

Research Article

Economic Dependence Relationship and Spatial Stratified Heterogeneity in the Eastern Coastal Economic Belt of China

Xianbo Wu  and Xiaofeng Hui 

School of Management, Harbin Institute of Technology, Harbin 150001, China

Correspondence should be addressed to Xiaofeng Hui; xfhui@hit.edu.cn

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In this paper, the method of mutual information is used to study the economic dependence among the provinces in China's Eastern Coastal Economic Belt from 2015 to 2020, and the core structure of the dependence is depicted. The results show that, first of all, there is a wide range of economic dependence among the provinces in the Eastern Coastal Economic Belt, and the dependence changes with the different states of economic development. Secondly, the phenomenon of geographical clustering is not obvious. Most provinces maintain a strong economic dependence relationship with the economically developed provinces, and this dependence relationship is relatively stable, while the economically underdeveloped provinces are often on the edge of the dependence structure. Finally, the economically developed provinces maintain strong economic dependence with each other, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), and Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10). However, the former three provinces are more in the core position of this structure, that is, the other provinces maintain the stronger dependence relationship with these three provinces.

1. Introduction

At present, the development of China has entered a new era of comprehensively deepening reform and opening-up and is in a critical period of transforming from a stage of high-speed growth to a stage of high-quality development. After more than 40 years of reform and opening-up, China's economic and social development has made remarkable achievements. Among them, the urbanization rate has exceeded the 50% dividing line and has entered the middle and late stage of rapid development. Strengthening the cooperation of regional space, promoting the integrated development, and then obtaining a higher level of division of labor and transforming potential demand into actual demand are not only an important way to continue or maintain the current high-speed growth but also the direction of the evolution of the spatial structure of a mature economy.

In the past decades, on the basis of summing up the practical experience of China's regional coordinated development, the 11th Five Year Plan for national economic

and social development has put forward a comprehensive and systematic strategy for regional development, that is, to implement the strategy of the development of the western region, the revitalization of the northeast area, the rise of central China, and the leading development of the eastern region. Since then, the four regional development strategies have become the pillar of China's overall regional development strategy. In recent years, at the national level, more attention has been paid to the construction of the top-level design, and more attention has been paid to the overall planning and integrity of regional planning. Whether it is the overall consideration of the four regional development strategies, or the demonstration role of the coordinated development of Beijing-Tianjin-Hebei on the coordinated development of the national region, all of them put forward strong direction and guidance for local economic and social development, and the coordinated development of the region adapts to China's future regional development strategy, conforms to the development concept of regional opening, cooperation, and coordination, and is conducive

to strengthening regional economic integration, continuously improving the efficiency of factor spatial allocation, and improving the quality and efficiency of regional development.

Nowadays, China has formed a targeted overall regional development strategy based on the four regions of the east, the middle, the west, and the northeast of China, while the policies and resource concentration in the eastern coastal areas have gradually formed since the 1990s. As one of the Three Golden Support Belts in the development of China's regional integration, the Eastern Coastal Economic Belt plays an important leading and exemplary role in deepening China's reform and opening-up, accelerating the formation of a new regional coordinated development mechanism with strong overall planning, orderly competition, green coordination, and win-win sharing, and promoting regional coordinated development. The Eastern Coastal Economic Belt is not only an important engine of China's economic development, but also an important base of scientific and technological innovation. Its total GDP accounts for nearly 70% of mainland China, and the number of listed companies accounts for nearly 3/4 of mainland China. Among the 12 provinces in China's Eastern Coastal Economic Belt, there are not only China's political center, Beijing; China's economic and financial center, Shanghai; but also the forefront of China's reform and opening-up, Guangdong; and the important eastern central provinces of the Yangtze River Economic Belt and the Yellow River Economic Belt, Jiangsu, Zhejiang, and Shandong. Therefore, exploring the economic dependence relationship and the core dependence structure among the provinces in the Eastern Coastal Economic Belt plays an important role in the sustainable economic development of this region in China.

Regional economic integration refers to the process of achieving a certain commitment, contract or forming a certain form of regional economic cooperation organization among cities in a specific region, to seek the liberalization of regional commodity circulation or factor flow and the optimization of production division, and on this basis to form a unified product and factor market, and a unified economic and social policies or systems. At present, scholars have carried out a series of studies on the coordinated development of regional economy, regional connection, and interaction, and the dynamic mechanism of regional economic development. Among them, in the research method of regional spatial connection, gravity model is usually used to measure the interaction strength between cities, which has become one of the main forms to study the evolution pattern and spatial network of cities [1, 2]. In the research content, the related research studies focus on the economic effect, institutional structure, and influencing factors of regional integration from the aspects of regional industrial transfer and innovation agglomeration, so as to further analyze the dynamic mechanism of coordinated development of regional economy [3–6].

In addition, some studies focus on the interaction and dependence among various units in regional integration from the aspects of regional linkage development and complementary relationship, industrial cluster [7], institutional

performance [8], industrial competitiveness [9], industry city interaction [10], and spatial evolution of regional ties [11, 12]. At the same time, academia and policy-making departments are increasingly aware of the regional coordinated development, which plays a more and more important role in the sustainable development of each unit in the region, and even in a wider range of cities and industries. More and more scholars carry out the research and analysis from the respect of institutional arrangement, functional positioning, competitiveness, and linkage development to analyze the coordinated and sustainable regional development, and the relevant research studies mainly focus on the coordination of system and main interests, industrial ecology, linkage, and sustainable development [13, 14]. The literature on the spatial pattern of regional coordinated development mainly focuses on the spatial-temporal evolution of regional development gap [15], the spatial pattern of regional ecological difference [16], the influencing factors of regional development imbalance [17], the influencing factors of regional income gap [18], the influencing factors of regional green development [19], and the spatial pattern of urban-rural coordinated development [20]. Among them, Ma uses the theory of system dissipative structure to conduct quantitative research on the coordinated development of regional economy and establishes a system coordination evaluation model based on the grey relational theory with annual GDP as the order parameter, and evaluated and measured the degree of regional coordinated development [21]. Qi et al. construct a systematic analysis framework of low-carbon collaborative development in Beijing-Tianjin-Hebei and propose to build a regional low-carbon collaborative development path from three levels of government, industry, and consumers [22]. Fan et al., from the perspective of coordinated development of regional economy and ecological environment, combine regional expansion with ecological compensation, construct a regional economy and ecological coordinated development model, and take Fuzhou coastal area as an empirical study case to conduct in-depth discussion on regional expansion prediction, ecological compensation, and regional spatial simulation [23].

Due to the complex nonlinear characteristics of economic time series, it is not only dominated by certain deterministic laws but also shows random characteristics, that is, it has the characteristics of time-varying, randomness, and fuzziness, and the traditional econometric model could not meet the measurement of regional economic dependence. Therefore, in order to further improve the accuracy of calculation, entropy theory is applied to the study in economic time series [24–27]. This paper uses the method of mutual information to construct the economic dependence relationship among the provinces in China's coastal economic belt and shows the dependence results and core structure of the dependence relationship by means of heat map and maximum spanning tree. The rest of this paper is organized as follows. Section 2 mainly introduces mutual information and kernel density estimation methods. Section 3 is the selection of data and basic mathematical statistics. Section 4 is the main results and analysis of the results, and Section 5 is the conclusion.

2. Methods

In this study, mutual information and kernel density estimation are used to calculate the economic dependence relationship among the provinces in the Eastern Coastal Economic Belt of China. Compared with the previous studies, mutual information and kernel density estimation have the following advantages. First of all, some studies have proved that the economic time series often show the characteristics of nonlinear; however, mutual information could not only be used to calculate the dependence relationship between variables under the linear condition, but also be applied in the nonlinear condition. Besides, mutual information is model-free, so it is not necessary to set the model in advance. Finally, the kernel density estimation method does not depend on the specific assumptions of data distribution, which makes the estimation more accurate.

2.1. Mutual Information. The definition of information entropy was given by Shannon in the 1940s, and it has been considered that information entropy could be used to measure the uncertainty of the event. According to the definition given by Shannon, the entropy of a discrete random variable x could be expressed as

$$H(X) = - \sum_{x \in \chi} p(x) \log p(x), \quad (1)$$

where χ is the set of all states of the random variable x and $p(x)$ is the probability of x . It measures the extent of uncertainty. The base of the logarithm is commonly chosen as 2, and the unit is bit.

For the two random variables x and y , the joint entropy between these two variables could be defined as

$$H(X, Y) = - \sum_{x \in X} \sum_{y \in Y} p(x, y) \log p(x, y), \quad (2)$$

where $p(x, y)$ is the joint probability of x and y .

The definition of MI between X and Y is given as follows [28]:

$$MI(X, Y) = \sum_{x \in X} \sum_{y \in Y} p(x, y) \log \frac{p(x, y)}{p(x)p(y)}. \quad (3)$$

According to formulas (1) and (2), MI could be rewritten as follows [29]:

$$MI(X, Y) = H(X) + H(Y) - H(X, Y). \quad (4)$$

MI measures the information which one variable discloses about another one, and if two variables are interdependent, their MI will be greater than zero. Stronger interdependence produces larger MI [30].

2.2. Kernel Density Estimation. Let $\mathbf{U} = \{\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_N\}$ be a d -dimensional real number variable, and the kernel density of its probability density function could be estimated as follows:

$$\hat{f}(u_j) = \frac{1}{Nh^d} \sum_{i=1}^n K\left(\frac{u_j - u_i}{h}\right), \quad (5)$$

where h is the window parameter, also known as bandwidth, and $K(\cdot)$ is the d -dimensional kernel function. Then, under the Gaussian kernel function, formula (5) could be transformed into

$$\hat{P}(\mathbf{u}_j) = \frac{1}{Nh^d} \sum_{i=1}^n \frac{1}{\sqrt{(2\pi)^d |S|}} \exp\left(-\frac{(\mathbf{u}_j - \mathbf{u}_i)^T S^{-1} (\mathbf{u}_j - \mathbf{u}_i)}{2h^2}\right), \quad (6)$$

where S is the value of the determinant of its covariance matrix.

The choice of bandwidth has a great influence on the estimation effect. According to reference [20], this paper selects the optimal bandwidth, as follows:

$$h = \left(\frac{4}{d+2}\right)^{(1/(d+4))} N^{(-1/(d+4))}. \quad (7)$$

The probability density of samples could be obtained by kernel density estimation, and then, the entropy formula could be obtained as follows:

$$H(\mathbf{U}) = -\frac{1}{N} \sum_{t=1}^N \log \hat{P}(\mathbf{u}_t). \quad (8)$$

Combined with formulas (4) and (8), we can get the final formula to calculate the mutual information value of the two variables, as follows:

$$I(X, Y) = -\frac{1}{N} \sum_{t=1}^N \log \hat{p}(x_t) - \frac{1}{N} \sum_{t=1}^N \log \hat{p}(y_t) + \frac{1}{N} \sum_{t=1}^N \log \hat{p}(x_t, y_t). \quad (9)$$

3. Data

This paper selects China's regional stock price index as the research object, which reflects the overall performance of listed companies in different regions of China's A-share market, depicts the development characteristics of the regional economy and capital market, and becomes an important indicator to measure the development of regions. The data selected in this paper come from the Wind database, and the time range of the data is from 5 January 2015 to 31 December 2020, a total of 6 years of index daily closing price. The numbers and index names are listed in Table 1.

According to the experience of the previous literature, this paper calculates the logarithmic return of each index according to formula (10), where $p(t)$ and $p(t-1)$ are the daily closing price of the regional index on dates t and $t-1$ respectively, and $R(t)$ is the logarithmic return of the regional index on date t .

$$R(t) = \ln P(t) - \ln P(t-1). \quad (10)$$

TABLE 1: The details of the 12 regional indexes.

No.	Index name	Code
1	Beijing index	CN6002
2	Fujian index	CN6003
3	Guangdong index	CN6005
4	Guangxi index	CN6006
5	Hainan index	CN6008
6	Hebei index	CN6009
7	Jiangsu index	CN6015
8	Liaoning index	CN6017
9	Shandong index	CN6021
10	Shanghai index	CN6024
11	Tianjin index	CN6026
12	Zhejiang index	CN6030

Since the calculating of mutual information needs the time series to be stationary, in this paper we apply augmented Dickey–Fuller (ADF) test to examine the stationarity of the 12 regional indexes series. Besides, the Jarque–Bera test is also used to examine whether the indexes series obey Gaussian distribution, and the results are shown in Table 2. It could be seen that all of the 12 regional indexes series are stationary and all of them do not obey Gaussian distribution.

4. Results and Discussion

4.1. MI Value among the Provinces. In this section, we first calculate the mutual information among the regional indexes of 12 provinces in the Eastern Coastal Economic Belt of China, which represents the degree of economic dependence among the provinces. In order to clearly observe the dependence and the change of the dependence between the provinces from the year 2015 to 2020, we use the heat map to express the calculation results of mutual information.

Figure 1 shows the economic dependence of the provinces in the Eastern Coastal Economic Belt of China in each year from 2015 to 2020. The numbers in abscissa and ordinate in the figure are the number of indexes of each province in Table 1, and the value of economic dependence is replaced by the colored squares in the figure. If the value of MI between province i and province j is nonzero, there exists an edge with the weight of the value of MI. In order to analyze the change of this dependence in these six years, this paper adjusts the maximum value of the thermal chart to 2.8, because in the above six years, the maximum value of mutual information among provinces is 2.7966, which is the mutual information value between Jiangsu (No. 7) and Zhejiang (No. 12) in 2016.

It can be seen from the results in Figure 1 that the economic dependence among provinces has changed greatly in the six years from 2015 to 2020, among which the economic dependence is stronger in 2015 and 2016, and in 2017, the dependence is the weakest. In terms of the degree of dependence among provinces, Hainan (No. 5) has the weakest economic dependence with other provinces in the above six years, while Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have strong economic dependence with each other. According to the ranking of total GDP of the

provinces in mainland China in 2019, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) ranked the second, third, and fourth place, respectively, in the 12 provinces of the Eastern Coastal Economic Belt, while Hainan (No. 5) ranked the last. Therefore, we can get a preliminary conclusion that the provinces with more developed economies maintain strong economic interdependence with each other, while the economic dependence between the provinces with poor economic development level and other provinces is weak.

Table 3 shows the average economic dependence of 12 provinces in China's eastern coastal area from 2015 to 2020. It can be seen that the average economic dependence of each province is the largest in 2016, whose value is 1.7498, while the average economic dependence of each province is the smallest in 2017, whose value is only 0.8556, which is less than a half of 2016. This also confirms the results shown in Figure 1.

From the results in Table 3, we can generally see the changes in the economic dependence among the provinces. Among them, in the years 2015 and 2016, due to the overheated phenomenon of China's economy in these two years, a large number of bubbles appear in the capital market, especially the stock market. This overheated phenomenon of economic development and capital market increase the economic activities and capital flows in the eastern coastal areas, thus enhancing the economic links among the provinces in the region. In order to alleviate the phenomenon of overheated economy and drastic fluctuations in the capital market, the Chinese government subsequently introduced a series of measures. Therefore, in 2017, the economic interdependence among provinces reaches the lowest value of 0.8556 in six years, only 48.90% of that in 2016. In 2018 and 2019, the economic dependence among provinces increases steadily. However in 2020, because of the outbreak of COVID-19, especially the strictly closed management in the first half of 2020, the frequency of the flow of funds, goods, and personnel among the provinces is greatly reduced, which makes the dependence relationship among the provinces in 2020 be the minimum after 2017 and the value is only 1.2268.

Next, we calculate the node strength of economic dependence among provinces in the Eastern Coastal Economic Belt of China from 2015 to 2020. The node strength reflects the sum of mutual information values between each province and the other 11 provinces in each year, as follows:

$$NS_i = \sum w_{ij}. \quad (11)$$

Among them, W_{ij} is the mutual information value (economic dependence) between province i and province j .

Figure 2 shows the node strength of each province in the six years. The abscissa is the number of each province in Table 1, and the ordinate is the value of node strength. In order to compare the changes of node strength of each province in different years, the value range of node strength in the ordinate is set as 0–25.

From the results shown in Figure 2, it can be seen that, in the six years from 2015 to 2020, the node strength of each

TABLE 2: Statistical characteristics of the 12 regional indexes.

No.	Mean	Std. dev.	Skewness	Kurtosis	ADF statistic	Jarque-Bera statistic
1	$6.38e-05$	0.0149	-1.0635	9.1520	-35.9878***	2579.38***
2	$3.83e-04$	0.0156	-1.0168	8.3178	-35.2657***	1973.27***
3	$4.30e-04$	0.0163	-0.9243	7.3282	-36.3008***	1348.43***
4	$-1.74e-04$	0.0178	-1.0625	7.9552	-33.9727***	1769.66***
5	$-3.40e-04$	0.0181	-0.9089	6.0244	-34.3165***	757.98***
6	$6.50e-05$	0.0186	-0.8247	6.8638	-35.2829***	1074.40***
7	$3.26e-04$	0.0176	-0.9911	7.3350	-35.3176***	1383.16***
8	$-1.47e-04$	0.0182	-1.1442	8.3958	-34.9918***	2091.15***
9	$3.25e-04$	0.0176	-1.0762	7.7907	-35.3807***	1679.15***
10	$4.73e-05$	0.0164	-0.9857	9.1630	-35.6746***	2548.80***
11	$-4.23e-05$	0.0191	-1.0779	7.4558	-35.5162***	1491.51***
12	$3.35e-04$	0.0182	-0.9918	7.1405	-35.2817***	1283.14***

***Statistical significance at the 1% level.

province changes greatly, that is, the total economic dependence between one province and the other 11 provinces has a great difference in different years. The difference is mainly reflected that the node strength is in a higher position in 2015 and 2016, which decreases rapidly in 2017 and rises steadily in 2018 and 2019. Although the node strength of individual provinces decreased in 2020, the overall change is not significant. From the point of view of node strength of each province, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) always maintain a high node strength, which indicates that these three provinces not only maintain a large economic dependence with each other (the conclusion in Figure 1), but also maintain a strong economic dependence with the other provinces, while Hainan (No. 5) has the weakest economic dependence in all six periods. The above conclusions are consistent with the results in Figure 1 and Table 3. In addition, from Figures 2(d)–2(f), the economic dependence among provinces has remained stable throughout the three years from 2017 to 2020 after the economy stabilization policy implemented by the Chinese government in 2017. Though affected by COVID-19 in 2020, the node strength of all provinces decreases to varying degrees, but it does not change by a large margin. Table 4 shows the standard deviation of node strength of the 12 provinces from 2018 to 2020, from which we can see the change of node strength of each province in these three years.

It can be seen from the results in Table 4 that Guangdong (No. 3), Jiangsu (No. 7), and Shanghai (No. 10) have the smallest standard deviation of node strength, while Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) have the largest standard deviation of node strength. Combined with the economic development level of each province, it can be seen that the node strength of economically developed provinces fluctuates less, that is, the economic dependence between these provinces and the other 11 provinces is relatively stable, while for those provinces with poor economic development level, whose node strength fluctuates greatly, that is to say, the overall economic dependence between these provinces and the other 11 provinces is not stable and is greatly affected by the external environment. In particular, the standard deviation of node strength of Hainan (No. 5)

reaches 2.0089; combined with Figures 2(d)–2(f), we can see that after the adjustment of the economy in 2017, the node strength of the province increases significantly from 2018 to 2019, but in 2020, it drops to the level in 2018 because of the COVID-19.

Based on the analysis of the above results, we can draw the following conclusions. First of all, the economic dependence among the provinces in China's eastern coastal economic belt changes with the change of economic development status. In the overheated stage of economy, such as 2015 and 2016, the dependence is relatively strong, while in the stage of contraction of economic development or in the stage of total demand reduction, such as 2017 and 2020, the dependence is relatively weak. Secondly, the economic dependence between each province and the other provinces is also different. The economically developed provinces, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), not only always maintain a strong dependence with each other, but also maintain a strong dependence with the other provinces in terms of node strength, while Hainan (No. 5) has the weakest economic dependence with the other provinces. Therefore, it could be concluded that the economically developed provinces maintain strong economic dependence not only among themselves, but also with other provinces, while the economically less-developed provinces have weak economic dependence with other provinces. Finally, the node strength of the developed provinces fluctuates less, and the economic dependence with other provinces is more stable, while the node strength of the provinces with relatively poor economic development level fluctuates more, and the economic dependence with other provinces is less stable, which is greatly affected by the external environment.

4.2. Maximum Spanning Tree. The maximum spanning tree is an effective method to clearly depict the core structure of the dependence relationship of each node. By selecting the maximum edge weight between two nodes, the dependence relationship between the two nodes is constructed [31]. Figure 3 shows the results of depicting the core structure of economic dependence among 12 provinces in China's

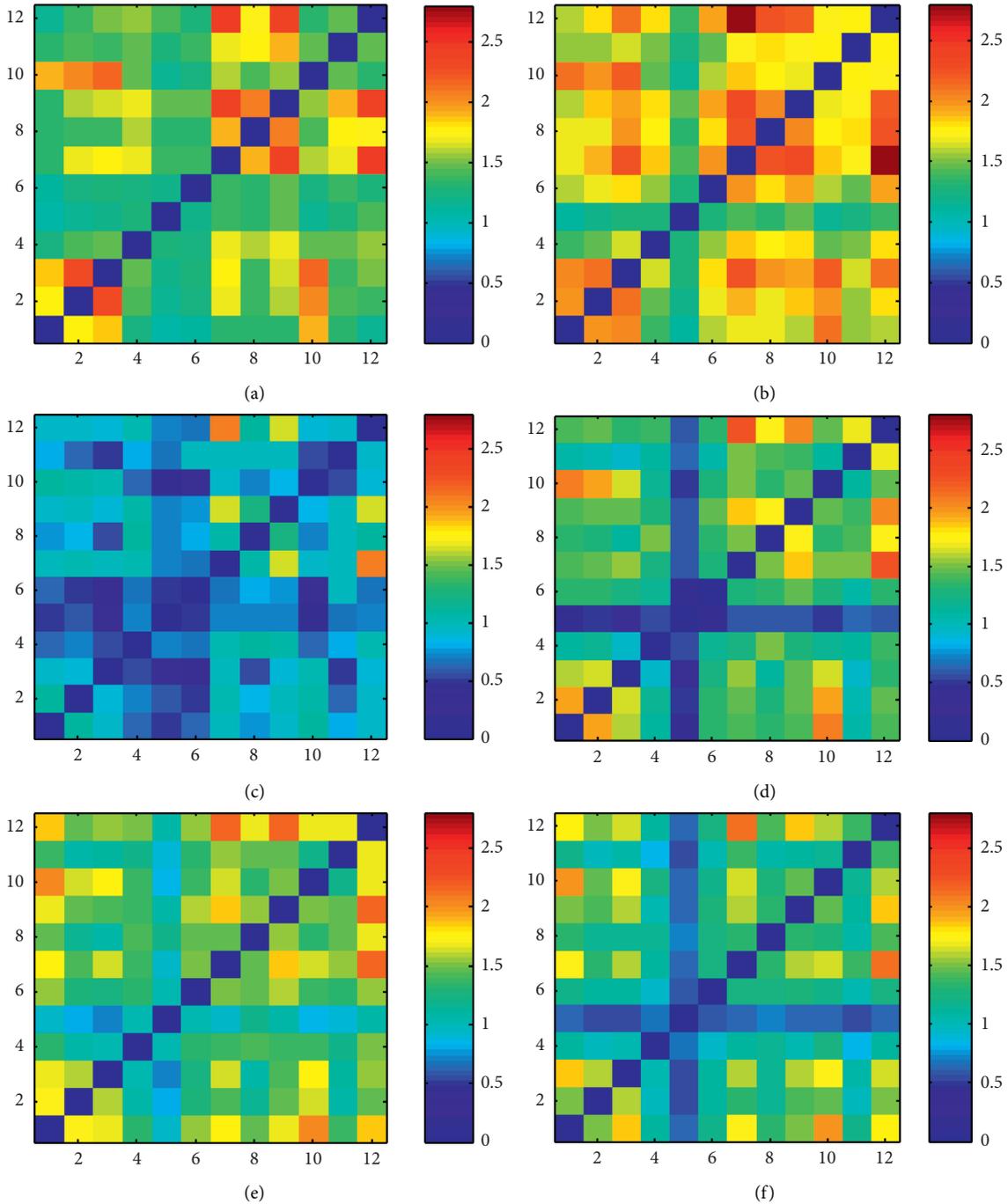


FIGURE 1: Colormaps of the MI among the 12 provinces during the six years. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

TABLE 3: Average MI between regional indexes in the six years, respectively.

	2015	2016	2017	2018	2019	2020
Average MI	1.5362	1.7498	0.8556	1.2797	1.4088	1.2268

Eastern Coastal Economic Belt from 2015 to 2020 by using the maximum spanning tree method.

As is shown from the results in Figure 3, first of all, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have the largest number of sides, respectively, in the six years

from 2015 to 2020, that is, the number of provinces maintaining the strongest economic dependence with the above three provinces is the largest. Among them, Jiangsu (No. 7) has five sides in 2016 and three sides in 2017; Shandong (No. 9) has five sides in 2015 and three sides in

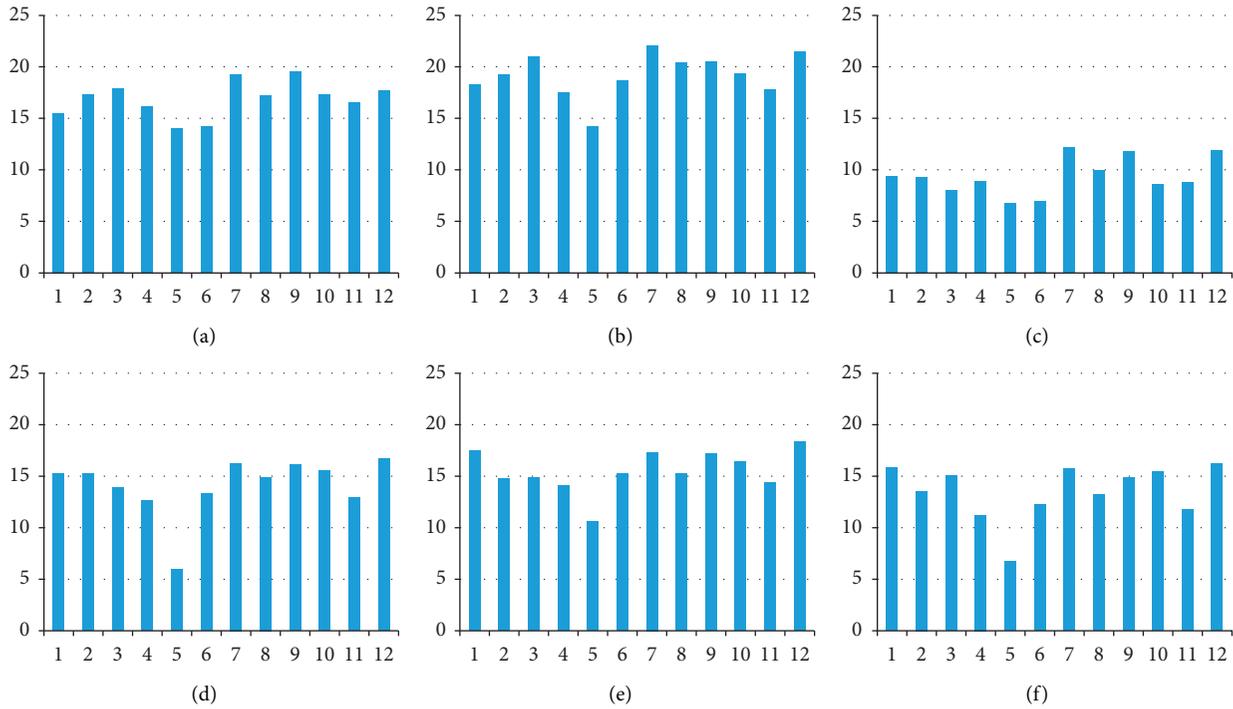


FIGURE 2: The NS value of the 12 provinces' indexes in the six years. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

TABLE 4: The standard deviation of NS of the provinces, respectively, during 2018 to 2020.

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
Standard deviation	0.9439	0.7207	0.4932	1.1538	2.0089	1.2575
	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
Standard deviation	0.6778	0.9111	0.9747	0.4364	1.0424	0.9161

2018; Zhejiang (No. 12) has three sides in 2017 and 2018, six sides in 2019 and four sides in 2020; the more sides there are, the more provinces have the strongest economic dependence with them. In addition, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have always maintained a close dependence relationship. In 2015 and 2016, the three provinces maintain a structure of No. 9-No. 7-No. 12; from 2017 to 2020, the three maintain a structure of No. 7-No. 12-No. 9; this conclusion also echoes and enriches some of the conclusions in Section 4.1.

Secondly, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10), which are also the developed provinces in the eastern coastal area of China, have always maintained the strongest economic dependence except in 2018, and most of the time, the number of edges between the above three provinces and the other provinces is very few, almost at the edge of the maximum spanning tree every year, which is different from the performance of Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12). Guangdong (No. 3) is the first economically developed province in mainland China, and Beijing (No. 1) and Shanghai (No. 10) are, respectively, the political and economic centers of China, whose

infrastructure and economic development strength and potential are at the best level. However, these three provinces are like Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) and do not maintain the largest dependence with other provinces.

Finally, for the less economically developed provinces, Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) are in the marginal position in the past six years, which shows that these three provinces have only one largest edge connected with other provinces, and the dependence with other provinces is weak.

4.3. Spatial Stratified Heterogeneity. Spatial stratified heterogeneity (SSH), as a basic phenomenon in geography study, is a quantitative index used to show that the variance in the layer is less than that among layers. As a practical statistical method, the method has been widely used in the measurement of spatial differentiation or spatial stratification in climate characteristics, air quality, land resource management, and regional economic development level [32–36]. In this study, the economic development dependence of the 12 provinces in the Eastern Coastal Economic Belt of China has been measured by using the methods of mutual information and maximum spanning tree, and the core structure of the dependence has also been described. The results show that there is an obvious spatial stratified phenomenon in the economic dependence relationship among the above provinces, that is, the close economic dependence relationship is always maintained among some individual provinces, but the economic dependence among other provinces is weak.

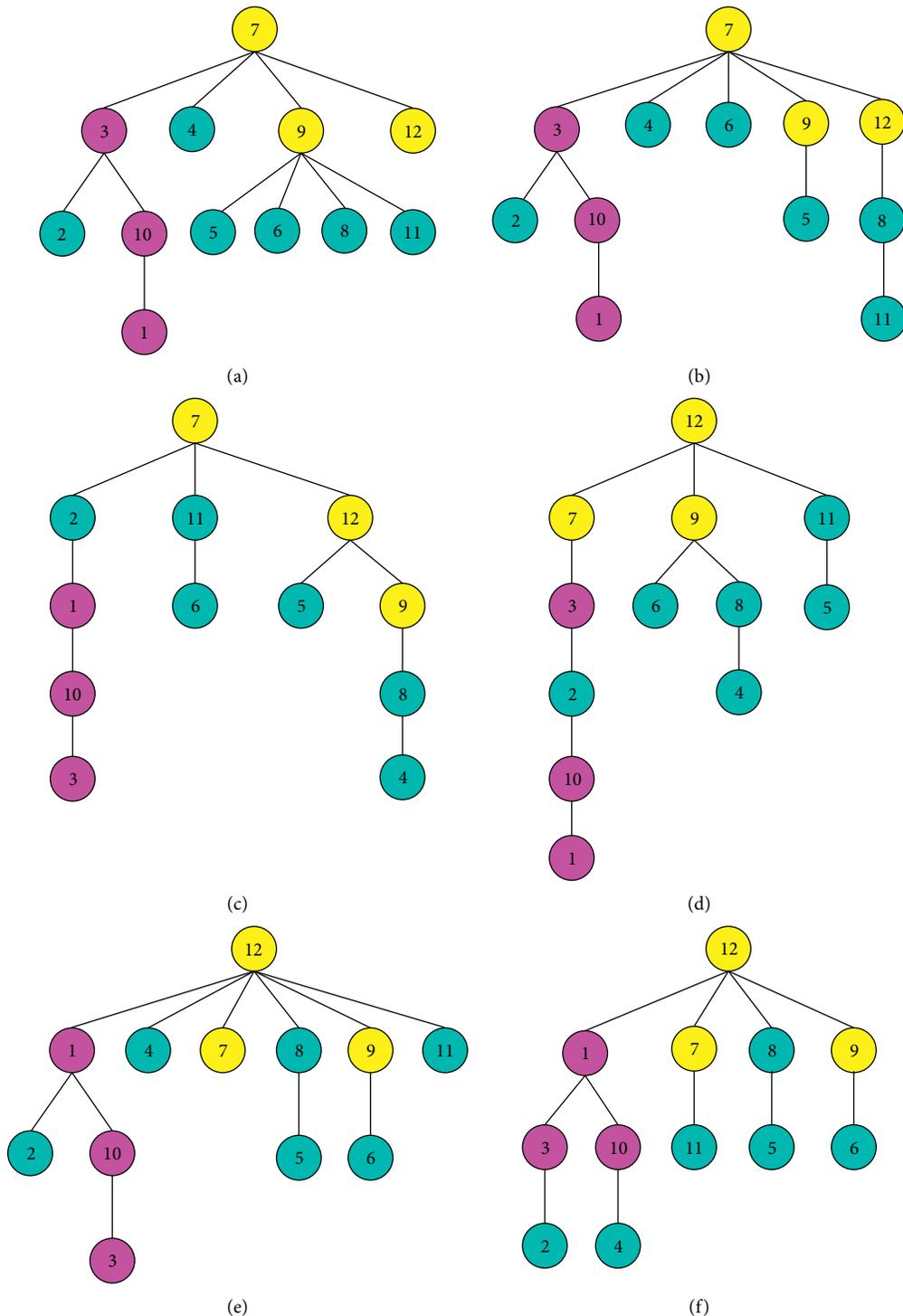


FIGURE 3: Maximum spanning trees (MSTs) of the 12 provinces. (a) 2015. (b) 2016. (c) 2017. (d) 2018. (e) 2019. (f) 2020.

In this study, MI and SSH are used to measure the spatial stratified heterogeneity. Firstly, the core structure of the economic dependence relationship among the provinces in the Eastern Coastal Economic Belt of China is constructed by MI and maximum spanning tree. By observing the core structure of economic dependence from 2015 to 2020,

several major spatial stratification categories of the 12 provinces are summarized, for example, some provinces always maintain strong economic dependence with each other, while some provinces are always on the edge of the core structure of the economic dependence relationship. Based on the above identified spatial stratification categories,

SSH is used to determine which kind of spatial stratification categories is the most suitable from the quantitative perspective. Therefore, SSH could be considered as the accuracy and supplement to the results of MI and maximum spanning tree.

According to the characteristics of economic dependence among provinces, the 12 provinces in the Eastern Coastal Economic Belt of China could be divided into several levels. However, the core structure and level division of economic dependence among the provinces in Figure 3 are summarized according to the results of the maximum spanning tree in the six years from 2015 to 2020. In order to describe the economic dependence structure and level division more scientifically, in this study, the method of geographic detector is used to compare the results of several level divisions, so as to select the most accurate one.

Geographic detector is a statistical method to detect spatial stratification, the q value is used to measure the degree of spatial differentiation in the range of $[0, 1]$, and the expression is shown as follows:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}, \quad (12)$$

where $h = 1, \dots, L$ is the stratification of variables, N_h and N are the unit numbers of layer h and the whole area, respectively, and σ_h^2 and σ^2 are the variance of layer h and the whole region, respectively.

From the results of the colormaps and the maximum spanning tree, it could be seen that the 12 provinces in the Eastern Coastal Economic Belt of China could be divided into the following four categories, namely, (A) (1), (3), (7), (10), (12) and (2), (4), (5), (6), (8), (11); (B) (1), (3), (10), (2), (4), (5), (6), (8), (11), and (7), (9), (12); (C) (1), (3), (10), (2), (8), (11), (4), (5), (6), and (7), (9), (12); (D) (1), (3), (7), (9), (10), (12), (2), (8), (11), and (4), (5), (6). Among them, the spatial stratification structure A means the 12 provinces of the whole Coastal Economic Belt are divided into two levels, the provinces with the number of (1), (3), (7), (9), (10), (12) as one level and the provinces with the number of (2), (4), (5), (6), (8), (11) as another level. The meanings of stratification structure B, C, and D are the same as that of A.

q_A , q_B , q_C , and q_D are used to represent the q value of the above four kinds of spatial differentiation structures, and it is found that the relationship among the above four kinds of structures q values is $q_B > q_C > q_A > q_D$; this shows that structure B could better reflect the spatial stratification relationship among the provinces in the Eastern Coastal Economic Belt of China, that is to say, the 12 provinces in China's Eastern Coastal Economic Belt should be divided into three levels, namely, (1) Beijing (3) Guangdong (10) Shanghai at the same level, (7) Jiangsu (9) Shandong (12) Zhejiang at the same level, and (2) Fujian (4) Guagnxi (5) Hainan (6) Hebei (8) Liaoning (11) Tianjin at the same level.

Based on the above results, we can find the phenomenon of geographical clustering, that is, the two adjacent geographical units often show strong dependence, is not

obvious in the eastern coastal provinces of China. For example, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10) maintain the strongest dependence with each other in almost all periods, but in terms of geographical location, these three provinces are separated by at least the other two provinces. On the other hand, the phenomenon of geographical clustering is also reflected to some extent. For example, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) have always maintained the strongest dependence, and in the geographical position, these three provinces are adjacent. Besides, Jiangsu (No. 7) and Zhejiang (No. 12) are the two important provinces in the lower reaches of the Yangtze River Economic Belt, and with the deepening of the construction of the Yangtze River Delta urban agglomeration, the degree of integration between the two provinces is deeply enhanced. In addition, Hainan (No. 5) is the only island province among the 12 eastern coastal provinces in this study. Compared with the close links between other eastern coastal areas brought by dense road and railway traffic, the economic main body of Hainan (No. 5) has no strong links with other provinces, so it shows that the economic dependence between Hainan and other 11 provinces is the weakest in the past six years.

4.4. Dynamic Evolution of the Dependence Relationship.

The above two sections have analyzed the economic dependence and the core structure of the 12 provinces in China's Eastern Coastal Economic Belt in the past six years from 2015 to 2020. In this part, the sliding window method will be used to measure the dependence from a dynamic perspective. In this study, the width of the sliding window is set to 150, and the sliding distance of each window is set to 20. The reason is that, for the data of 150 trading days in each window, it can guarantee the amount of data needed for mutual information calculation, and the data of 20 trading days in each sliding are just corresponding to one month, which is more convenient in analysis. According to the above settings of window width and sliding distance, this study can be divided into 66 windows.

Figure 4 shows the provinces with the maximum and minimum node strength in all 66 sliding windows, that is, the provinces with the strongest and weakest overall economic dependence with the other 11 provinces. The number of abscissae in Figure 4 represents the position of the window, and the number of ordinates represents the index of 12 provinces in Table 1. It can be seen from the figure that, in almost all the windows, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) are the provinces with the strongest node strength. While the provinces with the least node strength are all concentrated in Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6), this conclusion is consistent with the above static analysis.

It is displayed in Table 5 that, in the 66 sliding windows, with which one, a certain province maintains the strongest dependence relationship, in other words, which province is most closely related to the certain one. For example, if the maximum weight of province A connects province B, then we add 1 to the position of matrix (A, B), and the initial value

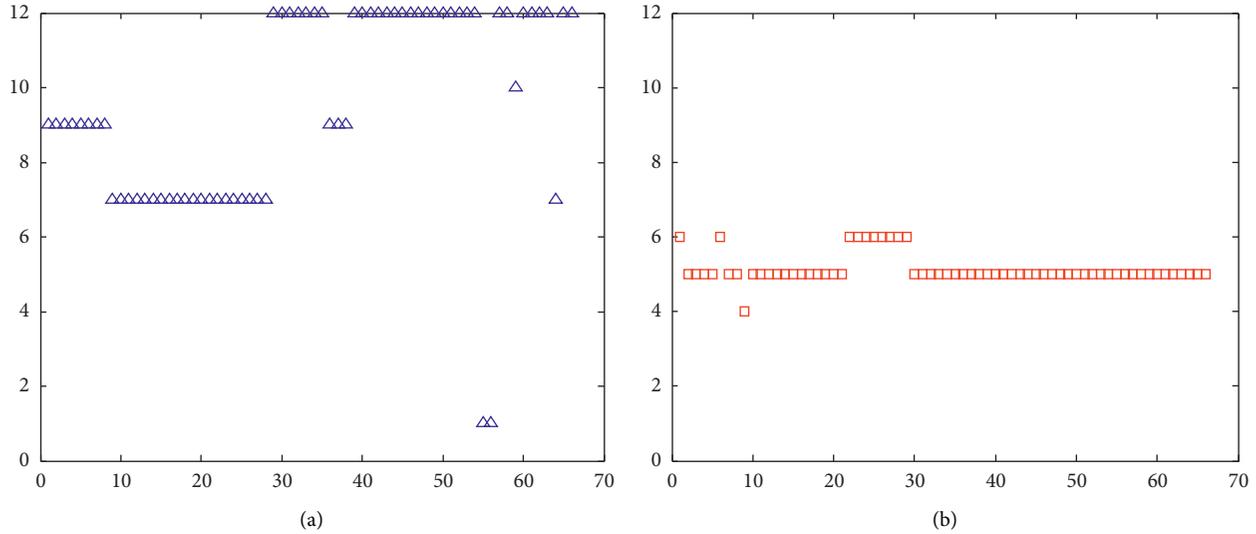


FIGURE 4: The province indexes with the largest or smallest node strength. (a) The largest node strength. (b) The smallest node strength.

TABLE 5: Total number of the strongest edge between the indexes in rolling windows.

No.	1	2	3	4	5	6	7	8	9	10	11	12	Sum
1	0	11	7	0	0	0	1	0	0	46	0	1	66
2	24	0	30	0	0	0	4	0	0	7	0	1	66
3	7	18	0	0	0	0	12	0	0	28	0	1	66
4	0	0	0	0	0	0	17	24	5	11	0	9	66
5	0	0	0	6	0	0	2	21	23	0	10	4	66
6	4	0	2	0	0	0	11	9	28	1	9	2	66
7	0	0	0	0	0	0	0	0	1	0	0	65	66
8	1	0	0	1	0	0	8	0	26	0	0	30	66
9	0	0	0	0	0	0	25	0	0	0	0	41	66
10	45	5	16	0	0	0	0	0	0	0	0	0	66
11	0	0	0	0	0	7	8	5	9	6	0	31	66
12	3	0	0	0	0	0	56	0	7	0	0	0	66
Sum	84	34	55	7	0	7	144	59	99	99	19	185	—

of position (A, B) is 0. It can be found from Table 5 that the table is not symmetric because the maximum weight edge of province A may connect province B, while the maximum weight edge of province B may connect another province C, which leads to asymmetry.

It can be seen from the results in Table 5 that, first of all, Jiangsu (No. 7) and Zhejiang (No. 12) have the most number of times obtaining the strongest dependence with the other provinces, 144 times and 185 times, respectively. This shows that, for the other 11 provinces, of the whole 726 times (66×11) strongest economic dependence, keep the strongest economic dependence with Jiangsu (No. 7) 144 times and keep the strongest economic dependence with Zhejiang (No. 12) 185 times. The other provinces with the most number of times obtaining the strongest dependence with the other provinces are Shandong (No. 9), Shanghai (No. 10), and Beijing (No. 1), and the times are 99, 99, and 84, respectively, and all of the above provinces are economically developed provinces in the Eastern Coastal Economic Belt of China. On the other hand, Guangxi (No. 4), Hainan (No. 5), and Hebei (No. 6) have the least number of times obtaining the

strongest dependence with the other provinces. Especially, in Hainan (No. 5), the times are 0, and this shows that, for the other 11 provinces, none of their 726 times strongest economic dependence connected with it. This also echoes the above research conclusion, that is, each province is more willing to maintain a strong economic dependence with the developed provinces and rarely maintain a strong economic connection with the less developed provinces.

Secondly, Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12) maintain the strongest dependence with each other. Among the 66 windows, respectively, Jiangsu (No. 7) maintains the largest edge with Zhejiang (No. 12) 65 times and with Shandong (No. 9) once. Shandong (No. 9) maintains the largest edge with Jiangsu (No. 7) 25 times and with Zhejiang (No. 12) 41 times. Zhejiang (No. 12) maintains the largest edge with Jiangsu (No. 7) 56 times and with Shandong (No. 9) 7 times. In particular, for Jiangsu (No. 7) and Zhejiang (No. 12), with the construction of the Yangtze River Economic Belt and the deepening of the construction of the Yangtze River Delta urban agglomeration, Jiangsu and Zhejiang are closely related.

Finally, for Beijing (No. 1) and Shanghai (No. 10), Beijing (No. 1) maintains the strongest economic dependence with Shanghai (No. 10) in 46 windows, while Shanghai (No. 10) maintains the strongest economic dependence with Beijing (No. 1) in 45 windows. As China's political and economic centers, respectively, the economic dependence between Beijing and Shanghai could be explained from the perspective of the implementation of national policies and their special status in the international community. As the two most representative provinces in mainland China and they are the municipalities directly under the central government of China, in the implementation of the relevant policies of national high-tech enterprises and start-up enterprises, they always keep the same pace and give more preferential treatment and support to enterprises from talent, tax, capital, and other aspects. A large number of high-tech enterprises and start-up enterprises are headquartered in Beijing or

Shanghai, and branches will also be set up in these two municipalities. Therefore, the association of innovative enterprises will naturally bring closer economic dependence between the two provinces. At the same time, as the international metropolises, Beijing and Shanghai, the two municipalities directly under the central government, often receive equal attention from the international community, and a large number of foreign-funded enterprises, personnel, and capital enter these two provinces, which also increases the economic ties between them.

5. Conclusions

By using mutual information and maximum spanning tree, this study explores the core structure and changes of the economic dependence among provinces in the Eastern Coastal Economic Belt, which is the most dynamic area in the economic development of China. Based on the above results, the following conclusions can be drawn. First, there is a wide range of economic dependence between provinces in the Eastern Coastal Economic Belt of China. The dependence relationship changes with the degree of economic development. When the economic development is overheated and the capital market fluctuates abnormally, the dependence is stronger, while the economic development is in a contraction state or the total demand is relatively low, the relationship is weakened.

Secondly, the geographical clustering phenomenon of economic dependence among provinces in the Eastern Coastal Economic Belt is not obvious. Most provinces have strong economic dependence with economically developed provinces, such as Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), and this dependence is relatively stable, while less economically developed provinces are often on the edge of the dependence structure. In addition, the economically developed provinces also maintain strong economic ties with each other.

Finally, Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10) maintain strong economic dependence mutually, especially Beijing and Shanghai, as the political and economic centers of China, respectively, and as the two most representative international metropolises, maintain strong economic ties. However, the above three provinces are not in the core position in the core structure of dependence, not like Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), which indicates that the other provinces in Eastern Coastal Economic Belt are more willing to keep the strong dependence with Jiangsu (No. 7), Shandong (No. 9), and Zhejiang (No. 12), rather than Beijing (No. 1), Guangdong (No. 3), and Shanghai (No. 10). Based on the above conclusions, in the process of China's future regional development, more attention should be paid to the development and stability of the economically developed provinces, so as to ensure the healthy and stable operation of the economy of the other provinces which keep the strong economic dependence with them. At the same time, as for the less-developed provinces, to strengthen the economic dependence with other provinces, especially with the economically developed provinces is crucial, so as to promote

the economic construction of less-developed provinces and realize the balanced and sustainable development of the whole regional economy.

Data Availability

All data used are downloaded from the WIND database, and the details are shown in Table 1 of this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Xianbo Wu and Xiaofeng Hui proposed the research framework together. Xianbo Wu collected the data, finished the computation, and wrote the paper. Xiaofeng Hui provided some important guidance and advices during the process of this research.

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