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ORIGINAL RESEARCH ARTICLE

Order, scale structure and coupling types of coastal port city system from the perspective of multi-function

Jianke Guo*, Lulu Wu, Bo Li, Yafeng Qin

Key Research Base of Humanities and Social Sciences of Ministry of Education, Institute of Marine Sustainable Development, Liaoning Normal University, Dalian 116029, Liaoning Province, China. E-mail: jkGuo98@163.com

ABSTRACT

Using the rank scale rule, taking 47 major port cities in China from 2001 to 2015 as research samples, this paper discusses the rank scale characteristics and hierarchical structure of coastal port city system from a multi-functional perspective, and divides the coupling type of multi-functional development based on shipping logistics. The research shows that: 1) from 2001 to 2015, the scale-free area of manufacturing function order scale distribution in the coastal port city system appeared bifractal structure, the hierarchical segmentation characteristics appeared, and the other functions were single fractal; From the perspective of long-term evolution, only the order and scale distribution of shipping logistics function has developed from centralization to equilibrium, while the business function, manufacturing function (scale-free region I), modern service function and population distribution function are in a centralized situation. 2) The hierarchical structure of coastal port city system has gradually changed from pyramid structure to spindle structure, and generally formed five levels: national hub, regional hub, regional sub center, regional node and local node. 3) From the perspective of multi-functional coupling types, the traditional functions of port cities are generally ahead, while the high-end service functions lag behind, and the improvement speed of urban functions is slow and tends to be flat, indicating that the multi-functional development of China's coastal port cities is still at a low level, and the industrial system structure needs to be further optimized. 4) From the perspective of port cities at different levels, the functions of regional hub cities and regional sub central cities are in the stage of rapid growth; regional and local node cities are still in the growth stage of traditional functions such as industry and commerce.

Keywords: Port City System; Sequence Size Distribution; Hierarchy; Coupling Type

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Ports and cities not only organically combine production and circulation, but also develop together and promote each other. Coastal and river areas will inevitably form a series of port city systems with different sizes and characteristics, and become an organic hub system for the country to communicate domestic and foreign international trade[1]. Urban system is a hot issue in urban geography, but there has been little research on port city system for a long time. The reasons are as follows: on the one hand, due to the discontinuous distribution of ports and their cities, there are more studies on port system from the perspective of traffic geography, but less on port city system from the perspective of urban geography; on the other hand, in a long period of time, the number of regional ports is small, the functional convergence between ports and port cities, and the competition of goods supply hinder each other's economic ties, and the relevance and systematicness are not strong. Over the past 40 years of reform and opening up, the development of ports in China's coastal areas has changed with each

passing day, new ports have been emerging, and the characteristics of port regionalization are obvious. The coastal urban belt has become a port urban belt. Port cities have not only greatly increased in number, but also formed a continuous distribution in space. Especially with the strengthening of shipping network connection and logistics, the division of labor among large, medium and small ports is becoming more and more obvious, and they are more closely connected with each other. In this context, it is feasible and necessary to deeply study the port city system.

The research on urban system mainly focuses on the theoretical content of "three structures and one network", namely regional spatial structure, hierarchical scale structure, and functional type structure and network system organization[2]. Among them, the research objects involved in the study of functional type structure are relatively rich, such as national prefecture level cities, central plains urban agglomeration, Yangtze River economic belt urban agglomeration, central Liaoning urban agglomeration, etc. [3–7]; in terms of research methods, urban functions are classified and identified by general description method, statistical analysis method, factor analysis, location entropy and other methods. As a special type of city, the port function of port city is the basic function. With the development of port industry system, more and more other port industries and even non port industries are gradually attracted, so as to promote the multi-functional development of port city. However, at present, domestic research on port cities mostly focuses on port city relations, port city spatial structure, port city competitiveness and sustainable development capacity[8–13]. The deficiencies are as follows:

1) From the perspective of urban system, most of them focus on a single port city or port city port and shipping logistics, trade and other aspects, and there are few studies on exploring the hierarchical structure and relationship of port city system from the perspective of urban system. 2) In terms of methodology, the rank scale rule is mostly used in the study of hierarchical scale structure of urban system, but there are few attempts in the study of port city system[14]; this rule is also widely used in the fields of floating population, tourism flow, oil flow, traffic flow and so on[15–19]. However, most of them measure the scale distribution with a single index, and the comparative research on the rank scale from the multi-functional perspective has not been carried out.

In view of this, based on the theory of port function evolution and the characteristics of urban development, this paper selects five representative functions of port cities, uses the rank scale rule to describe the multi-functional scale distribution characteristics of port city system from multi-dimensional indicators, and constructs the coupling relationship between basic port and shipping functions and other functional scales based on the rank scale rule, This paper discusses the multi-functional differentiation and development of China's port city system[20].

1. Research methods and data sources

1.1 Rank scale rule of port city system

The rank–scale model of urban distribution starts from the whole urban system, reflects the relationship between the size of different cities and their rank in the whole system, and can evaluate the distribution of urban system in a country or region[14]. In 1913, the law was proposed by German scholars. In 1935, American linguistics professor obtained Ziff's law through statistical analysis. The basic formula of Lotka model now widely used is:

$$P_i = \frac{P_i}{P_i^q} \text{ or } P_i = P_1 \times R_i^{-q} \quad (1)$$

In the formula, *Pi* is the city scale at *i* level and P_1 is the first city scale; q is Zipf index; R_i is the order of city *i*. Based on different functions and referring to Formula (1), it is concluded that the basic form and logarithmic form of the calculation formula of port city system rank scale in this paper are as follows:

$$F_i = \frac{F_1}{R_i^q} \text{ or } F_i = F_1 \times R_i^{-q} \quad (2)$$

$$1\mathrm{n}\, F_i = 1\mathrm{n}\, F_1 - q1\mathrm{n}R_i \quad (3)$$

In the formula, F_i is the functional scale of the port city at i level, and F_1 is the functional scale of the first port city. Zipf index (q value) has the following properties: when $q = 1$, the ratio of the first city to the smallest city in the urban system is the number of cities in the whole urban system; when $q < 1$, the scale of high-level sub cities is not very prominent, and there are more and dominant cities in the middle order; when $q > 1$, the urban scale distribution is relatively concentrated, the urban scale distribution is quite different, and the urban primacy is high. If q becomes larger, the concentrated force is greater than the dispersed force; if q becomes smaller, and the scattered force is greater than the concentrated force. When $q \to \infty$, there will be only one city in the system; when $q = 0$, the size of cities in the urban system is equal.

1.2 Multi-functional coupling type division based on bit order scale rule

1.2.1 Construction of multi-functional index system of port city

The intergenerational division of ports is not based on time period. Different ports in China have different development levels, intergenerational differences and functional characteristics. In 1999, the United Nations Conference on Trade and Development (UNCTAD) proposed: so far, the international developed ports have entered the fourth generation[21]. Many scholars have explained the evolution theory of port function: the main functional characteristics of the first generation port are transportation transfer function; the second generation of port functions are characterized by industry, commerce and value-added services; the third generation port features logistics and cargo information flow services; the fourth generation ports are characterized by resource allocation and global hub functions. The multi-functional development of the port also drives the diversification of the functions of the city where the port is located. Therefore, we regard shipping logistics, commercial trade, modern manufacturing and modern service as the four functions of port cities. In addition, in order to reflect the economic vitality and attraction of modern port cities, we have especially increased the function of population distribution. Based on this, the multi-functional scale evaluation index system of port city system (**Table 1**) is constructed to further characterize the function of port city.

Table 1. The multi-functional scale evaluation index system of port city system

Functional type index	
Shipping logistics function	Total freight volume, water freight volume, port cargo throughput, port container throughput and port foreign trade throughput.
Commercial trade function	Total retail sales of social consumer goods, total sales of wholesale and retail goods above the quota, employees of wholesale and retail units, total amount of foreign capital actually utilized in the current year, and number of wholesale and retail enterprises above the quota.
Manufacturing function	The indexes above designated size include total output value of industries, total profits of industrial enterprises, current assets of industrial enterprises, number of industrial enterprises, and employees of manufacturing units.
Modern service function	Various loan balances of financial institutions, various deposit balances of financial institutions, employees of financial institutions, number of inbound international tourists, employees of information transmission, computer service industry and software industry.
Population distribution function	Total passenger volume, railway passenger volume, highway passenger volume, water passenger volume and civil aviation passenger volume.

1.2.2 Classification of multi-functional coupling types

Ideally, the function scale of high-grade port cities is larger and the level is higher, accounting for a greater proportion in different function sequences, while that of low-grade cities is the opposite; under the multi-functional coordination and interaction mechanism of port city, the development levels of different functions are unified. In the double logarithmic curve of rank order scale, it shows that the rank order of each functional scale of high-grade port city is higher, while that of low-grade city is on the contrary. The double logarithmic curves of different

functional scales of any port city coincide. In reality, the curves are misaligned.

According to the double comparison relationship between different functional scale and the proportion of functional scale, the development differences between port city functions can be measured from two aspects and the port city can be explored based on the coupling type characteristics of multi-functional development level in the city. The specific calculation formula is as follows:

$$\Delta F_i = \ln(F_{bi}/F_{ai}) = \ln F_{bi} - \ln F_{ai} \quad (4)$$

$$\Delta S_i = \ln\left(\frac{F_{bi}}{\sum_{i=1}^{n} F_{bi}} / \frac{F_{ai}}{\sum_{i=1}^{n} F_{ai}}\right) = \ln\frac{F_{bi}}{\sum_{i=1}^{n} F_{bi}} - \ln\frac{F_{ai}}{\sum_{i=1}^{n} F_{ai}} \quad (5)$$

In the formula, F_{ai} is the port function scale (shipping logistics function), F_{bi} is the urban function scale (commercial trade function, manufacturing function, modern service function and population distribution function), and n is the number of cities. The ΔF_i obtained from the above formula reflects the comparison relationship between the functional scale of the port city, and ΔS_i reflects the comparison relationship between the functional status of the port city. Based on this, four coupling types can be divided (**Table 2**).

Table 2. The basis and characteristics of coupling type classification of port city system

Type	ΔF_i	ΔS_i	Characteristics
Absolute leading type	>0	>0	The urban functional scale and status in the urban system are higher than the port functional scale.
Relatively advanced type	>0	<0	The urban functional scale is higher than the port functional scale, and its position in the urban system is lower than the port functional scale.
Relative lag type	<0	>0	The urban functional scale is lower than the port functional scale, and its position in the urban system is higher than the port functional scale.
Absolute lag type	<0	<0	The urban functional scale and status in the urban system are lower than the port functional scale.

1.3 Overview of the study area and data sources

Taking the coastal port cities as the research sample, this paper selects 47 major port cities based on the historical evolution and importance of ports and the development status of port cities, of which only cities below Nanjing are selected along the Yangtze River; according to the division of port groups and the availability and continuity of index data in the national coastal port layout plan issued by the Ministry of Communications in 2006, the port city samples are finally determined as: port city groups around the Bohai Sea (Tianjin, Dandong, Dalian, Yingkou, Jinzhou, Tangshan, Cangzhou, Qinhuangdao, Yantai, Weihai, Qingdao and Rizhao); Yangtze River Delta port urban agglomeration (Shanghai, Suzhou, Ningbo, Lianyungang, Zhoushan, Nanjing, Nantong, Wenzhou, Changzhou, Wuxi, Jiaxing, Taizhou, Taizhou, Yangzhou and Zhenjiang); Pearl River Delta port urban agglomeration (Guangzhou, Shenzhen, Zhuhai, Shantou, Shanwei, Huizhou, Dongguan, Zhongshan, Yangjiang, Jiangmen and Maoming); southeast coastal port urban agglomeration (Fuzhou, Putian, Quanzhou and Xiamen); southwest coastal port urban agglomeration (Zhanjiang, Beihai, Qinzhou, Fangcheng and Haikou).

In view of the availability of port data, the time series is determined as 2001–2015. The urban index data is from China Urban Statistical Yearbook (2002–2016), the port index data is from China port Yearbook (2002–2016), and the tourism index data is from China Regional Economic Development Yearbook (2002–2014)[22–24]. Some missing data come from provincial and municipal yearbooks and Statistical Bulletins, and individual data are fitted by mathematical methods. Because the data units of each index are not unified, the data are standardized, and the five indexes under each function are weighted and summed by entropy method to obtain the

scale of each function.

2. Rank scale distribution of coastal port city system from a multi-functional perspective

2.1 Comparative analysis of size distribution of different functional bit sequences

Since the 21st century, Chinese cities, especially the eastern port cities, have developed well. Due to its unique location advantages and the support and guidance of national policies, the port city belt has gradually evolved into a port city system with high urbanization level, strong economic development speed and close international trade exchanges in eastern China. All cities have also become port cities with multi-functional characteristics. Using Formula (3) for 2001–2015, simulated regression analysis was carried out for each functional scale of the port city system, and the goodness of fit of the curve was as high as 90%, which proved that the rank scale rule can be used to explain the scale distribution characteristics of the port city system. The scatter diagram of various functions of the port city system and the double logarithm fitting curve of bit order scale (**Figure 1**) are as follows.

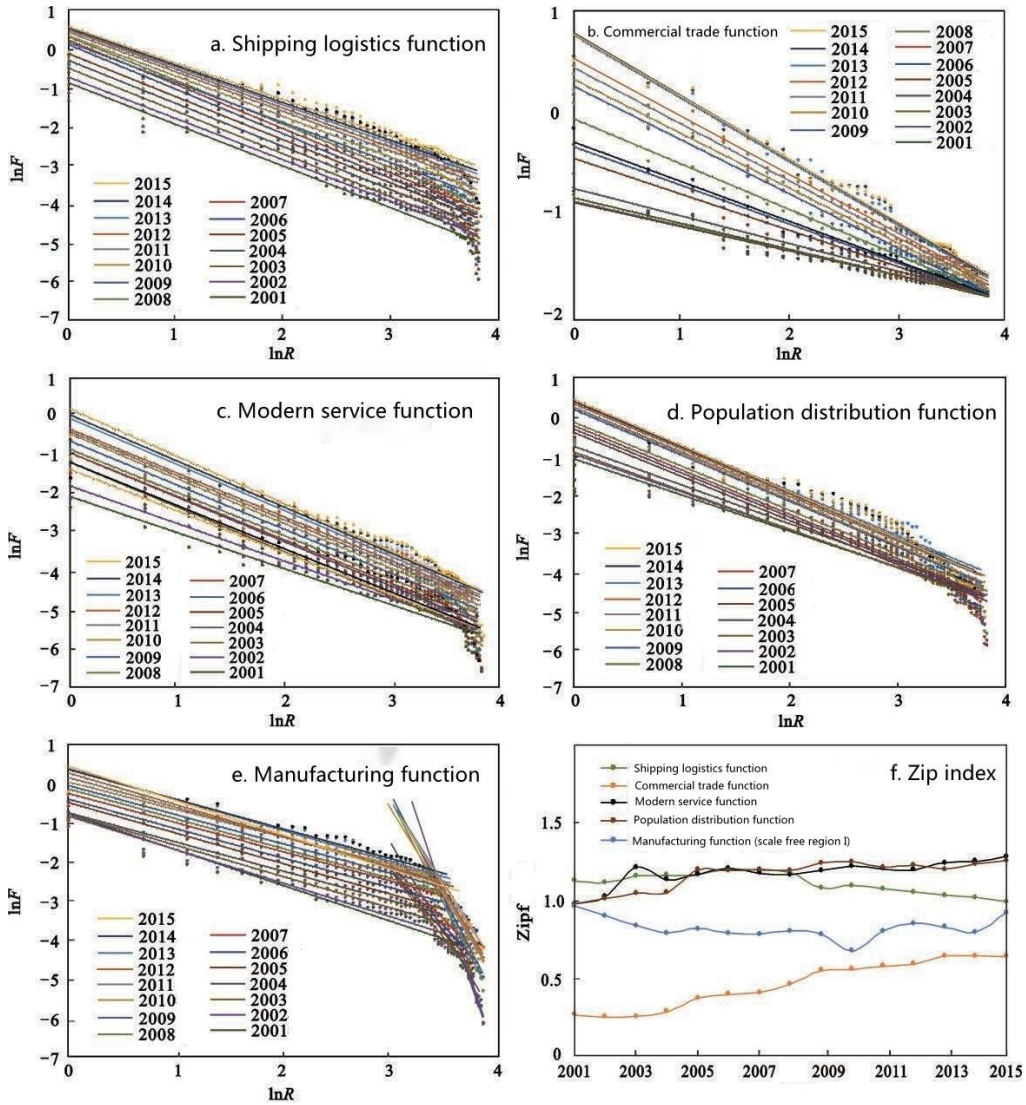

Figure 1. The multifunctional rank-size double logarithm fitting curve and Zipf exponential curve of port city system.

2.1.1 Change track of bit order scale distribution

The distribution structure, trend and growth characteristics of each functional scale of coastal port city system have different characteristics. 1) In terms of fractal structure, there are two regions with

high fitting in the manufacturing function rank scale curve, which is a significant bifractal structure, with obvious hierarchical segmentation characteristics. The number of cities in scale-free region I is much higher than that in scale-free region II, while the other functions are single fractal structure. From the perspective of Zipf index, the Zipf index of business function and manufacturing function (scale-free region I) is less than 1, and its rank scale distribution is currently in the stage of equalization; In contrast, the Zipf index of shipping logistics, modern services and population distribution functions is more than 1, and the rank scale distribution is in the centralized stage. 2) From the curve characteristics and long-term evolution characteristics of scale distribution, the growth characteristics of each function are different while realizing scale expansion. The scale of Commerce and trade functions shows a significant "funnel-shaped" divergent growth. The growth rate of large-scale port cities is significantly faster than that of small and medium-sized cities. The scale distribution tends to be unbalanced, and the concentrated force is greater than the decentralized force. The scale of other functions is generally characterized by parallel growth: for example, the scale of modern service and population distribution functions is parallel and divergent growth, which means that the growth rate of large-scale port cities is relatively fast, and the scale distribution still tends to centralization; in the bifractal structure of functional scale of manufacturing industry, the distribution of urban scale in scale-free area tends to be centralized; only the scale of shipping logistics function tends to be parallel and convergent, that is, small and medium-sized cities continue to develop and catch up with large cities, and the scale distribution is gradually balanced. 3) Compared with the development characteristics of shipping logistics function, the business function is quite different. As a traditional function of port, this function is integrated into the evolution of urban function earlier in the process of continuous refinement of social division of labor, and can develop independently to a certain extent; modern services, population distribution and other high-end service industries are easier to land in high-level port cities and give full play to their derivative potential. At present, the main body with stronger economic vitality and population distribution capacity is still a few high-level port cities, which is highlighted by the centralized distribution of modern service and population distribution functions of high-level port cities, and the scale is significantly higher than that of low-level port cities.

2.1.2 Comparison of changes in urban order

Comparing and calculating the urban order of various functions in 2001 and 2015 (**Table 3**), the results show that: 1) from the perspective of total change, the adjustment and change range of urban order in shipping logistics and population distribution function is obvious. Among them, cities with more than 10 shipping logistics functions are Rizhao, Yingkou, Tangshan, Cangzhou, Taizhou, Huizhou,

Table 3. The changes in port city order adjustment in 2001–2015

Function type	Regional port city system	Bohai Rim (12 ports)		Yangtze River Delta (15 ports)		Pearl River Delta (11 ports)	
	Total variation	Total variation	Unit variation	Total variation	Unit variation	Total variation	Unit variation
Shipping logistics function	300	24	2	30	2	12	1.09
Commercial trade function	192	10	0.83	14	0.93	20	1.82
Manufacturing function	166	10	0.83	18	1.20	8	0.73
Modern service function	170	10	0.83	4	0.27	12	1.09
Population distribution function	292	22	1.83	24	1.60	18	1.64

Note: the value is the absolute value of urban rank change in 2001 and 2015.

Qinzhou and Dandong; cities with a ranking of more than 10 are Qinhuangdao, Zhuhai, Maoming, Jiaxing, Zhongshan and Wenzhou. During this period, the in-depth adjustment of the port system and the reorganization and integration of the port area made the urban order change greatly, and a stable pattern has not yet been formed. Cities with more than 10 cities in the population distribution function are Zhanjiang, Nantong, Weihai and Beihai; more than 10 cities with a decline in rank are Dongguan, Shantou, Maoming, Dalian, Wenzhou and Cangzhou. The change of urban order in this function mostly reflects the strength of urban attraction. Regional economic level differences, traffic accessibility and industrial capital flow have become important factors affecting urban population agglomeration. 2) The order of manufacturing functional cities has changed steadily and developed mature. As the core function of the second generation port, the adjustment range of urban order in the manufacturing function is the smallest, which shows that most coastal port cities in China are still in the transformation stage from the second generation port to the third generation port, and the port industry is the leading industry of many port cities.

2.2 Difference of multi-functional rank scale distribution among the three coastal port urban agglomerations

2.2.1 Change track of bit order scale distribution

The study uses Formula (3) to conduct simulated regression analysis on the functional scale of the three port city clusters from 2001 to 2015, and proves that the rank scale rule can be used to explain the scale distribution characteristics of regional port city system. The function scatter diagram and bit order scale double logarithm fitting curve (**Figure 2**) are as follows. There are both similarities and differences in the change trajectories of the order scale distribution of various functions in the Bohai rim, Yangtze River Delta and Pearl River Delta. 1) The change track of the rank scale distribution of the three regional trade and modern service functions is highly consistent. On the one hand, the change track of the rank scale distribution of trade functions presents a "funnel shape" in the three regions, and the degree of centralization is more obvious. With the evolution of time, the growth range of trade functions in port cities becomes larger, and the distribution of trade functions in port city system shows an obvious Matthew effect. On the other hand, the change track of the rank scale distribution of modern service functions represented by finance, computer and information services shows a weak decentralized trend in the three regions. 2) There are great differences in the functional order scale distribution trajectories of shipping logistics, manufacturing and population distribution in the three regions. The scale-free area of the functional order scale distribution of shipping logistics and population distribution around the Bohai Sea changed from single fractal to double fractal in 2007 and 2008, respectively; the bifractal structure of manufacturing function in the Pearl River Delta changed to single fractal in 2013, and the overall bit order scale distribution structure tends to be stable. In contrast, with the function of single fractal structure, the change trajectories of bit order scale distribution show a roughly parallel trend, and the difference of scale distribution changes little. 3) From the overall situation of the three regions, the five functions of cities in the Yangtze River Delta have obvious sequence and scale distribution characteristics, and the port city system structure is relatively stable. The order scale distribution characteristics of the four functions in the Pearl River Delta are obvious, while the order scale characteristics of manufacturing functions have strong volatility, and many years do not have the overall order scale distribution characteristics. In the Bohai Rim region, there are two functions: shipping logistics and population distribution. The rank scale distribution shows strong volatility, and many years do not have the characteristics of rank scale distribution. From a multi-functional perspective, the regional order scale distribution characteristics of Bohai rim, Yangtze River Delta and Pearl River Delta are relatively obvious, and the development degree of regional port city system still needs to be strengthened.

2.2.2 Comparison of changes in urban order

From the perspective of the three regions, the change of the order of multi-functional development of port cities. On the whole, the change of the order of cities in the Pearl River Delta region is the largest, and the order distribution in the Yangtze River Delta region is the most stable (**Table 3**), but the specific conditions of each function are different. 1) In terms of functions, the Pearl River Delta region in shipping logistics and manufacturing functions, the Bohai

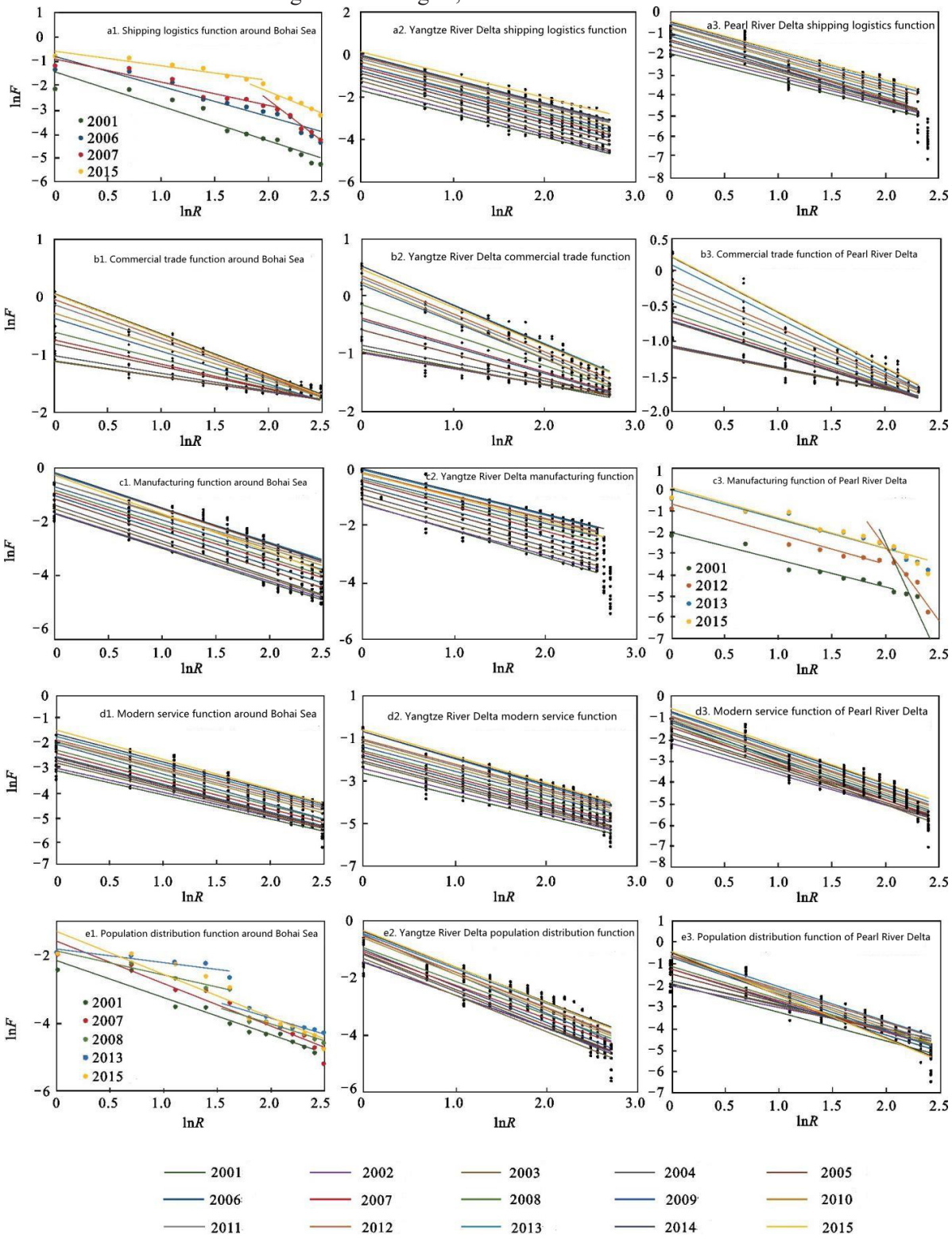

Figure 2. The multi-functional rank-size logarithm fitting curve of three major port urban agglomerations.

Rim region in commerce and trade functions, and the Yangtze River Delta region in modern service and population distribution functions have small adjustment range and stable development. 2) There are cities with large adjustment range in each region. For example, in the Bohai Rim region, the ranking of Qinhuangdao decreased by 5 in the shipping logistics function; population distribution work in Cangzhou fell by 5 places and Weihai rose by 4 places; Rizhao ranked fourth in the manufacturing function. Yangtze River Delta: Jiaxing dropped 8 places and Taizhou rose 5 places in shipping logistics function; in the function of population distribution, Wenzhou dropped by 5, Zhenjiang dropped by 5 and Taizhou increased by 5. Pearl River Delta region: Maoming dropped 4 places and Huizhou increased 5 places in shipping logistics function; Huizhou dropped 6 places in trade function; in the modern service function, Zhuhai rose 4 places and Dongguan fell 5 places in the population distribution function.

3. Hierarchical structure, coupling type and multi-functional development level of port city system

3.1 Hierarchical structure characteristics of port city system

The hierarchical structure of urban scale is a comprehensive reflection of the status and role of cities in the urban system, and it is an important basis for detecting the internal distribution pattern of the urban system. Traditionally, urban hierarchy is often reflected by population and land scale indicators, but its scale cannot be completely equal to the hierarchical level. The grade of cities with large population or wide land area may not be high, and the population or land scale of cities with the same grade may not be equal. Therefore, the classification of port city scale hierarchical structure by using multi-functional scale index system can better illustrate the strength of urban comprehensive strength. The rank scale method can also reflect the hierarchical structure characteristics of urban system based on scale-free area, but the hierarchical division is not detailed enough and has certain subjectivity in the determination of hierarchical boundary. The principle of fuzzy clustering analysis is to divide different categories according to the membership degree of each data point to the clustering center and obtain the clustering grade results. The most commonly used fuzzy mean algorithm (i.e. fuzzy c-means algorithm, referred to as FCM) is a data clustering method based on the optimization of the objective function and different from the traditional hard clustering algorithm, It can describe the urban system level more accurately. Based on MATLAB-lab9.0 software platform, this paper takes the size of five major functions as the data source for cluster analysis of port city system, and obtains the hierarchical division results of port city system scale in 2001 and 2015 (**Table 4**).

3.1.1 Time evolution of hierarchy

From 2001 to 2015, the hierarchy of port city system gradually changed from pyramid structure to spindle structure. 1) In 2001, the level of the coastal port city system showed a pyramid structure. There are 38 regional and local port cities, accounting for 80.85% of the port city system; there are 6 regional sub central port cities, accounting for 12.77%; there are only two regional hub port cities, accounting for 4.26%, Guangzhou and Tianjin respectively; Shanghai's comprehensive strength is second to none. It has developed into an important material import and export channel, and the annual port throughput has exceeded 200 million tons, gradually establishing its position as a national hub. 2) In 2015, with the reduction of the number of low-level port cities, the number of middle and high-level port cities increased, and the level of port city system gradually transitioned to spindle structure. The number of regional and local nodes decreased to 31, and the proportion decreased to 65.96%. Zhanjiang, Huizhou and other port cities are upgraded to regional nodes; Wuxi, Wenzhou, Fuzhou, Nantong, Dongguan, Quanzhou and Xiamen rose by one level; the number of middle and high-level regional hubs and regional sub centers has increased significantly, an increase of 7 compared with 2001. Among them, Shenzhen, Suzhou and Ningbo have risen from the third level regional sub centers to the ranks of regional hubs.

Table 4. The classification of port city system based on fuzzy clustering

Levels	2001		2005	
	Proportion	**City**	**Proportion**	**City**
National hub	2.13%	Shanghai	2.13%	Shanghai
Regional hub	4.26%	Guangzhou, Tianjin	10.64%	Guangzhou, Tianjin Shenzhen, Suzhou, Ningbo
Regional sub center	12.77%	Qingdao, Shenzhen, Suzhou, Dalian, Ningbo, Nanjing	21.28%	Qingdao, Dalian,Nanjing, Xiamen, Wuxi, Wenzhou, Fuzhou, Dongguan, Nantong, Quanzhou
Regional node	42.55%	Zhoushan, Wenzhou, Xiamen, Wuxi, Fuzhou, Yantai, Dongguan, Quanzhou, Zhuhai, Haikou, Changzhou, Tangshan, Nantong, Taizhou, Jiaxing, Zhenjiang, Qinhuangdao, Maoming, Zhongshan, Jiangmen	34.04%	Tangshan, Yantai, Lianyungang, Jiaxing, Zhoushan, Weihai, Taizhou, Huizhou, Zhongshan, Changzhou, Zhuhai, Jiangmen, Zhanjiang, Zhenjiang, Yangzhou and Taizhou
Local node	38.30%	Zhanjiang, Huizhou, Taizhou, Yangzhou, Weihai, Cangzhou, Lianyungang, Jinzhou, Yingkou, Putian, Dandong, Rizhao, Yangjiang, Beihai, Shanwei, Fangcheng, Qinzhou, Shantou	31.91%	Haikou, Yingkou, Dandong, Jinzhou, Qinhuangdao, Cangzhou, Rizhao, Putian, Shantou, Shanwei, Yangjiang, Maoming, Beihai, Qinzhou, Fangcheng

3.1.2 Spatial distribution of hierarchical structure

1) Bohai rim, Yangtze River Delta and Pearl River Delta are high-level port city agglomeration areas. The top three port cities Tianjin, Shanghai and Guangzhou in 2001 and the top six port cities in 2015 are mostly distributed in the Bohai rim, Yangtze River Delta and Pearl River Delta. Among them, the number of regional hub port cities in Yangtze River Delta is more than that in other two places. Its unique geographical location makes it develop multi-layer and high-level cities. From the perspective of urban multi-functional development, the level of port cities in the southeast coast has been improved, with strong multi-functional development potential. In contrast, the underdevelopment of high-level port cities along the southwest coast is significant. Zhanjiang has replaced Haikou as the regional node of multi-functional development in the region. 2) Based on the hierarchical division, the development hubs, sub centers and important nodes of the three main regions can be preliminarily defined. In the Bohai Rim region, Tianjin is the regional hub, Qingdao and Dalian are the sub centers, and Tangshan and Yantai are important nodes; in the Yangtze River Delta region, Shanghai, Suzhou and Ningbo are regional hubs, Nanjing, Wuxi, Wenzhou and Nantong are sub centers, and Lianyungang and Jiaxing are important nodes; in the Pearl River Delta region, Guangzhou and Shenzhen are regional hubs, Dongguan is the sub center, Huizhou and Zhuhai are important nodes.

3.2 Urban multi-functional development level based on coupling classification

3.2.1 Lag of high-end service functions

Based on the classification of coupling types (**Table 5**), on the basis of port and shipping development, the functional development levels from high to low are business function, manufacturing function, population distribution function and modern service function, indicating that the traditional functions of port cities are generally ahead of development, while the high-end service functions lag behind. 1) From the development track of the basic functions of shipping logistics, driven by the upgrading of ports and container multimodal transport, the scale of shipping logistics in the port city system has accelerated. From 2001 to 2015, the overall container throughput increased from 25.545 million TEU to 19.958 million TEU; the overall port cargo throughput increased from 1.55 billion t to 9.243 billion t; the overall foreign trade throughput increased from 626 million t to 4.56 billion t. The elements of traditional business functions were first integrated into the process of urban development and became the beginning of

multi-functional development of port cities. Subsequently, while the port land agglomeration, the port industry has gradually become a strong driving force for the rapid development of the port city. At present, in addition to national and regional central and sub central cities, more port cities are still in the stage of industrialization, and the function of industry and trade is still the main function of cities. 2) Among the high-end functions, modern service functions involve various high value-added industries such as finance, information and tourism, with intellectual support, capital guarantee and information transmission as the important support. In particular, modern port cities pay more attention to crossing space constraints through multimodal transport and communication technology to realize the interconnection of functional networks, Therefore, such functions are only well developed in a few high-level port cities. The lag of population distribution function reflects that there is still much room to improve the economic activity of port cities at all levels. Whether the socio-economic benefits of people flow, cargo flow and other factor flows brought by shipping logistics have realized the maximum efficiency transformation has become the main problem affecting the vitality of port cities. The multi-functional development of the whole port city system is still at a low level, and the industrial system structure needs to be further optimized. 3) The development speed of urban functions is generally lower than that of port functions, but it cannot be ignored that port functions have become an important support for urban development. The probability of their direct effect on urban functions is gradually decreasing, but the indirect effect cannot be underestimated. Once port functions disappear in the environment of urbanization development, the port city system is bound to face major adjustments.

3.2.2 There are obvious regional differences in multi-functional development of port cities

1) On the basis of the development of port and shipping functions, the business functions are well developed in the south of the Yangtze River Estuary. The opening period of the region is early. With the in-depth development of marketization, it drives trade circulation, and has outstanding advantages in business and economic integration; The Pearl River Delta region has mature manufacturing functions, of which more than 90% of the cities are advanced in manufacturing functions; cities with well-developed modern service functions are mostly distributed in the Yangtze River Delta and southeast coastal areas. Due to the dense container routes and wide influence range in this area, a modern logistics industry platform integrating trade information, financial capital and other elements has been formed earlier, which has driven the improvement of the modern service function level of the whole city. In contrast, the function of modern service industry in southwest coastal area lags behind obviously; in terms of population distribution function, the number of lagging cities in each region has increased, especially in the Bohai Rim region. 2) Looking at all regions (**Figure 3**), the multi-functional development level of cities around the Bohai Sea is different, especially the multi-functional development level of port cities in Liaoning province is low; the multi-functional development level of the Pearl River Delta region is the most balanced. The high-end service function development of the Yangtze River Delta region has an absolute advantage. The multi-functional development potential of the southeast coastal region is the largest, while the functional level of the southwest coastal region is not high.

3.2.3 The diversification of urban functions is closely related to the multi-functional development of ports

Due to the intergenerational differences of ports, the influence of port functions on the functional evolution of the city is different, which also leads to the hierarchical differences of port city development to a certain extent. 1) In addition to loading, unloading, warehousing and land and water transfer, the second generation port mainly adds value through commercial and industrial activities, so commerce and manufacturing are its core functions. It is not difficult to see that most of the four and five level port cities only have the leading advantages in trade and manufacturing functions, and the other functions

Table 5. The number and proportion of coupling cities based on different levels of scale

Function type	2001					2005				
	Level (quantity)	Absolute advance	Relative advance	Relative lag	Absolute lag	Level (quantity)	Absolute advance	Relative advance	Relative lag	Absolute lag
Commercial trade function	First class (1)	0	1 (100%)	0	0	First class (1)	0	1 (100%)	0	0
	Second class (2)	0	2 (100%)	0	0	Second class (5)	1 (20%)	4 (80%)	0	0
	Third class (6)	1 (17%)	5 (83%)	0	0	Third class (10)	7 (70%)	3 (30%)	0	0
	Fourth class (20)	20 (100%)		0	0	Fourth class (16)	11 (69%)	5 (31%)	0	0
	Fifth class (18)	17 (94%)	1 (6%)	0	0	Fifth class (15)	12 (80%)	3 (205)	0	0
	Total	38 (81%)	9 (19%)	0	0	Total	31 (66%)	16 (34%)	0	0
Manufacturing function	First class (1)	1 (100%)	0	0	0	First class (1)	0	0	0	1 (100%)
	Second class (2)	0	2 (100%)	0	0	Second class (5)	3 (60%)	0	0	2 (40%)
	Third class (6)	2 (33%)	1 (17%)	0	3 (50%)	Third class (10)	4 (40%)	0	0	6 (60%)
	Fourth class (20)	16 (80%)	2 (10%)	0	2 (10%)	Fourth class (16)	10 (63%)	0	1 (6%)	5 (31%)
	Fifth class (18)	8 (44%)	2 (11%)	0	8 (44%)	Fifth class (15)	6 (40%)	0	0	9 (60%)
	Total	27 (57%)	7 (15%)	0	13 (28%)	Total	23 (49%)	0	1 (2%)	23 (49%)
Modern service function	First class (1)	0	0	0	1 (100%)	First class (1)	0	0	1 (100%)	0
	Second class (2)	0	0	1 (50%)	1 (50%)	Second class (5)	0	0	3 (60%)	2 (40%)
	Third class (6)	0	0	3 (50%)	3 (50%)	Third class (10)	1 (10%)	0	4 (40%)	5 (50%)
	Fourth class (20)	0	0	16 (80%)	4 (20%)	Fourth class (16)	0	0	7 (44%)	9 (56%)
	Fifth class (18)	4 (22%)	0	6 (33%)	8 (44%)	Fifth class (15)	0	0	5 (33%)	10 (67%)
	Total	4 (9%)	0	26 (55%)	17 (36%)	Total	1 (2%)	0	20 (43%)	26 (55%)
Population distribution function	First class (1)	0	0	0	1 (100%)	First class (1)	0	0	1 (100%)	0
	Second class (2)	0	0	0	2 (100%)	Second class (5)	1 (20%)	0	1 (20%)	3 (60%)
	Third class (6)	2 (33%)	0	0	4 (67%)	Third class (10)	1 (10%)	0	3 (30%)	6 (60%)
	Fourth class (20)	14 (70%)	0	0	6 (30%)	Fourth class (16)	4 (25%)	0	2 (13%)	10 (63%)
	Fifth class (18)	12 (67%)	0	0	6 (33%)	Fifth class (15)	3 (20%)	0	1 (7%)	11 (73%)
	Total	28 (60%)	0	0	19 (40%)	Total	9 (19%)	0	8 (17%)	30 (64%)

Note: 1. The data of coupling type is: number of cities (accounting for% of the same level). 2. The hierarchy standard is: first class, equivalent to the national hub of this year; second class is equivalent to a regional hub; third class is equivalent to a regional sub center; fourth class is equivalent to a regional node; fifth class is equivalent to a local node.

lag significantly, indicating that port industrialization and trade liberalization are still the essence of their development. The advantages of trade logistics brought by ports cannot form high-quality transformation and docking, and the development of high-end service functions is insufficient. Regional and local node port cities are in a relatively independent stage of industrial and trade development, and most of their ports are in the second generation. 2) The third generation port focuses on the improvement of commerciality and comprehensive service capacity. While building into a trade logistics center, it also has the distribution functions of goods, information, talents, capital and technology. The integration of advantageous functions of regional hub and regional sub center port cities has made the modern port cities take shape. Combined with their port and shipping conditions, urban comprehensive strength and better

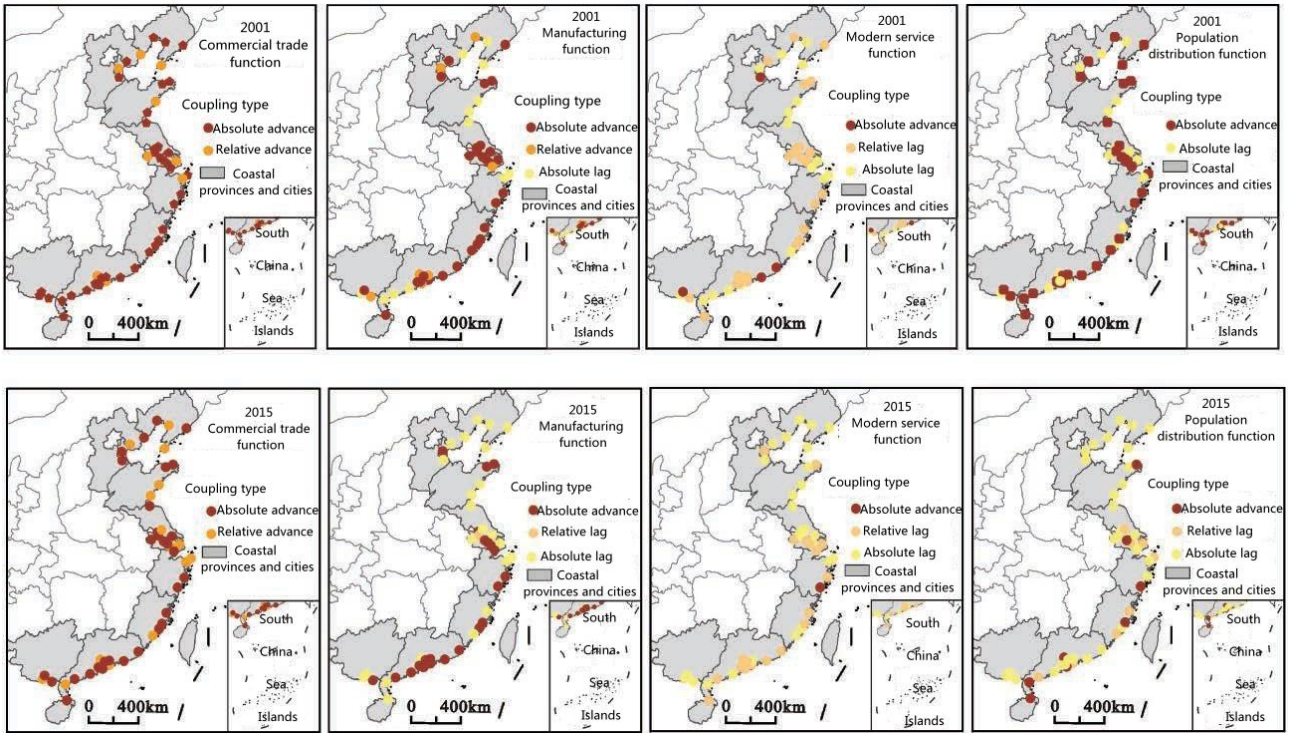

Figure 3. The spatial distribution pattern of functional coupling types in port cities.

development of most functions, it shows that the port cities at two levels are in the stage of diversified growth, and most of their ports are in the third generation, and continue to promote the multi-functional transformation and upgrading of port cities under the in-depth development of ports. 3) The fourth generation port is the main direction of port evolution in the world. Taking port containers as the main cargo and based on technology, capital and information, it has developed multi-dimensional core functions such as port logistics, modern service and population distribution, which has become an important link in the international supply chain. As one of the top ten ports in the global container throughput, Shanghai port has become a growth node of international economic activities. It can quickly respond to the international economic situation and provide differentiated services. It plays an absolute role in promoting the development of regional economic integration and is gradually moving towards the ranks of the Fourth Generation Ports. Taking this advantage, Shanghai is now a modern metropolis driven by the integration and radiation of various functional elements. It is a veritable national hub port city with leading functions.

4. Conclusion and discussion

Taking 47 major coastal port cities as research samples, this paper describes the distribution characteristics of multi-functional scale of port city system by using the ordinal scale rule of urban geography, analyzes and compares the regional differences of multi-functional scale structure of the three major port city clusters, and constructs the coupling relationship between basic port and shipping functions and other functional scales based on the ordinal scale rule. This paper discusses the multi-functional differentiation and development of port city system. The main conclusions are as follows: 1) the distribution structure, trend and scale growth characteristics of each functional scale have different characteristics. From 2001 to 2015, only the scale-free area of the scale distribution of the functional order of the manufacturing industry was a bifractal structure with hierarchical characteristics, and the other functions were a single fractal structure; the scale distribution of shipping logistics function has gradually developed from centralization to equilibrium, the scale distribution of business function and manufacturing function (scale-free region I) has transitioned from equilib-

rium to centralization, and the scale distribution of modern service function and population distribution function has always been in a centralized situation. Modern services and other high-end service industries are easier to land in high-level port cities and give full play to their derivative potential. At present, the main body with stronger economic vitality and population distribution capacity is still a few high-level port cities. 2) By comparing the regional differences in the scale of functional order, the distribution and change trajectory of the scale of business function and modern service function order of port cities in the three regions are highly consistent; there are great differences in the functional order distribution trajectories of shipping logistics, manufacturing and population distribution. From the perspective of multi-function, the sequence scale distribution characteristics of the three port city clusters around the Bohai Sea, the Pearl River Delta and the Yangtze River Delta are relatively significant, but a few of the functional scale distribution show bifractal characteristics, and the development degree of the regional port city system still needs to be enhanced. 3) From 2001 to 2015, with the reduction of the number of low-level port cities and the increase of the number of middle and high-level port cities, the pyramid structure of port city system will gradually transition to spindle structure; based on the hierarchical division, it can be preliminarily defined that in the Bohai Rim region, Tianjin is the regional hub, Qingdao and Dalian are the sub centers, and Tangshan and Yantai are important nodes; the Yangtze River Delta region Shanghai, Suzhou and Ningbo are regional hubs, Nanjing, Wuxi, Wenzhou and Nantong are sub centers, and Lianyungang and Jiaxing are important nodes; in the Pearl River Delta region, Guangzhou and Shenzhen are regional hubs, Dongguan is the sub center, Huizhou and Zhuhai are important nodes. 4) From the perspective of multi-functional coupling types, the traditional functions of port cities are generally ahead of the development, while the high-end service functions lag behind, and the improvement speed of urban functions is generally slow and tends to be flat. The multi-function of port cities is closely related to the multi-function evolution of ports. Based on the development of the second generation of ports, regional and local node port cities are still in the growth stage of traditional functions such as industry and trade; while the regional hub and sub central port cities realize the deepening development of the third generation ports, the urban functions show the characteristics of diversification and integration; in the process of moving towards the fourth generation of ports, Shanghai has become an important growth node of international economic activities and a truly national hub port city.

On the whole, the sequence scale structure and functional coupling type characteristics of the port city system can comprehensively reflect the development of each function. The division of leading and lagging types takes the basic shipping logistics function of port cities as the comparison object, which reveals the internal correlation between port upgrading and the transformation of urban function scale. The expansion of port city functional scale promotes the formation of intercity functional network. In the future, we should focus on the networking characteristics of port cities to comprehensively judge the internal relationship of the port city system.

Conflict of interest

The authors declare that they have no conflict of interest.

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