Interaction Analysis and Sustainable Development Strategy between Port and City: The Case of Liaoning

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Abstract: Although port-city interaction and sustainability are becoming increasingly essential, prospering regional economy and facilitating international shipping trade, problems of their mismatch and incoordination have also been aroused. Thus, research on their relationship is necessary to generate profound enlightenment on how to achieve healthy and benign development for ports and cities. In this paper, a typical Chinese port-city group, six ports and their corresponding port cities in Liaoning are selected as research objects. Firstly, a grey relative relational model and a coupling coordination degree model based on entropy weight method are applied to analyse the port-city interactive trend and degree as well as exploring the relative impacts among internal factors in port and city subsystems. Then, a sustainability analysis box of correlation–coordination is constructed to further investigate the sustainable development status. Finally, strategies for the port-city sustainable development are proposed. The results indicate the six port-city systems have not strongly correlated and are in the stage of coordinated development. Only Dalian and Yingkou have realized sustainable development. Thus, there is still much room for improvement. Measures such as resources integration and dislocation development should be taken into account to optimize the sustainable and coordinated development of the port-city systems.

Keywords: port-city system; grey relation; relative correlation degree; coupling degree; coupling coordination degree; sustainability

1. Introduction

Ports and cities are two different spatial economies that are always in the dynamic changes of interaction and interdependence. Ports undertake the roles of a logistics node, a hub connecting water and land transportation, a key open gateway and an important source of urban export-oriented economy, through which cities can strengthen trade with the outside world. Being the economic and social centre of the region, cities work as spatial carriers, the foundation and a necessary condition for port development [1,2]. Thus, the development of ports and port cities can never be separated and always depends on each other to a certain extent. With the acceleration of economic globalization and trade integration, the world shipping industry enjoys a continuous growth and it is important for regions to rely on international trade and cooperation. Thus, ports and port cities are playing indispensable roles of crucial platforms in international trade. Additionally, China's implementation of the 21st Century Maritime Silk Road Initiative has helped to boost and upgrade ports and port cities [3] so that they are bearing greater responsibilities in international business. In turn, the port-city

interaction will also foster international cooperation and promote the regional economic development so as to facilitate the initiative.

However, problems of the port-city like mismatch, competition for space resources, ecological environment and the connection of water and land transportation still exist and are even becoming more and more obvious, resulting in the port-city incoordination and a restriction on their progress [4]. The port-city relationship needs to achieve balanced and harmonious development from the aspects of spatial layout, economic ties, industrial layout and ecological environment. Thus, coordinated and sustainable development has become a long-term goal that the port-city should always pursue and an inevitable choice if the complex port-city system wants to get promoted mutually for long. Therefore, exploration of the interaction and sustainable development of port-city systems is an important guarantee to ensure the development of the coastal economic zone and better play the role of the marine economy in prospering international trade.

The coastal ports in Liaoning serve as the open gateway to Northeast China and a significant trade exchange platform for Northeast Asia. The port cluster mainly serves for the three provinces in Northeast China and part of Eastern Inner Mongolia. More than 85% of foreign trade products in the hinterland go through the port cluster [5]. Liaoning coastal port and city group not only shoulders a significant responsibility for the revitalization of Northeast China, but also promotes a new round of reform and opening up in Liaoning to cooperate with Northeast Asia. The port-city interaction is closely related to whether Liaoning can smoothly transform and upgrade the port-city relationship, conform resources to realize the port-city integration, give full play to the regional advantages and build a comprehensive transportation corridor. In addition, it is also about Liaoning seizing the opportunities of the times to devote to the construction of Belt and Road Initiative and undertake the important task of revitalizing Northeast China. In the meanwhile, the sustainability of the port-city interaction is a realistic choice to actively respond to the requirements of global sustainable development as well as the only way to develop an intelligent and green port-city. In this background, the paper proposes a sustainability analysis model of the port-city interaction based on the grey correlation-coupling coordination degree model. Additionally, six ports and their corresponding cities in Liaoning are selected as research targets to test the validity and applicability of the model. This sustainability analysis model is finally used to discuss the sustainable development of Liaoning port-city interaction. Therefore, this paper analyses the interactive level, trend and correlation among internal factors in Liaoning port-city systems and evaluates the sustainability of their interaction. By exploring the real relationship between ports and cities as well as their interactive and coordinated degree, problems in their interaction can be discovered. The ultimate goal of this paper is to put forward targeted and effective advice based on these problems and improve this kind of relationship. There are diversified ways to study the port-city interactive relationship. More mature methods, the correlation degree model and the coupling coordination degree model, are selected in this paper to measure the correlation degrees and the coordination degrees which have a potential progressive relationship in port-city interaction. Consequently, the combination of the two can be reasonably used to determine the port-city interactive level and trend. Then a sustainability box of correlation degree–coordination degree is constructed to analyse the sustainable development of their interaction. Based on the study above, sustainable and coordinated development strategies are proposed in order to build a healthier and better relationship between ports and cities.

2. Literature Review

Ports have gone through a long developing history around the world. With an increasingly important part ports and port cities play in international trade, research on the development, trend and law of the port-city relationship have attracted worldwide attention. Early scholars focused more on the port-hinterland relationship in spatial structure. British geographer Bird [6] first started discussing the port-hinterland relationship based on British ports and put forward a general port model, namely any port model. According to the expansion of port physical facilities, the model divided the development

of ports into three stages: layout, expansion and specialization. After that, Robinson [7], Hoyle [8], et al., constantly revised the general port model and proposed the port interface evolution model and some other models through the verification in actual ports. The traffic network model put forward by Taaffe [9], four stages of port development proposed by Notteboom [10] later, as well as the general port model are all classical and predominant theories to study the spatial model of ports and cities.

With the advancement of modern technology, ports develop towards intelligence gradually, making the data of the ports and cities available. Thus, scholars have begun to apply mathematical models to analyse their relationship quantitatively mainly in the following three aspects: the port-hinterland economic relationship, the port-city spatial relationship and the port-city coordination. (1) In terms of the port-hinterland economy: By combing the influence of macro environment and micro factors, César Ducruet [11] conducted an empirical analysis of the typical ports and their hinterland in Europe and Asia using relative concentration index, the results of which had certain universal applicability for the division of port-city relationship. Jung [12], Bottasso [13], et al., analysed the impacts of port economic development in Korea and Europe on their regional economies according to panel data. Based on port throughput and relevant urban economic indicators, Jung [12] studied the relationship between input and output of the port-city and found that with the changes of logistics and economic structure, the economic effect of ports on cities was gradually decreasing. Braun and Tramell [14] established an econometric model on the basis of Canaveral Port to study the direct and indirect economic contribution that ports made to cities. Using the panel data of different regions in China from 1999 to 2009 and the Granger causality, Song [15] analysed the relationship between the investment in port infrastructure construction and regional economic development. Lee [16] and Mina Anna [17] studied the impacts of port development on urban economy from the aspects of the change of port transportation cost, port infrastructure construction and port activities respectively to explore their direct and indirect relationship. Abdullah [18] and other scholars took Malaysian ports as research objects to analyse the impacts of urban economic development on ports and the relationship between port development and urban life quality. (2) With regard to the port-city spatial relationship, studies were mainly concentrated on the two stages of their relationship. In the first stage, ports and cities were closely related in space and relevant studies mainly discussed the positive effects between them. Taking the Seine Axis as research target, Merk [19] and other scholars quantified the impacts of port performance on the urban economy, society and environment during ten years and stressed the close association between ports and cities. Guo et al. [20] held the view that in the internationally renowned cities with port-city integration like New York, Hamburg and Rotterdam, ports were crucial in urban development and regional economy. Ports and cities relied on each other in limited space. Ravetz [21] doubted the immutable port-city relationship and believed at first, cities did attach themselves to ports since ports served as a centre of regional trade and logistics. However, their association was gradually weakened as a result of spatial restriction. In the second stage, mutual constraints between them gradually drove ports away from cities. After evaluating the performance of Hamburg Port within ten years, Merk et al. [22] proposed an opinion that ports generated a negative effect on cities and cities could not depend on ports for better development because of limited land, poorly developed logistics and the siphon effect caused by ports. Research done by Daamen et al. [23] revealed not only economic ties but also geographical and spatial relations were attenuating. Huang et al. [24] reckoned that in the background of economic globalization, ports were implementing a series of expansions, leading to the gradual transfer of land, transportation and environmental problems from ports to inland cities and accelerating the separation of them. However, they also believed in the future, they would interact again through reconstruction and renewal. (3) In the research on the port-city coordination, Llovera [25], Jeong [26], Jorrit [27], et al., selected ports in Latin America, Europe, Korea, Ghana and so on as their research objects. The effects of ports on urban spatial structure, policy and economy, and the impacts of urban morphology on port development were explored by the means of metrology and system dynamics so that better strategies and systems could be designed to facilitate the port-city coordination. From the perspective of policy and system, Tom [28] studied the interaction between several famous

ports and cities in Europe and held the view that the quality of their systems often had a homogeneous effect on ports. Ducruet [11] compared and analysed the similarities, differences and development trends of the relationship between 121 ports and their corresponding cities in Asia and Europe, and believed port-city relationship was in an inferior position at present. Jason Monios [29] argued the main link of the port-city interaction was regional logistics. Ports and inland distribution of logistics as well as their coordination affected the common development of the port-city. Zhao and Xu [30], et al., believed the port-city relationship was weakening from a stronger level, so QAP (Quadratic Assignment Procedure) and regression models were used to verify it and eventually, they found there was indeed a positive port-city correlation but it did not make port cities superior to ordinary cities in attracting investment. Karel [31] and other scholars contended the interface relationship of the port-city was geometric which could couple the heterogeneous participants in port-city systems and carried out an empirical analysis based on Netherlands and Ghent, Belgium. Taking Shanghai and Shanghai Port as study objects in the research on port-city interaction, Chen [32] and other scholars constructed the algometric growth model to analyse the relationship between port throughput and urban population.

During the recent decade, the concept of sustainability has gone deep into every aspect of our lives. At first, environmental sustainability and ecological sustainability were put forward in order to resolve the contradiction between the environment and the economy [33]. Then, while addressing issues in this aspect, the balance of social development was also paid wide attention and sustainable economy and sustainable management were proposed [34]. In 2012, the United Nations convened the World Summit on Sustainable Development in Rio de Janeiro and emphasized again that reasonable governance and solving the contradiction among the economic, environmental and social development had become the key to sustainable development. Therefore, the concepts of green economy and social sustainability were put forward, making sustainability the banner of world development [35,36]. Due to the gradual penetration of environmental protection awareness, scholars have begun to pay attention to the impacts of port development on ecological civilization. To study the impacts of environmental policies on ports, Woo and Daniel [37] took Fushan Port as an example and adopted the simulation method based on system dynamics to prove that the formulation and selection of urban environmental policies can cause a positive or negative effect on ports. Xiao and Lam [38] applied the system theory and formulated the system framework of port-city sustainable development from the aspect of port-city relationship, port system and city system, aiming at maximizing the positive effects of port-city relationship on economy and society and reducing the negative effects on environment. Schipper [39] and other scholars applied the method of evidence-based knowledge which involved ranking various long-term port plans and port vision documents against a set of social, economic and environmental key performance indicators (KPIs) in order to evaluate and interpret future outcomes and the sustainability of port-city development plans quantitatively and qualitatively. Witte et al. [40] reckoned that encouraging start-ups of port-city interface was beneficial to port innovation and provided new economic development directions for the port-city. Taking Montreal and Rotterdam as examples, scholars studied how to promote start-ups and conditions for their development. Lam J and Yap W [41] aimed to explore how policy-makers could achieve a sustainable balance among economic, social and environmental development of the port-city. Based on the system theory.

From the above literature, it is apparent that great achievements have been made in the research on port-city relationship. With plenty of theories, methods and models applied in the evaluation of port-city relationships the contents cover many fields, such as the evolution, trend, mutual promotion and restriction of port-city development and the effects of port-city coordination as well. In general, there are several characteristics in previous studies. From the aspect of the research object, most of them view ports and cities as independent system to evaluate their relationship and only a few treats them as a whole port-city system. With respect to the scale of ports and port cities, the world-famous ports and large or medium-sized ports are usually more preferred instead of the regional and smaller ones. For research methods, the existing studies focus on the port-city correlation degree, coupling degree or coordination degree separately and never combine the measurements together. Additionally,

they are also lacking in the sustainability analysis. In this paper, a typical Chinese port-city group, Liaoning coastal port and city group is selected as the research target as a whole, the development strategies of which can be a proper representative of the Chinese ports and cities. Except for Dalian Port and Yingkou Port, the remaining four are all regional and small ports which are seldom studied. In regard to research methods, this paper combines the correlation degree, the coupling degree or the coordination degree together to analyse the port-city interaction from different aspects comprehensively and systematically. In the meanwhile, a sustainability analysis box is constructed to evaluate the trend and the degree of the sustainable development of Liaoning port-city systems. By comparing horizontally and vertically and analysing the interactive results, suggestions on how to maintain the port-city coordination and sustainability are put forward.

3. Background of Ports and Cities in Liaoning

3.1. Current Development Situation of the Ports

As the only coastal province in Northeast China, Liaoning adopts the development mode of "ports prospering cities". At present, there are six ports in operation in Liaoning, including four larger ones, Dalian Port, Yingkou Port, Dandong Port and Jinzhou Port and two smaller ones, Panjin Port and Huludao Port [5]. In 2017, the throughput of Liaoning ports reached 1.13 billion tons, rising by 3.2% than that in the last year. Until now, there have been 421 productive berths in Liaoning ports with an annual currency capacity of 620 million tons. Among the top 20 ports in global cargo throughput, Liaoning Dalian Port ranks 11th and Yingkou Port ranks 13th. Generally speaking, the port development in Liaoning is scientific and orderly, and great progress has also been made in intelligent and green port construction. Accounting for 72.12% of the whole province in terms of cargo throughput, Dalian Port and Yingkou Port develop rapidly and healthily so that they are gaining significant competitive advantages in domestic and foreign shipping markets.

According to the relevant statistics about Liaoning ports from 2008 to 2017 (shown in Figures 1 and 2), the coastal ports in Liaoning maintained a strong growth momentum. Both port cargo throughput and the container throughput increased at a rapid speed especially in Dalian Port and Yingkou Port, where the throughput grew incredibly fast and kept ahead continuously, consolidating their positions of the main large ports in Liaoning and striving for greater competitive advantages at home and abroad. Dandong Port and Jinzhou Port followed closely and gave full play to the characteristics of regional ports. After 2014, the developing scale of Dandong port surpassed that of Jinzhou Port. As supporting ports, Panjin Port and Huludao Port were not as good as the other four in terms of the throughput, but they developed steadily and were gradually strengthening the port operation capacities.

Despite the relative concentration of the geographical locations of the coastal ports in Liaoning, their market positioning, main types of goods and the functions they undertake are quite different (shown in Table 1) just like their differences in scales and operational capacities. Dalian Port and Yingkou Port are major large-scale and container ports, important import and export ports and main commercial ports in Liaoning. Additionally, Dalian Port is also a typical tourist port in China [42] while Yingkou Port focuses more on loading and unloading, shipment and some other services. Jinzhou Port and Dandong Port are key regional ports in Liaoning acting as crucial transportation hubs in Northeast China, the developing scale and port construction of which are both in the middle level and can meet the construction requirements of local ports. Dandong Port pays more attention to international trade while Jinzhou Port is an industrial port based on the petrochemical industry. Panjin Port and Huludao Port work as supporting ports with relatively smaller construction scales and lower port operation capacities, both of which are trade and shipment ports that transport oil and bulk cargo.
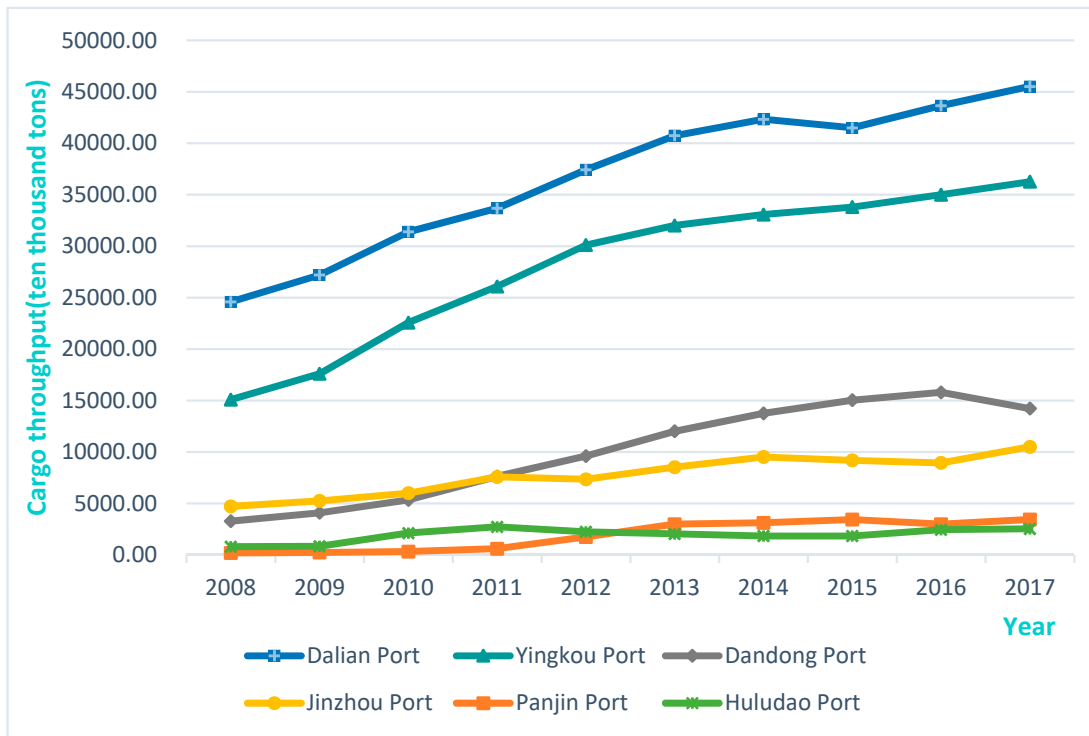
Figure 1. Cargo throughput of the coastal ports in Liaoning from 2008 to 2017. Source: Authors' elaboration based on raw statistical data from China Ports Yearbook (2008–2017).

Figure 2. Container throughput of the coastal ports in Liaoning from 2008 to 2017. Source: Authors' elaboration based on raw statistical data from China Ports Yearbook (2008–2017).
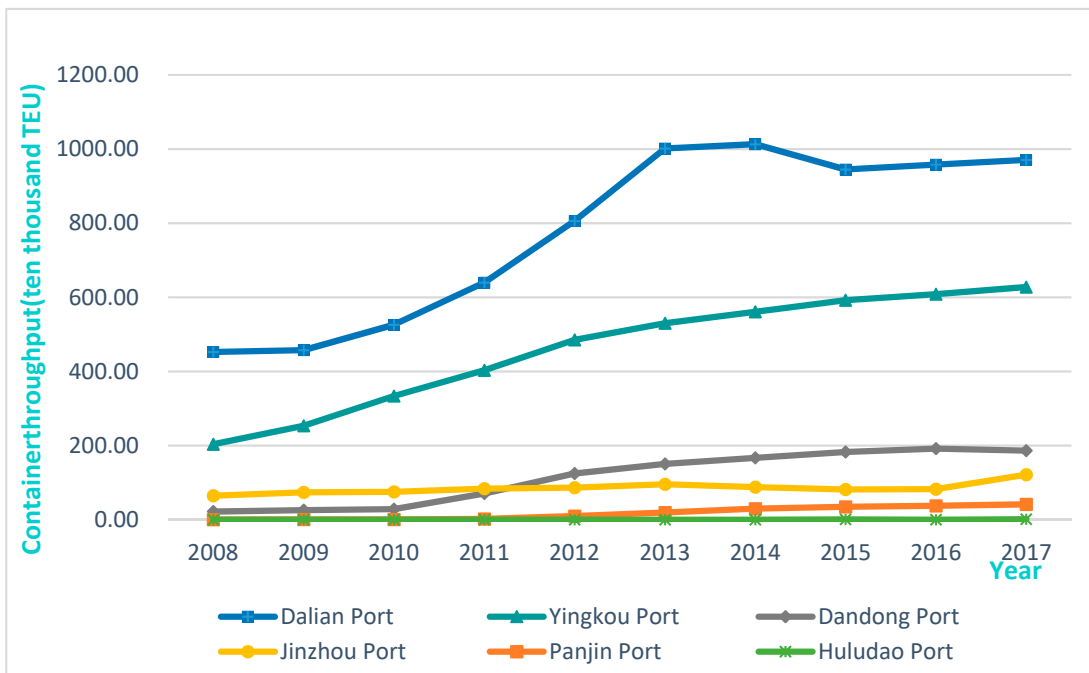
Table 1. Comparison of the coastal ports in Liaoning. Source: Authors' elaboration based on information from Liaoning coastal port layout planning, http://www.ln.gov.cn/index.html.

Ports	Major Hinterland	Functional Orientation	Main Types of Goods Transported	Route Coverage
Dalian Port	Three northeastern provinces and regions in eastern Inner Mongolia	Main port, import and export gateway in Northeast China, important international hub port, shipping centre in Northeast Asia	Petroleum, ore, coal, iron and steel, grain, containers, dry bulk cargo, etc.	Domestic coastal ports, major international container ports
Yingkou Port	Three provinces in Northeast China and regions in eastern Inner Mongolia	Main port, the second largest open port, logistics centre in Northeast China and Northeast Asia, hub of waterway trade and one of the important port for international trade	Oil, iron ore, cement, containers, dry bulk cargo, etc.	Domestic coastal ports, major ports in Northeast Asia
Jinzhou Port	Regions in western Liaoning	Key regional port, transportation hub of Northeast China, the deep-water port with the highest latitude along the coast of China	Coal, oil, ore, steel, grain, etc.	Domestic coastal ports
Dandong Port	Dandong City and surrounding towns	Key regional port, international trade port in the northernmost end of China's coastline, the grand channel to the sea in the east of Northeast China	Containers, grain, ore, steel, coal, etc.	Domestic coastal ports
Panjin Port	Panjin City and surrounding towns	General supporting port, multifunctional comprehensive port	Petrochemical product, coal, oil, etc.	Domestic coastal ports
Huludao Port	Regions in western Liaoning	General supporting port	Petrochemical products, grain, building materials, etc.	Domestic coastal ports

3.2. Current Development Situation of the Cities

The Liaoning coastal economic zone is the key region in the revitalization of the Northeast China and is also an important gateway for fully opening up to Northeast Asia which exerts considerably strategic effects in the process of regional coordination and promotes a new round of reform. According to Figure 3, the economy of Dalian, Dandong and the other four coastal cities has grown steadily and continuously since 2008. Although after 2013, the economy in all regions declined to a certain extent, with the largest and the most significant decline in 2016, it has begun to pick up and maintained a certain growth trend until now. From the perspective of each region, the development of each port city in the economic zone vary dramatically. Dalian plays a crucial part in Liaoning coastal economic zone whose economy has left that of the others far behind and even has exceeded the sum of the economy of the other five port cities during several consecutive years. Yingkou, Jinzhou and Panjin enjoy approximately the same developing scale and keep the growing trend. Compared to the other port cities, Dandong and Huludao develop at a relatively slow speed with their economic scales small and backward.

In addition, the six port cities studied in this paper are all actively developing towards modern and intelligent green cities in urban construction, social civilization, environmental protection, etc. Dalian, known as the Pearl in the North or Hong Kong in the North, is an important leader in the Northeast Revitalization Strategy and always ranks first in terms of urban civilization, urban construction and cultural construction. Possessing prominent port advantages and abundant resources, Yingkou is believed to be one of the most charming and liveable cities with good working and tourist conditions and colourful culture as well. Dandong is also a famous tourist city located in the national border cooperation zone and is called the "South in the North". It is highly open and rich in silk and geothermal resources. Panjin thrives because of oil and is known as the "New Petrochemical Town". It is a significant base of petroleum and petrochemical industry, as well as a typical tourist city in Liaoning. Due to its outstanding achievements in green city construction, it has become a pilot city for the construction of a "no waste city". Jinzhou and Panjin are important commercial and tourist cities whose developing levels are gradually improving and accomplishments of urban civilization and green city construction are becoming more and more remarkable.
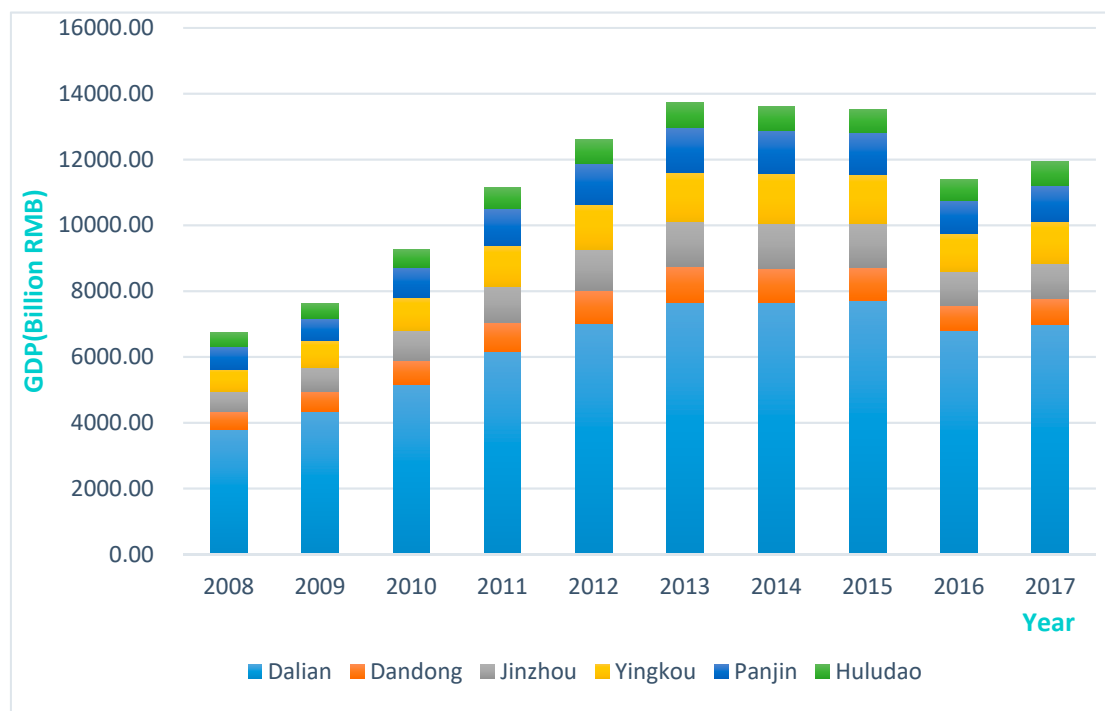
Figure 3. Economic development situation of the port cities in Liaoning from 2008 to 2017. Source: Authors' elaboration based on raw statistical data from statistical bulletins on social and national economy and social development of different places (2008–2017).

4. Research Design

4.1. Indicator System Construction

The port-city interactive system is extremely complicated not only because it is liable to be affected by external factors but also due to the complexity of port system and city system themselves [43]. Instead of two parts, ports and cities are two subsystems in the port-city interactive system which should be a balanced and integrated system [44]. Six ports and their mother cities in Liaoning are selected as study objects in this paper and each port and its mother city are regarded as an integrated system to form six port-city systems. Each port-city system is relatively complex and interrelated that can be divided into a port subsystem and a city subsystem. Based on the scientific, rational, representative, data available and operational principles, 31 indicators are selected. X_1-X_6 are indicators measuring the port subsystems. Namely, X_1-X_3 are used to evaluate the operational capacity of the ports while X_4-X_6 are applied to measure the construction capacity of the ports. Compared to port subsystems, city subsystems are even more complicated and wide-ranged. Y_1-Y_{25} are indicators to measure the city subsystems. The urban development are evaluated from the comprehensive economic level (from Y_1 to Y_9), the life quality level (from Y_{10} to Y_{14}), the urban construction level (from Y_{15} to Y_{20}) and the ecological environment level (from Y_{21} to Y_{25}).

From the variables mentioned above, a comprehensive port-city interaction indicator system made up of port and city subsystems is constructed as illustrated in Table 2.

Table 2. Comprehensive interaction indicator system of port-city systems. Source: China Ports Yearbook, China Statistical Yearbook.

Target Layer	Criterion Layer	Indicator Layer	Indicator Variables	Units
Port subsystem	Operational capacity of ports P_1	Cargo throughput	X_1	Ten thousand tons
		Foreign trade throughput	X_2	Ten thousand tons
		Container throughput	X_3	Ten thousand TEU
	Construction capacity of ports P_2	Length of docks	X_4	meters
		Number of berths	X_5	
		Currency capacity	X_6	Ten thousand tons
City subsystem	Comprehensive economic level U_1	Gross local product	Y_1	One hundred million yuan
		Proportion of tertiary industry	Y_2	%
		Total investment to fixed assets	Y_3	One hundred million yuan
		Total imports and exports	Y_4	Ten thousand dollars
		Total retail sales of consumer goods	Y_5	Ten thousand yuan
		Total foreign capital actually utilized	Y_6	Ten thousand dollars
		Local financial revenues	Y_7	Ten thousand yuan
		per capita disposable income	Y_8	Yuan
		Total tourism income	Y_9	One hundred million yuan
	Life quality level U_2	Population	Y_{10}	Ten thousand people
		Urban employees at year end	Y_{11}	Ten thousand people
		Average salary of employees	Y_{12}	Yuan
		Number of health care institutions	Y_{13}	
		Number of college students every 100,000 people	Y_{14}	Per 100,000 people
	Urban construction level U_3	Per capita urban road area	Y_{15}	Square meters
		Number of buses in operation at year end	Y_{16}	Vehicle
		Built-up Area	Y_{17}	Square kilometres
		Business volume of post and telecommunications	Y_{18}	Ten thousand yuan
		Passenger traffic volume	Y_{19}	Ten thousand people
		Freight volume	Y_{20}	Ten thousand tons
	Ecological construction level U_4	Green coverage rate in built-up areas	Y_{21}	%
		Urban landscape and green space area	Y_{22}	Hectares
		Generation of general industrial solid waste	Y_{23}	Ten thousand tons
		Total discharge of wastewater	Y_{24}	Ten thousand tons
		Total emissions of industrial waste gas	Y_{25}	One hundred million standard cubic meters

4.2. Research Methodology

Due to the differences in space, development and objectives of ports and cities, the port-city relationship has already been fairly complicated. Additionally, their relationship is constantly changing, making it even more complex. At first, ports and cities were limited to initial relation and in that period, the transportation transit worked as the medium to connect ports and cities, on which the cities relied heavily to promote foreign trade. As the scale of cities and ports increased, they were closely related and developed harmoniously. Ports became one of the major contributors to the urban economy because the shipping business and the port-vicinity industry promoted by them grew into pillar industries in urban development. In turn, more foreign investments attracted by cities were concentrated in coastal economic zone, making cities a powerful driving force in port development. Finally, self-development of the port-city has been realized. When ports and cities both reach a certain scale, they can perform their own functions well on the basis of their interaction and developing foundation accumulated circularly for mutual prosperity. Ports have gradually become the growth poles for urban economy while cities have developed into the energy stations of ports. This paper attaches more emphasis to the

periods from the initial port-city relation to their coordinated development. Therefore, grey relative relational analysis model and coupling coordination degree model are applied to subjectively and scientifically reflect the degree and the mode of the interaction between the comprehensive port-city developing levels. Additionally, by using relative correlation degrees, the influencing degree of city indicators related to ports and port indicators affecting cities differently in the port-city systems are measured. In addition, coupling degrees and coordination degrees are used to help evaluate the comprehensive developing abilities of port-city systems and the trend of their coordination. Finally, a sustainability analysis box of time-weighted correlation and coordination degrees is designed to discuss the interactive and sustainable degree of different port-city systems.

4.2.1. Data Preprocessing

Due to the fact that the port-city interaction indicator system involves indicators of multiple dimensions and directions which are quite different in nature, we adopt extremum method to preprocess positive indicators to eliminate the impacts of raw data on the evaluation process in dimension and quantity. The original matrix Z in the indicator construction in the port-city systems consists of i indicators and j evaluating objects, so the standardization of positive indicators z_{ij} can be computed as follows:

$$z'_{ij} = \frac{z_{ij}}{\max(z_{ij})} \tag{1}$$

The standardization of negative indicators z_{ij} can be computed as follows:

$$z'_{ij} = 1 - \frac{z_{ij}}{\max(z_{ij})} + \left\{ 1 - max\left[1 - \frac{z_{ij}}{\max(z_{ij})} \right] \right\} \tag{2}$$

After the standardization of positive and negative indicators using Equations (1) and (2), the standard matrix Z′ in the port-city systems can be determined.

4.2.2. Relational Model of Port-City Systems in Liaoning

As independent systems, ports and cities are huge and complex systems that integrate economy, policy, infrastructure, transportation and environment. More compound and complex as a port-city system is, they just coincide with the characteristics of a grey system, namely complexity and uncertainty. Thus, grey relative relational analysis is applied in this paper to measure the correlation degrees among the factors in individual port or city system and the overall port-city correlation degree. The grey relative relational analysis is a way to measure the correlation degrees among factors according to similarities or differences of factors' development trends. It is comprised of the absolute correlation degree, the relative correlation degree and the comprehensive correlation degree. Drawing upon the method of Wang and other scholars [45], this paper uses the relative correlation degree to measure the correlation between ports and cities in Liaoning, the advantages of which lies in the fact that it has nothing to do with the specific data, rather, its result is related to the relative quantity of the initial point. The calculation process is as follows:

Assuming that the characteristic sequence X represents indicators of port systems and the related factor sequence Y represents indicators of city systems, the behaviour sequence constituted by them is demonstrated as follows:

$$\begin{aligned} X &= (x(1), x(2), \cdots, x(n)) \\ Y &= (y(1), y(2), \cdots, y(n)) \end{aligned} \tag{3}$$

Sequence initialization:

$$\begin{aligned} X'_0 &= \left(x'_0(1), x'_0(2), \cdots, x'_0(n) \right) \\ Y'_0 &= \left(y'_0(1), y'_0(2), \cdots, y'_0(n) \right) \end{aligned} \tag{4}$$

Change of the initial points to zero:

$$
\begin{aligned}
X_0^0 &= \left(x_0^0(1), x_0^0(2), \cdots x_0^0(n) \right) \\
Y_0^0 &= \left(y_0^0(1), y_0^0(2), \cdots y_0^0(n) \right)
\end{aligned}
\tag{5}
$$

According to the computation method of the relative correlation degrees, the accumulated value and the absolute value of the related factor sequence and the characteristic sequence of indicators are computed below:

$$
|D_0| = \left| \sum_{i=2}^{n-1} x_0^0(i) + \frac{1}{2} x_0^0(n) \right|
\tag{6}
$$

$$
|D_i| = \left| \sum_{i=2}^{n-1} y_0^0(i) + \frac{1}{2} y_0^0(n) \right|
\tag{7}
$$

$$
|D_i - D_0| = \left| \sum_{i=2}^{n-1} \left(y_0^0(i) - x_0^0(i) \right) + \frac{1}{2} \left(y_0^0(n) - x_0^0(n) \right) \right|
\tag{8}
$$

Based on Equation (9), the relative correlation degree ρ_{0i} between the characteristic sequence X of ports and the related factor sequence Y of cities can be determined:

$$
\rho_{0i} = \frac{1 + |D_0| + |D_i|}{1 + |D_0| + |D_i| + |D_i - D_0|}
\tag{9}
$$

4.2.3. Coupling Coordination Degree model of Port-City Systems in Liaoning

In order to further measure the coordination degree of each port system and its corresponding city system as a whole, this paper builds the coupling coordination degree model based on the entropy weight method. First, the entropy weight method is used to identify the weights and then, the comprehensive developing levels of each port system and city system are measured individually according to Equations (10) and (11). After that, the coupling coordination degree model is applied to calculate coupling degrees and coordination degrees. Here, coupling refers to an interactive and interdependent phenomenon between related factors in no less than two systems and reflects the intersection of coordinated development among subsystems. The coupling degree measures this kind of phenomenon and only reveals the coordination degree of related systems at that specific time instead of their changes. Additionally, coordination on the other hand, represents a type of harmonious and well-coordinated relationship among systems which implies the orderliness and overall balance in a sustainable development system. The coordination degree measures the cooperative level of all subsystems during a period of time. Based on the study of Tang et al. [46]. In 2015, the calculation process of the coupling coordination model is as follows:

Supposing that there are m evaluating indicators of ports and *n* evaluating indicators of cities in the port-city systems in Liaoning and the comprehensive developing levels of ports and cities in year *t* are denoted as $P(x, t)$ and $Q(y, t)$ respectively. Then:

$$
P(x, t) = \sum_{i=1}^{m} w_i x_{it}
\tag{10}
$$

$$
Q(y, t) = \sum_{j=1}^{n} w_j y_{jt}
\tag{11}
$$

where w_i and w_j refer to weights of port and city indicators respectively computed by the entropy weight method.

Then considering the comprehensive evaluating values of the two subsystems, the coupling degree *E* and the coupling coordination degree F can be determined:

$$E = 2\sqrt{\frac{P(x,t) \times Q(y,t)}{[P(x,t) \times Q(y,t)]^2}} \tag{12}$$

$$F = \sqrt{E \times T} \tag{13}$$

where T refers to the comprehensive coordination indicator:

$$T = \frac{(P(x,t) + Q(y,t))}{2} \tag{14}$$

The greater the value of the coupling degree and the coordination degree is, the higher the coordination level of a port-city system is and the more orderly and balanced their development is. According to the method of Liu [47], the coordination degrees can be classified into several grades which are illustrated in Table 3 considering the actual situation of this paper.

Table 3. Classification of the coupling coordination degrees of port-city systems in Liaoning.

Development Stages	Coordination Grades	F
Low-quality degenerating stage	Serious disorders	0~0.2
	Disorders	0.2~0.4
Antagonistic running-in stage	On the verge of disorders	0.4~0.5
	Reluctantly acceptable coordination	0.5~0.6
Coordinated development stage	Coordination	0.6~0.8
	High-quality coordination	0.8~1

4.3. Data Sources

The raw data of the port subsystems in the paper comes from Statistical Yearbook of Chinese Ports from 2008 to 2017, Liaoning Maritime Bureau (http://www.ln.msa.gov.cn/) and the statistical bulletins on social and national economy and social development of different places (http://www.stats.gov.cn/tjsj/zxfb/201902/t20190228_1651265.html). The raw data of the city subsystems are collected from Statistical Yearbook of Liaoning (http://www.ln.stats.gov.cn/), Statistical Yearbook of Dalian (http://www.stats.dl.gov.cn/) from 2008 to 2017 and the statistical bulletins on social and national economy and social development of different places.

5. Results of the Case Study Analysis

5.1. Correlation of the Port-City

5.1.1. The Correlation Degrees

According to Equations (1)–(9), the port-city correlation degrees in Liaoning from 2008 to 2017 can be calculated as illustrated in Table 4. From it, changes, especially increases in the correlation degrees ranging from 0.3 to 0.8, are clearly demonstrated. From the perspective of time, the port-city correlation degrees were between 0.3 and 0.4 in 2008, reflecting a relatively weak correlation and inconspicuous interdependent and interactive effects between them. In the following several years from 2009 to 2012, the correlation degrees reached a medium level, suggesting that their relationship was enhancing. Ports, as an important determinant in promoting port cities, were backed by them in turn. From 2013 to 2017, higher correlation degrees from 0.6 to 0.8 indicated relatively stronger interaction and interdependence between ports and cities and they gradually became indispensable

factors, strong supports and powerful driving forces for the development of each other. In the aspect of ports, the port-city correlation degrees changed with similar development trends which differed so little before 2015 in particular. Though tiny, the discrepancies never totally disappeared. According to the average correlation degrees: Yingkou (0.592) > Dalian (0.571) > Dandong (0.570) > Jinzhou (0.563) > Huludao (0.554) > Panjin (0.552).

Table 4. Port-city correlation degrees in Liaoning. Source: Authors' calculation using Equations (1)–(9) based on raw statistical data.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average Values
Dalian	0.374	0.412	0.454	0.486	0.578	0.633	0.695	0.652	0.684	0.740	0.571
Yingkou	0.374	0.430	0.539	0.529	0.589	0.642	0.672	0.659	0.727	0.762	0.592
Dandong	0.378	0.430	0.451	0.508	0.583	0.672	0.665	0.674	0.650	0.693	0.570
Jinzhou	0.375	0.434	0.456	0.474	0.590	0.650	0.709	0.647	0.600	0.690	0.563
Panjin	0.367	0.404	0.455	0.484	0.557	0.610	0.651	0.625	0.658	0.709	0.552
Huludao	0.390	0.459	0.490	0.509	0.543	0.631	0.618	0.606	0.593	0.704	0.554

5.1.2. The Relative Correlation Degrees among Internal Factors

Tables 5 and 6 represent the relative correlation degrees between the sum of the characteristic sequence and the corresponding urban comprehensive indicators, the sum of the related factor sequence and the corresponding port comprehensive indicators in Liaoning port-city systems, respectively. In Table 5, the relative correlation degrees between the sum of the characteristic sequence and the comprehensive indicators in the layer of urban criteria are demonstrated. Considering each port-city system, the sum of the factor sequence of urban comprehensive economic level has the strongest relative correlation with all port indicators, followed by the urban construction level, life quality level and the ecological environment level. In terms of port indicators, the optimal characteristic sequence in the relative correlation degrees between port characteristic sequence and urban comprehensive indicators is the length of docks, then the number of berths, followed by the currency capacity, the cargo throughput, the foreign trade throughput and the container throughput. Among them, the top two characteristic sequences in Dalian and Jinzhou are the port cargo throughput and the foreign trade throughput, while in Yingkou, the currency capacity and the cargo throughput, in Dandong and Panjin, the length of docks and the number of berths and in Huludao, the number of berths and the currency capacity. Therefore, the urban comprehensive developing levels in different port-city systems can cause distinct effects on port development. For instance, the specific aspects and focuses of mutual effects may vary. However, generally speaking, the economic level promotes port development most which is mainly embodied in cargo throughput and productive berth construction. In addition, there is also a difference in the relative correlation degrees between port-city systems and port characteristic sequence. In general, according to the impacts of the urban comprehensive developing levels on the port comprehensive development: Yingkou > Dalian > Jinzhou > Dandong > Huludao > Panjin.

In Table 6, the relative correlation degrees between the sum of the related factor sequence and the comprehensive indicators in the layer of port criteria are demonstrated. Considering the sum of urban characteristic sequences corresponding to port comprehensive indicators, the port development capacity is greater than the port operation capacity in the driving role of ports in urban development. The scale of port construction reveals the energy levels of ports and works as the foundation of port operation capacity, and that is the reason why the port development capacity is so significant. In the sequence of urban factors, the optimal related factor sequence is the import and export trade, then the per capita disposable income, followed by total emissions of industrial waste gas, total retail sales of consumer goods and gross local product. The worst and second worst related factor sequences are the green coverage rate in built-up areas and the business volume of post and telecommunications. It implies that the impacts of ports on cities mainly lie in the international trade and local economic

development and are also closely related to pollution control but have little to do with post and telecommunications and regional greening. In the meanwhile, for port-city systems, the optimal and suboptimal factor sequences are very different, too. In Dalian, they refer to the number of health care institutions and total emissions of industrial waste gas, and in Yingkou, they are freight volume and gross local product, while in Dandong, total emissions of industrial waste gas and local financial revenues, in Jinzhou, the number of college students per 100,000 people and the number of buses in operation at year-end, in Panjin, total investment to fixed assets and total emissions of industrial waste gas, and in Huludao, the number of health care institutions and total investment to fixed assets. From all of the above, in spite of the differences of the impacts of ports on cities, they mainly focus on the aspects of economy, transportation and pollution control. Generally speaking, according to the impacts of port comprehensive developing levels on the urban comprehensive development: Yingkou > Dalian > Jinzhou > Dandong > Huludao > Panjin.

Table 5. Relative correlation degrees between the sum of characteristic sequence and urban comprehensive indicators in Liaoning port-city systems. Source: Authors' calculation using Equations (1)–(9) based on raw statistical data.

		X_1	X_2	X_3	X_4	X_5	X_6
Dalian	U_1	7.198	6.757	7.722	5.470	5.026	6.309
	U_2	3.993	3.994	3.734	3.382	3.241	3.731
	U_3	4.443	4.411	4.059	4.420	4.217	4.552
	U_4	4.045	4.223	3.597	3.411	3.180	3.921
	Total	19.679	19.384	19.112	16.683	15.664	18.513
Yingkou	U_1	7.563	7.488	7.449	6.541	6.169	7.551
	U_2	3.664	3.365	3.318	4.363	3.930	3.727
	U_3	4.086	3.807	3.764	4.459	4.828	4.127
	U_4	3.633	3.582	3.524	3.479	3.557	3.604
	Total	18.947	18.242	18.054	18.842	18.484	19.009
Dandong	U_1	6.562	7.342	5.636	7.574	6.722	6.747
	U_2	3.083	3.450	2.794	3.555	3.850	3.167
	U_3	3.558	3.910	3.282	4.356	4.952	3.639
	U_4	3.183	3.611	2.845	3.576	3.484	3.282
	Total	16.386	18.313	14.557	19.060	19.009	16.834
Jinzhou	U_1	7.112	7.517	5.898	5.493	5.387	6.184
	U_2	3.700	3.598	3.720	3.759	3.711	3.783
	U_3	4.248	3.972	4.609	4.622	4.550	4.480
	U_4	3.435	3.137	3.730	4.008	3.929	3.587
	Total	18.493	18.224	17.957	17.882	17.576	18.035
Panjin	U_1	5.538	4.640	4.777	7.303	7.402	5.782
	U_2	2.584	2.511	2.521	3.231	3.061	2.650
	U_3	3.166	3.021	3.041	4.348	4.108	3.296
	U_4	2.632	2.517	2.533	3.532	3.378	2.734
	Total	13.920	12.688	12.872	18.415	17.950	14.462
Huludao	U_1	6.521	4.889	5.212	7.022	6.554	7.059
	U_2	3.315	3.030	2.721	3.565	3.504	3.545
	U_3	3.937	3.349	3.377	4.027	4.807	4.241
	U_4	2.923	2.664	2.757	3.185	3.823	3.472
	Total	16.696	13.932	14.067	17.799	18.688	18.318

Table 6. Relative correlation degrees between the sum of related factor sequence and port comprehensive indicators in Liaoning port-city systems. Source: Authors' calculation using Equations (1)–(9) based on raw statistical data.

	Danlian		Yingkou		Dandong		Jinzhou		Panjin		Huludao	
	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
Y_1	2.631	1.776	2.652	2.459	2.011	2.475	2.484	2.038	1.552	2.152	1.774	2.609
Y_2	1.95	2.338	1.841	2.302	1.562	1.648	1.67	1.893	1.563	2.289	1.626	1.836
Y_3	2.626	1.768	2.41	2.478	2.153	2.541	2.216	1.771	1.604	2.512	1.933	2.592
Y_4	2.232	2.265	2.773	2.278	2.261	2.466	2.43	1.853	1.645	2.317	1.697	2.495
Y_5	2.325	1.692	2.766	2.293	2.256	2.469	2.431	1.915	1.586	2.489	2.01	2.456
Y_6	2.432	1.717	2.782	2.119	2.323	2.437	2.457	1.988	2.167	1.884	1.902	1.726
Y_7	2.486	1.73	2.342	1.907	2.462	2.381	2.143	1.744	1.668	2.261	1.967	2.394
Y_8	2.68	1.828	2.482	2.466	2.037	2.486	2.533	2.109	1.553	2.158	1.795	2.646
Y_9	2.316	1.69	2.452	1.96	2.474	2.141	2.163	1.751	1.618	2.426	1.918	1.88
Y_{10}	1.683	2.383	1.573	1.671	1.548	1.615	2.06	2.671	1.505	1.561	1.561	1.64
Y_{11}	2.045	2.322	2.095	2.618	1.781	2.17	1.883	2.389	1.509	1.617	1.598	1.648
Y_{12}	2.641	1.789	2.452	2.47	1.848	2.329	2.451	1.975	1.546	2.079	1.908	2.594
Y_{13}	2.66	1.951	2.116	2.631	2.418	2.406	2.222	1.774	1.533	1.909	2.304	2.331
Y_{14}	2.69	1.908	2.112	2.629	1.732	2.053	2.403	2.444	1.522	1.777	1.694	2.401
Y_{15}	1.652	2.353	1.85	2.323	1.826	2.276	2.199	2.586	1.521	1.763	1.69	2.402
Y_{16}	1.93	2.347	1.895	2.43	1.899	2.451	2.289	2.539	1.521	1.758	1.74	2.287
Y_{17}	2.708	1.889	1.902	2.447	1.678	1.925	1.999	2.645	1.538	1.967	1.69	2.235
Y_{18}	1.74	2.42	1.592	1.718	1.604	1.747	1.661	1.873	1.507	1.586	1.769	1.737
Y_{19}	2.175	2.329	1.735	2.054	1.741	2.075	2.462	2.236	1.555	2.189	1.669	2.269
Y_{20}	2.709	1.851	2.682	2.442	2.003	2.472	2.218	1.772	1.587	2.489	2.103	2.146
Y_{21}	1.709	2.393	1.591	1.715	1.546	1.61	1.787	2.165	1.507	1.587	1.578	1.68
Y_{22}	2.704	1.893	1.954	2.56	1.734	2.058	2.182	2.598	1.529	1.858	1.7	2.128
Y_{23}	2.537	2.04	2.736	2.366	2.265	2.464	1.753	2.086	1.535	1.94	1.77	2.563
Y_{24}	2.248	2.247	1.629	1.804	1.632	1.815	2.471	2.016	1.522	1.769	1.651	2.105
Y_{25}	2.667	1.939	2.829	2.195	2.462	2.395	2.109	2.659	1.588	2.491	1.646	2.004

5.2. Coordination of the Port-City

5.2.1. The Comprehensive System Evaluation

Using Equations (10)–(13), the scores of comprehensive developing levels, the coupling degrees and the coordination degrees of the six ports and their corresponding cities are determined. The comprehensive evaluation levels of the ports and the cities are then clearly demonstrated in Figure 4. As is depicted in Figure 4, the average developing level of these ports and cities belongs to the upper and middle level. Specifically speaking, Dalian, Yingkou, Jinzhou and Dandong enjoyed above-average development most of the time in the decade while the development in Panjin and Huludao fell behind slightly. From a more general point of view, the level and speed of urban development are slightly higher than those of ports. In Dalian, Yingkou and Jinzhou, ports have a slight development advantage but in Dandong, Panjin and Huludao, cities are better developed than ports and the gap is much wider in Panjin and Huludao. At the same time, the development of Liaoning ports and cities concentrates on the regions with high-level urban development. Regions with low-level port

development and high-level urban development mainly include Huludao, Panjin and Dandong and regions with high-level port and urban development are situated in Dalian, Yingkou and Jinzhou. Except for Dalian, there are both low-level ports and urban developments existing in other regions.
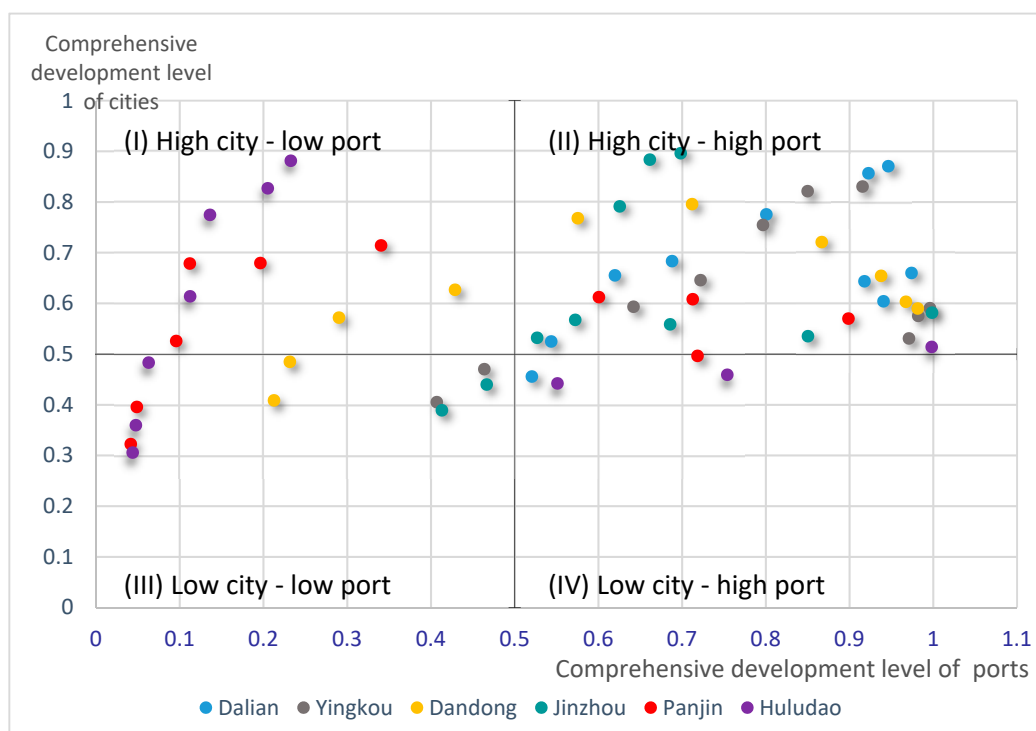

Figure 4. Comprehensive evaluation of ports and cities in Liaoning. Source: Authors' calculation using Equations (10)–(11) based on raw statistical data. Note: High city means high comprehensive evaluation levels of the city, high port means high comprehensive evaluation levels of the port, and vice versa.

5.2.2. The Coupling Degrees and the Coordination Degrees

The coupling degrees and the coordination degrees of Liaoning port-city systems are computed and shown in Table 7. With respect to the coupling degrees, relatively high degrees of the six port-city systems from 0.624 to 1 indicate that under static condition, the six systems coordinate with each other fairly well and develop from a running-in stage towards high-level coupling and even benign resonance coupling. Specifically, regions except Panjin and Huludao reached high-level coupling in which Dalian, Yingkou and Huludao shared the similar development trend and had the coupling degree of 1 for several times from 2008 to 2013, suggesting that in that period, ports and cities had the strongest coordination and there was a benign resonance coupling as well as a transition to a new ordered structure within the systems. Panjin and Huludao went through the running-in and high-level coupling stage and show a fluctuating growth trend at present. Dandong always stayed in a high-level coupling and fluctuating growth stage which reached the coupling peak in 2013 with an inverted S-shaped development trend. Based on the average values, the order of the coupling degrees of Liaoning coastal port-city systems can be: Dalian (0.994) > Jinzhou (0.991) > Yingkou (0.988) > Dandong (0.972) > Panjin (0.972) > Huludao (0.790).

The coupling degree can only indicate the coordination degree of two systems in static state rather than the value or changes of the coordination degrees. Overall, the coordination of Liaoning port-city systems is growing. It achieved its highest value from 2013 to 2014, and declined to the bottom in 2015 and then began to pick up gradually until 2017, the difference between the coordination degrees of the six port-city systems was rather slight. The coordination degrees ranged from 0.340 to 0.953, suggesting that Liaoning port-city systems underwent a low-quality degenerating stage and then

gradually stepped into a coordinated development stage. Disorders and on the verge of disorders occurred before 2010 but, most of the time, the port-city systems were in a stage of coordinated or well-coordinated development. Although the development trends of all systems were basically the same in the decade, they still varied significantly in specific regions. In general, based on the average values, the order of the coordination degrees of Liaoning port-city systems can be: Dalian (0.848) > Yingkou (0.825) > Jinzhou (0.787) > Dandong (0.768) > Panjin (0.623) > Huludao (0.583). According to the coordination degrees and corresponding grades, the coordination degree order of Liaoning coastal port-city systems could be classified into three types. Dalian, Yingkou and Jinzhou were in the stage from coordination to high-quality coordination, and Dandong developed from reluctantly acceptable coordination, coordination to high-quality coordination, while Panjin and Huludao experienced disorders, on the verge of disorders, reluctantly acceptable coordination, coordination and eventually high-quality coordination.

Table 7. Coupling degrees and coordination degrees of Liaoning port-city systems. Source: Authors' calculation using Equations (12)–(14) based on raw statistical data.

		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Average Values
Coupling degrees	**Dalian**	0.998	1.000	1.000	1.000	1.000	0.999	0.999	0.984	0.976	0.981	0.994
	Yingkou	1.000	1.000	0.999	0.998	1.000	1.000	0.999	0.956	0.965	0.967	0.988
	Dandong	0.949	0.935	0.945	0.982	0.990	0.998	0.996	0.973	0.968	0.984	0.972
	Jinzhou	1.000	1.000	1.000	1.000	0.993	0.990	0.992	0.995	0.974	0.965	0.991
	Panjin	0.634	0.624	0.721	0.697	0.834	0.935	1.000	0.983	0.997	0.975	0.840
	Huludao	0.661	0.642	0.638	0.723	0.713	0.813	0.798	0.970	0.994	0.947	0.790
Coordination degrees	**Dalian**	0.698	0.731	0.798	0.828	0.888	0.943	0.953	0.877	0.868	0.895	0.848
	Yingkou	0.637	0.683	0.786	0.826	0.881	0.914	0.934	0.847	0.867	0.876	0.825
	Dandong	0.543	0.579	0.638	0.720	0.815	0.868	0.889	0.874	0.872	0.885	0.768
	Jinzhou	0.633	0.673	0.728	0.755	0.839	0.874	0.890	0.787	0.821	0.873	0.787
	Panjin	0.340	0.372	0.473	0.525	0.604	0.702	0.779	0.773	0.811	0.846	0.623
	Huludao	0.340	0.362	0.417	0.512	0.570	0.673	0.642	0.767	0.703	0.846	0.583

5.3. Interaction and Sustainability of the Port-City

5.3.1. Interaction Analysis

According to the weighted average calculation of correlation degrees, coupling degrees and coordination degrees, the overall situation of the port-city systems in Liaoning during the past ten years is obtained (shown in Figure 5). From the perspective of the correlation degrees, the port-city correlation trend is rising. Before 2009, ports and cities were weakly correlated and from 2009 to 2012, they were moderately correlated. After 2012, they entered a relatively strong correlation stage while at present, they still have not reached a strong correlation level. The correlations before 2014 realized an accelerating growth but slowed down after 2014 and then increased again after 2016. All show that there are closer relationships and more significant and obvious interactions between ports and cities in Liaoning now. In terms of the coupling degrees, relatively high levels of coupling from 0.867 to 0.979 and the development from high-level coupling to benign resonance coupling imply a strong and relatively stable type of port-city coordination which specifically means ports work as a powerful driving force for cities and in turn cities give full play to the supporting role of space and hinterland. The coupling degrees before 2013 grew in a relatively rapid speed and slowed down and even declined to a certain extent after 2013. According to the comprehensive evaluation, this was because some mismatches in scale and speed between port and urban development gradually emerged. Before 2013, ports developed in a smaller scale and slower speed than cities, except Dalian and Yingkou. However, after then, the opposite happened and ports exhibited superiority in scale and speed over

cities. During this period, the synchronous development of the two lasted for a relatively short period. In terms of the coupling coordination degrees, the overall Liaoning ports and cities developed from the antagonistic running-in stage to the coordinated stage. Before 2012, their coordination levels ranged from 0.376 to 0.573 and were reluctantly acceptable. After that, ports and cities realized coordinated development with the coordination degrees from 0.640 to 0.717 but still did not achieve high-quality development. Therefore, it is evident to see the growth of the port-city coordination degrees and now the development is relatively stable. As the comprehensive levels of port and urban development rise, ports and cities keep a stable interaction and an increasing coordination. However, their coordination at present is still not in high quality with the coordination degrees less than 0.8, indicating that there is still plenty of room if the comprehensive levels of port and urban development and in particular, the urban construction would like to get promoted. The port-city interaction needs to be strengthened to drive them to develop towards a more orderly and benign direction.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Coupling degree	0.874	0.867	0.884	0.900	0.921	0.956	0.964	0.977	0.979	0.970
Coordination degree	0.532	0.567	0.640	0.694	0.766	0.829	0.848	0.821	0.824	0.870
Correlation degree	0.376	0.428	0.474	0.498	0.573	0.640	0.669	0.644	0.652	0.717
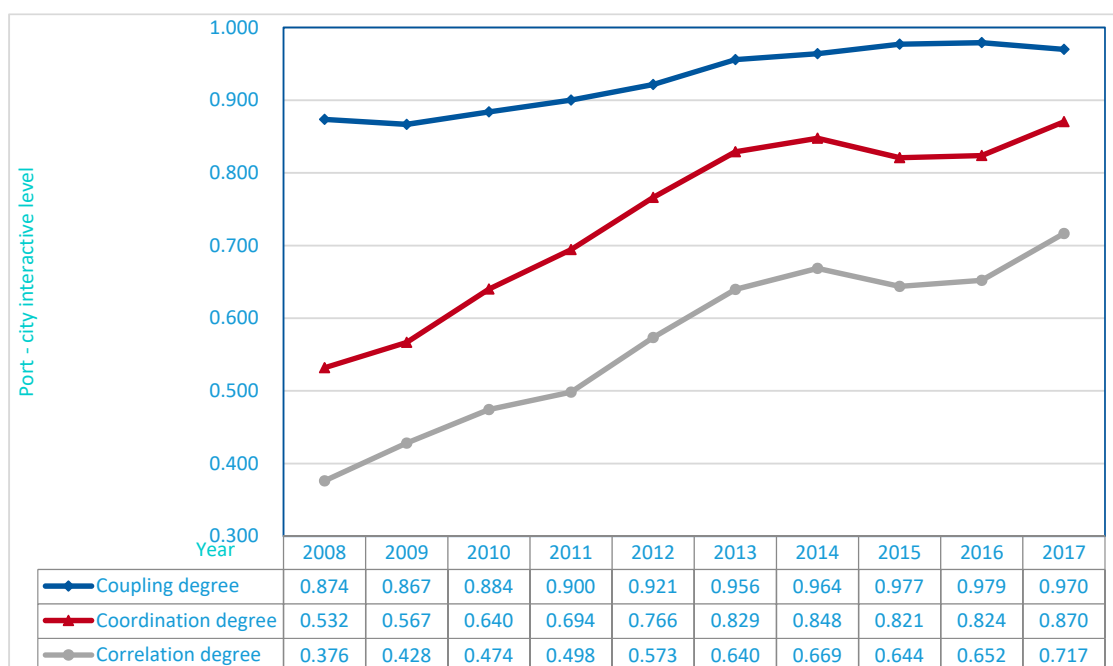
Figure 5. Overall interaction of port-city systems in Liaoning. Source: Authors' elaboration based on data from Tables 4 and 7.

5.3.2. Sustainability Analysis

From the above analysis, the correlation degree measures the relevance between ports and cities, that is, the degree of similarities or differences in their development trend, and indicates the port-city interactive trend. A high correlation degree reflects good mutual promotion and great reciprocal influence between ports and cities while a low correlation degree means they differ in the development status and exert little influence on each other. Additionally, the coordination degree measures the cooperative and harmonious relationship between ports and cities which represents the degree of the port-city interactive development. In the coordination stage, the port-cities have no conflicts, such as over-concentration or spatial constraints. However, in a more general sense, sustainable development is the long-term goal of port-city systems. Both the correlation and coordination are part of the sustainability for port-city development. Therefore, it is of certain significance to use the combination of correlation and coordination, as well as the continuity of time, to express the sustainability of the port-city interactive development. That is to say, the port-city relationship maintains an interactive development trend and also achieves certain coordination within a period of time. As is shown in Figure 6, a port-city sustainability analysis box combining the correlation degree and coordination

degree is built in this section, which includes four development types, namely, the correlation type, the coordination type, the sustainability type and the unsustainability type.
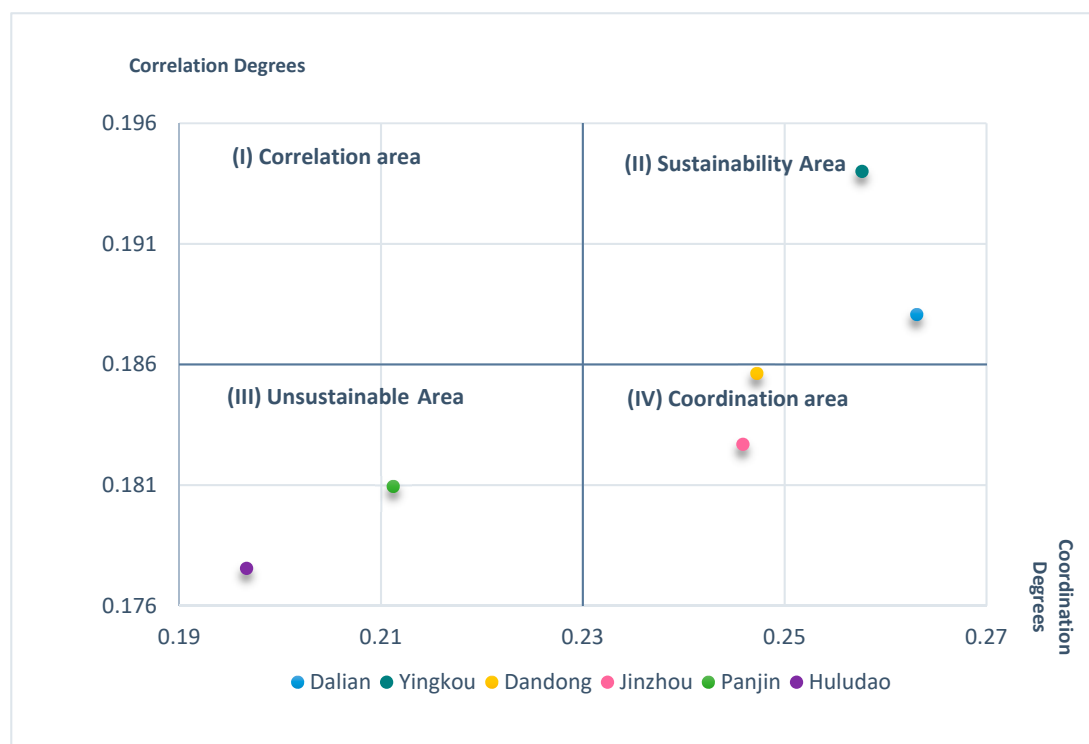

Figure 6. Port-city development types. Source: Authors' elaboration based on data from Tables 4 and 7.

In our evaluation, two factors, namely the quality of correlation and coordination degrees, as well as time series, are mainly considered. Since both of them have an equal impact on overall sustainability, 50% weight is given to each factor. The impacts of the correlation and coordination quality on the sustainability vary with time and it is believed that it generates the greatest effect on overall sustainability in recent two years while its impact at the initial time is the least, so different weights are given to the quality at different times. Finally, time-weighted correlation and coordination degrees are used to represent the port-city sustainability. Figure 6 shows the box of weighted correlation and coordination degrees to indicate the evaluation of overall port-city sustainability in Liaoning. The six port-city systems are mainly distributed in the first, third and fourth quadrants. Among them, Yingkou and Dalian are in the area of high correlation and high coordination which means they have achieved primary sustainability. The results agree with the current situation of the port-city systems in Liaoning. Among coastal ports in Liaoning and even Northeast China, Dalian and Yingkou belong to important and rapidly developing ports in the aspects of port scale and operational capacity. With their port development stressing emphasis on the coordination with local society, culture and environment and their hinterland having outstanding economic, social and civilization levels, Dalian and Yingkou are progressing towards comprehensive and sustainable development. Dalian enjoys a better coordinated port-city development but the correlation in Yingkou is stronger. Dandong and Jinzhou are in a position of low correlation and high coordination and belong to the sustainable running-in stage. They have not achieved sustainability yet but a relatively good development trend in the port-city interaction can be seen. Dandong and Jinzhou are key ports and coordinate well with the regional development, but they have not fully achieved the synchronous and positive port-city development because their development in port operation, scale construction and comprehensive level of city is restricted by local resources. All those mentioned above, together with their functional orientation and historical development in the Liaoning coastal economic zone, will have a certain impact on the port-city sustainability. As general supporting ports, Panjin and Huludao are severely constrained by the

resources of all parties. Additionally, slow regional development, backward level of port infrastructure construction as well as a lack of operation and management capacity also make them fall far behind. Since they have low correlation and low coordination, their port-city relationship cannot be sustainable. Panjin and Huludao still have a long way to go in terms of sustainable port-city development.

6. Conclusions and Suggestions for Sustainable Development

6.1. Conclusions

In this paper, the Liaoning port and city group is taken as the study object to explore the port-city relationship in different regions. Firstly, the development situation of the six ports and their corresponding cities in Liaoning is reviewed according to the panel data from 2008 to 2017, based on which the research on the correlation degrees, coordination degrees and sustainability evaluation are designed. Then, this paper breaks through previous studies on the relationship between a single port and its corresponding city and combines the measurement methods of correlation degrees and coordination degrees together. A sustainability box of the correlation-coordination is also constructed to comprehensively and systematically explore the interaction between ports and cities in Liaoning. After the calculation of the sustainability of the six port-cities, the validity and applicability of the proposed model are verified. Finally, this paper can be concluded as follows:

(1) The correlation degrees of Liaoning port-city systems experienced stages from weak correlation to relatively strong correlation but strong correlation was not achieved from 2008 to 2017 as explained in Section 5.1.1. The correlation degrees varied dramatically from regions, among which Yingkou and Dalian had the highest degree while Panjin had the lowest. This indicates that the port-city interaction is mainly affected by their scales. Additionally, there is still plenty of room for further improvement of the port-city correlation.

(2) Considering the impacts of the internal factors in the port-city systems on the correlation degrees, the urban comprehensive indicators related most and least closely to ports are the comprehensive economic level and the ecological environment level, respectively. The port comprehensive indicator related most closely to cities is the development capacity of the ports. This reflects the port-city correlation mainly depends on their association in the economy and trade which can be embodied in indicators like foreign trade income, port throughput, etc. [48].

(3) Problems of the mismatch of the developing levels of ports and cities in the six regions have been aroused and, in general, the developing levels of the cities are higher than that of the ports. However, this kind of relationship is not immutable, and the development of port subsystems and city subsystems will change with time and some other uncertain external factors. Due to the particularity and complexity of ports and cities, unexpected risks often occur [49]. However, Dalian keeps a relatively steady pace at all times with both high-level port and city development trends.

(4) Basically, all regions in the Liaoning port-city systems stay at a high coupling level and Dalian, Jinzhou and Yingkou almost share the same coupling degree. The coordination degrees of the six systems were all over 8 in 2017, indicating that they achieved the high-quality coupling stage. There were only differences in the coordinated development stages of the port-city during the 10 year range. The port-city coordination both in static state (namely, the coupling degree) and in dynamic state (namely, the coordination degree) reveals a benign interaction and well-coordinated development trend.

(5) The sustainable development of the port-city interaction is not so optimistic. Only ports and cities in Dalian and Yingkou have achieved primary sustainability while, in Dandong and Jinzhou, their relationship is in the sustainable running-in stage. Additionally, more attention should be paid to the sustainable development of ports and cities in Panjin and Huludao. Based on the analysis above, the port-city correlation needs to be further improved and high-quality coordination ought

to be strengthened and maintained if ports and cities would like to keep a relatively high-level interaction and a sustainable development trend.

6.2. Suggestions for Sustainable Development of the Port-City

With respect to regional competition or economic trade, the port-city relationship is playing a more and more important role. To boost regional development and international trade, not only are powerful port cities and ports at a high energy level, but also their dynamic coordination and its sustainability are needed. As a crucial gateway open to Northeast Asia, an important node of the 21st century maritime Silk Road and a key region in the Northeast Revitalization Strategy, it is of great significance for the coastal ports in Liaoning to strengthen coordination and correlation with port cities and maintain sustainability. Hence, combined with the conclusions made by the paper, suggestions for the port-city coordination and sustainability in Liaoning are proposed in the following several aspects:

(1) Construct the port-city coordination mechanism, integrate coastal resources and improve the utilization of coastline and marine resources. Based on the analysis in Section 5.3.1, high-level coupling, relative strong coordination and correlation have been shown in Liaoning port-city systems but strong correlation and high-level coordination have not been achieved yet. It indicates that although there is indeed a mounting demand for the port-city interaction, a high-quality and smooth developing relation has not been established. Therefore, Liaoning ports and cities are supposed to enhance correlation and coordination and, at the same time, maintain the sustainability of the cooperated and coordinated development on the premise of high-level coupling. Firstly, government policymakers should construct coordination mechanisms for the port-city co-development and try to avoid the situation of "one port, one city and one government". Instead, the maximization of overall benefits ought to be set as the major goal for the development of the Liaoning port group to plan rationally and to develop integrally and interactively [50]. Port positioning and exploitation of coastal and marine resources should be combined with the development of port cities and industrial layout. Secondly, an integrated provincial port and shipping platform should also be constructed to realize resources and information sharing and avoid the waste of resources, such as unhealthy competition and the duplicate development of port functions and positioning.

(2) Regard the key correlated factors as the breakthrough point to promote the sustainability of port coordination. From the analysis of the paper, the economic developing level of ports and the urban construction level are urban factors related most closely to ports while the development capacity of ports is the most closely related factor to cities. Thus, the essential factors are supposed to be used to facilitate the sustainability of coordinated development. Firstly, more emphasis should be attached to the economic agglomeration to attract investments, strengthen industrial agglomeration, promote the growth of emerging industries and enhance interactive development with coastal and shipping industries. Secondly, promoting the construction of modern intelligent cities from infrastructure, transportation, communications, high-tech and some other aspects should be paid much attention. Ports should start from promoting their infrastructure construction capacity and optimizing allocation of resources like water depth, berths, facilities and operational techniques of coastal ports. Additionally, a reasonable allocation of resources will enhance the port-city interaction dramatically [51]. Additionally, a centralized management platform for big data informatization ought to be built to improve the ports' currency capacity and then to upgrade the energy level and enhance the operational capacity of ports. At the same time, the correlation between port development and ecological environment as well as the life quality should also be strengthened in order to facilitate the sustainability of social civilization and ecological resources from the port-city sustainable coordination.

(3) Support self-growth of the port-city to reach the goal by different means. As is indicated in this paper, despite a higher average developing level of cities than ports in Liaoning during the ten years, the comprehensive developing level of ports increases continuously at present and

was over 0.9 in 2017 compared to the level of approximately 0.6 of cities. Due to this mismatch, separate strategies should be established to achieve the goal of coordination. According to the principle of the cycle of accumulative causation, ports and cities are in high-level coupling and have an obvious correlation and their self-growth is the ultimate goal of coordinated and sustainable development. Therefore, ports and cities are supposed to formulate different strategies according to the current construction and development level as well as establishing a reward-and-punishment mechanism to promote the comprehensive development level from all aspects [52]. Cities should continue their development, upgrade their economic and intellectual levels, increase residents' well-being and make efforts to realize the integrated goal of ecological environment sustainability. Additionally, ports also play a pivotal role in trade, transportation, transit, storage and diplomatic gateways. In the process of enhancing their comprehensive development strength separately, their interaction in economy, transportation and industries ought to be taken into account as well to achieve common prosperity.

(4) Adhere to the strategy of differentiated and coordinated development and realize the advantage complementation by dislocation development. In terms of the development of each port-city system analysed above, the order of the correlation degrees is: Yingkou > Dalian > Dandong > Jinzhou > Huludao > Panjin. The order of the coupling degrees is: Dalian > Jinzhou > Yingkou > Dandong > Panjin > Huludao. Additionally, the order of the coordination degrees is: Dalian > Yingkou > Jinzhou > Dandong > Panjin > Huludao. There are significant differences among the development in different port-city systems so all ports should be clearly classified in terms of functional orientation, port and shipping industry, development plan, etc., so as to establish a strategy of differentiated and coordinated development with the purpose of common interests and avoid disorderly and vicious competition [53]. Dalian and Yingkou are the best in their overall performance and there is a fierce competition between them. While maintaining a coordinated and sustainable development, they should also give full play to their respective characteristics, clarify their functional orientation and avoid ineffective competition. As key regional ports, Jinzhou and Dandong have clear superiority in development and have accelerated in the port-city coordination. Thus, the coordinated relationship should be further enhanced to push the diversified and intelligent development forward. Panjin and Huludao work as supporting ports and their development is slightly backward. In consequence, port and urban construction should continue to be optimized and good relationship should also be built into port relations.

(5) Accelerate the construction of green and intelligent ports, steadily promote intelligent city development and improve the port-city interaction and sustainability. The sustainable development levels of the port-city interaction at present are not so optimistic. Only ports and cities in Dalian and Yingkou have achieved primary sustainability while, in other regions, further development is desperately needed. The sustainability of a port-city system depends on the sustainable development of both the two subsystems separately and their overall interaction. For the port subsystem, Liaoning ports should accelerate the construction towards green and intelligent ports as well as taking proper and timely measures to transform and upgrade ports. In addition, high-tech information technology are supposed to be introduced to facilitate the upgrading and updating of port industry and facilities with the logistics network and innovative technologies applied in ports. Intelligent ports have a significant impact on productivity, value-added services and employment [54]. They focus more on the rational utilization of land space, the protection of ecological environment and the construction of port culture to better integrate into port cities on the premise of maintaining and even promoting the port energy level. From the perspective of the city subsystem, intelligent cities should be planned and built. Cities ought to actively adopt innovative technologies and highly information-oriented management methods, increase the utilization rate of urban space and adjust industrial structure so as to adapt to the economic spillover effects caused by high-demand port business [55]. Moreover, it is

also suggested that port cities are supposed to give full play to the positive impacts brought by ports and strive for more competitive advantages in international trade. Finally, the port-city interaction should also be reconsidered and positioned. According to the different development stages and current situation of ports and cities, unique development paths should be formulated and joint efforts are needed to achieve the strong correlation, high coupling and high-quality coordination between ports and cities.

6.3. Limitations and Prospects

Although this paper has made some contributions to the port-city interaction and sustainability and the results can also provide some reference for relevant departments in promoting port-city sustainability, there are still several limitations in this study. Firstly, due to the very example of Liaoning port-city group based on which port-city interaction have been discussed and the particularity of the research methods, it is difficult to generalize the results to ports and cities elsewhere. Additionally, this paper only focuses on the port-city correlation, coordination and their sustainability in static state, so it is lacking in further study about the dynamic development trend of the port-city system. However, with the availability of data and the improvement of research methods in the future, we believe long-term research of the port-city interaction from the aspect of spatial dynamic can be achieved so as to explore the law of dynamic evolution of ports and cities and realize healthy, green and sustainable development. In addition, reasonable hypotheses are not established in this paper to carry out empirical research, which is exactly the direction of our improvement and breakthrough in future studies.

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