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Evaluation and strategy development of port-industry-city integration: A China's case

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A B S T R A C T

In large economies of high-volume international trade, such as China, the concept of regional port integration requires the establishment of provincial-level port companies and the consolidation of major local ports. While port reform at the provincial/regional level has seen considerable success, the current state-of-the-art studies on port integration mainly focus on two-dimensional analysis (e.g., port-city and port-industry), which reveals a remaining research gap in the evaluation of the port-Industry-City (PIC) integration from a new three-dimensional perspective. This study aims to develop a new method enabling the assessment of the impact of provincial reform at the PIC level. The method can deliver a new comprehensive evaluation index system and a new coupling coordination degree model (CCDM) to facilitate PIC integration. Moreover, a critical analysis is conducted on the main trends, primary obstacles, and impact of port reform models at the PIC level. Real big data describing prefecture-level cities is collected and used to conduct a case study of coastal ports across different provinces in China. The results reveal an overall upward trend of the comprehensive development index, which is especially evident after the port reforms. Furthermore, significant strategic developments are proposed in the implementation of regional port reform. Except for Zhenjiang, southern and central cities perform better than those in northern regions. Consequently, this study makes new contributions to enabling the quantification of the impact of the reform on PIC integration and laying the groundwork for decision-makers seeking to determine appropriate port management models.

1. Introduction

As port functions continue to evolve, port system reforms are being progressively implemented worldwide. Port reform refers to the transformation of management models across four key dimensions: administrative entities, management functions, operational mechanisms, and legal systems (Cai et al., 2024; Cheng et al., 2022). The primary objective is to improve port efficiency, service quality, competitiveness, and sustainability, enabling ports to better adapt to shifting market demands and emerging environmental challenges. However, the motivations and impacts of these reforms vary significantly between countries (Buor, 2024). For instance, Mexico introduced port reform in the 1990s to improve competitiveness in the global trade market (Villa, 2017). Spain's port reform led to significant advancements in its ports' technological change and efficiency over time (González & Trujillo, 2008). Although the Japanese government has undertaken port reforms since the 1990s to address the declining international competitiveness of Japan's container ports, cargo handling volumes have continued to decrease. Within the global maritime container network, the centrality rankings of Keihin and Hanshin ports have dropped significantly, whereas major ports across Asia have consistently maintained high rankings (Sugimura et al., 2023). Given the prevailing uncertainties, evaluating the impacts of port reforms remains a primary objective for many researchers (Pilcher & Tseng, 2017). Relevant research has focused on various key areas, including evaluating performance changes following governance reforms (Brooks & Pallis, 2008), analyzing the socio-cultural environment of reformed ports while considering the specificities of local environments (Debrie et al., 2013), and developing methods for assessing the enhancement of port competitiveness resulting from reforms (Cheng et al., 2022).

Among the reforms, port integration attracts increasing attention, particularly from large economies of high-volume international trade

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such as China. In response to evolving societal demands and in pursuit of maximizing benefits throughout China's contemporary history, the administrative paradigm of port governance in the country is undergoing significant transformations. This progression encompasses a centralized phase from 1954 to 1984, a dual-track system from 1984 to 2003, and a phase of decentralization from 2003 to 2015, culminating in a semi-centralized approach from 2015 onwards (Chen et al., 2020; Cullinane & Wang, 2006). During the centralized management stages, the focus on the public attributes of ports came at the expense of market dynamics, leading to slow port development. The subsequent dual-track system introduced a balance between public oversight and market-oriented practices, resulting in the rapid development of China's ports. Nevertheless, the full decentralization of port authorization to local governments led to fragmented planning, disorderly expansion, and intense homogeneous competition among ports. To address these issues and support the development of world-class ports, the concept of a semi-centralized phase was proposed, building on the foundation of the previous three phases. The semi-centralized phase is also known as regional port integration, which refers to the reorganization and consolidation of port resources within a particular province. Thus, provincial ports are integrated through administrative and economic measures. Provincial port groups are typically established to facilitate the centralized administration and operation of the majority of ports within the region (Zhang et al., 2021b). However, the complete implementation of the integration reform in China's coastal provinces has not been achieved, as the market participants within the system have shifted from numerous local port companies to a limited number of provincial port groups (Feng et al., 2019). While integration efforts alleviate internal competition within provinces, they may also create challenges, such as weakening the relationship between ports and their supporting cities (Zhang et al., 2021). This detachment risks undermining the integrated development and synergies between ports and urban areas, highlighting the need for forward-looking planning and adaptive strategies to ensure sustainable and balanced growth in China's port sector.

Port cluster refers to a collection of interdependent firms engaged in port-related activities within the same port area, which share similar development strategies that generate competitive advantages in relation to the cluster's external environment (Zhang et al., 2025). Port clusters at the provincial level are predominantly under the jurisdiction of provincial governments or managed by large-scale state-owned enterprises, all under the aegis of the central government. These entities possess a substantial portfolio of port assets, wield significant bargaining leverage, and exhibit robust investment capabilities (Chen et al., 2020). In the reform process, the change in equity structures and market competition entities poses a primary challenge. Overall, the integration processes of provincial regional ports in Zhejiang, Jiangsu, Shandong,

Fig. 1. The investigated area.

and Liaoning achieved notable breakthroughs, marked by the establishment of provincial port groups in 2015, 2017, 2018, and 2019, respectively. The Mixed Reform implemented by the China Merchants Group leads to a vertical linkage mode of integration in Liaoning, which contrasts with the top-down integration approach led by provincial state-owned enterprises in Zhejiang, Jiangsu, and Shandong. Diverse approaches can lead to achieving varying levels of PIC, requiring a new indexing system to benchmark, standardize, and evaluate the integration for rational strategic development at both national and international levels. This study aims to develop a new method enabling the assessment of the impact of regional reform at the PIC level and lays the groundwork for decision-makers seeking to determine appropriate port management models. Considering data availability and the fact that regional port integration began in 2015, coastal port cities were selected for this study. Fig. 1 presents the locations of the port cities in the research areas.

Numerous studies have confirmed that ports serve as significant catalysts for urban development (Efimova & Gapochka, 2020; Lonza & Marolda, 2016). Research on the relationships between ports and cities has a long history, with scholars extensively examining various aspects, including the economic impact of ports on urban areas (Zhao et al., 2023), their hierarchical scale and distribution (Xu et al., 2021), interaction models and processes between ports and cities (Guo & Qin, 2022), and the interplay between ports and urban environments (Chen et al., 2022; Gonzalez-Aregall & Bergqvist, 2020). At the level of port-industry relationships, scholars investigate topics such as the role of port infrastructure in improving supply chain integration for industries (Park & Dossani, 2020), ports concentration and competition, and strategies for industrial transformation and upgrading (Li et al., 2022; Yang et al., 2019).

The Ministry of Transport of the People's Republic of China issues its guidelines for Building World-Class Ports (MOT, 2019), emphasizing the degree of PIC integration as a key indicator of a port's economic impact. Subsequently, local governments roll out specific action plans for PIC integration, such as Tianjin's "Policy Measures for Promoting High-Quality Integration of Port, Industry, and City Development" (TMPG, 2023). PIC integration extends the traditional port-city relationship to include a focused integration on the industry. It represents an urban economic model where the city relies on the port and centers around port-related industries. The goal is to foster a new development pattern where ports, cities, and industries coexist and thrive, emphasizing the enhancement of complementary and symbiotic relationships among these three elements. Research on PIC integration has primarily concentrated on challenges encountered at different development stages, addressing policies, legal regulations, and port management (Taylor & McDonald, 2023; Zhou et al., 2023).

In light of the state-of-the-art developments described above in PIC, the main research challenges associated with port reform and the PIC system, particularly in evaluating their effects, remain as follows:

(1) Existing methods for assessing port reforms are criticized in terms of their precision, breadth and standardization. Quantitative approaches focusing on economic impacts require reliable evaluation methods for both direct and indirect effects, while qualitative analysis could arguably introduce subjective bias.
(2) The aforementioned studies have not specifically investigated the correlation between port-related industries and ports, nor have they analyzed ports, cities, and industries as three subsystems.
(3) Comparative studies on the development of PIC integration before and after port reforms are limited, although such research is vital for evaluating the impact of port system reforms.

Thus, there exists a significant research gap, particularly in the comparative assessment of PIC integration before and after port reform.

The main contributions of this study are therefore outlined below:

(1) It investigates the reform of port integration in China and assesses the coupling effect by considering ports, cities, and industries as three interactive subsystems. This approach involves isolating the industrial subsystem to explore deeper into the interconnections between ports, cities, and industries.
(2) It introduces a comprehensive PIC integration evaluation index system, utilizing the proposed CCDM to measure changes before and after the implementation of regional port integration policy through defined specific indicators.
(3) It delves into the underlying factors contributing to these changes. Its findings serve as a valuable resource for developing global port management models and shaping the future trajectory of port and urban growth.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive review of the existing literature. Section 3 describes the methodology proposed to conduct this study. A comparative analysis of the PIC evaluation results is presented in Section 4, followed by detailed discussions and implications. Finally, Section 5 presents the conclusions.

2. Literature review

In Section 2.1, the impact of ports on urban economic development and environmental quality, as well as industries related to ports and trade, is primarily explored. In Section 2.2, the selection of evaluation methods and indicators is addressed. Through a review of relevant literature, the achievements and limitations of existing studies are analyzed to establish a theoretical foundation for future research.

2.1. Port-industry-city interactions

Ports, as critical transportation infrastructure, have multifaceted impacts on cities. Thus, in recent decades, the contribution of coastal ports to urban economies has been extensively investigated. For example, Li (2019) used econometric analysis to illustrate the correlation between port or container throughput and regional GDP, revealing their intrinsic relationship. Hidalgo-Gallego and Núñez-Sánchez (2023) assessed the impact of ports on city economies, particularly their role in creating employment opportunities within port areas. Therefore, local economic development encompasses not only GDP but also other critical factors like population, employment, area, and intellectual property, showcasing the interaction between port and urban development (Bottasso et al., 2014).

Ports function as more than just transportation hubs; they also attract various shipping-related elements to port cities, including logistics parks and free trade zones. This clustering positively impacts both the ports themselves and the surrounding cities (Cai et al., 2021; Fan et al., 2022). Due to their strategic coastal locations, shipping-related industries tend to concentrate on coastal port cities, particularly premium shipping services, thereby fostering their development into international shipping centers (Wan & Luan, 2022). Furthermore, ports contribute not only directly but also indirectly to the economy of cities, although quantifying these indirect contributions accurately can be challenging due to the involvement of multiple industries. Over the past 30 years, China's port industry has developed by leaps and bounds. An effective method has been developed for quantifying both the direct and indirect contributions of the port industry by considering industrial linkage effects, the production-inducing effects of port investment, the supply shortage effects of port losses, and employment-inducing effects. This provides a relatively effective method of assessing the economic contributions of the port industry, although the results are still somewhat coarse (Wang & Wang, 2019).

With the increased environmental awareness, the relationship between ports and urban environments has gained increasing attention. Current discussions revolve around sustainable development in both ports and urban environments (Kong & Liu, 2021). While stringent environmental policies may increase costs for port enterprises, they also lead to improvements in urban air quality and other environmental aspects, along with the social responsibility of port development (Chen & Lam, 2018). Therefore, environmental factors must be carefully considered in the relationship between ports and cities (Ducruet et al., 2024). For instance, research by Chen et al. (2022) explored the coupling effect between port city development and the environment using indicators such as energy and electricity consumption and air quality, illustrating the synchronous development of Shanghai's port economy and urban environment.

On the other hand, the hinterland of a city serves as a vital source of cargo for ports, thus playing a pivotal role in their sustainable development. Intense competition in the hinterland can affect the growth of port throughput (Wan & Luan, 2022). Ports not only influence their host cities but also have positive effects on the surrounding areas, particularly industries that heavily rely on imports and exports. The relationship between ports and industry clusters is intricate (Zhang & Lam, 2016). According to the supply shortage effect, the industries primarily affected by port activities are primarily manufacturing and tertiary sectors (Wang & Wang, 2019). Commonly used indicators for characterizing industrial development include industrial structure (e.g., industrial output value), employee proportion, and industrial scale (e.g., the number of large-scale enterprises and their output values) (Gan et al., 2020).

Government-led investment attraction typically drives the development of local industries, especially when governments recognize the pivotal role of ports and prioritize port-related industries (Pettit, 2008). The regional integration of Chinese ports, where primary management rights are often held by provincial entities, will reduce the shareholding ratio for local governments (Zhang et al., 2021). Therefore, it is particularly crucial to motivate the government to develop ports, as also reflected in the evaluation of the PIC coupling effect.

Despite the close relationship of port-city-industry, the existing literature focuses largely on port-city and/or port industry integration, as evidenced by Appendix 1. It leaves a significant research gap to investigate a new and effective method that enables the assessment of port-city-industry integration, given their natural in-between close-loop interdependency.

2.2. Review of methods and indicators for evaluating PIC integration

Various approaches exist for evaluating the interactions and mutual influences between systems, including both qualitative and quantitative analyses. Quantitative methods primarily involve statistical econometrics, utilizing continuous data series for specific port and city analyses, as shown in Table 1. In examining the mutual relationship between port and urban economic development, Bottasso et al. (2014) used a spatial panel econometric framework to highlight spillover effects and estimate the direct and indirect effects associated with port activities. This method effectively captures spatial dependencies and quantifies spillover effects. However, it relies heavily on high-quality panel data and may oversimplify complex interactions by assuming linear relationships. Furthermore, Akhavan (2017) hypothesized a four-phase model as a tool for investigating the changing spatial and functional dynamics at the port city interface from the 1900s to the 2010s. While this model provides a historical perspective and a structured framework for understanding long-term changes, its qualitative nature may limit its precision and generalizability across different contexts. Chang et al. (2014) and Santos et al. (2018) conducted input-output analyses on how port sectors impact a particular economy. Input-output analysis is effective in quantifying direct and indirect economic impacts and identifying interdependencies between sectors. However, it is inherently static, assuming fixed production coefficients, and does not account for dynamic changes or technological advancements over time. Additionally, Luo, Ding, Chen, & Kuang, 2023 established a system dynamics model to explore the relationship between ports and regional economies. System dynamics is particularly useful for capturing feedback loops and simulating long-term trends, making it well-suited for analyzing complex systems. However, it requires extensive data and relies on subjective assumptions for model construction, which may affect the accuracy and reliability of the results.

CCDM is the primary approach to investigating the impact of coupling effects. It has been proven to be an effective means of obtaining coupling effect indices between different systems (Chen et al., 2022). CCDM has significant advantages in analyzing the coupling relationships between complex systems. It quantifies the degree of coordination between systems, providing clear indicators for studying multi-system interactions. Moreover, it is applicable to various fields, such as economics, environment, and society, and allows for the integration of different weighting methods to meet diverse research needs. Additionally, CCDM is also capable of revealing dynamic coupling relationships, enhancing its adaptability and utility. Nevertheless, the results of CCDM

Table 1
Specific indexes.

Subsystem	Indicator Name	References	Indicator Characteristics
Port	P_1: Port cargo throughput	(Valenzuela et al., 2023)	Infrastructure conditions and facilities (reflecting the port's competitiveness)
	P_2: Number of productive terminal berths	(González & Trujillo, 2008)	
	P_3: Unit berth throughput (throughput/berth length)	(Cheung & Yip, 2011)	
	P_4 Port quantification (throughput/ throughput capacity)	(Wu et al., 2022)	
	P_5: Main business income	(Santos et al., 2018)	Reflecting the port's operating conditions
	P_6: Total profit		
Industry	I_1: Number of employees in the secondary industry	(Liu et al., 2018)	Reflecting industry city interaction
	I_2: Number of employees in the tertiary industry	(Cheung & Yip, 2011)	
	I_3: GDP share of the secondary industry output value	(He et al., 2023)	Reflecting the position of industry in the national economy
	I_4: GDP share of the tertiary industry output value	(Chang et al., 2014)	
	I_5: The number of industrial enterprises above designated size	(Yilmaz, 2022)	Reflecting the economic contribution
	I_6: Value added of industrial enterprises above designated size	(Dadashpoor & Taheri, 2023)	
City	C_1: GRP per capita	(Akhavan, 2017)	Reflecting the living standard of city residents and the contribution of PIC integration
	C_2: Fixed asset Investment	(Lonza & Marolda, 2016)	Reflecting the economic level of the city
	C_3: Total retail sales of consumer goods	(Guo et al., 2020)	Reflecting economic prosperity
	C_4: Total value import and export	(Santos et al., 2018)	
	C_5: Economic Value	(Wang & Wang, 2019)	Reflecting sustainable economic development
	C_6: Fine rate of atmospheric environment quality	(Chen et al., 2022)	Reflecting environmental quality

are somewhat dependent on the selection of indicators and the accuracy of weighting methods, and the calculation process can become increasingly complex when dealing with multiple systems and large datasets (Kong & Liu, 2021). To address this weakness, an objective weighting method and a comprehensive framework are proposed in this study. Additionally, a sensitivity analysis of subsystem weights is conducted to evaluate their impact and enhance the robustness of the results.

Before conducting coupling analysis, it is necessary to determine the weight of each indicator using such methods as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Chen et al., 2022), the Entropy Weighting Method, the Analytic Hierarchy Process (AHP) (Gan, Shi, Hu, Lev, & Lan, 2020), and the Principal Component Analysis (PCA) (Wang, 2022). Among these methods, the Entropy Weighting Method stands out for its objectivity, as it relies purely on the variability of data to determine weights, avoiding subjective biases. This makes it particularly suitable for studies requiring a high degree of impartiality and consistency. In comparison, TOPSIS is straightforward and easy to implement but may oversimplify the ranking process. AHP incorporates expert judgment, which can be valuable in some contexts, but it is prone to inconsistency in pairwise comparisons. PCA effectively reduces dimensionality but may compromise the interpretability of the original indicators. Given its ability to objectively reflect the inherent characteristics of data, the Entropy Weighting Method is a robust choice for determining indicator weights in coupling analysis.

This study primarily explores changes in the PIC coupling effect before and after port reform, and the CCDM has been proven to be an effective means of obtaining coupling effect indices between different systems (Chen et al., 2022). The challenge lies in the selection of indicators and the analysis of key influencing factors. This study identified evaluation indicators through a literature search and inductive reasoning and employed the obstacle degree model to extract the key influencing factors (Han et al., 2021). CCDM provides a robust framework for analyzing coupling effects, while the Entropy Weighting Method offers an objective approach to determining indicator weights. The combination of these two methods ensures a more reliable and impartial analysis of coupling relationships.

After a thorough review of the Web of Science and Scopus databases, Appendix 1 not only highlights the research gaps in the study of the relationships between ports, cities, and industries but also presents the key indicators used in such studies. From Appendix 1, it can be seen that the key indicators at the port level include port throughput, container throughput, port capacity, coast length, terminal area, number of quay cranes, storage capacity, number of berths, passenger number, port revenue, port profits, and port investments. At the urban level, the key indicators are Gross Domestic Product (GDP), Gross Regional Product (GRP), employment numbers, output value of the secondary and tertiary industries, infrastructure investment, total import and export value, urban development, ecological construction, total retail sales of consumer goods, fixed asset investment, urban freight volume, environmental protection investment, environmental energy consumption and environmental pollution (e.g., emissions of SO_2, NO_2, PM2.5, and PM10), as well as other air quality indicators.

The aforementioned indicators categorize both urban and industrial metrics under the umbrella of urban development indicators. However, the impacts of port integration are multifaceted, extending beyond a simple increase in throughput to significant effects on cities and industries. The current lack of research on the PIC system leads to an incomplete understanding of the consequences of port integration, with few studies comparing the impacts before and after reform. Through a holistic analysis of ports, industries, and cities as the three subsystems of PIC, deeper insights into their relationships can be newly gained and populated to guide the PIC development of other countries in the world.

3. Methodology

3.1. Systematic framework and evaluation indicator system

This section outlines a new methodology to investigate the coordination dynamics within the PIC system and to analyze China's major coastal port cities from an applied research perspective using real data from 2015 to 2021, focusing on three main aspects: (1) identification of crucial influencing factors at the PIC integration level, (2) development of a new framework for evaluating the PIC system, and (3) a comparative analysis to evaluate the coupling coordination degree.

Initially, the study explores the coupling coordination relationship and detailed indicators for the PIC system's evolution cycle. The relationship among these three can be summarized as a cyclic and interactive coupling mechanism: ports drive industries by exerting pressure and providing promotion, industries stimulate urban development, in turn, offer support while imposing restraints on the development of ports and industries. This dynamic relationship involves both synergistic effects and inherent tensions, requiring proper planning and coordination to achieve sustainable development among the three (see Fig. 2).

Subsequently, an integrated approach is used to calculate the PIC system's degree of coupling coordination, incorporating the entropy weight method, a comprehensive development index model, the CCDM, and the obstacle factors model.

Finally, through a comparative analysis of the PIC evaluation results, this study reveals the impact of regional port reform and identifies the key factors influencing the level of PIC integration. Additionally, the analysis delves into the effects of equity changes during the port reform process, accompanied by a focused discussion on the implications. The comprehensive research methodology is visually outlined in Fig. 2.

The rationality of the indicator system directly affects the evaluation results. Based on the literature review presented in Section 2, the new comprehensive evaluation indexes for PIC integration are shown in Table 1. Variables appearing two or more times in Appendix 1 are selected as evaluation indices, while those of one occurrence are reserved in the questionnaire survey stage for the possibility of bringing them back to the list by the experts when and if any indicator's importance is underestimated in the first round screening by their appearance in the literature. The indicators assessing the development of ports are mainly chosen from two distinct categories. The first category is related to the conditions and facilities of the port's infrastructure, including cargo throughput, number of berths, unit berth throughput, and port quantification. The second category pertains to the port's operational performance, encompassing income from the main business and total recognized profit.

The industrial sector is represented by three categories. The first category emphasizes the interaction between industry and urban areas, incorporating the number of employees engaged in secondary and tertiary industries. The second category concentrates on the role of industry in the national economy, including the proportion of secondary and tertiary industries in the GDP. Finally, the third category focuses on the economic significance of the industrial sector, covering the quantity of industrial enterprises, and the number of industrial employees.

Regarding urban development indicators, four categories are chosen. The first category concerns the city's living standards, covering metrics such as per-capita GRP; the second category involves the economic status of the city, including various measures such as investment in fixed assets. The third category addresses the comprehensive economic state, considering factors such as the total retail sales of consumer goods and total foreign trade value; and lastly, the fourth category highlights the sustainable development of the economy, specifically through the economic content, which is measured by the ratio of residents' disposable income to per capita GRP.

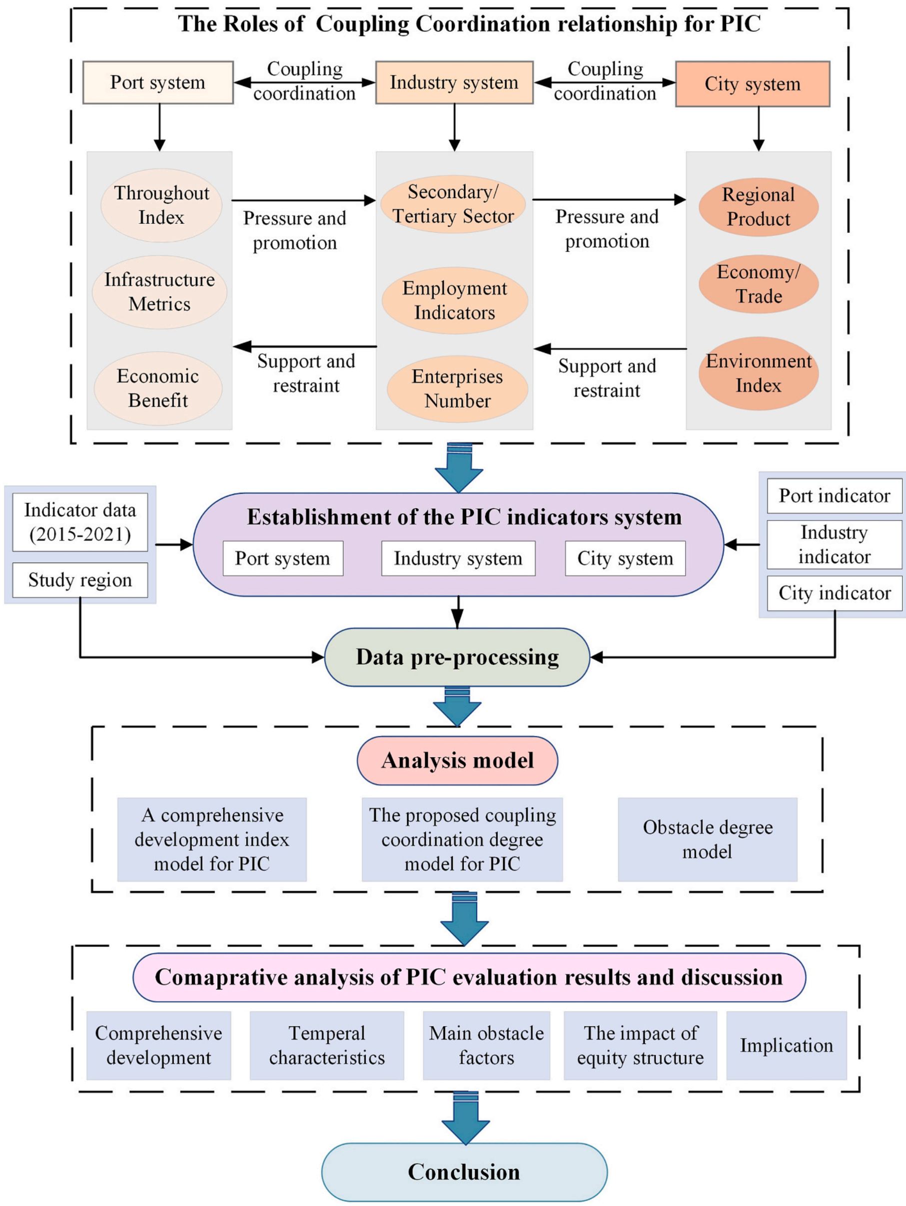

Fig. 2. The research framework of this study.

3.2. Data collection and processing

This study investigates the progress of PIC integration in 10 representative coastal port cities in the Chinese provinces of Zhejiang, Jiangsu, Shandong, and Liaoning, given their advanced PIC development state and geographical distribution in China. The selected cities include global, regional and local ports, located in the southern, central and northern areas. Both regional and economic impacts are taken into consideration. The cities are Ningbo-Zhoushan (Zhejiang); Suzhou, Nanjing, Zhenjiang, and Nantong (Jiangsu); Qingdao, Yantai, and Rizhao (Shandong); and Dalian and Yingkou (Liaoning). The analysis focuses on assessing the extent of PIC integration in the specified locations. The primary data are fused with raw data from multiple sources, including the China Statistical Yearbook 2015–2021, the China Port Yearbook, the statistical yearbooks of the individual provinces, the statistical bulletins of related cities, and the statistical yearbooks and annual reports of each port group.

The comprehensive development evaluation model is a multifactor assessment that focuses on the integration of the PIC relationship (Bian et al., 2022). The evaluation involves assigning weights to each index to accurately measure the level of integration. The entropy weight method, an important information weight model that has been extensively studied and practised, is then employed to calculate the indicators' weights, eliminating the influences of dimensions and the measurement scale (Kong & Liu, 2021).

Before calculating the weights, the initial data has to be devoid of dimensions. Extreme value theory is applied to standardize the original data and generate the x'^{k}_{ij} indicators, while the entropy method is used to determine the relative significance of each indicator (Han et al., 2021). The following formulas are used for the calculations:

Step 1. Extreme value theory is applied to standardize the raw data:

$$x'^{k}_{ij} = \frac{x^{k}_{ij} - Min_j}{Max_j - Min_j} \tag{1}$$

Step 2. Characteristic weighting of indicators is performed by:

$$p^{k}_{ij} = \frac{x'^{k}_{ij}}{\sum_{i=1}^{m}\sum_{k=1}^{l} x'^{k}_{ij}} \tag{2}$$

Step 3. The entropy value of each indicator is determined:

$$E_j = \left(-\frac{1}{ln(m^*l)}\right)\sum_{i=1}^{m}\sum_{k=1}^{l} p_{ij}^k.lnp_{ij}^k \quad (3)$$

Step 4. The indicators' weights are calculated:

$$w_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)} \quad (4)$$

where x_{ij}^k is the original data of the indicators, $x_{ij}^{\prime k}$ indicates the indicator that was obtained by standardizing the original data, Min_j denotes the minimum value of each indicator, Max_j is the maximum value of each indicator, p_{ij}^k represents the characteristic weight of each city indicator, E_j is the entropy value of each indicator, and w_j indicates the weight of each indicator. i represents the i^{th} coastal province, i =1,2⋯m, j is the j^{th} index, j =1,2⋯n, k denotes the k^{th} year, k =1,2⋯l, in this study, m=10, l=7, n =18.

Through using original data and applying Eqs. (1)–(4), the results presented in Table 2 are obtained.

3.3. Comprehensive development index model for the PIC level

The comprehensive development model assesses the overall degree of development of the three subsystems, and overarching PIC system. The evaluation is conducted using the following formulas:

$$P(x) = \sum_{j=1}^{o}\sum_{i=1}^{m}\sum_{k=1}^{l} x_{ij}^{\prime k}.w_j \quad (5)$$

$$I(y) = \sum_{j=o+1}^{p}\sum_{i=1}^{m}\sum_{k=1}^{l} x_{ij}^{\prime k}.w_j \quad (6)$$

$$C(z) = \sum_{j=p+1}^{n}\sum_{i=1}^{m}\sum_{k=1}^{l} x_{ij}^{\prime k}.w_j \quad (7)$$

$$T = \alpha P(x) + \beta I(y) + \lambda C(z) \quad (8)$$

where $P(x), I(y),$ and $C(z)$ are the comprehensive development index of the port, industry, and city subsystems, respectively; $x_{ij}^{\prime k}$ are standardized values of the factors; $o(=6), p(=12), n(=18)$ indicate the numbers of indicators; T is the comprehensive development index of the PIC system; and $\alpha, \beta,$ and λ are the influence coefficients of each subsystem on the whole system, which are often calculated as $\alpha+\beta+\lambda=1$.

Table 2
Weights of evaluation indicators for PIC integration development.

Indicator	The weight of each indicator with regard to local subsystem and global PIC perspectives	
	Global	Subsystem
P_1	3.68 %	14.78 %
P_2	4.68 %	18.79 %
P_3	2.24 %	9.00 %
P_4	5.64 %	22.64 %
P_5	6.23 %	24.99 %
P_6	2.44 %	9.80 %
I_1	3.36 %	6.55 %
I_2	2.77 %	5.39 %
I_3	17.68 %	34.43 %
I_4	18.56 %	36.14 %
I_5	5.28 %	10.27 %
I_6	3.71 %	7.22 %
C_1	2.08 %	8.75 %
C_2	3.31 %	13.97 %
C_3	5.51 %	23.21 %
C_4	3.85 %	16.24 %
C_5	7.20 %	30.34 %
C_6	1.78 %	7.50 %
Total	1.000	3.000

The coefficients can be determined through a combination of expert scoring to fit specific requirements in PIC evaluation. With regard to the existing literature, the undetermined coefficients are evenly distributed as $\alpha=\beta=\lambda=1/3$ (e.g., (Ai et al., 2016, Gan et al., 2020, Han et al., 2021, Kong & Liu, 2021, Liu et al., 2018, Wang et al., 2022).

3.4. Proposed CCDM for the PIC level

The CCMD evaluates the extent of interactions among various indicators related to ecological service levels. Coupling refers to the phenomenon where multiple systems interact and mutually affect one another. The strength of interaction within a system is quantified by the degree of coupling. The ultimate value of coupling coordination reflects the level of accomplished coordinated development (Lin & Tang, 2023).

By employing the CCDM, the degree of PIC integration in each city is calculated as follows (Liu et al., 2021):

$$C = 3^*\sqrt[3]{\frac{P(x)^*I(y)^*C(z)}{(P(x)+I(y)+C(z))^3}} \quad (9)$$

where C represents the degree of coupling, which reflects the strength of mutual influences among systems.

The CCDM is able to further reflect the degree to which the development of systems is coherent and harmonious. It is calculated using the formula below:

$$CCI = \sqrt{C^*T} \quad (10)$$

where CCI represents the degree of coupling coordination, which serves as an indicator of the extent of coupling within an interaction relationship. CCI also reflects the quality of coordination and signifies the level of coordinated development among different subsystems (Bian et al., 2022).

Table 3 shows the criteria for the degree of coupling coordination. The larger the value of the CCI, the higher the degree of coupling.

3.5. Analysis of obstacles

The obstacle degree model is applied to reveal specific obstacles that hinder the PIC system's collaborative growth (Wang, 2022). This model is particularly effective at breaking down complex interactions into quantifiable factors, allowing for a more nuanced understanding of what exactly constitutes a barrier in different scenarios. It is frequently employed alongside the CCDM (Zhang, 2021). In this study, the following obstacle degree model is used:

$$O_j = \frac{w_j^*\left(1-x_{ij}^{\prime k}\right)}{\sum_{j=1}^{n} w_j^*\left(1-x_{ij}^{\prime k}\right)} \quad (11)$$

where O_j represents the obstacle degree, w_j represents weight, $1-x_{ij}^{\prime k}$ is the degree of deviation between the standardized indicator value and its optimal value.

Table 3
Classification criteria for the degree of coupling coordination of the PIC system.

Range of Coordination Level	Classification Stages	Development Level
$0.00 \le CCI \le 0.20$	Weak coordination	Seriously imbalanced
$0.21 < CCI \le 0.40$	Slightly weak coordination	Imbalanced
$0.41 < CCI \le 0.60$	Average coordination	Moderately coordinated
$0.61 < CCI \le 0.80$	Slightly strong coordination	Well-coordinated
$0.81 < CCI \le 1.00$	Strong coordination	Highly coordinated

4. Comparative analysis of PIC evaluation results and discussion

The results of the comprehensive development index and the coupling degree are presented in this section. By comparing *CCI* changes across different regions or periods, trends, fluctuations, and key factors are identified. Finally, specific implications and sensitivities are proposed based on the conclusions, helping to explore potential impacts and provide recommendations for policy-making, future research, and practical applications.

4.1. Comprehensive development index evaluation

4.1.1. Results of comprehensive development index T

Applying Eqs. (5)–(8), the corresponding calculation results are presented in Table 4. Furthermore, Fig. 3 shows a comparative analysis of the calculation outcomes ranging from 2015 to 2021. The comprehensive development index for the 10 major coastal port cities exhibits an overall upward trajectory. Ningbo-Zhoushan in Zhejiang demonstrates a consistent growth pattern, with an average growth rate of 6.51 %. In 2021, the comprehensive development index of Ningbo-Zhoushan reached a score of 0.538, surpassing that of the other cities except Qingdao.

Overall, the cities in Jiangsu Province show a steady growth trend, although the comprehensive development index of the three cities, apart from Suzhou, remains relatively low. Suzhou demonstrates a steady increase from 0.296 to 0.394 between 2015 and 2021, with an average annual growth rate of 4.93 %. In comparison, the rates for Nanjing, Zhenjiang, and Nantong are 5.37 %, 6.86 %, and 7.75 %, respectively. Following the completion of port integration in 2017, the annual average growth rate slightly increased compared to the period before integration.

For the cities in Shandong, the year 2018, when port reform was completed, marks a turning point. Before 2018, there is an overall downward trend, which shifts to a rapid upward trend afterwards. From 2015 to 2021, Qingdao, Rizhao, and Yantai experienced average annual growth rates of 6.74 %, 18.41 %, and 11.82 %, respectively. However, from 2017 to 2021, these rates increase significantly to 18.84 %, 38.49 %, and 26.46 %. In 2021, Qingdao achieved the highest score of 0.593, surpassing the other nine cities. Following the reform, the pace of growth increased, with Rizhao showing the highest acceleration and Qingdao the lowest.

Among the northern port cities, Dalian and Yingkou in Liaoning exhibit comparatively lower comprehensive development index values. Although the absolute values are modest, Yingkou shows an impressive growth rate of 20.86 % from 2019 to 2020, and Dalian experienced a notable growth rate of 9.61 % from 2020 to 2021, indicating significant potential for future growth.

4.1.2. Analysis of comprehensive development levels

Overall, the values of the comprehensive development index are relatively low. Except for Qingdao, Ningbo-zhoushan, and Yantai, whose indices exceed 0.4; all other port cities have indices of 0.3 or lower. In 2021, Qingdao has the highest scores, followed by Ningbo-Zhoushan, with both having similar absolute values of around 0.6. Qingdao and Ningbo-Zhoushan both belong to international port cities. As of 2023, Ningbo-Zhoushan is ranked third globally in container throughput and first in cargo throughput, while Qingdao holds fifth and fourth, respectively. Clearly, in terms of port throughput, Ningbo-Zhoushan Port outperforms Qingdao Port. However, following port integration, the comprehensive development index of Qingdao experiences a rapid surge. In 2020, its growth rate soared by 63.81 % compared to 2019, with a three-year average growth rate from 2019 to 2021 reaching 18.84 %, significantly higher than Ningbo-Zhoushan's of 6.51 %. This suggests that the impact of port integration on Qingdao is better than that on Ningbo-Zhoushan. Moreover, it also indicates that the comprehensive development index is a composite metric, with port throughput representing just one facet of it.

The comprehensive development index results of the ten cities reveal that port cities within the same province exhibit relatively consistent trends, particularly pronounced in Shandong province. Additionally, larger cities in the same province tend to have lower growth rates in the comprehensive development index compared to smaller cities, which is especially evident after the port reforms. In Liaoning, after the port reform, the average annual growth rate of Yingkou exceeds Dalian by over 11 %, compared to a difference of just 7 % before the reform. Shandong and Jiangsu have a similar trend. Port resource integration generally has positive impacts on port cities, with smaller cities benefiting even more. It also elucidates that larger ports are the primary obstacles during the integration process, whereas smaller ports are more inclined to integrate.

Table 4
Results of comprehensive development index.

Region	2015	2016	2017	2018	2019	2020	2021
Ningbo-Zhoushan	0.370	0.377	0.412	0.443	0.476	0.486	0.538
Suzhou	0.296	0.302	0.328	0.336	0.353	0.367	0.394
Nanjing	0.170	0.173	0.187	0.190	0.206	0.213	0.232
Zhenjiang	0.090	0.095	0.091	0.096	0.133	0.143	0.126
Nantong	0.129	0.138	0.147	0.167	0.197	0.187	0.200
Qingdao	0.515	0.464	0.292	0.278	0.331	0.543	0.593
Rizhao	0.299	0.298	0.110	0.137	0.138	0.342	0.344
Yantai	0.356	0.357	0.180	0.213	0.210	0.421	0.433
Dalian	0.157	0.161	0.154	0.177	0.166	0.168	0.198
Yingkou	0.090	0.111	0.113	0.128	0.119	0.170	0.168

4.1.3. Implications of comprehensive development index

The integration of provincial ports marks a pivotal advancement in the reform of China's port systems and sets a precedent for global port reform initiatives. The decentralization era, spanning from 2003 to 2015, significantly propelled the growth of China's ports, and this progress is reflected in their throughput rankings. However, the transition from merely large to truly influential ports remains a critical hurdle. In pursuit of elevating its ports to global prominence, China has embarked on an ambitious journey of provincial port reform, targeting the cultivation of world-class, influential maritime gateways.

The investigation of the comprehensive development index reveals that reforms at the PIC level typically manifest their positive outcomes with a significant difference between big cities and small cities in the same province, especially evident after the port reforms. This insight underscores the necessity of policy bias and resource consolidation for large ports at the beginning of such reforms. It also highlights the variability in the impact across different locales, emphasizing the need for tailored approaches in addressing the unique challenges and leveraging the distinct advantages of each port city.

4.2. Results and discussion of the coupling coordination index

4.2.1. Results of CCI

The *CCI*, as determined by Eqs. (9)–(10), is presented in Table 5 and Fig. 4. The findings suggest that the *CCI* of the ten major coastal port cities exhibits consistent increases over the investigated period. Ningbo-Zhoushan transitioned from average to slightly strong coordination in 2017 and achieved a score of 0.690 in 2021, marking its entry into the category of well-coordinated development.

Furthermore, Suzhou, Nanjing, Zhenjiang, and Nantong in Jiangsu show consistent development rates. Suzhou leads a shift from a state of average to slightly strong coordination, surpassing a score of 0.6 by 2020. However, the overall coordination levels of the other three cities remain relatively low, with Nanjing and Nantong maintaining an average level, while Zhenjiang stays at a slightly weak level.

The changes in Shandong present a different trend. Between 2015

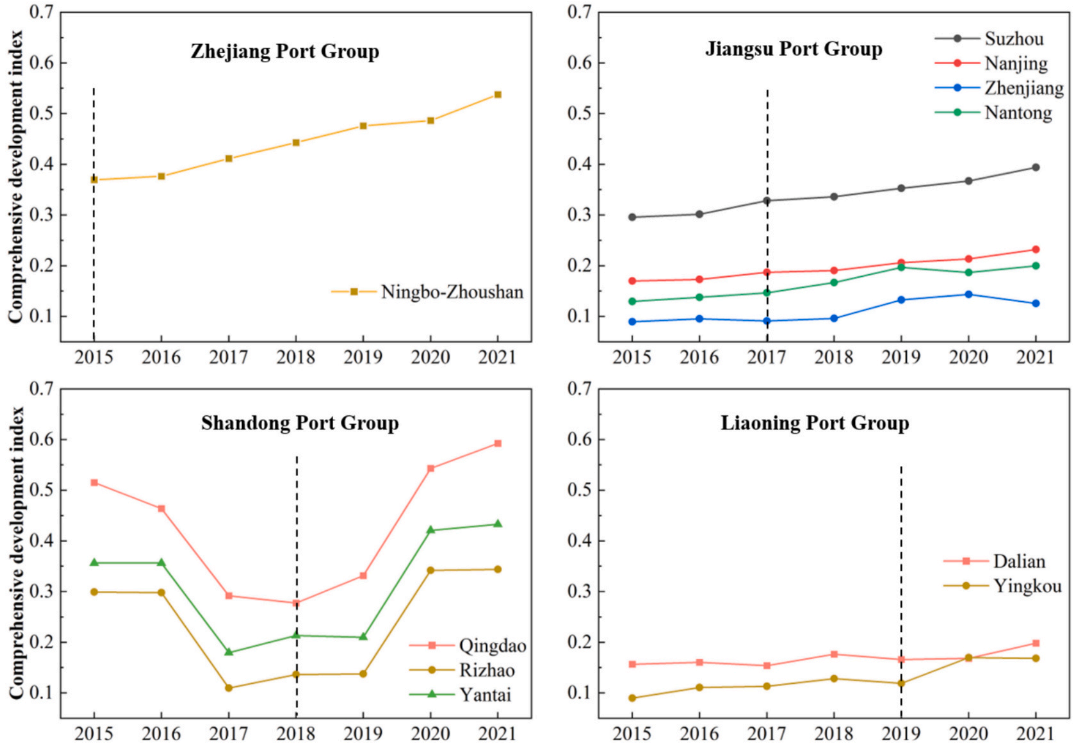

Fig. 3. Results of calculating the PIC comprehensive development index for different port groups (2015–2021).
(Note: The dashed line indicates the establishment time of the port group.)

Table 5
Results of *CCI* of the PIC system.

Region	2015	2016	2017	2018	2019	2020	2021
Ningbo-Zhoushan	0.565	0.579	0.603	0.621	0.642	0.656	0.690
Suzhou	0.530	0.537	0.557	0.559	0.572	0.583	0.600
Nanjing	0.404	0.406	0.416	0.424	0.438	0.439	0.458
Zhenjiang	0.294	0.302	0.296	0.305	0.343	0.360	0.346
Nantong	0.359	0.370	0.381	0.404	0.438	0.425	0.437
Qingdao	0.702	0.654	0.506	0.497	0.531	0.724	0.763
Rizhao	0.468	0.470	0.289	0.314	0.314	0.540	0.544
Yantai	0.538	0.538	0.413	0.440	0.438	0.621	0.633
Dalian	0.353	0.339	0.337	0.359	0.357	0.354	0.378
Yingkou	0.223	0.212	0.212	0.228	0.228	0.258	0.257

and 2018, the *CCI* values decrease. However, after 2018, there is a rapid increase, with Qingdao and Yantai surpassing 0.6 by 2021, reaching a state of slightly strong coupling. Moreover, the *CCI* values in 2021 exhibit a substantial improvement compared to those in 2015. In 2021, the *CCI* of Qingdao is the highest among the ten coastal cities, reaching 0.763.

Dalian and Yingkou in Liaoning exhibit comparatively lower coupling levels than other cities. Specifically, the *CCI* of Dalian remains below 0.4 before 2020, while Yingkou consistently stays below 0.3, with a slightly weak coordination status.

4.2.2. Temporal distribution characteristics

To visually observe the changes in *CCI*, Fig. 5 illustrates the annual coupling status for each city. In 2021, it is evident that Ningbo-Zhoushan, Suzhou, Qingdao, and Yantai achieved a slightly strong coupling level, while Zhenjiang, Dalian, and Yingkou exhibited relatively low coupling levels. Except for Zhenjiang, southern and central cities perform better than those in northern regions, primarily due to the slow growth rates of their ports, industries, and cities.

Port reforms have the most significant impact on improving the *CCI* in Shandong. Upon the completion of port reforms in Shandong in 2018, the *CCI* of all three cities was elevated by one level. Following regional integration in Shandong ports, both cargo and container throughput grow steadily, especially in Yantai and Rizhao, resulting in notable economic benefits for the ports. The establishment of dedicated departments by the Shandong Provincial Port Group to improve PIC integration degree significantly enhances the coordination level of these subsystems after 2019, culminating in a peak in 2021.

Various integration paths and modes lead to distinct port development models. Liaoning port reform employs a vertical integration strategy, which is different from the other three provinces. Following the port reform, although the *CCI* of Dalian and Yingkou remains relatively low, the growth rate is noticeable. Despite limited improvement in throughput, the ports achieve significant increases in main business income and profits benefiting from investment from China Merchants Group. Additionally, significant cost reduction and efficiency improvements are observed, suggesting that the integration paths and modes can influence ports' development model.

4.2.3. Implications of CCI

The current objective of provincial-level port reforms is to enhance the PIC integration. A high level of PIC integration would promote comprehensive improvement across the three subsystems. *CCI* has elucidated two critical insights that hold substantial implications for both the national context and the broader sphere of global port reform.

(1) Comprehensive evaluation framework.

By considering ports, industries, and cities as three interconnected subsystems of equal importance, this study has pioneered a more holistic approach to understanding the synergies and tensions within the connections between ports, industries, and cities. This broader perspective enriches the conventional port city evaluation indices and validates the use of the CCDM in exploring these complex relationships, thus paving the way for its further application in diverse contexts.

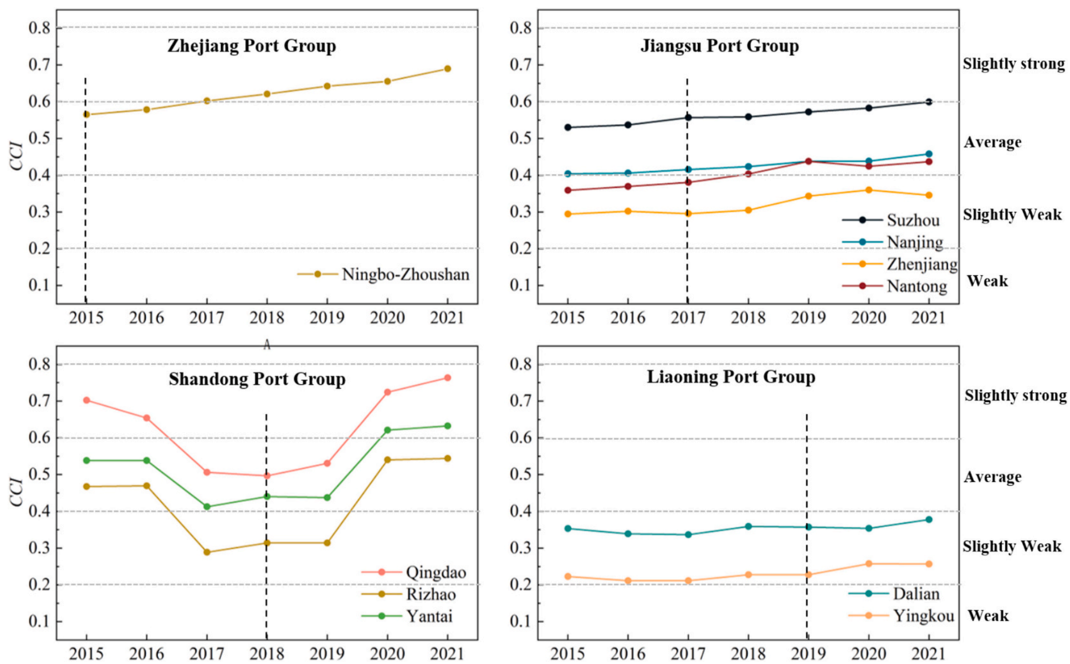

Fig. 4. Changes in the *CCI* by city, 2015–2021.

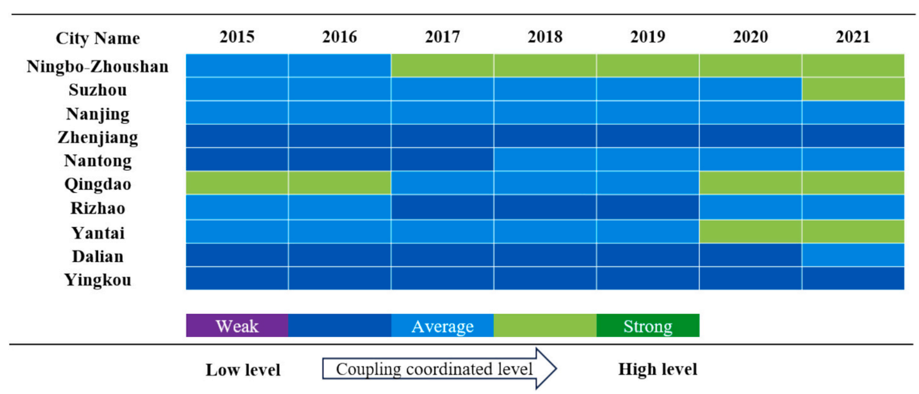

Fig. 5. Annual coupling coordination states of 10 cities.

(2) Diverse integration strategies.

The paper outlines the diverse approaches taken by provinces, including the top-down integration model spearheaded by provincial state-owned enterprises in Zhejiang, Jiangsu, and Shandong, as well as Liaoning's vertical integration strategy, which involves central enterprises. This diversity in approaches provides valuable lessons on the effectiveness and potential pitfalls of different integration models, thereby offering a comparative basis for other regions contemplating similar reforms. This paper suggests that the long-term efficacy of these strategies requires further investigation, inviting detailed research to extend the analysis over a longer period.

Overall, the implications drawn from this study not only contribute to the refinement of China's ambitious endeavour to develop world-class ports but also offer significant insights for global port reform efforts. They advocate for a nuanced understanding of port integration dynamics and the adoption of informed context-specific strategies.

4.3. Main obstacle indicators

4.3.1. Results of obstacle indicators

Table 6 outlines the top three indicators that hinder the synergistic development of the three subsystems in each city. First place is awarded 3 points, second place 2 points, and third place 1 point. The total score for each indicator is then calculated, with higher scores indicating

Table 6
Main obstacle indicators.

City	Port			Industry			City		
	Rank			Rank			Rank		
	1	2	3	1	2	3	1	2	3
Ningbo-Zhoushan	P_6	P_3	P_5	I_4	I_3	I_6	C_3	C_5	C_4
Suzhou	P_5	P_4	P_2	I_4	I_3	I_5	C_3	C_4	C_2
Nanjing	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_4
Zhenjiang	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_4
Nantong	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_4
Qingdao	P_2	P_4	P_1	I_3	I_4	I_5	C_5	C_3	C_4
Rizhao	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_2
Yantai	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_4
Dalian	P_5	P_4	P_2	I_4	I_3	I_5	C_5	C_3	C_2
Yingkou	P_5	P_2	P_4	I_4	I_3	I_5	C_5	C_3	C_2
Total score	$\boldsymbol{P_5}$	$\boldsymbol{P_4}$	$\boldsymbol{P_2}$	$\boldsymbol{I_4}$	$\boldsymbol{I_3}$	$\boldsymbol{I_5}$	$\boldsymbol{C_5}$	$\boldsymbol{C_3}$	$\boldsymbol{C_4}$

Note: "1" indicates that the obstacle degree of the indicator ranks first; "2" indicates that it ranks second; and "3" indicates that it ranks third.

greater importance. The top three overall indicators are shown in Table 6. Within the port system, the main business income (P_5) significantly affects the collaborative dynamics within the PIC framework. Following closely in the second and third place is the port quantification (P_4) and number of productive terminal berths (P_2). In the industrial domain, the paramount indicator of influence is the GDP share of the tertiary industry output value (I_4), followed by the GDP share of the secondary industry output value (I_3) and the number of industrial enterprises above the designated size (I_5). Conversely, in the urban system, the top three determinants are the economic value (C_5), total retail sales of consumer goods (C_3) and the total value of imports and exports (C_4).

4.3.2. Analysis of main obstacle indicators

Comparing and analyzing the results of obstacle indicators with the overall weights (see Fig. 6), a consistent pattern is revealed. The indicators with higher weights correspond to higher obstacle scores. However, the obstacle degree model may have different results and convey more information for each city. For the Ningbo-Zhoushan Port subsystem, P_6 ranks first instead of P_5.

The results indicate that within the port subsystem, P_5, P_4, and P_2 are the top three obstacles. Main business income reflects the port's financial stability and serves as a key indicator of its operational performance and market competitiveness. It not only demonstrates the port's ability to generate revenue from core activities but also underscores its direct contribution to the local and regional economy, playing a vital role in facilitating trade, creating jobs, and driving economic growth. Port quantification reflects the saturation level of a port and has significant implications for its development capability and potential. The number of productive terminal berths reflects a port's infrastructure and facilities while serving as a key indicator of its operational capacity, efficiency, and competitiveness. It highlights the port's ability to handle cargo, accommodate larger vessels, and support diverse trade, shaping its appeal to shipping lines and its role in regional and global trade networks.

In the industrial subsystem, I_4 and I_3 demonstrate absolute importance, consistently ranking as the top two indicators across ten cities. Except for Qingdao, I_4 consistently ranks higher than I_3 in terms of obstacles. This suggests that the proportion of GDP in the tertiary sector is more significant for PIC integration than the proportion in the secondary sector. The following important indicator is I_5. As China has advanced manufacturing, The number of industrial enterprises above the designated size is an important representation of the manufacturing industry. A developed manufacturing industry is a major source of maritime cargo. On the other hand, disruptions in port services would have the greatest impact on the manufacturing industry, which is consistent with the findings of Zhang and Lam (Zhang & Lam, 2016).

In the urban subsystem, C_5 and C_3 are the two most frequently appearing indicators. C_5 reflects both the standard of living and the sustainable development of the economy. Examining the ratio allows for a comprehensive evaluation of overall economic well-being and stability, providing insights into the region's prosperity and economic sustainability. Fluctuations in the total retail sales of consumer goods can reflect the economic climate and serve as a crucial reference for evaluating economic performance. C_4 represents the total value of imports and exports, signifying a critical aspect of global trade. Noteworthily, approximately 75 % of world trade relies on maritime transportation, with the shipping industry being a fundamental driver of international trade (Lane & Pretes, 2020). It highlights the indispensable role of maritime shipping in facilitating and enabling trade activities.

4.3.3. Implications of obstacle indicators

The results of the obstacle indicators reveal the key indicators of each subsystem in various cities, providing the following main insights:

(1) Differentiated obstacle indicators.

The obstacle degree index identifies key indicators for each subsystem in each city. Notably, when primary obstacle indicators vary across cities, local governments should take into account both common and unique indicators in their policy formulation. For instance, in Ningbo-zhoushan port, total profit (P_7) is prioritized from the obstacle analysis, suggesting that the port's policies should focus on enhancing overall profitability and financial performance. In contrast, in Suzhou port, the main business income (P_6) is more significant, indicating that the port needs to concentrate on increasing revenue from its core business

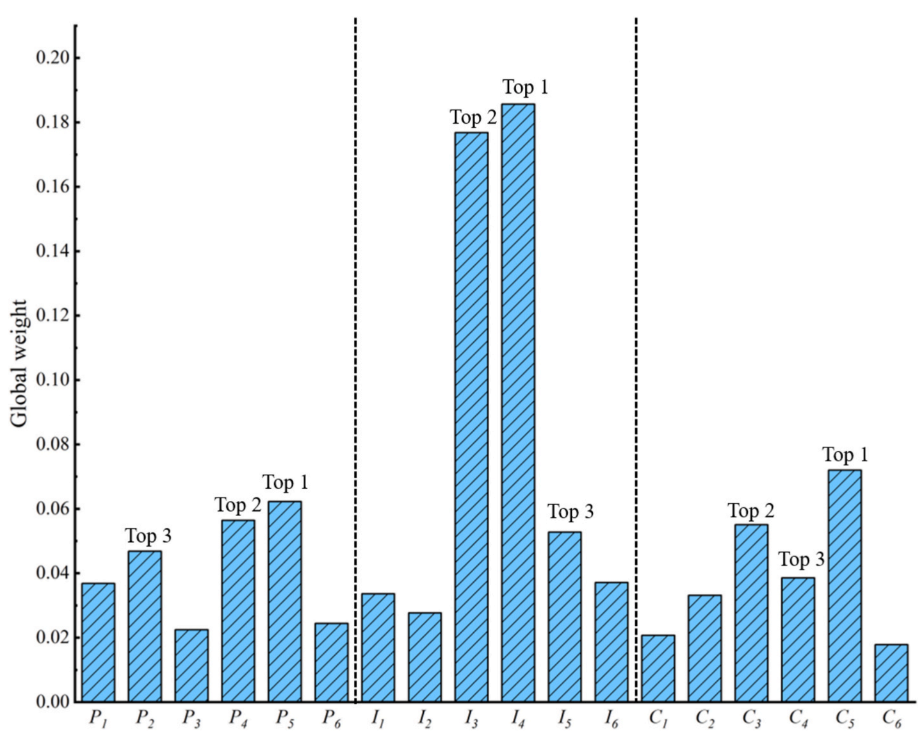

Fig. 6. Global weight of indicators.

activities. Developing a differentiated policy system that addresses these specific factors can offer targeted support for the sustainable integration of PIC.

(2) Developing port-compatible industries.

In the port and industrial sectors, container throughput and the GDP share of the tertiary industry are the primary obstacle indicators. This suggests that developing port-compatible industries tailored to the specific characteristics of each city is crucial for enhancing PIC integration. For example, the *CCI* results in Jiangsu Province show that Zhenjiang performs relatively poorly. Zhenjiang primarily handles bulk cargo, with a very small container throughput. Therefore, for Zhenjiang, expanding container cargo sources or developing industries related to bulk cargo are important pathways to improve PIC integration. Fully leveraging the port's engine role and promoting container transportation development can significantly improve PIC integration.

4.4. Sensitivity analysis

Previous studies often set the weights of the three subsystems equally at 1/3 each when calculating their coupling effects (Wang et al., 2022). This study focuses on investigating the impact of port reforms on PIC integration. Therefore, a sensitivity analysis of the port weight is conducted. This approach enables an accurate assessment of the port system's true contributions to overall performance, providing a comprehensive evaluation of the impact of port reforms. Using $\alpha = \beta = \lambda = 1/3$ as the baseline, the weight of α is gradually increased and set to $\alpha = 1/2, \beta = \lambda = 1/4$; $\alpha = 2/3, \beta = \lambda = 1/6$; $\alpha = 0.8, \beta = \lambda = 0.1$; and $\alpha = 1.0, \beta = \lambda = 0$. The changes in *CCI* values and the growth rates of various cities are obtained to generate insightful implications in the ensuing sections.

4.4.1. Port-driven development

As the weight of ports increases, *CCI* values for Ningbo-Zhoushan, Dalian, and Yingkou consistently rise each year, though at varying growth rates. Specifically, as illustrated in Fig. 7, Ningbo-Zhoushan exhibits a steady average annual growth rate of 6.3 %. Dalian shows an average growth rate of 5.8 %, while Yingkou demonstrates a more pronounced average annual growth rate of 6.7 %.

With the increasing importance of ports, *CCI* values also rise, highlighting the dominant role ports play in PIC integration. The faster the growth, the more evident the port's dominance becomes. Among the three cities, Yingkou Port demonstrates the most significant dominance in PIC integration.

Despite Zhejiang and Liaoning employing different methods of integration, their equity structures are comparable. For instance, Zhejiang Port Group holds complete ownership of Ningbo-Zhoushan Port, giving it total control over its operations. On the other hand, Liaoning Port Group has full ownership of Dalian port and over 51 % ownership in Yingkou port, with the remaining shares held by creditor banks. Despite this, Liaoning Port Group retains full operational control of both ports. This similarity in equity structures provides the foundational conditions for a port-driven model of integration.

Since 2015, Zhejiang Province has unified all ports, including marine and inland ports, progressing from the integration of Ningbo and Zhoushan Ports. The construction of the Yiwu-Ningbo-Zhoushan open corridor has facilitated the synergy of four types of ports - seaport, airport, inland port, and information port - thereby establishing a major international logistics corridor (ZPDRC, 2021). These efforts have expanded cargo sources for Ningbo-Zhoushan Port, ensuring continuous and stable growth and providing a solid foundation for port-driven development. The stable growth rate indicates the positive impact of the overall integration of PIC.

Since 2019, the average growth rate of the *CCI* for Dalian has shown a modest increase compared to the period before 2019, while Yingkou has experienced more noticeable growth. The Liaoning Port Group has deepened its cooperation with the Liaoning provincial government in multiple areas, including port operations, logistics transportation, park development, and financial services. This cooperation extends beyond traditional port operations to encompass a wider range of activities, enhancing upstream and downstream linkages. The Taiping Bay in Dalian has been transformed into a front port-central zone-back city model, fostering positive interactions between industrial park development and free trade zone construction (SAPAC, 2020). This model effectively addresses the integration of PIC. While the short-term effects of these policies may not be very evident, this is a highly beneficial development model for PIC integration in the long term.

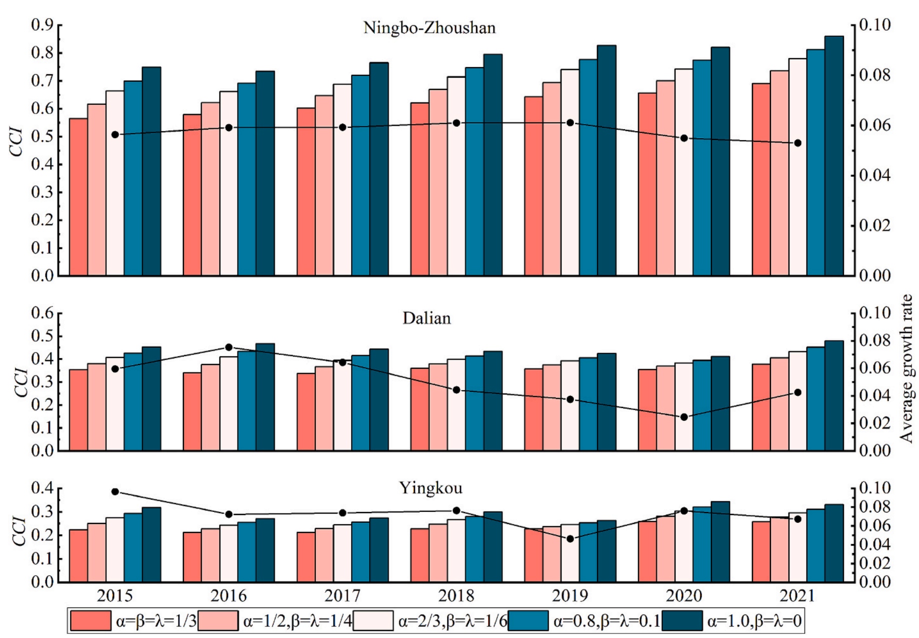

Fig. 7. Sensitivity of Ningbo-zhoushan, Dalian and Yingkou.

4.4.2. Non-port-driven development

Fig. 8 illustrates that as ports become more significant, the CCI values for Suzhou, Nanjing, and Nantong show a marked downward trend, all experiencing negative growth. Over the past seven years, the average growth rate for Suzhou is −5.2 %, for Nanjing −1.4 %, and for Nantong −1.1 %. The smaller the negative growth rate, the weaker the port's dominant role becomes. Therefore, Suzhou port has the least impact on PIC, followed by Nanjing port and Nantong port. The results suggest that the ports in these three cities are not the main drivers for the PIC development, relying instead on both industry and city.

On the other hand, Zhenjiang shows a markedly different trend. Zhenjiang consistently maintaines a positive annual growth rate, averaging 3.2 %. Notably, in 2019 and 2020, the growth rates reach 6.5 % and 5.2 %, respectively, highlighting a robust port-driven economic performance.

To identify the reasons behind this discrepancy, the equity structures of four ports are examined (see Fig. 9). Jiangsu Port Group owns 61.04 % of Suzhou port and 55 % of Nanjing port, with the local government holding the remaining shares. Nantong port is fully controlled by the local government. In contrast, the equity of Zhenjiang port is entirely held by Jiangsu Port Group. Among the four ports, Zhenjiang local government is the only one that does not possess any shares in Zhenjiang port, whereas the other three port cities typically hold around 40 % or more of the shares.

Both the *CCI* results in Section 4.2.1 and the sensitivity analysis indicate that PIC integration in Zhenjiang is worse than in the other three cities in Jiangsu. The equity structure is likely a significant contributing factor. Thus, if the local government of a port city does not participate in equity at all and lacks a dedicated department for promoting PIC integration, then the equity structure will severely impact the connection between the port, city, and industries. Consequently, this lack of industrial cohesion will hinder the port's full potential.

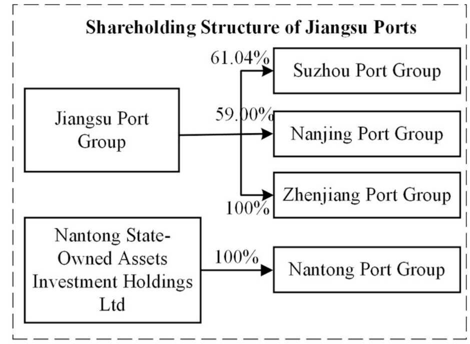

Fig. 9. Structure of port equity in Jiangsu.

4.4.3. Mixed driven development

The *CCI* values of the three cities in Shandong Province demonstrate a consistent trend (see Fig. 10). With increasing port weight, there is a clear positive growth from 2017 to 2019. Qingdao experiences an average growth rate of 5.1 %, Rizhao 8.6 %, and Yantai 3.8 %. During this period, port development takes precedence in PIC integration. However, starting in 2020, the influence of ports gradually declines, with Rizhao and Yantai showing more significant changes, leading to a shift in dominance towards cities and industries.

Shandong Port Group has full ownership of Qingdao, Yantai, and Rizhao. Furthermore, the group implements a specialized division that primarily focuses on the integration of various industries and urban areas. Its main functions include the integration of industries and cities, the construction and management of port industrial parks, and the revitalization of obsolete ports and urban areas. Shandong Port Group commits to enhancing PIC integration in 2020 and devises construction projects with substantial investments exceeding 1776.3 billion RMB. Consequently, since 2020, a significant enhancement has occurred in the PIC integration for Qingdao, Yantai, and Rizhao.

4.4.4. Implications of sensitivity analysis results

Sensitivity analysis contributes to a reanalysis of sensitive factors to identify patterns and improve the reliability of results. In analyzing the coupling relationships between subsystems, the weights of each

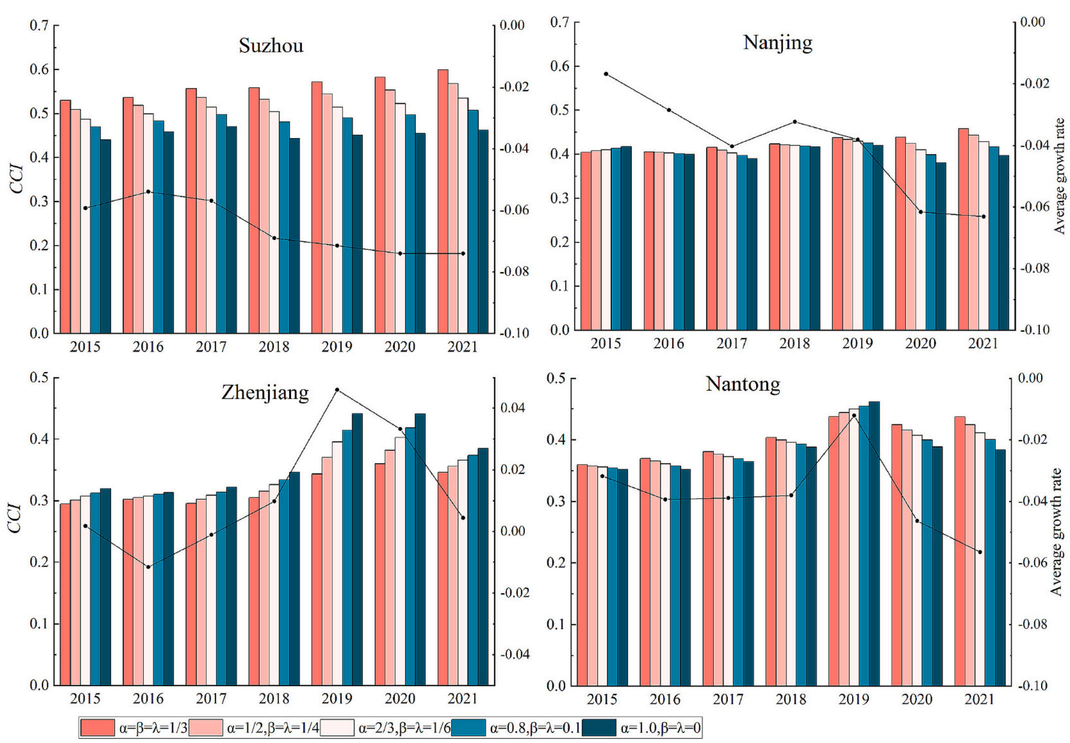

Fig. 8. Sensitivity of Jiangsu cities.

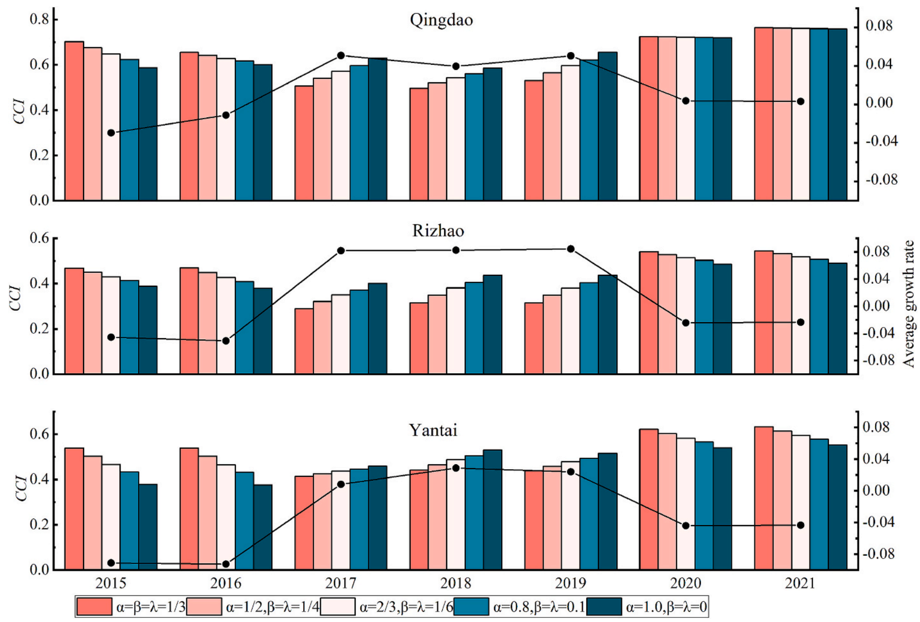

Fig. 10. Sensitivity of Shandong cities.

subsystem are critical parameters. This study makes significant contributions through sensitivity analysis as follows:

(1) Breakthrough in subsystem weight.

Breaking away from the traditional practice of assigning equal weights to the three subsystems, the study explores the changes in coupling relationships when changing the weights of the port systems. Based on the different patterns of coupling results, three distinct driving types of PIC integration are summarized, providing a clearer view of the impact of port reform on PIC. This approach significantly enriches the research on the effects of port reform.

(2) Equity allocation strategies.

The alteration of equity is the most crucial and challenging aspect of port reform. Exploring the impact of equity on PIC provides a vital reference for equity alteration schemes in port reform. PIC integration requires mutual support between local governments, ports, and industries. The lack of any party will hinder the integration progress. Sensitivity analysis reveals the impact of equity on PIC more clearly, and the conclusions obtained can provide an important basis for regional port reform. However, the optimal level of involvement from local governments remains to be explored and may require further observation over an extended period.

5. Conclusions

This study proposes a new comprehensive evaluation index system for evaluating the development of PIC integration for port cities. The comprehensive development index model is developed, and the CCDM is applied to investigate the effect of provincial reform on the PIC integration level in China using 10 representative coastal cities as illustrative cases and their associated data from 2015 to 2021. There are three primary findings drawn from the study, as follows:

First, the comprehensive development index for all the investigated port cities exhibits an overall upward trend, with cities within the same province displaying relatively consistent patterns. Notably, larger cities (e.g. Ningbo-zhoushan, Qingdao, Suzhou and Dalian) tend to have slower growth in the comprehensive development index compared to smaller cities (e.g. Yantai, Rizhao, Nanjing, Zhenjiang, Nantong and Yingkou) in the same province. This disparity becomes more pronounced following the implementation of port reforms and could largely be attributed to two key factors: (1) larger cities, having already achieved a higher level of development, encounter diminishing marginal returns on further investments, and (2) smaller cities, benefiting more directly from the reforms, experience accelerated growth due to improved infrastructure and expanded economic opportunities. These findings highlight the differentiated impact of port reforms on cities of varying sizes.

Second, Ningbo-Zhoushan, Suzhou, Qingdao, and Yantai achieve a slightly strong coupling level, while Zhenjiang, Dalian, and Yingkou exhibit relatively low coupling levels. This variation cannot be attributed solely to geographical factors but is more closely linked to port specialization, functional roles, and the degree of integration with their local industries. For instance, Zhenjiang Port's emphasis on bulk cargo transshipment, coupled with its limited integration with local industrial activities, results in weaker coupling effects. Similarly, the positive economic growth in Liaoning Province, coupled with negative cargo throughput growth at Dalian and Yingkou, contributes to their weaker performance. These findings suggest that economic structure, industrial base, and port functionality are more influential in determining coupling levels than geographic location alone.

Third, the obstacle degree model is used to identify the key indicators that hinder the development of the three PIC subsystems. Specifically, main business income (P_5), the GDP share of the tertiary industry output value (I_4), and the economic value generated (C_5) are recognized as the most significant obstacles within the port, industrial, and city subsystems, respectively. P_5 reflects the port's financial stability and operational performance, highlighting its ability to generate revenue, support regional economies, and contribute to employment and economic growth. I_4 emphasizes the critical role of service-oriented economic activities in fostering PIC integration, indicating that the tertiary sector plays a more pivotal role than the secondary sector in achieving sustainable and balanced development. Finally, C_5 provides a comprehensive measure of regional economic vitality and long-term sustainability, offering valuable insights into the overall prosperity and resilience of the local economy. These indicators offer a robust analytical framework for understanding the dynamics of PIC integration and underscore the significance of financial performance, industrial structure, and economic sustainability in influencing the integration and development of PIC systems.

There are a few limitations which inspire future studies in the field. First, the variable selection and weighting methodologies used in the analysis may introduce potential biases or shortcomings. Due to limitations in data availability, such as the difficulty in obtaining detailed data on economic activities specifically related to the shipping industry, broader indicators from the secondary and tertiary sectors were used as substitutes. While this approach ensures feasibility, it may not fully capture the unique characteristics of the shipping industry, potentially leading to biases in the results and the weighting process. Future studies could address this issue by incorporating more granular and industry-specific data to enhance the precision and reliability of the findings. Second, extending the timeframe of analysis beyond the 2015–2021 period could provide deeper insights into the long-term and enduring effects of the observed trends and policy impacts. Lastly, the optimal level of local government involvement remains unclear and warrants further investigation through extended observation and analysis. Addressing these limitations in future research could significantly improve the robustness and applicability of the findings.

CRediT authorship contribution statement

Tiaolan Yu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Huanhuan Li:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tianlan Zhou:** Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis. **Nan Zhao:** Writing – original draft, Visualization, Validation, Resources, Formal analysis, Data curation. **Zaili Yang:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Appendix 1
Survey of the existing literature.

Study theme	Study places	Year	Variable	Methods	Results	References
Port-city	Plymouth, South West England, 116 ports from Europe	1989–1991, 2000–2006	PT, NP, E, NJ	Observational method; GMM-System estimator	The two reach entirely contradictory conclusions: the former asserts that ports are not particularly effective instruments for economic development, while the latter contends that ports play a vital role in influencing regional economic growth.	(Gripaios & Gripaios, 1995) (Bottasso et al., 2014)
Port-city	South Korea	2000–2013	Population, GDP, economic growth rate, port investment, PT, CT	Solow model	Container ports significantly enhance regional economic growth.	(Park & Seo, 2016)
Port-city	20 world-leading container port cities	2013	Terminal area, berth length, number of quay cranes, CT, land area, energy consumption, labour, GDP, CO_2 emissions	DEA	Prevailing policies affect levels of sustainable development between the port and city system.	(Chen & Lam, 2018)
Port-city	Barcelona	2012-2017	CT, emission of SO_2, NO_2, PM2.5, PM10,	Mathematical statistics	Past and present hinterland initiatives that could successfully facilitate the growth and resilience of this port city.	(Gonzalez-Aregall & Bergqvist, 2020)
Port-city	Shanghai, China	2010–2017	PT capacity, PT, port pressure, GDP, port revenue, port profit, port investment, port demand, waste solid discharge, wastewater discharge, waste gas discharge, energy occupation, and water resources occupation.	System dynamics	increases in sea transportation activity and economic pull coefficients help to propel the growth of port–city GDP to a certain extent, but also cause environmental pollution and resource wastage.	(Li et al., 2019)
Port-city	Liaoning, China	2008–2017	PT, CT, Length of docks, Number of berths, GRP, Proportion of tertiary industry. Life quality, urban construction, ecological construction	Entropy weight method; CCDM	the six port-city systems have not strongly correlated and are in the stage of coordinated development.	(Liu et al., 2019)
Port-city	16 port-city pairs in China	2000–2016	PT, GDP, PI, SI, TI, TRSCG, FT	second-generation panel method	PI promotes TI.	(Cong et al., 2020)
Port-city	Saint Petersburg and Leningrad Province	2000–2015	PT, E, GRP	Five sequential stages	PT promotes GRP but has a weak influence on regional employment.	(Efimova & Gapochka, 2020)
Port-city	Main coastal port cities in China	2001–2015	PT, fixed-assets investment, total industrial output value, total retail sales of consumer goods, tertiary	DCI	The strength of port–city relationships are not related to port or city size, but	(Guo et al., 2020)

(continued on next page)

Appendix 1 (*continued*)

Study theme	Study places	Year	Variable	Methods	Results	References
			industrial output value, and urban freight volume		the development stage of the port or city.	
Port-city	Shanghai, China	2000–2019	GDP, UP, TI, environmental protection investment, PT, CT, NCB, ecological environmental index	PCA, CCDM	The PT has a significant impact on economic development. Environmental protection investment can improve the economy and ecological environment.	(Chen et al., 2022)
City-industry	Lianyungang, Jinan, Sichuan, China	1995–2005, 1996–2014, 2000–2016	Traffic level, public service, environmental governance, population & employment, industrial structure and efficiency	CCDM, TOPSIS, Entropy method	The low development level and the slow development rate of the industry subsystem are the key constraints for low coordination.	(Ai et al., 2016, Gan et al., 2020, Liu et al., 2018)
City ERE system	Beijing-Tianjin-Hebei	2008–2017	Economic aggregate (GRP, fixed investment, import and export trade); economic benefit and structure; environment quality	CCI, the obstacle degree model, CCDM	A coupling coordination index was developed for the ERE system.	(Han et al., 2021, Wang et al., 2022)
Industry	33 cities in China	2002–2017	Energy input, labour force, capital stock, industrial output value, emission of SO_2, CO_2, COD	Fuzzy artificial neural network	The critical factors affecting industrial green competitiveness are identified.	(He et al., 2023)
Port Industry	31 provinces in China	2022	NB, CWB, LMC, the number of companies and establishments in port-related industries	Helix theory	The Port Industry Ecosystem (PIDES) in coastal areas is well-developed, with its scale closely linked to economic efficiency. However, 82 % of coastal areas must prioritize marine environmental protection in PIDES development.	(Zhang et al., 2025)

Note: Port Throughput (PT), Contain Throughput (CT), Gross Domestic Product (GDP), Gross Regional Product (GRP), Primary Industry (PI), Secondary Industry (SI), Tertiary Industry (TI), Total Retail Sales of Consumer Goods (TRSCG), Number of Passengers (NP), Employment (E), Number of Jobs (NJ), Number of Container Berths (NCB), Data Envelopment Analysis (DEA), Chemical Oxygen Demand (COD), Coupling Coordination Index (CCI), Economy-Resources-Environment system (ERE system), Dynamic Centralisation Index (DCI), Number of Berths of 10,000 Tons and Above (NB), Coastal Wharf Berths (CWB), and Length of Mainland Coastline (in kilometers) (LMC).

Data availability

Data will be made available on request.

References

Ai, J. Y., Feng, L., Dong, X. W., Zhu, X. D., & Li, Y. F. (2016). Exploring coupling coordination between urbanization and ecosystem quality (1985–2010): a case study from Lianyungang City, China. *Frontiers of Earth Science, 10*, 527–545. https://doi.org/10.1007/s11707-015-0531-6

Akhavan, M. (2017). Development dynamics of port-cities interface in the Arab middle eastern world - the case of Dubai global hub port-city. *Cities, 60*, 343–352. https://doi.org/10.1016/j.cities.2016.10.009

Bian, D. H., Yang, X. H., Xiang, W. Q., Sun, B. Y., Chen, Y. J., Babuna, P., … Yuan, Z. X. (2022). A new model to evaluate water resource spatial equilibrium based on the game theory coupling weight method and the coupling coordination degree. *Journal of Cleaner Production, 366*, Article 132907. https://doi.org/10.1016/j.jclepro.2022.132907

Bottasso, A., Conti, M., Ferrari, C., & Tei, A. (2014). Ports and regional development: A spatial analysis on a panel of European regions. *Transportation Research Part A: Policy and Practice, 65*, 44–55. https://doi.org/10.1016/j.tra.2014.04.006

Brooks, M. R., & Pallis, A. A. (2008). Assessing port governance models: Process and performance components. *Maritime Policy & Management, 35*, 411–432. https://doi.org/10.1080/03088830802215060

Buor, J. K. (2024). Analysis of port management and ownership models in Ghana between 1980 and 2020: Motivation and consequences. *WMU Journal of Maritime Affairs, 23*, 212–234. https://doi.org/10.1007/s13437-024-00331-y

Cai, J., Xin, K., & Zhou, Y. (2021). A dynamic panel data approach and HCW's method: Assessing the effect of China (Shanghai) free trade zone on local GDP. *Journal of Management Science and Engineering, 6*, 249–267. https://doi.org/10.1016/j.jmse.2021.06.004

Cai, L., Li, W., Zhou, B., Li, H., & Yang, Z. (2024). Robust multi-equipment scheduling for U-shaped container terminals concerning double-cycling mode and uncertain operation time with cascade effects. *Transportation Research Part C: Emerging Technologies, 158*, 104447. https://doi.org/10.1016/j.trc.2023.104447

Chang, Y.-T., Shin, S.-H., & Lee, P. T.-W. (2014). Economic impact of port sectors on south African economy: An input–output analysis. *Transport Policy, 35*, 333–340. https://doi.org/10.1016/j.tranpol.2014.04.006

Chen, C., & Lam, J. S. L. (2018). Sustainability and interactivity between cities and ports: a two-stage data envelopment analysis (DEA) approach. *Maritime Policy & Management, 45*, 944–961. https://doi.org/10.1080/03088839.2018.1450528

Chen, J. H., Zhang, W. P., Song, L., & Wang, Y. F. (2022). The coupling effect between economic development and the urban ecological environment in Shanghai port. *Science of the Total Environment, 841*, Article 156734. https://doi.org/10.1016/j.scitotenv.2022.156734

Chen, Y., Chao, Y., & Yang, D. (2020). Port recentralization as a balance of interest. *Research in Transportation Business & Management, 34*, 100374. https://doi.org/10.1016/j.rtbm.2019.100374

Cheng, J. N., Lian, F., & Yang, Z. Z. (2022). The impacts of port governance reform on port competition in China. *Transportation Research Part E: Logistics and Transportation Review, 160*, Article 102660. https://doi.org/10.1016/j.tre.2022.102660

Cheung, S. M. S., & Yip, T. L. (2011). Port City factors and port production: Analysis of Chinese ports. *Transportation Journal, 50*, 162–175. https://doi.org/10.5325/transportationj.50.2.0162

Cong, L. Z., Zhang, D., Wang, M. L., Xu, H. F., & Li, L. (2020). The role of ports in the economic development of port cities: Panel evidence from China. *Transport Policy, 90*, 13–21. https://doi.org/10.1016/j.tranpol.2020.02.003

Cullinane, K., & Wang, T. F. (2006). Port governance in China. *Research in Transportation Economics, 17*, 331–356. https://doi.org/10.1016/S0739-8859(06)17015-8

Dadashpoor, H., & Taheri, E. (2023). The evolution of port-city relations in the era of technological development: Case study of Bandar-Abbas County, Iran. *GeoJournal, 88*, 2423–2447. https://doi.org/10.1007/s10708-022-10752-y

Debrie, J., Lavaud-Letilleul, V., & Parola, F. (2013). Shaping port governance: The territorial trajectories of reform. *Journal of Transport Geography, 27*, 56–65. https://doi.org/10.1016/j.jtrangeo.2012.07.007

Ducruet, C., Polo Martin, B., Sene, M. A., Lo Prete, M., Sun, L., Itoh, H., & Pigné, Y. (2024). Ports and their influence on local air pollution and public health: A global analysis. *Science of the Total Environment, 915*, Article 170099. https://doi.org/10.1016/j.scitotenv.2024.170099

Efimova, E. G., & Gapochka, A. A. (2020). Seaports as drivers of regional economic development: The case of Saint Petersburg and Leningrad Province. *Case Studies on Transport Policy, 8*, 383–393. https://doi.org/10.1016/j.cstp.2019.10.003

Fan, G. H., Xie, X. K., Chen, J. H., Wan, Z., Yu, M. Z., & Shi, J. (2022). Has China's free trade zone policy expedited port production and development? *Marine Policy, 137*, Article 104951. https://doi.org/10.1016/j.marpol.2021.104951

Feng, H. X., Grifoll, M., & Zheng, P. J. (2019). From a feeder port to a hub port: The evolution pathways, dynamics and perspectives of Ningbo-Zhoushan port (China). *Transport Policy, 76*, 21–35. https://doi.org/10.1016/j.tranpol.2019.01.013

Gan, L., Shi, H., Hu, Y., Lev, B., & Lan, H. (2020). Coupling coordination degree for urbanization city-industry integration level: Sichuan case. *Sustainable Cities and Society, 58*, Article 102136. https://doi.org/10.1016/j.scs.2020.102136

González, M. A. M., & Trujillo, L. (2008). Reforms and infrastructure efficiency in Spain's container ports. *Transportation Research Part A: Policy and Practice, 42*, 243–257. https://doi.org/10.1016/j.tra.2007.08.006

Gonzalez-Aregall, M., Bergqvist, R., NG, A. K. Y., Monios, J., & Jiang, C. (2020). Green port initiatives for a more sustainable port-city interaction: The case study of Barcelona. In *Maritime transport and regional sustainability*. Elsevier. https://doi.org/10.1016/B978-0-12-819134-7.00007-1.

Gripaios, P., & Gripaios, R. (1995). The impact of a port on its local economy: The case of Plymouth. *Maritime Policy & Management, 22*, 13–23. https://doi.org/10.1080/03088839500000029

Guo, J., Qin, Y., Du, X., & Han, Z. (2020). Dynamic measurements and mechanisms of coastal port–city relationships based on the DCI model: Empirical evidence from China. *Cities, 96*. https://doi.org/10.1016/j.cities.2019.102440

Guo, J. K., & Qin, Y. F. (2022). Coupling characteristics of coastal ports and urban network systems based on flow space theory: Empirical evidence from China. *Habitat International, 126*, Article 102624. https://doi.org/10.1016/j.habitatint.2022.102624

Han, H., Guo, L., Zhang, J. Q., Zhang, K. Z., & Cui, N. B. (2021). Spatiotemporal analysis of the coordination of economic development, resource utilization, and environmental quality in the Beijing-Tianjin-Hebei urban agglomeration. *Ecological Indicators, 127*, Article 107724. https://doi.org/10.1016/j.ecolind.2021.107724

He, Y., Tang, C., Zhang, D. L., & Liao, N. (2023). Assessing the effects of the influencing factors on industrial green competitiveness fusing fuzzy C-means, rough set and fuzzy artificial neural network methods. *Ecological Indicators, 147*, Article 109921. https://doi.org/10.1016/j.ecolind.2023.109921

Hidalgo-Gallego, S., & Núñez-Sánchez, R. (2023). The effect of port activity on urban employment: An analysis for the Spanish functional urban areas. *Journal of Transport Geography, 108*, Article 103570. https://doi.org/10.1016/j.jtrangeo.2023.103570

Kong, Y. D., & Liu, J. G. (2021). Sustainable port cities with coupling coordination and environmental efficiency. *Ocean and Coastal Management, 205*. https://doi.org/10.1016/j.ocecoaman.2021.105534

Lane, J. M., & Pretes, M. (2020). Maritime dependency and economic prosperity: Why access to oceanic trade matters. *Marine Policy, 121*, Article 104180. https://doi.org/10.1016/j.marpol.2020.104180

Li, S., Haralambides, H., & Zeng, Q. C. (2022). Economic forces shaping the evolution of integrated port systems - the case of the container port system of China's Pearl River Delta. *Research in Transportation Economics, 94*, Article 101183. https://doi.org/10.1016/j.retrec.2022.101183

Li, Y., Zhang, X. H., Lin, K. Y., & Huang, Q. B. (2019). The analysis of a simulation of a Port-City green cooperative development, based on system dynamics: A case study of Shanghai port, China. *Sustainability, 11*. https://doi.org/10.3390/su11215948

Li, Z. W. (2019). Statistical analysis of the development of the port cluster economy in Beijing, Tianjin and Hebei. *Journal of Coastal Research, 94*, 692–695. https://doi.org/10.2112/SI94-137.1

Lin, B., & Tang, J. (2023). Impact of port-city coordination upon hinterland economy in Pear River Delta. *ICIC Express Letters, 19*, 289–297. https://doi.org/10.24507/ijicic.19.01.289

Liu, J., Zhou, J., Liu, F., Yue, X., Kong, Y., & Wang, X. (2019). Interaction analysis and sustainable development strategy between port and city: The case of Liaoning. *Sustainability (Switzerland), 11*. https://doi.org/10.3390/su11195366

Liu, J. G., Kong, Y. D., Li, S. J., & Wu, J. J. (2021). Sustainability assessment of port cities with a hybrid model-empirical evidence from China. *Sustainable Cities and Society, 75*, Article 103301. https://doi.org/10.1016/j.scs.2021.103301

Liu, W. J., Jiao, F. C., Ren, L. J., Xu, X. G., Wang, J. C., & Wang, X. (2018). Coupling coordination relationship between urbanization and atmospheric environment security in Jinan City. *Journal of Cleaner Production, 204*, 1–11. https://doi.org/10.1016/j.jclepro.2018.08.244

Lonza, L., & Marolda, M. C. (2016). Ports as drivers of urban and regional growth. *Transportation Research Procedia, 14*, 2507–2516. https://doi.org/10.1016/j.trpro.2016.05.327

Luo, J. Q., Ding, Y. Y., Chen, W. S., & Kuang, H. B. (2023). Modeling method and simulation of regional economy and port interactive development system dynamics. *Annals of Operations Research, 326*(04), 1–17. https://doi.org/10.1007/s10479-021-04438-w

MOT. (2019). Ministry of Transport of China: Guidelines for Building World-Class Ports [Online]. Available https://www.gov.cn/xinwen/2019-11/13/content_5451577.htm [Accessed].

Park, J. S., & Seo, Y. J. (2016). The impact of seaports on the regional economies in South Korea: Panel evidence from the augmented Solow model. *Transportation Research Part E: Logistics and Transportation Review, 85*, 107–119. https://doi.org/10.1016/j.tre.2015.11.009

Park, Y., & Dossani, R. (2020). Port infrastructure and supply chain integration under the belt and road initiative: Role of Colombo port in the apparel industry in South Asia. *Transportation Research Procedia, 48*, 307–326. https://doi.org/10.1016/j.trpro.2020.08.025

Pettit, S. J. (2008). United Kingdom ports policy: Changing government attitudes. *Marine Policy, 32*, 719–727. https://doi.org/10.1016/j.marpol.2007.12.002

Pilcher, N., & Tseng, P.-H. (2017). Can we really measure the impact of port governance reform? *Maritime Policy & Management, 44*, 981–994. https://doi.org/10.1080/03088839.2017.1380318

Santos, A. M. P., Salvador, R., Dias, J. C. Q., & Soares, C. G. (2018). Assessment of port economic impacts on regional economy with a case study on the port of Lisbon. *Maritime Policy & Management, 45*, 684–698. https://doi.org/10.1080/03088839.2018.1471536

SAPAC. (2020). *State-owned assets supervision and administation commission of the state council: Reorganization and integration of central and local authorities to reshape Liaoning ports [online]*. Available http://www.sasac.gov.cn/n2588025/n4423279/n4517386/n16335270/c16335432/content.html [accessed].

Sugimura, Y., Akakura, Y., Yotsushima, T., & Kawasaki, T. (2023). Evaluation of Japanese port policies through network analysis. *Transport Policy, 135*, 59–70. https://doi.org/10.1016/j.tranpol.2023.03.011

Taylor, G., & McDonald, M. (2023). In practice and in principle: 'Free market' discourses and container port reform in Australia. *Competition and Change, 28*, 67–92. https://doi.org/10.1177/10245294231181967

TMPG. (2023). *Tianjin municipal people's government: Tianjin policy measures for promoting high-quality integration of port, industry, and City development [online]*. Available https://www.tj.gov.cn/zwgk/szfwj/tjsrmzfbgt/202306/t20230608_6271501.html [accessed].

Valenzuela, H. C., Torres-Salinas, R., Grosser, G., Félez-Bernal, J., & Budrovich, J. (2023). Port-city symbiosis and uneven development: a critical essay on forestry exports and maritime trade from coronel, Chile. *Maritime Economics & Logistics, 25*, 381–405. https://doi.org/10.1057/s41278-022-00246-6

Villa, J. C. (2017). Port reform in Mexico: 1993–2015. *Research in Transportation Business & Management, 22*, 232–238. https://doi.org/10.1016/j.rtbm.2016.11.003

Wan, S. L., & Luan, W. X. (2022). Hinterland evolution and port growth decomposition: The case of Shanghai. *Journal of Transport Geography, 100*, Article 103334. https://doi.org/10.1016/j.jtrangeo.2022.103334

Wang, H. (2022). Comprehensive Development Evaluation of Main Inland Ports on the Yangtze River. In *2022 10th international conference on traffic and logistic engineering (ICTLE), 12–14 Aug. 2022* (pp. 134–138). https://doi.org/10.1109/ICTLE55577.2022.9902092

Wang, J. K., Han, Q., Wu, K. X., Xu, Z. T., & Liu, P. (2022). Spatial-temporal patterns and evolution characteristics of the coordinated development of industrial economy, natural resources and environment in China. *Resources Policy, 75*, Article 102463. https://doi.org/10.1016/j.resourpol.2021.102463

Wang, Y. X., & Wang, N. (2019). The role of the port industry in China's national economy: An input–output analysis. *Transport Policy, 78*, 1–7. https://doi.org/10.1016/j.tranpol.2019.03.007

Wu, Z., Woo, S. H., Lai, P. L., & Xiaoyi, C. (2022). The economic impact of inland ports on regional development: Evidence from the Yangtze River region. *Transport Policy, 127*, 80–91. https://doi.org/10.1016/j.tranpol.2022.08.012

Xu, Q. J., Huang, T. C., Chen, J. H., Wan, Z., Qin, Q. D., & Song, L. (2021). Port rank-size rule evolution: Case study of Chinese coastal ports. *Ocean and Coastal Management, 211*, Article 105803. https://doi.org/10.1016/j.ocecoaman.2021.105803

Yang, Z. Z., Guo, L. Q., & Lian, F. (2019). Port integration in a region with multiport gateways in the context of industrial transformation and upgrading of the port. *Transportation Research Part E: Logistics and Transportation Review, 122*, 231–246. https://doi.org/10.1016/j.tre.2018.12.009

Yilmaz, M. (2022). Assessment of the relationship between City and port in Mersin, Turkey. *Journal of Geography-Cografya Dergisi*, 183–191. https://doi.org/10.26650/JGEOG2022-1001157

Zhang, F. T., Sun, C. C., An, Y. Z., Luo, Y. G., Yang, Q., Su, W. C., & Gao, L. (2021). Coupling coordination and obstacle factors between tourism and the ecological environment in Chongqing, China: a multi-model comparison. *Asia Pacific Journal of Tourism Research, 26*, 811–828. https://doi.org/10.1080/10941665.2021.1925715

Zhang, Q., Hu, X., Li, Z., Zhou, Y., & Qi, X. (2025). Port's industry ecosystem construction: Empirical evidence from China. *Transport Policy*. https://doi.org/10.1016/j.tranpol.2025.01.005

Zhang, Q., Yan, K., & Yang, D. (2021). Port system evolution in Chinese coastal regions: A provincial perspective. *Journal of Transport Geography, 92*, Article 103031. https://doi.org/10.1016/j.jtrangeo.2021.103031

Zhang, Y., & Lam, J. S. L. (2016). Estimating economic losses of industry clusters due to port disruptions. *Transportation Research Part A: Policy and Practice, 91*, 17–33. https://doi.org/10.1016/j.tra.2016.05.017

Zhao, D., Li, Z. F., & Wei, D. (2023). Research on the symbiosis of port and city based on symbiosis theory: Empirical evidence from China's coastal port groups. *International Journal of Shipping and Transport Logistics, 16*, 210–230. https://doi.org/10.1504/IJSTL.2023.128578

Zhou, Y. T., Li, Z. F., Duan, W., & Deng, Z. (2023). The impact of provincial port integration on port efficiency: Empirical evidence from China's coastal provinces. *Journal of Transport Geography, 108*, Article 103574. https://doi.org/10.1016/j.jtrangeo.2023.103574

ZPDRC. (2021). *Zhejing provincial development and reform commission: The 14th five-year plan for the construction of the Yiwu-Ningbo-Zhoushan open corridor in Zhejiang Province [online]*. Available https://fzggw.zj.gov.cn/art/2021/7/15/art_1229123366_2311435.html [accessed].