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An Evaluation of the Coupling Coordination Degree of the Yangtze River Delta Port Cluster Based on Coupling Theory

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Abstract : *To quantitatively assess the correlation between subsystems within a port cluster and the overall coordinated development of the port group, the current paper evaluates the coordinated development of port clusters. First, we construct an evaluation index system for the coupling and coordination of port clusters. Next, we introduce the contribution index of port subsystems, coupling degree, and coupling coordination degree functions to formulate a coupling coordination evaluation model for the port cluster. Finally, we use the Yangtze River Delta port cluster as a case study for validation, specifically using empirical data from 2012 to 2021. The findings reveal distinct phased characteristics in the coupling and coordination of port clusters in the Yangtze River Delta, marked by a notable transition from "maladjustment" to "coordination." Further, sustained high coupling values over a decade indicate a significant level of competition and cooperation among ports within the Yangtze River Delta port cluster. Over time, this competitive and collaborative dynamic has progressively evolved toward a more positive and structured direction. Lastly, it is expected that the evaluation model proposed in this paper can be extrapolated to other port clusters to gauge the extent of coordinated development, thereby facilitating horizontal comparisons and vertical analyses.*

Key words : *port cluster, coupling coordination degree, Yangtze river delta, coupling theory, coordinated development*

1. Introduction

Ports serve as fundamental and pivotal infrastructure, strategic resources, and crucial pillars for economic and social advancement. Evolving from port development, port clusters emerge as interconnected systems resulting from the interplay of ports through competition and collaboration. With the ascendancy of world-class port clusters, the trajectory of Chinese port development is shifting from cutthroat competition and disarrayed operations towards cooperative synergy and concentrated growth. However, the delineation of when ports in proximity constitute a unified port cluster lacks a universally accepted methodology. Initiatives aimed at formulating port policies for clusters or gateways are observable worldwide. Notably, in China, policymakers designate the Yangtze River Delta Port Cluster, Bohai Rim Port Cluster, Pearl River Delta Port Cluster, Southeast Coastal Port Cluster, and Southwest Coastal Port Cluster as the five major port clusters.

Despite sharing proximal distance, similar geographical positioning, and transportation networks, ports within a cluster possess collective advantages. Nevertheless, due to distinct administrative jurisdictions and divergent local interests, instances of isolated development and cutthroat competition among ports are prevalent. Numerous studies have examined the competitive and cooperative dynamics among ports within the same cluster (e.g., Fan et al., 2015; Wang et al., 2018; Zhou et al., 2018). However, these studies primarily focus on inter-port competition and cooperation dynamics, neglecting comprehensive research on the overall coordinated development and degree of coordination within port clusters.

Within China's national economic planning policies concerning port development, an emphasis on enhancing the coordinated development of port clusters and fortifying comprehensive transportation hubs and logistics networks has emerged as a pivotal objective. Such coordinated development not only fosters the sustainable advancement of ports within clusters but also fuels the rapid growth of regional economies. While China's efforts in port integration and constructing port cluster layouts have yielded certain achievements, challenges persist, including redundant infrastructure construction and imbalanced resource allocation. Hence, this study employs the coupling coordination index to establish a coupling coordination evaluation model for port clusters, enabling the calculation and analysis of the coordinated development levels of individual port subsystems and the port group as a whole.

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2. Literature review

2.1 Research on Port Cluster

The integration of cluster theories into port studies commenced approximately two decades ago. Pioneering contributions in this domain include the works of Haezendonck (2001) and de Langen (2004), which laid the foundation for subsequent research endeavors. Noteworthy follow-up studies include those by Lambrou *et al.*(2008), Musso and Ghiara (2008), Roh et al.(2007), and Brett and Roe (2010). Within port studies, the conventional perspective characterizing ports as "transport nodes" has been firmly established (e.g., Button, 1993; Charlier & Ridolfi, 1994; Cooper, 1994; Goss, 1999; Pallis et al., 2010; Robinson, 2002). The "cluster perspective" complements this notion of ports as transportation hubs. Central to this cluster perspective is the acknowledgment that interdependent firms tend to cluster in port regions, leading to various forms of coordination and resource sharing.

2.2 Research on Coordinated Development of Port Clusters

Currently, numerous studies predominantly focus on the competitive dynamics and collaborative relationships within port clusters, as well as the strategic positioning of regional port development. Over the past decade, however, there has been a noticeable shift towards investigating the coordinated development of port clusters.

The exploration of coordinated development within port groups was virtually non-existent in China prior to 2001, with only one notable publication, "Dynamic Coordination between the Port Groups of Liaodong Peninsula and the Northeast Economy" by Ling Chengquan in 1989. Following China's accession to the WTO in 2001, the Chinese government implemented a series of policies aimed at opening maritime trade, subsequently initiating reforms in port management systems, fostering the coordinated development of regional port groups, and promoting port transformation and upgrading. As evidenced by data from the China Port Yearbook, since 2008, more than half of the world's top ten container ports have been located in China, solidifying its status as a prominent global port hub. With the successive introduction of policies and the increasing international competitiveness of Chinese ports, scholars have begun to recognize the importance of studying the coordinated development of port clusters as an integral component of port group research.

Numerous studies have centered on the coordinated development of port clusters, exploring three primary dimensions.

Firstly, scholars have examined the essence and defining features of coordinated development within port clusters. Various perspectives have been offered by different scholars regarding the conceptualization of coordinated development within port clusters. Despite differences in emphasis, scholars commonly concur that coordinated development within port clusters entails a group of ports sharing similar geographical locations and serving a common economic hinterland. Through the implementation of unified strategies and judicious planning that consider the interests of all stakeholders, a situation of synchronized and phased development is achieved.

The second aspect pertains to the primary factors influencing the coordinated development of port clusters. Scholars have extensively examined the role and impact of various factors, including information technology (Li et al., 2017; Wang, 2017), the relationship between ports and their hinterlands (Cheng & Wang, 2015; Fang, 2000), the activities of port enterprises themselves (Sun, 2018; Tian et al., 2016), and governmental policy factors (Wang & Yu, 2019; Zheng, 2018) on the advancement of port clusters.

The third aspect delves into the value derived from the coordinated development of port clusters. Firstly, the cluster perspective offers novel insights into the determinants of port competitiveness. For instance, cluster research highlights the significance of intra-cluster competition (Porter, 1998; as applied in Haezendonck, 2001). Secondly, while the traditional transport node perspective typically gauges port competitiveness based on throughput volume alone, the cluster perspective introduces additional performance metrics such as value added (Haezendonck, 2001; Haezendonck et al., 2000) and investment levels (Robinson, 2002).

2.3 Shortcomings in the Research on the Coordinated Development of Port Clusters

Research on port clusters as a whole did not commence early, with investigations into the coordinated development of port clusters emerging later. However, as the value of port clusters has grown, both the quantity and quality of research on their coordinated development have significantly increased.

Upon reviewing the research landscape, it appears that scholars place greater emphasis on the "development value" of port clusters rather than on the "development of port clusters" themselves. Nonetheless, research in this domain still exhibits three notable deficiencies: Firstly, the theoretical framework of research remains imperfect, and the developmental stage of the coordinated development framework for port groups is still evolving. Secondly, research methodologies predominantly rely on qualitative analyses. While many studies propose strategies based on current circumstances, the lack of universality in the conclusions inhibits comparisons between different port groups. Thirdly, existing quantitative analyses tend to segregate research on internal subsystems of port groups from investigations into the groups as a whole, resulting in more one-sided research outcomes.

3. Theoretical Basis of Coupling Coordination Model

3.1 What are Coupling Degree and Coupling Coordination Degree?

The concept of coupling originates from synergetic theory in physics, serving to gauge the correlation between modules within a system and the hierarchical order among its subsystems (Zhou, 2020). Benign coupling occurs when system elements operate harmoniously, cooperate effectively, and maintain close relationships, whereas vicious coupling arises when friction, confrontation, or estrangement characterizes the interactions among elements (Xing, 2019).

The study of coupling coordination assesses the extent of benign coupling within a system. It measures the harmony among internal system elements during development, providing a quantitative gauge of coordination levels and reflecting the system's progression from disorder to order.

In essence, the coupling coordination degree model initially employs the coupling degree to elucidate the interplay among various subsystems, and subsequently integrates the coordination degree to holistically assess the entire system. This model serves to depict the reciprocal influence and the extent of favorable interaction between systems. Due to its simplicity, ease of calculation, and intuitive results, it finds widespread application in empirical studies evaluating the coupling and coordinated development levels across various systems, including but not limited to the environment, economy, social development, urbanization, agriculture, industry, transportation, and population dynamics.

3.2 Connotation and Mechanism of Coordinated Development of Port Clusters

The port cluster functions as an integrated system comprising interacting and cooperating subsystems, thus making the coupling coordination theory originating from physics applicable to port clusters. On one hand, port cluster coupling pertains to the dynamic relationships formed by various subsystems within the port cluster through specific associations (such as policy orientation, cooperation, and competition) during the process of development and evolution. On the other hand, port cluster coordination involves the establishment of an orderly and stable state among the internal subsystems of the port cluster by mitigating inherent contradictions and conflicts, thereby maximizing the overall benefits of the complex system (Zhou & Yang, 2020).

Port cluster coupling and coordination represent complex and vital concepts, involving interactions and influences among multiple ports to form an organic whole, aiming at maximizing overall economic benefits (Ye & He, 2024). Firstly, the coupling coordination of port clusters underscores the mutual cooperation and collaboration among ports. Within a port cluster, each port possesses distinct advantages and characteristics, facilitating resource sharing and complementary advantages, thus enhancing the competitiveness of the entire port cluster. For example, large ports can leverage their economies of scale to handle bulk cargo transportation, while medium and small ports can specialize in transporting and servicing specific goods, thereby fostering a situation of coordinated and mutually beneficial development. Secondly, the coupling coordination of port clusters also manifests in their interaction with the hinterland economy. Strengthening ties with the hinterland economy enables ports to better understand market demands, optimize cargo transportation structures, and enhance logistics efficiency. Concurrently, the development of the hinterland economy provides ports with more sources of cargo and market opportunities, fostering a mutually beneficial development pattern (Ouyang & Zhu, 2023).

The coupling degree and coordination degree of port clusters mentioned above can be quantified using the coupling degree and coupling coordination degree, respectively. The coupling degree primarily aims to illustrate the level of correlation between subsystems or elements, while the coupling coordination degree focuses on portraying the overall efficiency and synergy of the system.

Building upon this framework, this paper constructs a comprehensive index to assess the coupling and coordinated development of various subsystems within the port group system. This index enables the reflection of not only the correlation degree of each subsystem but also the overall coordination of the system.

4. Construction of Yangtze River Delta Port Cluster Coupling Coordination Degree

4.1 Research Scope and Index Selection

The Yangtze River Delta, situated between the Yangtze River and the East China Sea, represents an amalgamation of the Yangtze River system, the Qiantang River system, and the Huaihe River system with the East China Sea. Characterized by a dense waterway network and abundant port resources, the region boasts prominent maritime infrastructure.

The Yangtze River Delta port cluster encompasses eight seaports, including Shanghai Port, Ningbo-Zhoushan Port, and Lianyungang Port, alongside approximately 40 inland river ports. Statistical data reveals that the total mileage of inland river waterways in the Yangtze River Delta region exceeds 36,000 kilometers, facilitating seamless integration between inland river ports and seaports, thereby establishing an efficient waterborne transportation network. In 2021, the cargo throughput of ports in the Yangtze River Delta accounted for an impressive 39.3% of the total coastal port throughput in China. The hinterland of the port cluster enjoys convenient transportation, a high level of economic development, and active foreign trade. Consequently, the Yangtze River Delta port cluster stands out as the port cluster boasting the highest port density and throughput in China.

As the Yangtze River Delta city cluster continues to evolve, the scope of the Yangtze River Delta port cluster undergoes corresponding changes, leading to fluctuations in the scale and number of ports. The port facilities within the Yangtze River Delta port cluster encompass coastal ports, Yangtze River ports, ports in other river systems, and lake ports. Taking into account data availability and comparability, this paper selects six coastal ports and eight inland ports within the Yangtze River Delta port cluster as the focal points of investigation (see Table 1).

Drawing inspiration from the enterprise production process, this paper establishes an evaluation index system comprising three dimensions: the input layer, process layer, and output layer. The input layer signifies the indices reflecting the economic development level of the port hinterland. The process layer encompasses the navigational conditions and infrastructure development of the port itself, serving as an intermediary indicator for converting hinterland logistics demand into port output. Lastly, the output layer signifies the current economic contribution and future development potential of the port.

Building upon this framework and consulting previous relevant literature, the selection of index criteria prioritizes scientific rigor, objectivity, data availability, completeness, and representativeness. Consequently, regional GDP, year-on-year GDP growth rate, import and export volume of foreign trade, and the proportion of tertiary industry value added in GDP are chosen as indices for the port input layer. Meanwhile, the number of production berths and the length of ports exceeding designated sizes are selected as indicators for the port process layer. Finally, cargo throughput, container throughput, and foreign trade throughput are identified as indicators for the port output layer (see Table 2).

The data for these indicators primarily originates from sources such as the China Urban Statistical Yearbook, the China Port Yearbook, and other pertinent data repositories. In instances where data is missing for certain years, the average value of the data from the preceding three years is utilized to ensure completeness.

Table 1 Ports of the Yangtze River Delta Port Cluster Defined in This Paper

Type of port	Port	Location	Administrative region
Seaport	Shanghai Port	The estuary of the Yangtze River and the East China Sea, and the central part of the continental coastline	Shanghai city
	Lianyun Port	Northeast of Jiangsu Province	Jiangsu Province
	Ningbo-zhoushan Port	Ningbo City, Zhoushan Islands	Zhejiang Province
	Jiaxing Port	North bank of Hangzhou Bay	Zhejiang Province
	Wenzou Port	Southern Zhejiang Province	Zhejiang Province
	Taizhou Port	Southeast Coast of Zhejiang Province	Zhejiang Province
Inland port	Nanjing Port	The middle and lower reaches of the Yangtze River	Jiangsu Province
	Nantong Port	The lower reaches of the Yangtze River, the central and northern regions of Jiangsu Province	Jiangsu Province
	Suzhou Port	Southeast of Jiangsu Province, along the Yangtze River	Jiangsu Province
	Zhenjiang Port	Intersection of Yangtze River and Beijing-Hangzhou Grand Canal	Jiangsu Province
	Anqing Port	the source of the Wanjiang River	Anhui Province
	Tongling Port	lower reaches of the Yangtze River	Anhui Province
	Wuhu Port	Junction of Qingyi River, Yuncao River and Yangtze River	Anhui Province
	Maanshan Port	South bank of the lower reaches of the Yangtze River	Anhui Province

Table 2 Evaluation index system of port group coupling coordination

Indicator Category	Indicator (Unit)	Data Sources	The Meaning of Indictor
Input Layer	Regional GDP (100 million yuan)	China Statistics Yearbook	reflects the economic development level of port hinterland cities
	Year-on-year growth rate of GDP (%)		reflects the economic development level of port hinterland cities
	Foreign trade import and export volume (US $100 million)		reflects the foreign trade situation of the port hinterland cities
Process Layer	The number of berths for production terminals	China Transport Statistics Yearbook	reflects the construction of port infrastructure
	The length of ports above designated size (m)		reflects the construction of port infrastructure
Output Layer	Cargo throughput (10000 tons)	China Port Yearbook	reflects the production and operation status of the port
	Container throughput (10000 TEU)		reflects the production and operation status of the port
	Foreign trade throughput (10000 tons)		reflects the production and operation status of the port

4.2 Calculation of Contribution Index Weight and Comprehensive Evaluation Value of Port Subsystem

Due to differences in dimension and magnitude among the selected raw data, it is imperative to standardize the raw data initially. Additionally, when employing the entropy method to compute index weights, the index data must be non-negative to ensure accuracy. Therefore, data must be adjusted accordingly to meet this requirement. x_{ij} represents the value of the j-th index of sample i, and u_{ij} represents the value of the j-th index of sample i after standardization and nonnegativization, where i=1, 2, m; j=1 , 2 , ... , n; M represents the number of samples and n represents the number of indicators. The specific methods are as follows.

For positive indicators, the formula for standardization and non-negative treatment is as follows:

$$u_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_j) - \min(x_j)} + 0.001 \quad (1)$$

For negative indicators, the formula for standardization and non-negative treatment is as follows:

$$u_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_j) - \min(x_j)} + 0.001 \quad (2)$$

The entropy method is used to calculate the weight of each index, which can avoid the interference of human factors on the data weight. Compared with some subjective weighting methods, entropy method is more objective and accurate. The specific calculation steps are as follows:

Step 1, calculate the proportion of the j-th index of sample i. The calculation formula is:

$$S_{ij} = \frac{u_{ij}}{\sum_{i=1}^{m} u_{ij}} \quad (3)$$

Step 2, calculate the entropy value h_j of each index, and the calculation formula is:

$$h_j = -\frac{1}{\ln m} \sum_{i=1}^{m} S_{ij} \ln s_{ij} \quad (4)$$

Step 3: calculate the difference coefficient of each index. The calculation formula is:

$$\alpha_j = 1 - h_j \quad (5)$$

Step 4, use the entropy method to calculate the weight w_j of each index. The calculation formula is:

$$w_j = \frac{\alpha_j}{\sum_{j=1}^{n} \alpha_j} \quad (6)$$

After completing the above normalization, standardization and weight calculation of raw data, we need to calculate the contribution index of the port subsystem. The contribution index of the port subsystem is the contribution degree of each subsystem of the port to the order degree of the port cluster, and it is also the basis for further calculation of the coupling coordination of the port cluster. Its calculation formula is:

$$u_i = \sum_{j=1}^{n} w_j u_{ij} \quad (7)$$

4.3 Calculation of Port Cluster Coupling Coordination Degree

Coupling degree is an index reflecting the degree of interaction between subsystems, and its calculation formula is:

$$C_n = n \cdot \{(u_1 \cdot u_2 \cdots \cdots u_n)/(u_1 + u_2 + \cdots u_n)^n\}^{\frac{1}{n}} \quad (8)$$

Where, Cn is the coupling value, and the value range is Cn ∈ [0,1]. When the value is 0, it belongs to the disordered coupling state, and when the value is 1, it belongs to the ordered coupling state. In other words, the closer its value is to 1, the stronger the orderliness of the port cluster system, the closer the connection between subsystems, and the closer the port cluster is to the coupling under the theoretical state.

Although the degree of coupling can measure the degree of interaction between subsystems, if all subsystems are at a low level of development, the degree of coupling between them is still high. Coupling coordination degree can not only measure the degree of interaction between subsystems, but also more objectively balance the level of coordinated development between quantum systems. Only when the coupling degree is high and each subsystem is at a high level of development, the value of coupling coordination degree is high, which indicates that the level of integration and development between subsystems is high. The calculation formula of coupling coordination degree between port group systems is:

$$D = (C_n T)^{\frac{1}{2}} \quad (9)$$

$$T = \sum k_i u_i \quad (10)$$

Where Cn is the coupling value, which is obtained from equation (8). T is the comprehensive synergy index of the system, that is, the overall synergy effect or contribution of the system. To avoid when the values of u_i are relatively low, it is possible to draw a conclusion that the coordination degree is relatively high. Here, the comprehensive evaluation index T of the composite system is used for correction, where $T = \sum k_i u_i$.

Here, k_i represents the weighting coefficient, indicating the importance of each port subsystem within the port cluster. Following the practice of previous studies, we consider the 14 ports in the Yangtze River Delta port cluster to be equally important, thus assigning a value of 1/14.

Table 3 Classification of coupling coordination types of port groups

Coupling coordination level	Coupling coordination degree (D Value)	Coupling coordination level evaluation	Coupling coordination level	Coupling coordination degree (D Value)	Coupling coordination level evaluation
1	[0, 0.1]	Extreme maladjustment	Ⅵ	[0.5,0.6]	Grudging coordination
Ⅱ	[0.1, 0.2]	Severe disorder	Ⅶ	[0.6,0.7]	Primary coordination
Ⅲ	[0.2, 0,3]	Moderate disorder	Ⅷ	[0.7,0.8]	Intermediate coordination
Ⅳ	[0.3,0.4]	Mild disorder	Ⅸ	[0.8,0.9]	Good coordination
Ⅴ	[0.4,0.5]	Borderline disorder	Ⅹ	[0.9,1]	Perfect coordination

Table 4 Coupled coordination degree of Yangtze River Delta port cluster (2012-2021)

Year	Coupling degree (Cn)	Comprehensive coordination index (T)	Coupling coordination degree (D)	State judgment
2012	0.791	0.184	0.382	Mild disorder
2013	0.952	0.227	0.465	Borderline disorder
2014	0.975	0.261	0.505	Grudging coordination
2015	0.969	0.319	0.556	Grudging coordination
2016	0.965	0.379	0.605	Primary coordination
2017	0.988	0.452	0.668	Primary coordination
2018	0.987	0.519	0.716	Intermediate coordination
2019	0.986	0.559	0.742	Intermediate coordination
2020	0.984	0.605	0.772	Intermediate coordination
2021	0.990	0.816	0.899	Good coordination

4.4 Classification of Coupling Coordination Types of Port Clusters

The value range of coupling coordination of port cluster (D) is ∈ [0,1]. According to the connotation of coupling coordination, the closer the D value is to 1, which means that the higher the degree of correlation between subsystems within the port cluster. In order to more accurately describe the degree of coupling and coordinated development of the port cluster system, the uniform distribution function method is used to classify the types of port cluster coupling and coordinated dispatching. Each type of name is referenced from previous studies. See Table 3 for details.

5. An Empirical Analysis on the Evaluation of Coupling Co-dispatch of Port Clusters in the Yangtze River Delta

5.1 Calculation of coupling co-dispatch of port groups in the Yangtze River Delta

According to the evaluation index system for coupling and coordination of port clusters outlined in Table 2, data for nine indices from 2012 to 2021 were collected and arranged for the 14 major ports within the Yangtze River Delta port cluster. Initially, the original data were standardized using formulas (1) and (2) to eliminate dimensional disparities. Subsequently, the weights of the nine evaluation indicators were determined using the entropy method, as per formulas (3), (4), (5), and (6), while the contribution index for each port subsystem was computed following formula (7). Next, formulas (8) and (10) were employed to calculate the coupling degree and comprehensive synergy index of the port cluster, with n set as 14, representing the total number of selected ports.

Finally, the coupling coordination degree of the port cluster was calculated using formula (9), with k_i assigned a value of 1/14 to reflect the comparable importance of each port subsystem in the integration and development of the port cluster. By following these formulas and steps, the coupling coordination degree of the Yangtze River Delta port cluster from 2012 to 2021 was determined and evaluated in conjunction with Table 3. The results are presented in Table 4.

5.2 Analysis and Evaluation of Port Cluster Coordination in the Yangtze River Delta

In the process of calculating the coupling degree and coupling coordination degree, the contribution index of

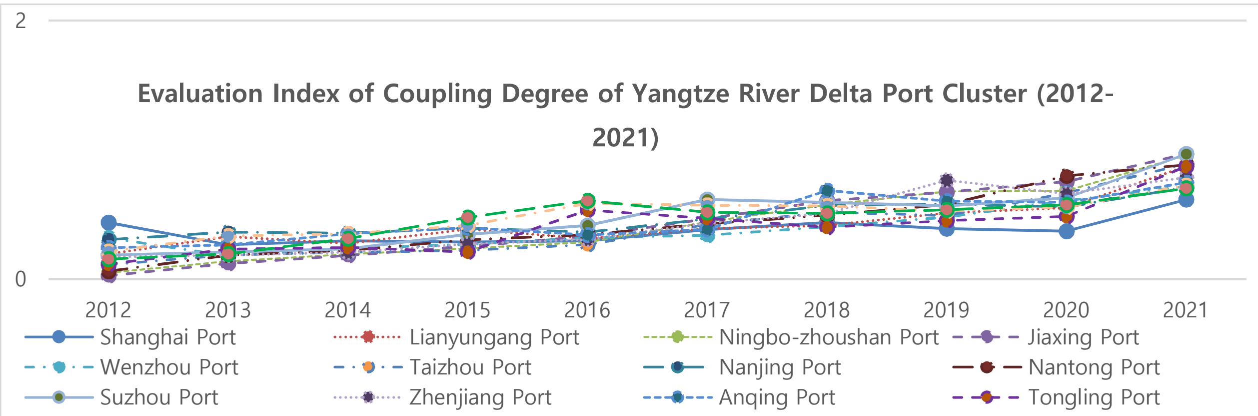

Fig. 1 Evaluation Index of Coupling Degree of Yangtze River Delta Port Cluster

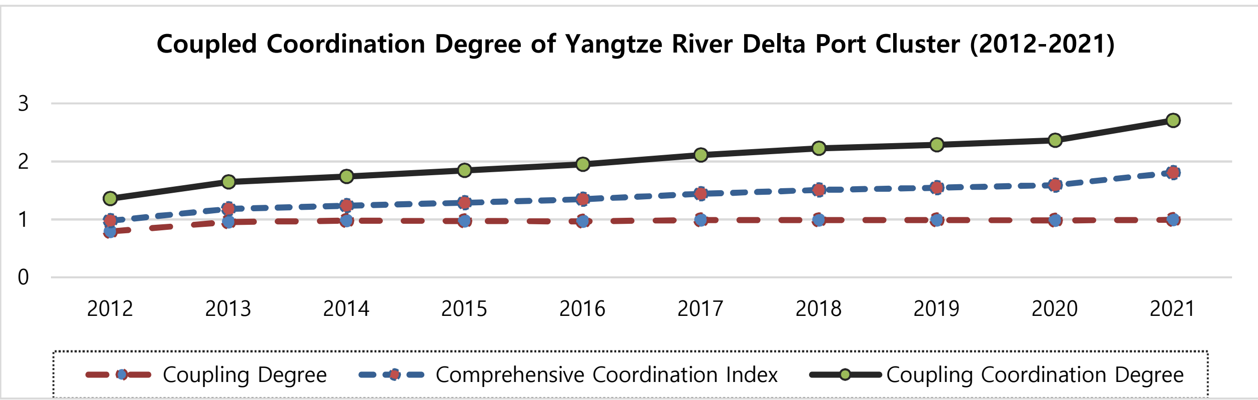

Fig. 2 Coupled Coordination Degree of Yangtze River Delta Port Cluster

each port subsystem to the port group, denoted as, is determined using formula (7). Figure 1 can be generated based on the calculated values of u_i. It is evident from Figure 1 that the contribution index of each port subsystem in the Yangtze River Delta towards the orderly development of the port cluster system generally exhibited an upward trajectory from 2012 to 2021, with notable increases observed, particularly in 2021.

To provide a more visually comprehensive depiction of the changing trends and relationships among the coupling degree, comprehensive coordination degree, and coupling coordination degree of the Yangtze River Delta port group, the findings from Table 4 are summarized in Figure 2.

From Figure 2, it is evident that the value of the coupling degree (Cn) has increased from 0.791 in 2012 to 0.990 in 2021. This suggests that the coupling degree of the Yangtze River Delta port cluster has consistently remained at a high level and is gradually exhibiting a trend towards benign coupling despite minor fluctuations. Simultaneously, the ongoing growth of the coupling degree indicates a strengthening interconnectedness among port subsystems in both cooperation and competition within the port cluster.

From the perspective of the comprehensive coordination index (T) of the port cluster, its value increased from 0.184 in 2012 to 0.816 in 2021, indicating a stable and sustained growth over the past decade. This suggests that the development of the internal subsystems of the port cluster has been relatively synchronous, and they are evolving towards a more competitive and interconnected system.

Regarding the port cluster coupling coordination (D), its value has undergone significant changes, rising from 0.382 in 2012 to 0.899 in 2021. The coupling coordination state has progressed steadily from the initial stages of mild maladjustment and near−maladjustment to the current stages of grudging coordination, primary coordination, and intermediate coordination, culminating in a state of good coordination by 2021. This indicates that the coordination degree of the Yangtze River Delta port cluster exhibits distinct phased characteristics, with an overall upward trend in coordination degree.

Based on the above analysis of the coupling degree (Cn), it is evident that the coupling degree of the Yangtze River Delta port cluster is high, and the level of coupling coordination degree development has also significantly improved over the past decade. This suggests that the subsystems of the port cluster demonstrate a high level of interaction, and only when these subsystems adapt to each other in terms of quantity and scale, and exhibit synchronous development speeds, can they collectively contribute to the overall efficient development of the port cluster.

6. Conclusions

This study utilizes the coupling coordination theory to construct a coupling coordination evaluation model for port clusters, using the Yangtze River Delta port cluster as a case study to validate the evaluation model.

Through the examination of the Yangtze River Delta port cluster, it is observed that the coupling and coordination within the cluster underwent a significant transformation from "maladjustment" to "coordination" during the period from 2012 to 2021, ultimately reaching a state of good coordination by 2021. Furthermore, in conjunction with the consistently high coupling values over the past decade, it is evident that there exists a notable degree of competition and cooperation among the ports. With the passage of time, this competition and cooperation have progressively evolved in a positive and structured manner, thereby enhancing the coordination degree of the port cluster and ultimately attaining the current state of good coordination.

The port cluster coupling coordination index utilized in this study is a comprehensive model derived from examining both the overall coordination degree of the port cluster and the correlation degree of each port subsystem. This research model addresses the shortcomings of previous studies by considering not only the interaction among port subsystems but also the overall development of port clusters. The coupling and coordination evaluation model of port clusters developed in this study provides a quantitative analysis and assessment framework, which can be applied to other port clusters, facilitating comparisons across different port clusters.

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