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Spatial Structural Pattern and Vulnerability of China-Japan-Korea Shipping Network

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Abstract: The economies of China-Japan-Korea (CJK) are complementary, with their proximity resulting in the three countries having a high degree of interdependence with respect to trade. Currently, trade among these countries relies mainly on port-centered shipping. The development of the shipping network is integral for in-depth integration of CJK trade. This paper analyzes the overall characteristics, centrality, spatial structure, and vulnerability of the CJK shipping network using the methods of complex network analysis, blocking flow theory, and interruption and deletion of hub ports. The main findings are as follows: 1) The CJK shipping network has a small average path length and clustering coefficient, and its degree distribution follows a power-law distribution, which make the network present obvious characteristics of a Barabási-Albert scale-free. 2) The characteristics of the multi-center point of the CJK shipping network can alleviate traffic pressure. At the same time, the network shows a clear hierarchy in the port transportation system, with cargo transport relying mainly on the 'hub port-hub port' connection. 3) The CJK shipping network is relatively stable. Compared with ports in Japan and Korea, the main hub ports in China have a greater impact on the stability of the shipping network, in particular those ports of the central coastal region, including Shanghai, Ningbo, and Lianyungang.

Keywords: complex network; blocking flow theory; Barabási-Albert scale-free network; regional differences; China-Japan-Korea

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1 Introduction

Recently, the focus of the world's economic development has begun to shift to Asia. This provides a unique opportunity for China-Japan-Korea (CJK) as the 'driving engine' of Asia's economy to seize development opportunities, expand fields of cooperation, and promote unity and self-reliance. Statistics show that the gross economy of CJK now accounts for 90% of the East Asian, 70% of the Asian, and 20% of the global economy. The development of CJK trade has become the leading factor in economic development. However, trade among the three countries accounts for only 10% of their total foreign trade, implying the potential to cooperate further. Trade cannot be separated from transportation infrastructure support. Because of port transportation' slower comparative cost and Japan's isolated islands that cannot connect with other countries by land, CJK trade relies mainly on port transportation. Therefore, presenting the spatial structural characteristics of this shipping network clarifies port functions and spatial location advantages, which in turn can provide a reference point for coordinated development and cooperation between different ports.

Complex network research was first used in the USA and was applied to social networks (Scott, 2000) and

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economic networks. For example, Watts applied a small-world network to economic aspects (Watts, 2006). Numerous scholars have applied complex networks to the field of traffic research (Wirasinghe and Vandebona, 1987; Coolen and Sherrington, 1993; Black, 2003; Taha and Piust, 2004; Ducruet and Lugo, 2013; Rodrigue *et al.*, 2013). Similar research in China began only later, and although it has achieved progress in relation to mechanisms, it has been mainly applied to economics, computer technology, control, *etc*. Applications in the field of transport are relatively few. Urban traffic networks have been the first objects for study in the field of traffic research (Gao *et al.*, 2005; Cai *et al.*, 2008), where researchers have taken urban public transportation as an example to analyze the complexity of traffic networks and their related problems. Subsequently, complex network research has been applied to the rail (Fan, 2007; He, 2007; Mo *et al.*, 2008; Zhao *et al.*, 2008) and aviation networks (Xue, 2008; Wang *et al.*, 2009; Wu and Pan, 2010; Jiao and Wang, 2014; Xu *et al.*, 2014). For example, Fan used the axis radiation theory of complex networks to analyze the logistics network of the China Railway Express (Fan, 2007). Complex networks have also been used to analyze moused aviation, rail transit and urban traffic transportation networks (Wang and Slack, 2000; Mo *et al.*, 2008).

As for research on the port network, many scholars use the Gini coefficient volume concentration factor to discuss the structural characteristics and the evolution of the current port system. However, studies on the application of complex network theory to the port transportation network are limited (Tian *et al.*, 2007; Li *et al.*, 2009; Mu *et al.*, 2009; Zeng and Teng, 2015). Tian *et al.* (2007) empirically analyzed Maersk's global maritime network and found that it presented both small-world and scale-free characteristics. Zeng and Teng (2015) used average path length, clustering coefficient, degree and distribution of degree to analyze the Silk Road network. Moreover, Mu *et al.* (2009) researched the topology of the ocean liner route network.

CJK trade has become an important factor within world economic development, therefore, contacts between the national shipping ports constantly contribute to the realization of East Asian integration. However, scholarly focus on the port and route network has been limited, and the emphasis on the network's structural features to reveal differences in the trade space is lacking. Moreover, disputes between countries over various islands have undermined the stability of the shipping network, which has become a major barrier to effective national foreign trade. Hub ports are typically the first targets of attack, which has important significance for the steady development of the entire shipping network. Therefore, this paper uses complex network theory to analyze the spatial structural characteristics of the CJK shipping network and then uses blocking flow theory and interruption and deletion of hub ports to discuss the vulnerability of the CJK shipping network. The goal is to provide a theoretical reference framework for in-depth development and security maintenance of the CJK shipping network.

2 Methods and Data Sources

2.1 Complex network method

2.1.1 Overall evaluation index

This study is based on the complex network method, using average path length, clustering coefficients, degree and the distribution of degree to analyze the characteristics of the CJK shipping network.

The average path length (Kaluza *et al.*, 2010) is the average length of the path between ports, which reflects the minimum number of times required to pass through the connection between two ports. By calculating the minimum path length of all ports, we can obtain the average path length of the entire network. For the CJK shipping network, as the average path length increases, the cargo transit times between two ports also increase, and the degree of direct connectivity between two ports decreases, as does the convenience of the entire network. Conversely, when the average path length decreases, the cargo transit times also decrease, and the degree of direct connectivity between two ports and the convenience of the entire network are higher. This can be expressed as follows:

$$L = \frac{2}{n(n-1)} \sum_{i=1}^{n} \sum_{j=i+1}^{n} d_{ij} \tag{1}$$

where d_{ij} is the length between nodes i and j; that is, the connection between ports i and j needs to go through the minimum number of edges, and n is the total number of port nodes in the CJK area; here, $n= 69$, L is the average path length of the whole network.

The clustering coefficient (Woolley-Meza *et al.*, 2011) reflects the connection between adjacent nodes in the shipping network. The higher the clustering coefficient, the easier it is to form regional agglomeration between a point and its surrounding nodes; the lower the clustering coefficient, the more difficult it is to form regional agglomeration in the spatial distribution. This can be expressed as follows:

$$C_i = \frac{2E_i}{k_i(k_i-1)} \tag{2}$$

where k_i is the number of ports directly connected to port i, $k_i\,(k_i-1)/2$ is the maximum number of edges of port i connected pairwise, and E_i is the real number of edges that port i connects, C_i represents the concentration level of the ports.

The clustering coefficient of the entire network is obtained by calculating the average value of the clustering coefficient of each port:

$$C = \frac{\sum_{i=1}^{n} C_i}{n} \tag{3}$$

where n represents the number of port nodes and C represents the average concentration level of the network. In the shipping network, the number of adjacent edges that directly connect with port i is its degree; the higher the degree of the port, the more routes go through it, and vice versa. The degree of the entire shipping network is determined by the average degree ($<k>$) value of each port:

$$<k> = \frac{\sum_{i=1}^{n} k_i}{n} \tag{4}$$

The degree distribution of the nodes (Xu *et al.*, 2007) in the network is described by the probability distribution function $p(k)$. To reduce the error caused by the small scale in the real network, this paper uses $M(k)$ to express the cumulative distribution function (Wang *et al.*, 2009) of $p\,(k)$:

$$M(k) = \sum_{k'=k}^{\infty} p(k) \tag{5}$$

where $M(k)$ is the distribution of the cumulative Percentage of the degree, $p(k)$is the probability distribution function of the ports' degree.

2.1.2 Local evaluation index

Centrality (Mo *et al.*, 2010) is an important reflection of the status of port nodes in the network and plays an important role in revealing the characteristics of the spatial structure of the shipping network. Centrality, closeness centrality, and betweenness centrality can show the direct accessibility, relative accessibility, transfer, and cohesion of the network nodes. Centrality (DC_i) can directly reflect the possibility of direct connection between a given node and other nodes in the network. Closeness centrality (CC_i) measures the minimum distance between a given node and other nodes, which reflects the relative accessibility of that node in the network. Betweenness centrality (BC_k) measures the number of times that the shortest path between all pairs of nodes passes through the given node, which reflects the transfer and convergence function of the node in the network. These quantities are given as follows:

$$\begin{aligned} DC_i &= \frac{k_i}{n-1} \\ CC_i &= \frac{\sum_{j=1, j\neq i}^{n} d_{ij}}{n-1} \\ BC_k &= \frac{2\sum_{i=1, j\neq k}^{n}\sum_{j\neq k}^{n} \frac{\&_{ij}{}^{2}}{\&_{ij}}}{n^2-3n+2} \end{aligned} \tag{6}$$

where $\&_{ij}$ represents the total number of shortest paths between nodes i and j.

2.2 Network vulnerability assessment method

2.2.1 Blocking flow theory

The stability of a shipping network is reflected mainly in the stability of cargo transport, that is, goods in the transport process do not encounter blocking phenomena. Once the shipping node is blocked, it is easy to gather too much traffic, thereby affecting the traffic capacity and sustainable development of the entire shipping network. This paper uses blocking flow theory to investigate shipping network stability. The model is as follows:

$$\begin{aligned} \Phi_A &= \sum\left\{\left[C(a) \mid v_i(a) = A\right]\right\} - \sum\left\{\left[C(a) \mid v_j(a) = A\right]\right\} \\ &= C_A^{+} - C_A^{-} \end{aligned} \tag{7}$$

where Φ_A represents the tolerance of port node A, tolerance is the sum of the initial points of port node A minus the sum of the end points of port node A, $v_i\,(a)$ is the start of arc a, and $v_j(a)$ is the end of arc a. Moreover, when $\Phi_A \geq 0$, port node A is impossible to fit into the structure; when $\Phi_A < 0$, port node A is easier to fit into the structure.

2.2.2 Rate of change of network characteristic value

To explore the vulnerability of the shipping network, this paper draws lessons from previous research methods (Wang *et al.*, 2016) through deleting the port nodes selectively and taking the rate of change of the average degree value, clustering coefficient, and average path length before and after as a quantitative indicator to then derive the vulnerability value of the network, as given by the following equations:

$$\Delta L = (1 - \frac{L_f}{L}) \times 100\%$$
$$\Delta C = (1 - \frac{C_f}{C}) \times 100\% \tag{8}$$
$$\Delta k = (1 - \frac{k_f}{k}) \times 100\%$$

where L and L_f, C and C_f, and k and k_f are the average degree, clustering coefficient, and distance value, respectively, before and after deleting one port node. ΔL, ΔC, and Δk are the rate of change in the average degree, clustering coefficient, and average path length value, respectively, after deleting one port node. The greater the rate of change of the network characteristic value is, the more obvious the vulnerability of the network will be.

2.3 Data sources and data processing

This paper analyzed the CJK shipping network, involving 69 ports and 296 routes, with a frequency of 76–702 (http://www.chinaports.com/shipline/hotline). Hot lines generally have large capacity and a wide range of services and are able to undertake most regional and inter-regional bulk cargo transport. Therefore, using hot lines to explore the characteristics of the route network structure is close to the real situation. Based on the frequency of routes between ports, we assign them a value of 1 when the frequency of the route is 1 or greater, however, it is difficult to distinguish the structural characteristics of each port. After repeated calculation, when the frequency of the route is 100 or more, we assign it a value of 1. This will be close to reality, and the structural differences will be more obvious. Finally, we obtain the 0–1 route connection matrix of the CJK shipping network. The data on trade volume are from the statistical yearbook of coastal provinces published in 2015.

3 Results

3.1 Characteristics of CJK shipping network

3.1.1 Overall characteristics of shipping network

The CJK shipping network presents an obvious pole-axial topological structure and a multi-hub axial radiation network, which can be a good solution to solve the contradiction between service concentration and hub congestion. Compared with the single hub radial network, the service of the multi-hub axial radiation network is relatively large. Moreover, the CJK shipping network shows BA scale-free network characteristics, with a small clustering coefficient and an average path length; the degree distribution follows the power-law distribution and has characteristics of robustness and vulnerability. Specifically:

(1) Average path length. The average path length of the overall CJK shipping network is 2.769. From the perspective of the frequency distribution of the path length, the ports whose path length is 2, 3, or 4 account for 28.98%, 68.11%, and 2.90%, respectively, which indicates that contact between ports is relatively limited, and the cargo transport needed is achieved in at least two or three transits. As such, 28.98% of the ports require two cargo transits, 68.11% three transits, and 2.90% four transits.

(2) Clustering coefficient (Fig. 1). The overall clustering coefficient of the CJK shipping network is approximately 0.33, and the concentration degree is low, mainly because shipping companies do not open direct cargo transports to ports that are relatively close or on already-existing shipping routes to maximize profit and reduce shipping costs. As shown in Fig. 1, in the entire shipping network, the cluster coefficients whose value is 0 account for 40.5% of the total ports, indicating that these ports are in the star structure of the shipping network, which is the only path between adjacent ports. The cluster coefficients whose value is 1 account for 28.99% of ports, and these ports are connected to adjacent ports. Only 30.43% of agglomeration coefficients are between 0.01 and 0.66, and most are below 0.1.

(3) Degree and the distribution of degree (Fig. 2). The degree of the CJK shipping network is 4.74, which indicates that each port can be connected with at least four

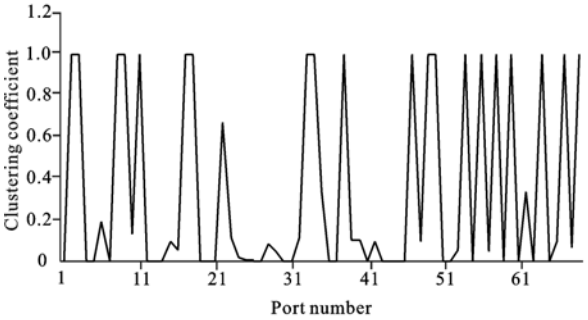

Fig. 1 Distribution map of port clustering coefficients

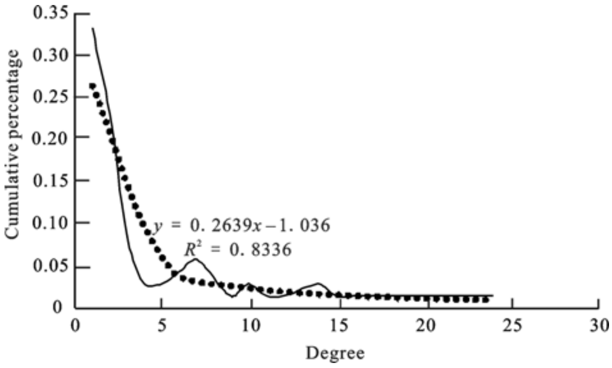

Fig. 2 Power-law probability of degree distribution

other ports. However, the network has an obvious ‘small-world effect’. Specifically, the degree of many ports in the CJK shipping network is low, the ports whose degree is 1 or 2 accounting for more than half. The average value is reflected mainly by Ningbo, Dalian, Busan, Kwangyang, and others to a high degree. By calculating the percentages of degree value and drawing the degree distribution diagram (Fig. 2), we find that the degree value distribution follows a power-law rather than a Poisson distribution, indicating that the CJK shipping network has scale-free characteristics. To further verify these characteristics, this paper used a simulation of the power-law curve fitting and obtained the node distribution probability curve as $p(k) = 0.2639x^{-1.036}$. It is obvious that the CJK shipping network has scale-free network characteristics and exhibits both robustness and vulnerability.

From Fig. 3, it can be seen that the clustering coefficient, degree, and path length index of each port are obviously different, and the data also show regional differences.

The network structure indexes for each country are obtained by calculating the average degree, clustering coefficient and path length. As shown in Table 1, the degrees of the ports in both China and Korea are higher, with average degrees above 5, which indicates that each port in China and Korea connects to at least five other ports, while the average degree of ports in Japan is approximately 2. Moreover, the number of ports in Japan that participate in the CJK shipping network is higher than that in China and Korea, and all ports can undertake foreign contacts. The relative dispersion of the port network system is not only conducive to easing of the pressure on Japanese hub ports but also enables them to achieve balanced city development. This is also a reason

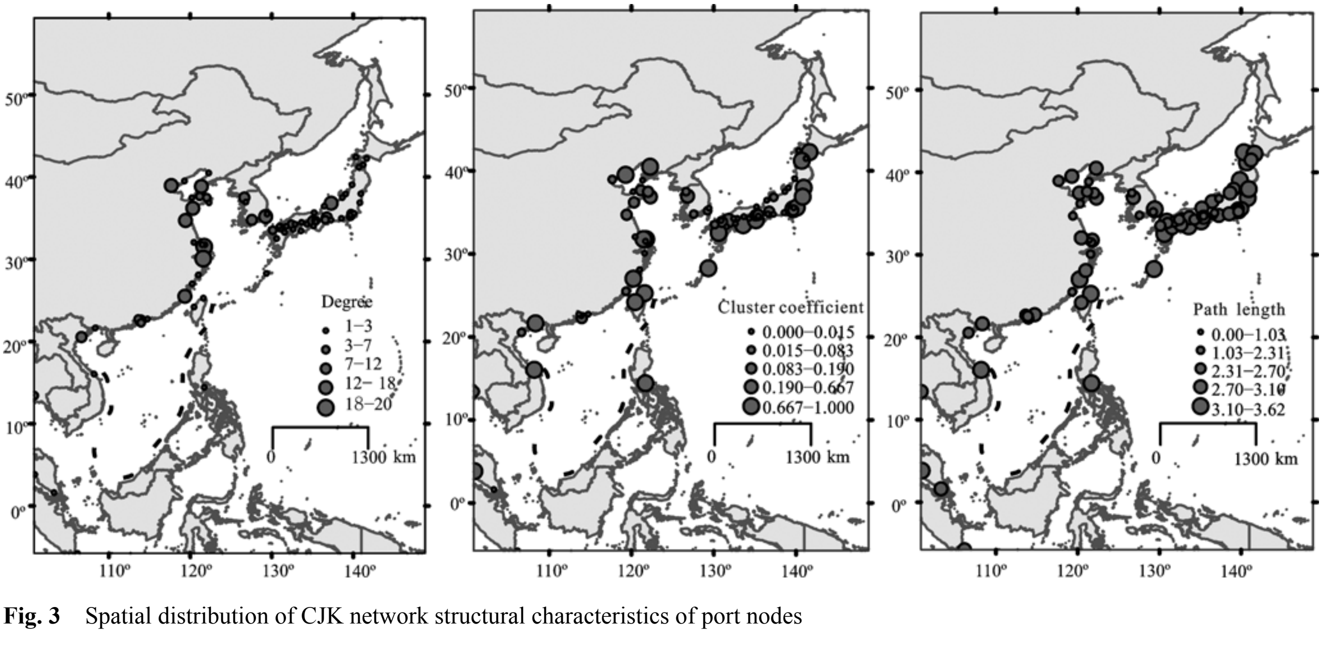

Fig. 3 Spatial distribution of CJK network structural characteristics of port nodes

Table 1 Port network structure index statistics

Country	Degree	Clustering coefficient	Average path length	Region	Degree	Clustering coefficient	Average path length
Korea	5.53	0.09	2.18	Northern China	5.95	0.28	2.20
China	6.19	0.31	2.20	Central China	8.08	0.26	1.85
Japan	2.59	0.28	2.52	Southern China	4.25	0.26	2.47

for the low degree of the ports in Japan. For the clustering coefficient, the average clustering coefficient of the network in Japan and China is approximately 0.3, but the clustering coefficient in Korea is relatively low, at just 0.1. For the average path length, Japan's path length is greater, which indicates that goods from China and Korea need to transit more times to exchange with Japan, but the number of times required to achieve freight transportation in China and Korea is approximately 2 or 3.

From a comparison of the network structure index of ports in China (Table 1), this paper first divides the Chinese coastal ports into northern, central, and southern areas; northern coastal areas include Tianjin, Hebei, Shandong, and Liaoning provinces, with nine ports; central coastal areas include Jiangsu, Zhejiang, and Shanghai port areas, with seven ports in total; southern coastal areas include Fujian, Guangdong, and Hainan provinces, as well as Hong Kong and Taiwan, with nine ports in total (Wang and Guo, 2016). The degree of the ports in the central coastal areas is approximately 8.0, which indicates that they connect with more than nine ports. As such, the traffic hub position is relatively obvious. The degrees of ports in the northern and southern coastal areas are 7 and 5, respectively, and a hub is not obvious. The average value of the clustering coefficients of ports in the three areas is roughly equivalent at approximately 0.26, which is relatively low. The average values of the path lengths of the ports in the northern, central, and southern coastal areas are approximately 2.20, 1.85, and 2.47, respectively, the central region requiring the lowest number of transits. However, the distance extension of the ports in the southern coastal region can increase transit times. Specifically, for the ports in China, contact between Shanghai (24) and Ningbo (20) ports and other ports in the shipping network is relatively high, but contact between Fuzhou (1) and Qinhuangdao (2) ports is relatively low; the greatest number of transit times that complete the cargo transport is for Fuzhou port (4.12); the minimum transit times are for Shanghai (2.11) and Qingdao (2.20) ports. For the ports in Japan, contact between Kobe (10) and Nagoya (9) ports and other ports in the shipping network is relatively high, but the number of ports that contact only one other port is also greater; the largest number of transit times that complete cargo transport is for Omaezaki port (3.52); the minimum transit times are for Osaka (2.22) and Kobe (2.27) ports. Contact between Kobe, Busan (14), and Guangyang (11) ports and other ports in the shipping network is relatively high, but for Ulsan (2) and Pyeongtaek (3) ports it is relatively low; the largest number of transit times that complete cargo transport is for Pyeongtaek port (3.35), and the minimum number of transit times is for Busan (1.93) and Guangyang (2.01) ports.

3.1.2 Central feature of CJK shipping network

This paper uses the 'centrality measures' module of UCINET 6.0 to judge network port centrality. As shown in Fig. 4, the network exhibits the 'group effect' phenomenon and forms port clusters by connecting core port nodes as centers with other small ports as auxiliary points. The network has distinct levels. Statistics show that trade in the CJK network is mostly done by the 'hub port–hub port' transport model, with dense route frequencies and a large number of companies operating on shipping routes. The formation of this type of goods transportation mode is related mainly to the radiation intensity of the core port area. In the case of China, the northern coast forms a cluster with Dalian, Qingdao, and Tianjin ports as the core node; for the central coast, the cluster is composed of Shanghai and Ningbo ports, and the southern coastal cluster is formed of Shenzhen, Xiamen, and Hong Kong ports. For Japan, the port cluster has Nagoya and Kobe ports as the core node. In Korea, Busan, Gwangyang, and Incheon form the port cluster as the core node. These core nodes can effectively dock with other small- and medium-sized ports and finally form a multi-hub network that reduces traffic pressure. At the same time, the Chinese cluster is more obvious, as Chinese ports have greater significance for the stability of the CJK shipping network. However, China's imbalance in port node development is more

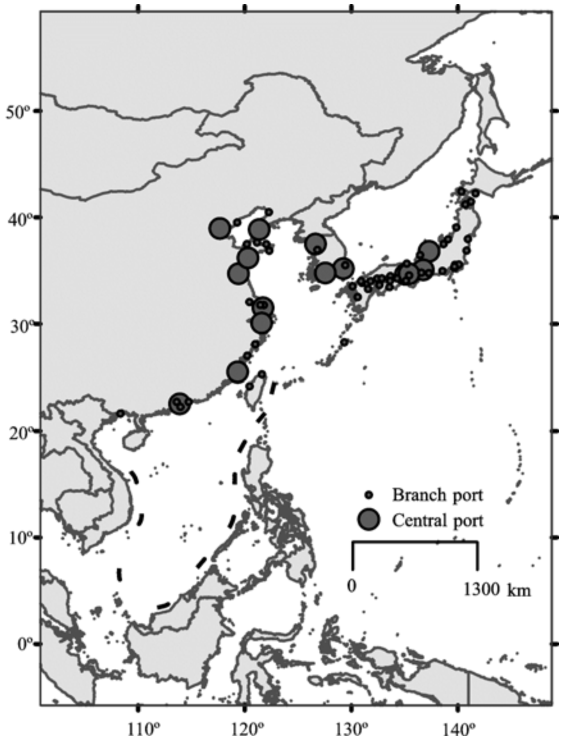

Fig. 4 Map of port node centers

obvious compared with Japan and South Korea. Therefore, we must put the center port as the concentration, radiation, and leading role in the development of the CJK regional economy.

Centrality is an important reflection of the status of port nodes in the network and plays an important role in revealing the characteristics of the spatial structure of the shipping network. Centrality, closeness centrality, and betweenness centrality can show the direct accessibility, relative accessibility, transfer, and cohesion of the network nodes.

As shown in Table 2, centrality, closeness centrality, and betweenness centrality of the ports in the CJK network are all high. This shows that the radiation range of hub ports is wider and the inland hinterland transport demand is greater, which can attract other port nodes to establish direct or indirect shipping links. At the same time, a hub in the entire shipping network plays a key role in transfer and cohesion. However, the centrality, closeness centrality, and betweenness centrality of some ports is lower, mainly because of the restrained space competition of other ports and the lower level of economic development of the hinterland. As such, it connects with only a limited number of hub ports, leading to a lower center of the port node status.

As for centrality, the ports with high central values are concentrated in China (8 of the top 10, the other 2 belonging to Korea). Among them, Shanghai (0.621) has the highest, far greater than Ningbo (0.485), which ranks second in the network. This is because Shanghai is located at the intersection of China's coast and the Yangtze River, offering a vast hinterland market and access by sea to an international market, which provides a large market potential. Shanghai connects directly with the 21 ports in the shipping network, greatly enhancing its radiation drive range. The centrality values of Busan and Gwangyang ports in Korea are only 0.34 and 0.26, respectively, mainly because most of the ports in Japan and Korea undertake external links particularly in Japan. This is different from the current situation regarding China's foreign trade, which relies mainly on hub ports. The proximity centrality distribution is contrary to the central spatial distribution, its level being higher in Japan and Korea than in China. For example, the closeness centrality of Busan (0.431), Incheon (0.419), and Kwangyang (0.418) ports in Korea is the

Table 2 Centrality of port nodes statistics

Port	Closeness centrality	Port	Centrality	Port	Betweenness centrality
Busan	0.431	Shanghai	0.621	Shanghai	0.511
Incheon	0.419	Ningbo	0.485	Busan	0.473
Guangyang	0.418	Tianjin	0.417	Ningbo	0.459
Shanghai	0.410	Dalian	0.400	Guangyang	0.449
Nagoya	0.395	Xiamen	0.391	Incheon	0.448
Kobe	0.390	Lianyungang	0.374	Xiamen	0.447
Osaka	0.388	Qingdao	0.357	Dalian	0.445
Xiamen	0.381	Busan	0.340	Lianyungang	0.442
Ningbo	0.378	Shenzhen	0.298	Nagoya	0.441
Qingdao	0.377	Guangyang	0.264	Qingdao	0.434

highest, and it is significant for Kobe (0.390) and Osaka (0.388) ports in Japan. The approach degree directly affects the link frequency of the other port nodes, which can help establish a trade network based on neighboring relationships. Betweenness centrality is similar in China and Korea, the status of transfers and cohesion in the network being equivalent. Among the ports, Shanghai (0.511) and Ningbo (0.459) ports in the central coastal region of China are most obvious, as the intersection of the China coastal zone and the Yangtze River provides suitable transfer to China's Yangtze River Valley andto China's south coast and the Southeast Asian countries. The transfer function is also obvious in Busan (0.473), Guangyang (0.449), and Incheon (0.448) ports, which undertake mainly goods transfers from China on their way to Japan.

3.2 Analysis of vulnerability of CJK shipping network

3.2.1 Analysis of stability of shipping network

The results of our analysis of the fluency of the CJK shipping network are given in Table 3. Overall, the tolerance range of the CJK ports lies mostly between –5 and 5, accounting for 72.9% of the total number of ports, which means that cargo transport is relatively smooth, and the degree of blockage is in the controllable range. Only a few ports display a relatively high degree of congestion, such as Pusan and Nagoya ports in Japan. Consequently, the stability of the CJK shipping network is relatively good, and the fluency of cargo transport is high.

Specifically, the tolerance range of the ports in Japan is mostly below 0, and the possibility of blockage is higher than for ports in China and Korea. The tolerance of ports in China is mostly above 0, cargo transport being relatively smooth. The reason for this is the quality of the trading relationship between China and Japan. Japan's foreign trade involves mainly the import of cheap, light industrial products, for which there is a large demand, leading to more import than export routes. China's trade situation is the opposite: it is a large producer of low-end products that have a large demand. Therefore, compared with the exit routes, the import route of the port in China is relatively larger, and goods transport is relatively smoother, resulting in a small possibility of blockage.

Table 3 Tolerance range statistics

Tolerance range	Percent (%)	Tolerance range	Percent (%)
$\Phi_A < -10$	3.7	$0 < \Phi_A < 5$	14.8
$-10 \leq \Phi_A < -5$	8.6	$5 < \Phi_A \leq 10$	4.9
$-5 \leq \Phi_A \leq 0$	58.1	$\Phi_A > 10$	9.9

Note：Φ_A represents the tolerance of port node A

3.2.2 Analysis of stability of shipping network

If a port is attacked, the route to it will be blocked, and the entire shipping network will suffer a chain reaction. For the shipping network as a whole, the main hub port has a close relationship with other ports and bears the function of goods transit. Moreover, its stability has a large influence on the shipping network. This paper selects ports with a degree value greater than 10 as attacked points and then interrupts and deletes the key port to analyze the stability of the shipping network.

As shown in Table 4, if the main port is attacked, route traffic in the network decreases, and the phenomenon of lost hot routes becomes serious. Furthermore, the clustering coefficient decreases, and the overall network becomes looser; average standard distances and goods transiting times both increase, which is not conducive to achieving shipping revenue maximization. Foreign trade in China relies mainly on the main hub port, while in Japan and Korea it relies on numerous ports, its distribution is relatively dispersed, and the influence on overall foreign trade is relatively small if ports are attacked. The different characteristics of the concentration or dispersion of foreign trade differentiates the influence of individual ports on the stability of the whole shipping network. The influence of ports in China is the greatest: if Shanghai and Ningbo are attacked, the change in the degree of the network is more than 4.8% and the hot lines reduce by a factor of 5000, with great impact on the entire network. Lianyungang, Qingdao, and Nagoya have the greatest impact on the overall shipping network clustering coefficient. After the impact, the network tends to disperse, and the agglomeration level is reduced by approximately 0.3%. If Lianyungang, Shenzhen, Tianjin, and Dalian are attacked, the average standard distance of the shipping network extends by more than 0.8%, which has great relevance for these ports, as cargo transit stations can reduce shipping costs. The influence of ports in Japan and Korea, however, is relatively limited. If Nagoya, Incheon, and Gwangyang are attacked, the degree reduces by approximately 2.5%, the clustering coefficient reduces by approximately 0.2%, and the standard

Table 4 Statistics of changes in the characteristic values of the shipping network after the impact on the main ports

Port	Change in degree (%)	Change in clustering coefficient (%)	Change in average path length (%)	Port	Change in degree (%)	Change in clustering coefficient (%)	Change in average path length (%)
Incheon	2.443	0.124	0.790	Qingdao	3.664	0.322	0.839
Nagoya	2.443	0.283	0.820	Xiamen	3.908	0.235	0.824
Guangyang	2.687	0.156	0.767	Lianyungang	4.152	0.271	0.866
Shenzhen	2.931	0.043	0.927	Dalian	4.396	0.000	0.881
Busan	3.420	0.124	0.736	Ningbo	4.885	0.000	0.843
Tianjin	3.420	0.145	0.885	Shanghai	5.862	0.011	0.805

distance increases by approximately 0.80%. The influence on the whole network therefore is not as obvious but still significant.

China relies mainly on hub ports for its involvement in the CJK shipping network, and if these ports are attacked, the shipping network suffers a greater impact, while other small- and medium-sized ports face limited impacts. The effects of different regions on the stability of the CJK shipping network are different. The change in the average degree is 2.74% if the ports in the central coastal areas are attacked, and the number of routes reduces significantly. The ports in the northern and southern coastal areas rank next, and their degrees of change are 2.03% and 1.24%, respectively. For the clustering coefficient, the influence of the ports in the southern coastal areas is the greatest, the degree of change being approximately 1.32%. This is related to the current state of China's foreign trade, as route development generally complies with the principles of the nearest distance; as such, the ports in the central and northern coastal areas are relatively near the CJK shipping network, and most of China's goods transfer is made through these regional ports. Simultaneously, the number of routes in the northern and central areas is relatively high (the ports in these areas having high clustering coefficients), and the changes in these areas are 1.09% and 0.84%, respectively. For average path length, if the ports in the northern, central, and southern areas are attacked, the transit times will increase by 0.96%, 0.82%, and 1.08%, respectively. The extension of path length, however, is not conducive to the maximization of the benefits of shipping. At the same time, this also extends the time cost of goods transport, directly affecting continued trade.

3.3 Relationship between network characteristics and trade

Considering data integrity and the distance decay effect of port hinterlands, this paper takes 11 coastal provinces in China as an example, and, based on data for the network characteristics of all provinces and their total trade with Japan and Korea, obtains the relationships between regional trade and network characteristics. The results are shown in Figs. 5–7.

There is an obvious positive correlation between the degree value of the shipping network and the regional trade quota (Fig. 5). This shows that the greater the degree of the region, the more closely linked the region is with other nodes in the network. The higher the degree value is, the greater the number of ports involved in the regional exchanges will be, which will increase the port hinterland of the port city and promote port trade to a larger hinterland.

There is a significant negative correlation between the clustering coefficient of the shipping network and the regional trade quota (Fig. 6), which shows that with an increase in regional trade, the clustering coefficient decreases. From the geographical perspective, the ports with high volumes of trade show a high hub network, and the number of the ports associated with them is relatively large, while the connections between adjacent nodes is relatively difficult, resulting in a decrease in the clustering coefficient. As an example, for Shanghai port, the clustering coefficient is only approximately 0.1, but the total trade is approximately 7.80 × 10^{11} USD.

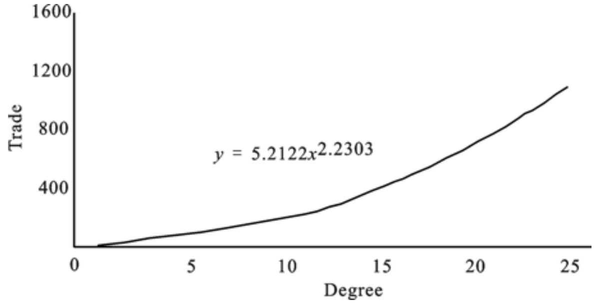

Fig. 5 Relationship between degree and trade

There is also a significant negative correlation between the path length of the shipping network and the regional trade quota (Fig. 7). The longer the path length is, the greater the number of transits between ports will be; the longer the period of time is required, the weaker the links between the ports and the lower the trade volume between the ports will be. However, the connections between ports will be easy, and the volume of trade will increase.

3.4 Hierarchical system of CJK shipping network

Creating the hierarchy of the port node in the shipping network has a direct impact on the efficiency of the entire regional trade. Therefore, it is important to build a shipping hub network system for the entire network. Centrality can reflect the importance of port nodes. Based on the three types of central data, this paper constructs a shipping network hierarchical system using cluster analysis. The results are described below.

From Fig. 8, the number of international hub ports is 13, including Shanghai, Ningbo, and Busan. The radiation range of the hinterland of these ports is relatively wide, and they operate on most foreign trade routes as an important gateway to foreign trade between these countries. For example, Shanghai's port container handling capacity is the second largest in the world and is the main export hub for chemical, agricultural, and oil products in the Asia Pacific region. The largest port in Korea, Busan, one of the world's five largest container ports, is an export hub for industrial machinery, electronics, petrochemicals, and textiles. Kobe, the largest container port in Japan, is an export hub for terminals, machinery, vehicles, electrical appliances, iron, and steel. The number of national hub ports is 9, including Xiamen, Shenzhen, Osaka, Yokohama, etc., and these play an important complementary role to the trade market inside and outside their respective countries. The number of regional port nodes is 30, involving water ports, off ports, Nanjing port, etc. These port nodes bear important transport routes in a certain area and are important for external economic connections to these areas. The number of city port nodes is 17, involving Wakayama, Jordi, Hong Kong, and Fuzhou, among others. These ports rely mainly on internal port city foreign trade for development. At the same time, the pressure of competition from other hub ports and foreign trade routes is relatively limited, so the overall development of these ports is limited.

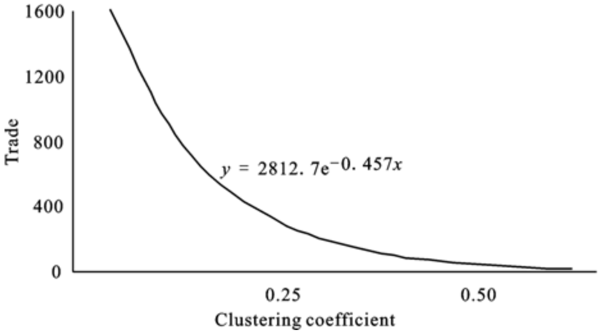

Fig. 6 Relationship between clustering coefficient and trade

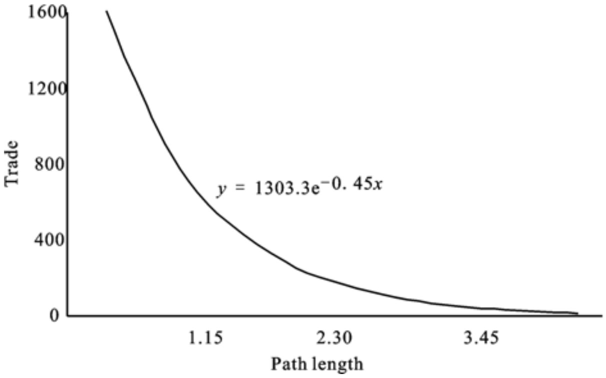

Fig. 7 Relationship between path length and trade

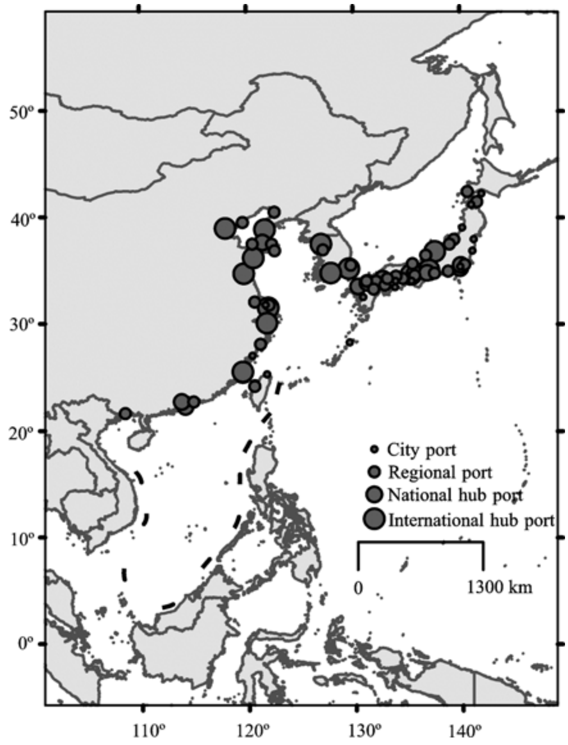

Fig. 8 Shipping network hierarchy diagram

4 Conclusions

This paper focuses on the CJK shipping port network using complex network analysis methods and clustering coefficient, average path length, degree and degree distribution to present the overall characteristics of the shipping network. In a subsequent analysis, blocking flow theory and interruption and deletion of hub ports are used to analyze the vulnerability of the shipping network and the importance of the hub port on the development of the CJK network. The results can be summarized as follows.

The CJK shipping network has a small average path length and clustering coefficient; its degree distribution follows the power-law distribution; the network presents obvious characteristics of BA scale-free networks and has the dual characteristics of robustness and vulnerability.

The CJK shipping network presents an obvious pole-axial to pological structure, that is, a multi-hub axial radiation network that can alleviate traffic pressure. China formed a port cluster by making Shanghai, Ningbo, and Dalian ports a center; Japan formed a port cluster by making Kobe and Nagoya a center; Korea formed a cluster by making the Busan, Kwangyang, and Incheon ports a center.

The regional differences in the CJK shipping network structure are obvious. China and Korea have a higher average degree than Japan. Compared with the ports in the northern and southern coastal areas, the ports in the central coastal areas of China have stronger hubs, with minimum transit times.

The stability of the CJK shipping network is relatively good; the fluency of cargo transport is high, and the possibility of blockage occurring in Japan is relatively higher than in China. Compared with ports in Japan and Korea, the main hub ports in China have a greater impact on the entire shipping network, especially those of the central coastal areas, such as Shanghai, Ningbo, and Lianyungang ports.

Based on the above findings, we put forward the following suggestions. First, based on a hierarchical port network to plan the CJK shipping system, the functions, roles, and status of each port need to be defined, while waste of resources and redundant construction involving competition between ports need to be reduced. Second, there is a need to establish a major port node maintenance mechanism, actively open up new channels, and shift 'hub port concentration' to 'edge diffusion' to reduce the impact of the main port node on the normal operation of trade. Third, with the central port node as backing, there needs to be a speeding up in the construction of other routes, a moderate degree of switching to small- and medium-sized ports, and incorporation of more hinterland cities into the scope of the network as a whole.

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