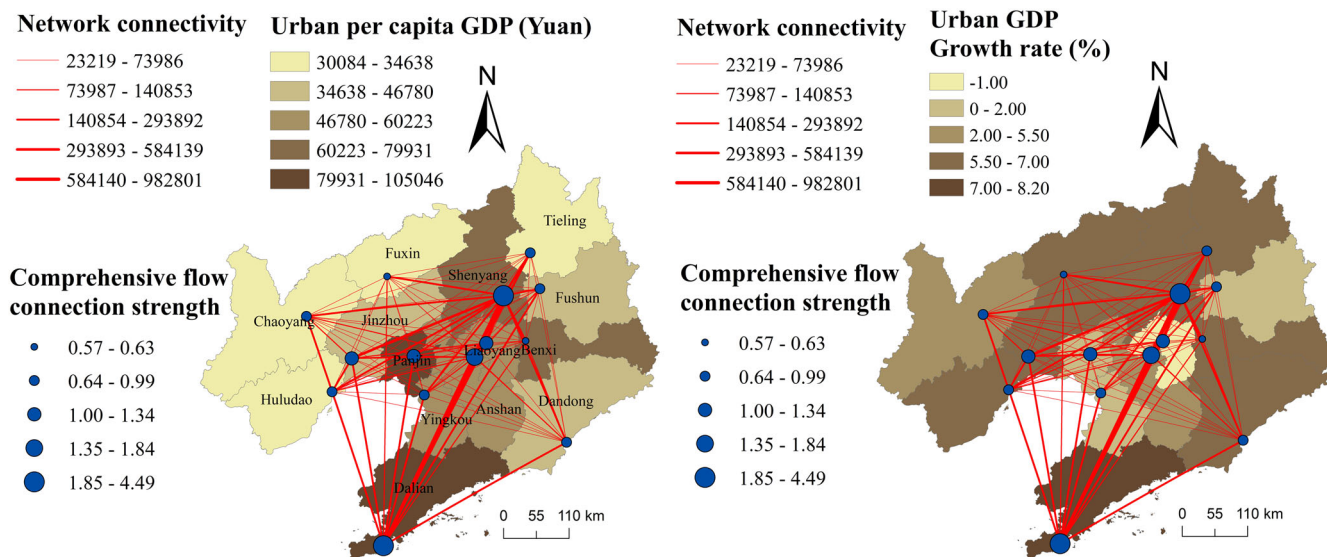
Fig. 6 Urban comprehensive flow connection network in Liaoning province. The larger the blue dot, the greater the sum of the strength of the connection flow between the city and other cities. On the left, the darker the regional color, the larger the GDP per capita; On the right, the darker the regional color, the greater the GDP growth rate of the cities in that region. The map was developed by the authors using ArcGIS Pro Version 3.0.3.
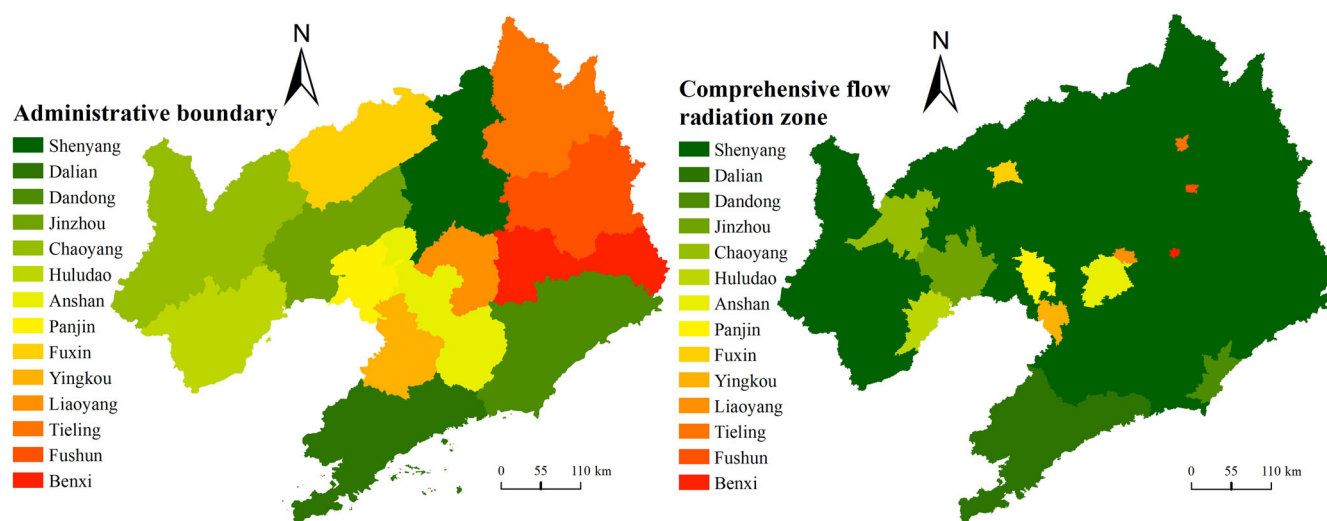

Fig. 7 Urban mobility radiation zone in Liaoning Province. The larger the area of mobility radiation, the more hinterland the city influences and the stronger the competitiveness of the city. The mobility radiation area of Shenyang occupies 80.8% of the area of Liaoning Province, occupying an absolute advantage. The map was developed by the authors using ArcGIS Pro Version 3.0.3.

relationship degree of urban network structure, the trend of urban traffic and the characteristics of "point-axis" theory, the urban axis of Liaoning Province can be roughly divided into four. Dalian and Shenyang constitute the north-south axis of key city development, which drives the development of surrounding regions, connects Shenyang economic circle and Liaoning coastal economic belt, and promotes the regional integrated development of Liaoning Province (Fig. 9).

Based on the main urban axis of Shenyang-Dalian, the internal area of Dalian coastal economic belt also has the structure of "one core, one axis and two wings", that is, Dalian plays the role of a leading city, with Dalian-Yingkou-Panjin as the main axis, Panjin-Jinzhou-Huludao as the Bohai Sea wing, and Dalian-Dandong as the Yellow Sea wing. The structure of one axis and two wings makes the regional economic development and foreign trade exchange of Liaoning coastal economic Belt with Dalian as the leader stable. Under the

background of economic globalization, full consideration should be given to the direction of major urban axes in Liaoning Province, the development of cities along the routes should be promoted, the development of key regions and the optimization of industrial layout should be strengthened, so as to realize the common development and regional integration of prefecture-level cities in Liaoning.

Group development model. Develop the pattern of urban spatial cluster development and strengthen urban connections within each region. Combined with the above analysis of the network connection degree of urban spatial structure in Liaoning Province and the comprehensive consideration of the geographical location among cities as well as the strength of cities, the spatial structure mode of urban cluster in Liaoning Province is divided into Shenyang urban group, Anliao urban group, West Liaoning urban group, and Dalian urban group (Fig. 9).
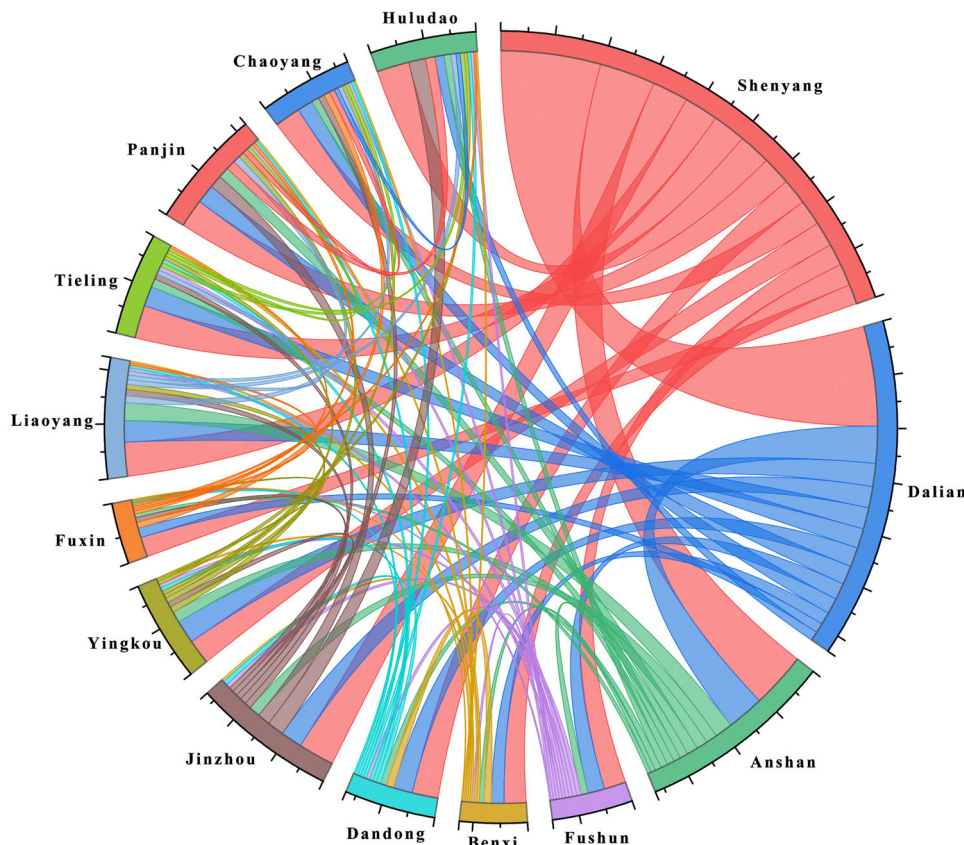
Fig. 8 Comprehensive flow topology map of Liaoning Province. The intensity of contact flow between Shenyang and other cities is the highest, and that between Dalian and other cities is the second highest, while that between marginal cities and other cities is low.
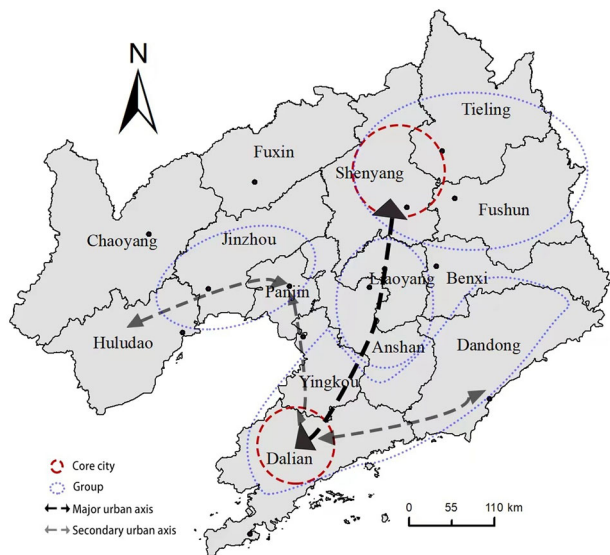
Fig. 9 Development model of urban network spatial structure in Liaoning Province. Liaoning Province has two core cities, Shenyang and Dalian, with Shenyang-Dalian as the main urban axis, forming Shenyang urban cluster, Dalian urban cluster.

Shenyang urban group includes Shenyang, Fushun, Tieling and Benxi. The four cities will jointly promote the optimization of urban industrial structure; Anliao urban group includes Anshan and Liaoyang. In the future, it should build the integration of Anliao culture and tourism based on Anshan industry and Liaoyang

history and culture; West Liaoning urban group includes Panjin, Jinzhou and Huludao. It will develop coastal tourism industries; Dalian Urban Group includes Dalian, Yingkou and Dandong, and the three cities will cooperate to strengthen the prosperous development of coastal tourism. Chaoyang and Fuxin, which cannot be radiated, can be integrated into the Beijing-Tianjin-Hebei metropolitan area, to develop a suitable economic culture, improve economic strength, and complete industrial upgrading.

Conclusion and discussion

Conclusions. The spatial structure of urban network is becoming multiple, comprehensive and three-dimensional. Based on the urban spatial network structure research system framework, this paper comprehensively uses multivariate data of population flow, logistics, fund flow and information flow among 14 prefecture-level cities in Liaoning Province. The urban spatial structure of Liaoning Province is analyzed from three aspects of urban hierarchical structure, dominant axis and radiation range. The urban network spatial pattern of Liaoning province is explored from three perspectives of urban spatial pattern, network pattern and mobility radiation area. In addition, the paper studies the future development model of urban network spatial structure in Liaoning Province from three levels: point, line and plane, and then draws relevant conclusions, discusses and analyzes the implications.

(1) Cities at different levels in Liaoning Province have different functions in the urban network. Shenyang and Dalian play a leading role, while Anshan and Jinzhou play the role of "transit hubs"; The radiation impact ranges of the first-level node city Shenyang and the second-level node city Dalian cover most areas of Liaoning Province, while the radiation

impact range of the third-level node city Anshan is small and has a certain bias.

(2) Liaoning Province presents a dual-core urban network pattern with Shenyang and Dalian as the main cities. The urban connection strength of Liaoning province decreases from the axis of Shenyang-Dalian to the periphery, and the urban network space of Liaoning Province presents a "core-edge" structure. The inner part of the province takes Shenyang as the core to form Shenyang economic circle. The outer coastal zone of the province takes Dalian as the core and intersects with Shenyang economic circle to form the urban spatial network of Liaoning Province; Shenyang mobility radiation area involves all cities in Liaoning Province and occupies an absolute advantage. Chaoyang and Huludao are located at the edge of Liaoning Province, and the form of each city's mobility radiation area reflects its competitiveness and influence area.

(3) The spatial structure of urban network in Liaoning Province should be further developed by the mode of "core city-axis-cluster". Strengthen the two core cities and develop their leading role in radiation; Based on the main urban axis of "Shenyang-Dalian", promote the development of "one core, one axis and two wings" structure of the internal region of Dalian coastal economic belt; Strengthen urban connections within each region of Shenyang urban group and Dalian urban group.

Discussion

In the face of the paradigm shift of urban network research, the researches were only limited to the judgment of single flow and were unable to comprehensively analyze the connection strength among cities. This paper analyzes the urban spatial structure and spatial network pattern of 14 prefecture-level cities in Liaoning Province through multivariate data, and discusses the development mode of urban spatial structure. However, there are still some problems that need to be discussed and deepened.

(1) Targeted research. Based on the characteristics of urban network structure in Liaoning Province, this paper analyzes the relationship strength, radiation range and future development mode of the typical cities (such as Shenyang and Dalian), concretizes and targets the spatial structure and pattern of urban network in Liaoning Province.

(2) Mechanism research. In this paper, the spatial structure of urban network in Liaoning Province is comprehensively analyzed based on the connection strength of flow elements, and the formation mechanism behind it will be deeply analyzed and discussed in the future.

(3) Multi-element research. In future data processing, private cars and other transportation modes will be taken into account while the number of transportation vehicles will be used to replace the population flow; In terms of logistics, transportation of large freight will be considered; In terms of data type, the formation mechanism will be deepened, and the big data information processing will be considered comprehensively.

Policy implications.

(1) Core cities should play a radiating and driving role. At the present stage, Liaoning Province presents a spatial pattern of dual-core development. The core cities Shenyang and Dalian should play a leading role in radiating and promoting the revitalization and development of the surrounding cities.

(2) The fringe cities should strengthen the synergy with the core cities. Under the trend of globalization, with the in-depth implementation of "Shenyang Modern Metropolitan Area" "Liaoning Coastal Economic Belt" and "Liaoning Northwest Strategy", the urban network of Liaoning Province will turn to diffusion effect in the future. The relationship between the peripheral cities and the core cities in Liaoning Province is strengthened, and the urban network tends to be balanced.

(3) Expand the financial gathering effect and brand driving effect of high-quality development of urban agglomeration. Under the general premise of the revitalization and development of Liaoning Province, optimize the policy of regional integration, integrate population flow, logistics, fund flow and information flow, and strengthen the circulation of services, functions and technologies within the city. It is more conducive to building a balanced, efficient and comprehensive urban network spatial structure in Liaoning Province by actively exchanging information and technology with the coastal area, the economic belt along the Yangtze River and the Beijing-Tianjin-Hebei region.

Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request. Some additional information are included in the supplementary file.

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Author contributions

ST and JJ conceived and designed the manuscript. ST, JJ, HL, and XL collected data and conducted analyses. ST, JJ, JY, and CF drafted the paper and proofreading.

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Additional information

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