

Assessment of international competitiveness and its driving factors for the Shandong Port Cluster

Guangxue Wan, Xiaomeng Huan and Chunlei Shen
School of Business, Shandong University, Weihai, China

Pan Yang and Shouyi Qiao

Institute of Blue and Green Development, Shandong University, Weihai, China, and

Lin Yang

School of Business, Shandong University, Weihai, China

Abstract

Purpose – Ports are fundamental and pivotal facilities and an important support for economic development. This paper aims to enhance the international competitiveness of Shandong’s port cluster and provides reference for accelerating the development of world-class maritime ports.

Design/methodology/approach – Based on the data of the Shandong port cluster from 2011 to 2023, this paper comprehensively employs the entropy method, Kernel density estimation and panel data model to systematically measure the international competitiveness level of the Shandong port cluster, and fully analyzes its distribution dynamic evolution characteristics and driving factors.

Findings – The research findings are as follows: firstly, the international competitiveness level of the Shandong port cluster is generally on the rise, but the differences among ports are relatively obvious. There are differences in the development levels of each port in the four dimensions of smart and green, economic efficiency, support capacity and integration and openness. Secondly, the dynamic evolution characteristics indicate that the volatility in the distribution center area of the international competitiveness level of the Shandong port cluster is relatively stable, and the changing trends of the competitiveness of each port are relatively stable. Thirdly, the analysis of driving factors indicates that the level of digital technology, relevant professional talents and industrial structure are the core driving factors.

Originality/value – This paper systematically evaluates the international competitiveness level of Shandong’s port cluster, identifies its driving factors and provides guidance for continuously improving the comprehensive service level of ports and shipping.

Keywords Shandong port cluster, International competitiveness, Driving factors

Paper type Research article

1. Introduction

Against the backdrop of deepening digitalization, networking, and intelligentization, enhancing the international competitiveness of ports constitutes an essential requirement for implementing national strategies such as “Maritime Power” and “Transportation Power” (Wang *et al.*, 2021; Yang *et al.*, 2022). As critical strategic assets in the globalization process, ports play an indispensable role in the modern economic system and serve as fundamental

© Guangxue Wan, Xiaomeng Huan, Chunlei Shen, Pan Yang, Shouyi Qiao and Lin Yang. Published in *Marine Economics and Management*. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at [Link to the terms of the CC BY 4.0 licence](#).

Funding: This work was supported by the Shandong Province Key R&D Program (Soft Science) Youth Project (No. 2024RKY0201), the National Social Science Fund Major Project of China (No. 20&ZD100) and the Shandong Provincial Youth Innovation Science and Technology Support Program for Universities (No. 2025RWE017).

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.



forces strengthening global economic and trade exchanges (Wang *et al.*, 2025; He and Xu, 2023). Strategically positioned at the maritime-terrestrial crossroads of the Belt and Road Initiative, Shandong Port links Japan and South Korea to the east, Eurasia to the west, ASEAN to the south, and Mongolia-Russia to the north, functioning as a pivotal hub for open development in Shandong and throughout the Yellow River basin.

In 2024, Shandong Port achieved a cargo throughput of 2.07 billion tons and container throughput of 45.023 million TEUs, demonstrating robust growth momentum. Significant progress has been made in smart and green port development, with Shandong becoming China's first "Smart Port Pilot Province" designated by the Ministry of Transport under its Transportation Power initiative. Qingdao Port leads globally in automated container terminal technology and handling efficiency, while clean energy sources accounted for 58% of the port's total energy consumption.

However, persistent challenges include uneven smart-port development, inadequate integration of maritime services with next-generation information technologies, and insufficient data security management. Assessing the international competitiveness level and driving factors of the Shandong Port Cluster represents a critical task for leveraging digital technologies to overcome transformation bottlenecks. This research holds substantial theoretical and practical significance for enhancing the international competitiveness of Shandong's port cluster, accelerating the development of world-class port facilities, and establishing a Northeast Asia international shipping hub center.

Ports play an increasingly pivotal role in economic development (Wan *et al.*, 2025). As fundamental and pivotal infrastructure, they contribute significantly to urban economies through multiple dimensions: port logistics services boosting hinterland economies, port-city development interactions, and impacts on international trade and global supply chains (Verschuur *et al.*, 2022). However, rapid economic expansion has generated substantial environmental challenges, with ecological constraints emerging as primary barriers to sustainable development for ports and their hinterland cities. Existing research predominantly addresses pollution from port industries, environmental efficiency evaluations of port cities, and green port initiatives (Qu *et al.*, 2023; Meng *et al.*, 2024). Consequently, in transitioning toward sustainability, ports are undergoing socio-ecological transformations—progressively advancing through digitalization, intelligence, and greening.

Advances in digital technologies serve as primary catalysts for port smart-green transformation, manifested through applications of IoT and digital twin technologies in maritime industries (Elsisi *et al.*, 2025; Rekabi *et al.*, 2025). Quantitative assessments of port transformation performance have been conducted using mathematical modeling approaches: game theory frameworks examining digital transitions, econometric analyses of technology's impact on port communication capabilities, and AI big data integration validating supply chain resilience (He *et al.*, 2023; Lu and Xu, 2024). Aligned with sustainable development goals, research has established smart port frameworks encompassing production operations, intelligent services, risk management, and smart scheduling (Li *et al.*, 2023), systematically evaluating performance across operational, environmental, energy, and safety dimensions.

Port cluster competitiveness assessment represents a critical research domain for understanding and enhancing the efficiency and sustainable development capabilities of regional maritime logistics. Existing studies have primarily employed methods such as indicator system evaluation, Data Envelopment Analysis (DEA), TOPSIS, cluster analysis, and literature reviews to investigate port cluster competitiveness. For instance, Wang *et al.* (2023) developed an indicator system encompassing four dimensions—port infrastructure, port operational scale, hinterland economic conditions, and port development potential—to evaluate the competitiveness of ports along China's Belt and Road Initiative. Mo *et al.* (2018) utilized an improved DEA model to measure the efficiency of Shenzhen's port logistics competitiveness. Kim (2016) applied the TOPSIS method to compare the competitiveness of ports in Korea and China. Xiao *et al.* (2025) conducted a regional classification and competitiveness analysis of Chinese coastal ports from perspectives such as port throughput

capacity, scale, development potential, and internal cluster development dynamics. [Luo et al. \(2022\)](#) performed a literature review on the relationships between port competition, cooperation, and competitiveness to clarify their interconnections.

It is evident that ports, as critical nodes ensuring the stability of global supply and industrial chains, are undergoing smart and green transformation. The process concerns not only the development of the shipping industry itself but also serves as a vital support for implementing the new development philosophy and fostering new quality productive forces in maritime sectors. While existing literature has yielded substantial research on the importance of ports and their smart-green transition, studies on the evaluation of international port competitiveness remain relatively limited. Moreover, few scholars have employed econometric analysis to explore the influencing factors of the international competitiveness of port clusters. This study responds to the national strategic deployment of building China into a strong maritime and transportation country. By assessing the international competitiveness of the Shandong port cluster within the context of the maritime power strategy, it aims to provide theoretical support for government authorities in developing world-leading smart, green, and safe ports, as well as promoting high-quality development in the port and shipping industry.

The potential marginal contributions of this paper are as follows: Firstly, focusing on the Shandong port cluster, this study constructs an evaluation system for its international competitiveness from four dimensions: smart-green development, economic efficiency, supporting capacity, and integration and openness. Based on this framework, it compares and analyzes the developmental differences in international competitiveness among Qingdao Port, Rizhao Port, and Yantai Port. Secondly, using the kernel density estimation method, this paper conducts an in-depth analysis of the dynamic evolution characteristics of the international competitiveness of the Shandong port cluster. This approach expands and deepens research related to port competitiveness evaluation, shifting the focus from static comparisons of individual ports to a dynamic understanding of the evolutionary patterns of competitiveness across the port cluster as a whole. Thirdly, applying econometric analysis methods, this paper further investigates the driving factors of the international competitiveness of the Shandong port cluster. It specifically examines the impact of port-related digital technologies, professional talent, and high-value-added industries, providing directional guidance for different ports to achieve coordinated and synergistic development, build stronger core competitive advantages, and establish a world-class port cluster.

2. Research methods and data sources

2.1 Entropy weight method

This study employs the objectively weighted entropy method to measure the comprehensive competitiveness level of the Shandong Port Cluster. This approach is adopted primarily because all selected indicators are quantitative in nature, do not include subjective indicators, and values its objectivity in determining weights, and effectively minimizing human interference. The specific computational procedures are as follows ([Wan et al., 2025](#)):

Step 1: Taking the standardization of positive indicators as an example, begin with standardizing the indicator data.

$$X_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

Step 2: Calculate the proportion p_{ij} of the sample data for the j -th indicator of the i -th port:

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}} \quad (2)$$

Step 3: Calculate the information entropy e_j for the j th indicator:

$$e_j = -k \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (3)$$

Where, $k > 0$, $e_j \geq 0$.

Step 4: Calculate the internal variability coefficient g_j for the j th indicator:

$$g_j = 1 - e_j \quad (4)$$

Step 5: Define the weight of sample values ω_j ,

$$\omega_j = \frac{g_j}{\sum_{j=1}^m g_j} \quad (5)$$

2.2 Kernel density estimation

Kernel density estimation is a non-parametric statistical method characterized by strong robustness, used to describe the distribution pattern and dynamic evolution of variables (Wang et al., 2025). The specific formula is as follows:

$$f(x) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{X_i - \bar{x}}{h}\right) \quad (6)$$

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (7)$$

The density function of random variable X is $f(x)$. N denotes the number of ports, X_i represents independent and identically distributed observations, \bar{x} indicates the mean value, $K(\cdot)$ stands for the Kernel density (this study employs the Gaussian kernel function), and h signifies the bandwidth. By analyzing changes in the position, shape, and kurtosis of the Kernel density curves across different periods, the distribution characteristics and polarization trends of smart agriculture development levels can be visually reflected.

2.3 Panel data model

This study employs a panel data model to investigate the driving factors influencing the international competitiveness level of the Shandong Port Cluster, constructing the model as follows (Yang et al., 2024):

$$\begin{aligned} \text{compet}_{it} = & \beta_0 + \beta_1 \text{dig}_{it} + \beta_2 \text{edu}_{it} + \beta_3 \text{labor}_{it} + \beta_4 \text{str}_{it} + \beta_5 \text{elec}_{it} \\ & + \beta_6 \text{pgdp}_{it} + \gamma_i + \nu_t + \varepsilon_{it} \end{aligned} \quad (8)$$

To reduce the potential impact of heteroscedasticity and volatility in the sample, logarithmic transformation is applied to indicator data with large magnitudes. The dependent variable $compet_{it}$ denotes the international competitiveness level of port i in year t . Explanatory variables include: (1) *dig*: Digital technology level, measured by the annual count of key digital technology inventions; (2) *edu*: Education level, proxied by enrollment in regular higher education institutions; (3) *labor*: Labor force level, reflected by employment in information transmission, computer services, and software industries; (4) *str*: Industrial structure, gauged by the tertiary sector's share of GRP; (5) *elec*: Energy consumption level, represented by industrial electricity usage; (6) *pgdp*: Per capita gross regional product.

2.4 Data sources

Given data availability and consistency, this study examines the international competitiveness level of the Shandong Port Cluster using three representative ports (Qingdao Port, Rizhao Port, Yantai Port) from 2011 to 2023. Data were primarily sourced from China Port Yearbook, China City Statistical Yearbook, Shandong Statistical Yearbook, the Ministry of Transport, and statistics published by the United Nations Conference on Trade and Development.

3. The measurement and distribution dynamic evolution of Shandong port cluster international competitiveness level

3.1 Development of a comprehensive evaluation index system for the international competitiveness of Shandong Port Cluster

Ports constitute crucial strategic resources in the process of economic globalization and serve as pivotal hubs for global resource allocation (Nie *et al.*, 2025). Leveraging its unparalleled geographical advantages, leading terminal facilities, favorable business environment, and well-developed collection-distribution network, the Shandong Port Cluster plays an indispensable role in driving regional economic and social development while ensuring the stability and efficiency of global industrial and supply chains. The Shandong Provincial Three-Year Action Plan for Building a World-Class Port Cluster (2023–2025), promulgated in 2023, emphasizes accelerating the development of a world-class port cluster characterized by safety and efficiency, smart and green operations, economic effectiveness, strong supporting capacity, and integrated openness. Due to constraints in accessing safety-related data and the fact that convenience-related indicators are already incorporated within the existing evaluation framework, this study did not establish “safety and efficiency” as an independent criterion. Accordingly, this study measures the international competitiveness of the Shandong Port Cluster across four dimensions—smart and green development, economic efficiency, supporting capacity, and integrated openness—to highlight its pivotal position and comprehensive strength within global supply chains. The indicator system is presented in Table 1.

The characterization of smart and green development for the international competitiveness of the Shandong Port Cluster primarily focuses on the Green Collection-Distribution Ratio and Digital Intelligence Patent Applications, where the former is measured by the proportion of railway and waterway freight volume to reflect the decarbonization level and environmental performance of port transportation structures, while the latter is obtained through manual retrieval of patent data for Qingdao, Rizhao, and Yantai ports from patent databases to characterize innovation capabilities and application potential in intelligent technologies.

The characterization of economic efficiency for the international competitiveness of the Shandong Port Cluster primarily focuses on port shoreline utilization efficiency, cargo throughput of major coastal ports, and GDP of hinterland cities. Shoreline utilization efficiency is calculated as container throughput per unit terminal length (Chen *et al.*, 2025), characterizing the intensive utilization and output efficiency of port shoreline resources. Cargo throughput further reflects ports' scale effects, operational efficiency, and hub status within

Table 1. Comprehensive evaluation index system for international competitiveness of Shandong port cluster

First-level indicator	Secondary indicators	Third-level indicators
International Competitiveness Level of Shandong Port Cluster	Smart and Green	Proportion of Green Collection and Distribution Transport Number of Port Digitalization-related Patent Applications
	Economic Efficiency	Utilization Efficiency of Port Shorelines Cargo Throughput of Major Coastal Ports Port's Hinterland GDP
	Supporting Capability	Length of Productive Berths Number of 10000ton Berths Number of Related Practitioners
	Integration and Openness	Hinterland Openness Level Port Connectivity Foreign Trade Throughput

Source(s): Authors' own creation

global trade networks (Wang *et al.*, 2020). Port development relies on robust economic foundations and industrial support from hinterland cities, where hinterland GDP directly reflects the regional economic scale and vitality underpinning ports, serving as a key factor in measuring port development potential and market demand (Meng *et al.*, 2024).

The characterization of supporting capacity for the international competitiveness of the Shandong Port Cluster primarily focuses on operational terminal length, number of 10,000-ton-class berths, and relevant workforce size (Lin *et al.*, 2024). Here, operational terminal length represents the scale of infrastructure and maximum physical handling capacity. The number of 10,000-ton-class berths effectively reflects specialized service capabilities for accommodating large modern vessels and handling bulk cargo/containers. The workforce metric specifically selects employment figures in transport, warehousing, and postal sectors to measure professional human resources supporting port operations, logistics organization, and ancillary services.

The characterization of integrated openness for the international competitiveness of the Shandong Port Cluster primarily focuses on hinterland openness, port connectivity, and foreign trade throughput. Hinterland openness is measured by the ratio of actual utilized foreign investment to GDP, characterizing the depth of hinterland economy's integration into global capital flows and its attractiveness to foreign investment—serving as a crucial economic foundation for port openness functions. Port connectivity reflects liner shipping route density and port accessibility, with data sourced from the Liner Shipping Connectivity Index published by the United Nations Conference on Trade and Development. This metric directly demonstrates a port's nodal status in global shipping networks, breadth of connections with worldwide ports, and operational efficiency, constituting a core indicator for measuring international shipping hub functionality. Foreign trade throughput represents the scale and activity level of ports' direct participation in international trade, serving as the most immediate manifestation of their capacity to support open economies and sustain global supply chain operations.

3.2 Analysis of measurement results

From 2011 to 2023, the international competitiveness of the Shandong port cluster has achieved a leapfrog improvement (Figure 1), increasing from 1.2533 in 2011 to 1.5886 in 2023, with an average annual growth rate of 2.1%, highlighting the crucial role of ports as

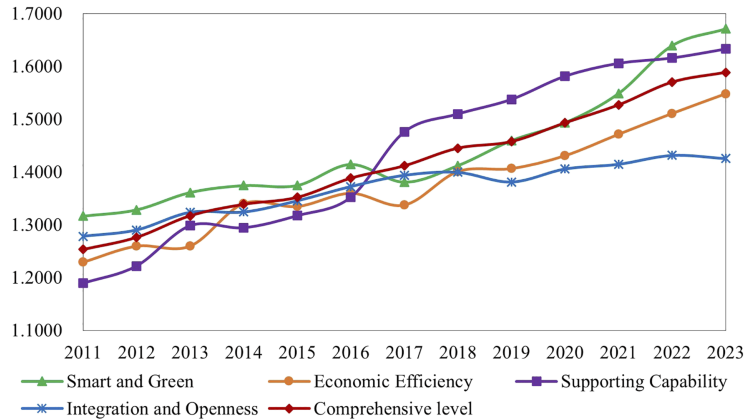


Figure 1. International Competitiveness Level of Shandong Port Cluster from 2011 to 2023. Source(s): Authors' own creation

strategic fulcrum for economic globalization. Among them, the level of smart green was at the leading position in 2011–2016 and 2022–2023, with an increase of 27%, and reached the peak of the index at 1.6713 in 2023. This is mainly attributed to the continuous advancement of the smart and green transformation of ports, highlighting the breakthrough achievements made by Shandong Ports in the fields of digital and intelligent empowerment and low-carbon development. The supporting capacity has grown at a rate of 37.3%, becoming the fastest-growing dimension, reflecting the leapfrog development of hardcore infrastructure. The economic efficiency dimension grew steadily by 25.9%, and the container throughput per unit of shoreline increased by 40%, confirming the remarkable achievements of intensive resource management. The growth rate of the dimension of openness and integration has slowed down due to the fluctuations in the global trade pattern. However, the foreign trade throughput has exceeded the 1 billion tons mark, demonstrating the resilience and potential of Shandong Port in deeply integrating into the global industrial chain and supply chain.

3.3 Comparative analysis of port competitiveness

Port differential analysis Qingdao Port, Rizhao Port, and Yantai Port exhibit gradient progression and differentiated leapfrogging in international competitiveness, with resource integration and specialized operations reshaping the regional port landscape (Figure 2). From 2011 to 2023, the competitiveness of Shandong's three major ports steadily increased, yet their development paths and growth rates diverged significantly.

Qingdao Port led decisively, its composite index rising from 1.6026 to 1.9866, a 23.9% increase, primarily attributable to globally leading smart port construction, strengthened status as an international hub port, and high-value-added industries, highlighting its radiating capacity as a Northeast Asia shipping center.

Rizhao Port's international competitiveness index rose from 1.0826 to 1.4228, a 31.4% increase—the highest growth rate among the three ports—but with noticeable volatility; it experienced a brief decline due to the commodity cycle between 2015 and 2017, followed by a significant index surge after 2020 driven by the operational launch of its 400,000-ton ore berth, with bulk commodities like iron ore and crude oil accounting for 78% of throughput, cementing its role as a specialized bulk cargo hub.

Yantai Port maintained steady growth, increasing from 1.0746 to 1.3564, a 26.2% rise, with acceleration notably picking up from 2021 onward, benefiting from explosive growth in roll-on/roll-off (ro-ro) transport for commercial vehicles and the establishment of a two-way

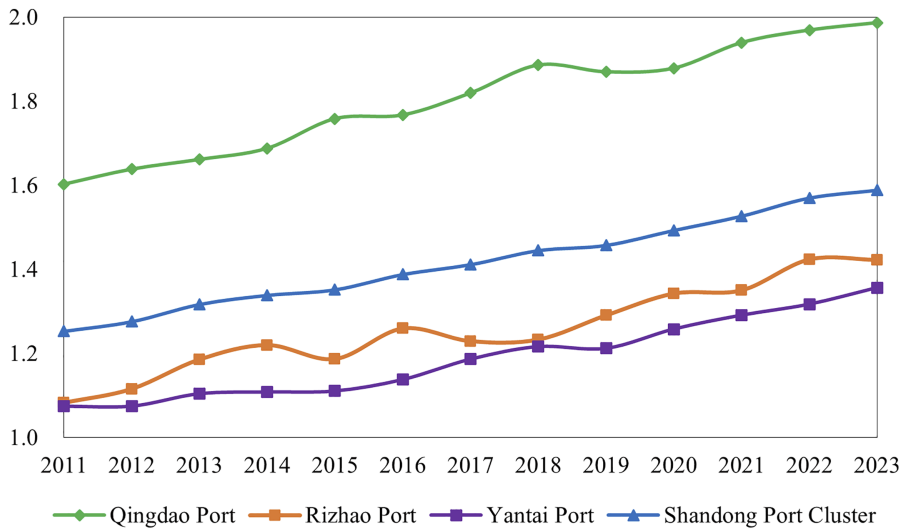


Figure 2. Analysis of international competitiveness differences in Shandong port cluster from 2011 to 2023. Source(s): Authors' own creation

China-Africa logistics corridor, building differentiated competitive advantages through specialized operations.

From a dimensional perspective, Qingdao Port leads Rizhao Port, Yantai Port, and the Shandong Port Cluster in all four dimensions: smart and green development, economic efficiency, supporting capacity, and integrated openness (Figure 3).

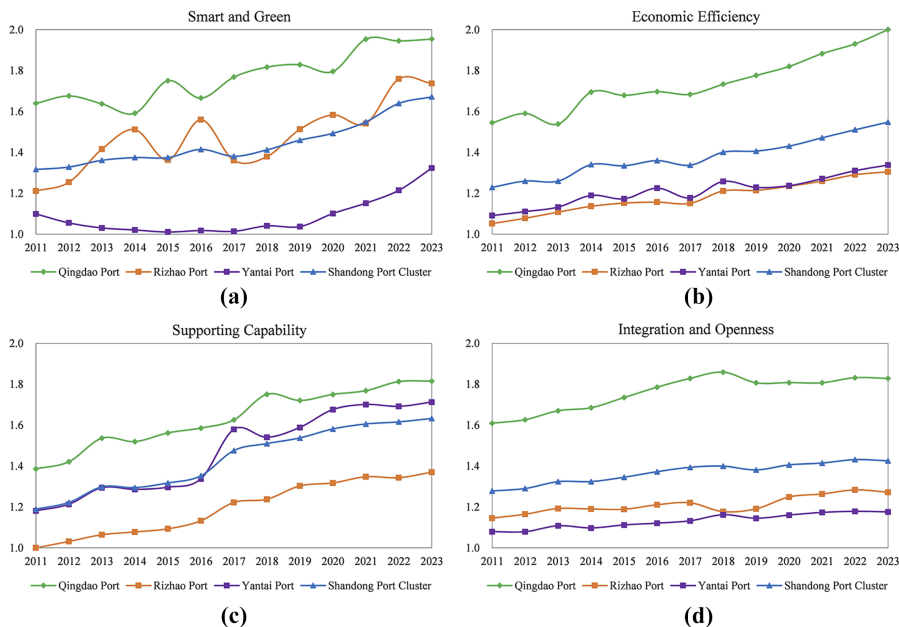


Figure 3. Dimensional disparity analysis of competitiveness in Shandong port cluster from 2011 to 2023. Source(s): Authors' own creation

In the smart and green dimension, Qingdao Port maintains a continuous leading position, with its index reaching 1.9538 in 2023 and showing a stable growth trend, reflecting its sustained leadership in green and intelligent technology application and operational efficiency enhancement. Rizhao Port exhibits significant volatility in this dimension, rising from 1.0826 to 1.7369, demonstrating its rapid catch-up and transformative breakthroughs through increased investment in smart and green initiatives following strategic adjustments. Yantai Port follows a steady upward trajectory, increasing from 1.0522 to 1.3564, highlighting its progress in advancing port digitalization, clean transformation, and continuously improving sustainable development capabilities.

In the economic efficiency dimension, the indices of Qingdao Port, the Shandong Port Cluster, Yantai Port, and Rizhao Port were distributed as follows: Qingdao Port's index rose from 1.5448 in 2011 to 2 in 2023, Rizhao Port's increased from 1.0518 to 1.3051, and Yantai Port's grew from 1.0910 to 1.3381, all showing an overall upward trend. This pattern indicates that the operational efficiency and economic benefits of the Shandong Port Cluster as a whole have continuously improved, with resource integration and synergistic effects among ports becoming increasingly evident. These developments have jointly driven the optimization of regional logistics efficiency and reflect the growing competitiveness of the Shandong Port Cluster as a key shipping hub in Northeast Asia.

In the supporting capacity dimension, the ranking is Qingdao Port > Yantai Port > Rizhao Port. Qingdao Port demonstrates significant leadership owing to its world-class deep-water berths, advanced transport network, robust economic hinterland support, and pivotal role as an international shipping hub in Northeast Asia. Yantai Port secures the second position by leveraging its status as a key gateway port in the Bohai Rim, favorable natural conditions, and specialized cargo operations. While Rizhao Port possesses scale advantages and deep-water capabilities for bulk dry cargo transportation, its supporting capacity remains relatively weaker. This outcome highlights opportunities for Yantai and Rizhao ports to optimize their supporting capabilities in enhancing international competitiveness.

In the integrated openness dimension, the hierarchy is Qingdao Port > Rizhao Port > Yantai Port, reflecting differences in their integration into global trade networks and service capabilities for an open economy. Qingdao Port ranks first due to its strategic positioning as a hub port, the geographical advantage of the China (Shandong) Pilot Free Trade Zone Qingdao Area, a dense network of international shipping routes, and dominant positions in both container throughput and cargo throughput. Rizhao Port, as a pivotal hub of the Belt and Road Initiative and a global energy/bulk raw material transshipment base, connects with over 100 countries and 500 ports. It operates 37 domestic and 12 international container routes, forming a development pattern of "east-west mutual support and land-sea coordinated linkage." Thus, its openness surpasses that of Yantai Port. Yantai Port, despite being the world's largest bauxite import port, China's top trade port with Africa, the world's largest fertilizer export port, China's fifth-largest commercial vehicle logistics hub, and third-largest foreign trade export port among coastal ports, lags in openness due to its comparatively lower density and breadth of international shipping routes relative to Qingdao and Rizhao ports.

3.4 Kernel density estimation results

Figure 4 illustrates the distribution and dynamic evolution trends of the international competitiveness level of the Shandong Port Cluster during the observation period. The analysis reveals that the central region of the competitiveness distribution exhibits relatively stable volatility, with no prominent peaks, indicating consistent trends in the competitiveness evolution of individual ports. This outcome fully reflects the significant achievements made by Shandong ports since 2019 in actively promoting port integration. During the integration period, dividends accelerated, clarifying the functional positioning and shipping route layouts of Qingdao Port, Rizhao Port, and Yantai Port. This has fostered a cluster effect with specialized division of labor and collaboration, further enhancing the overall international

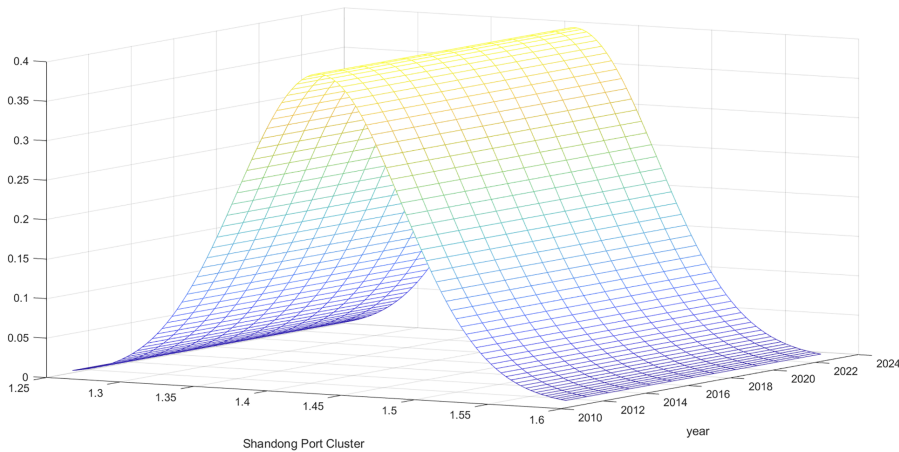


Figure 4. Kernel density distribution of competitiveness level in Shandong port cluster from 2011 to 2023.
Source(s): Authors' own creation

competitiveness of the Shandong Port Cluster. Additionally, leveraging regional advantages such as the China-South Korea Free Trade Zone, the cluster has deepened its economic hinterland reach and improved international service capacity and efficiency.

4. Analysis of driving factors for international competitiveness of Shandong port cluster

This study employs a panel data model to investigate the drivers of international competitiveness in the Shandong Port Cluster, conducting estimations sequentially using Pooled *OLS*, *FE*, *FGLS*, and *PCSE* models. The panel setting *F-test* results indicate significant individual effects, allowing for intercept terms across cross-sectional units. Further Hausman testing demonstrates the superiority of the fixed effects model over the random effects model, establishing the fixed effects model as the baseline. Modified Wald testing revealed significant groupwise heteroskedasticity in the model. Thus the study adopted two approaches to address model specification issues: performing regression with *FGLS* and applying *PCSE* to correct standard errors in the *OLS* model. Generally, when the functional form of the conditional variance is difficult to specify, researchers tend to prefer the *OLS* + *PCSE* method. The regression results are shown in [Table 2](#).

Regression results indicate that the international competitiveness of the Shandong Port Cluster is influenced by multiple factors. The coefficient for digital technology is significantly positive at the 1% statistical level, suggesting that a 1% increase in digital technology adoption drives a 0.114% improvement in the cluster's international competitiveness. In recent years, propelled by advancements in *AI*, big data, *5G*, and blockchain, smart ports have emerged as a critical driver for the port and shipping industry. The level of intelligence and greening has become a vital metric for evaluating port competitiveness. Digital technologies deeply penetrate the entire port operational chain, systematically reshaping the core capabilities of the Shandong Port Cluster in operational efficiency, ecological synergy, and service innovation. This enables the cluster to secure a strategic position in the global wave of maritime digitalization, further consolidating its status as an international hub.

This study measures labor force quality using the number of employees in information technology, computer services, and software industries. Regression results show that the labor force coefficient is significantly positive at the 1% level, indicating that a 1% increase in high-skilled labor boosts the cluster's international competitiveness by 0.175%. This finding

Table 2. Panel data regression results

Variable	(1) Pooled OLS	(2) FE	(3) FGLS	(4) PCSE
<i>Dig</i>	0.207*** (0.0638)	0.0509*** (0.0161)	0.0488*** (0.0134)	0.114*** (0.0352)
<i>Edu</i>	-0.0715 (0.0480)	0.0797*** (0.0265)	0.0734*** (0.0241)	-0.0506 (0.0396)
<i>Labor</i>	0.182*** (0.0434)	0.0523*** (0.0115)	0.0554*** (0.00930)	0.175*** (0.0444)
<i>Str</i>	0.616* (0.350)	-0.119 (0.0873)	-0.0764 (0.0694)	0.638*** (0.237)
<i>Elec</i>	-0.0224 (0.0583)	0.0289* (0.0116)	0.0317*** (0.0116)	-0.0250 (0.0531)
<i>Pgdp</i>	-1.038*** (0.264)	0.0845 (0.0766)	0.0760 (0.0588)	-0.548*** (0.198)
<i>_cons</i>	10.68*** (2.931)	-0.778 (0.853)	-0.629 (0.708)	5.333*** (1.964)
<i>F test</i>		292.63***		
<i>Hausman test</i>		292.63***		
<i>Modified Wald test</i>				141.29***

Note(s): * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; standard errors in parentheses
Source(s): Authors' own creation

underscores that in the digital era, a workforce represented by highly skilled IT professionals effectively facilitates ports' intelligent and green transformation, serving as a key element in building international competitive advantages. On one hand, such talent contributes to optimizing port operation algorithms, enhancing ship loading/unloading efficiency and yard turnover rates, while providing data-driven insights for route optimization and operational decisions. On the other hand, these professionals enable innovation in port service models and strengthen supply chain resilience across the port value chain.

At the industrial level, the study employs the proportion of tertiary industry in *GRP* as a measure. Regression results confirm a positive impact of industrial structure on competitiveness, significant at the 1% level. This robustly validates that a modern service-oriented industrial system serves as a key structural force enhancing port competitiveness. An expanding tertiary sector provides foundational support for developing high-value-added industries within the port cluster. For instance, the agglomeration of modern services, such as shipping finance, information consulting, and maritime law, enables comprehensive, specialized, and internationally integrated service solutions for shipping companies and cargo owners. This significantly elevates the service capacity of ports and reinforces their pivotal role in global shipping and trade networks.

The coefficients for education level and energy consumption are negative and statistically insignificant, while per capita *GDP* shows a significantly negative effect. Potential explanations include: (1) The current competitiveness enhancement of Shandong ports relies more on industry-specific skilled talent than generalized educational attainment, highlighting the need for future talent development programs to align with sectoral demands; (2) Energy consumption pressures may be offset by energy-saving technologies adopted during the cluster's proactive smart and green transition; (3) The negative impact of per capita *GDP* suggests that as Shandong Province advances high-quality economic development, accelerated shifts toward technology-intensive and high-value-added industries may trigger temporary resource misallocation.

5. Conclusions and policy recommendations

Based on data from 2011 to 2023, this study evaluates the international competitiveness of the Shandong Port Cluster and employs the kernel density estimation method to analyze the distribution dynamics of its competitiveness. Regression models are used to examine the driving factors of its international competitiveness level. The main research findings are as follows:

Firstly, the international competitiveness of the Shandong Port Cluster has shown a steady upward trend during the study period, though its overall level still requires improvement. The port cluster is gradually transitioning toward intelligent and eco-friendly development.

Secondly, the international competitiveness levels of Qingdao Port, Rizhao Port, and Yantai Port exhibit significant differences, with Qingdao Port generally outperforming Rizhao and Yantai Ports. This reflects variations in the functional positioning and development pathways of each port.

Thirdly, the volatility of the core distribution area for the international competitiveness of the Shandong Port Cluster remains relatively stable, with Qingdao, Rizhao, and Yantai Ports demonstrating consistent trends in competitiveness changes.

Fourthly, the international competitiveness of the Shandong Port Cluster is driven by factors such as digital technology, labor force, and industrial structure. Among these, port-related digital technologies, port-specialized talent, and high value-added industries in port areas represent critical areas requiring breakthroughs.

Based on the research findings, the following policy implications can be drawn:

Firstly, with the overarching goal of building a world-class port cluster, empower the construction of smart and green ports through digital technologies. Shandong should leverage its national strategic positioning to actively promote the coordinated development of digital and green transitions, systematically advance digital infrastructure construction and clean energy applications in ports. Simultaneously, strengthen top-level policy design to comprehensively enhance the operational capacity and competitiveness of the Shandong Port Cluster within the global shipping and trade network.

Secondly, clarify the functional positioning of each port to promote leapfrogging improvements in port competitiveness through differentiated development strategies. Fully utilize the advantages of the Shandong Port Group to scientifically plan the specialized functions and development characteristics of Qingdao Port, Rizhao Port, and Yantai Port, avoiding homogeneous competition among ports. For instance: Qingdao Port should focus on developing high-end shipping services, Rizhao Port should enhance its energy and raw material supply capabilities, Yantai Port should strengthen its role as a trade hub, thereby forming a complementary and synergistic development pattern within the port cluster.

Thirdly, attract and cultivate port-specialized professionals to provide intellectual support for enhancing international competitiveness. Implement industry-university-research collaboration mechanisms to develop targeted talent training programs for port and shipping sectors, particularly high-skilled professionals. Concurrently, enhance vocational training for relevant personnel and optimize the talent development ecosystem to ensure sustained intellectual support for upgrading the international competitiveness of the Shandong Port Cluster.

Data availability

Data will be made available on request.

References

- Chen, J.R., Choi, J.W. and Seo, Y.J. (2025), "Environmental efficiency assessment of coastal ports in China: implications for sustainable port management", *Marine Pollution Bulletin*, Vol. 211, 117436, doi: [10.1016/j.marpolbul.2024.117436](https://doi.org/10.1016/j.marpolbul.2024.117436).

- Elsisi, M., Amer, M., Su, C.L., Aljohani, T., Ali, M.N. and Sharawy, M. (2025), "A comprehensive review of machine learning and Internet of Things integrations for emission monitoring and resilient sustainable energy management of ships in port areas", *Renewable and Sustainable Energy Reviews*, Vol. 218, 115843, doi: [10.1016/j.rser.2025.115843](https://doi.org/10.1016/j.rser.2025.115843).
- He, Y. and Xu, X. (2023), "Spatial correlation network structure of port performance and its drivers: a case study of Chinese coastal ports", *Ocean and Coastal Management*, Vol. 244, 106780, doi: [10.1016/j.ocecoaman.2023.106780](https://doi.org/10.1016/j.ocecoaman.2023.106780).
- He, X., Hu, W., Li, W. and Hu, R. (2023), "Digital transformation, technological innovation, and operational resilience of port firms in case of supply chain disruption", *Marine Pollution Bulletin*, Vol. 190, 114811, doi: [10.1016/j.marpolbul.2023.114811](https://doi.org/10.1016/j.marpolbul.2023.114811).
- Kim, A.R. (2016), "A study on competitiveness analysis of ports in Korea and China by entropy weight TOPSIS", *The Asian Journal of Shipping and Logistics*, Vol. 32 No. 4, pp. 187-194, doi: [10.1016/j.ajsl.2016.12.001](https://doi.org/10.1016/j.ajsl.2016.12.001).
- Li, K.X., Li, M., Zhu, Y., Yuen, K.F., Tong, H. and Zhou, H. (2023), "Smart port: a bibliometric review and future research directions", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 174, 103098, doi: [10.1016/j.tre.2023.103098](https://doi.org/10.1016/j.tre.2023.103098).
- Lin, X., Jing, X., Cheng, F. and Wang, M. (2024), "Exploration of port environmental efficiency measurement and influential factors in the yangtze river delta Pilot free trade Zone", *Marine Pollution Bulletin*, Vol. 206, 116766, doi: [10.1016/j.marpolbul.2024.116766](https://doi.org/10.1016/j.marpolbul.2024.116766).
- Lu, B. and Xu, X. (2024), "Digital transformation and port operations: optimal investment under incomplete information", *Transport Policy*, Vol. 151, pp. 134-146, doi: [10.1016/j.tranpol.2024.04.008](https://doi.org/10.1016/j.tranpol.2024.04.008).
- Luo, M., Chen, F. and Zhang, J. (2022), "Relationships among port competition, cooperation and competitiveness: a literature review", *Transport Policy*, Vol. 118, pp. 1-9, doi: [10.1016/j.tranpol.2022.01.014](https://doi.org/10.1016/j.tranpol.2022.01.014).
- Meng, H., Xu, H., Cui, Y. and Liu, J. (2024), "International container intermodal competitiveness: an empirical study from Chinese hub ports", *Ocean and Coastal Management*, Vol. 254, 107178, doi: [10.1016/j.ocecoaman.2024.107178](https://doi.org/10.1016/j.ocecoaman.2024.107178).
- Mo, Y., Zhao, Y., Li, S. and Liu, X. (2018), "Evaluation of port logistics competitiveness based on DEA", *IOP Conference Series: Earth and Environmental Science*, Vol. 189 No. 6, 062041, doi: [10.1088/1755-1315/189/6/062041](https://doi.org/10.1088/1755-1315/189/6/062041).
- Nie, J., Shen, J. and Chen, Y. (2025), "The effect of new quality productivity on port sustainability: evidence from China", *Journal of Sea Research*, Vol. 204, 102575, doi: [10.1016/j.seares.2025.102575](https://doi.org/10.1016/j.seares.2025.102575).
- Qu, Y., Kong, Y., Li, Z. and Zhu, E. (2023), "Pursue the coordinated development of port-city economic construction and ecological environment: a case of the eight major ports in China", *Ocean and Coastal Management*, Vol. 242, 106694, doi: [10.1016/j.ocecoaman.2023.106694](https://doi.org/10.1016/j.ocecoaman.2023.106694).
- Rekabi, S., Sazvar, Z., Tavakkoli-Moghaddam, R. and Dolgui, A. (2025), "Developing a green multi-modal dry port-seaport logistics network enhanced by the internet of things and machine learning", *Computers and Industrial Engineering*, Vol. 207, 111270, doi: [10.1016/j.cie.2025.111270](https://doi.org/10.1016/j.cie.2025.111270).
- Verschuur, J., Koks, E.E. and Hall, J.W. (2022), "Ports' criticality in international trade and global supply-chains", *Nature Communications*, Vol. 13 No. 1, p. 4351, doi: [10.1038/s41467-022-32070-0](https://doi.org/10.1038/s41467-022-32070-0).
- Wan, Z., Nie, A., Chen, J., Pang, C. and Zhou, Y. (2025), "Transforming ports for a low-carbon future: innovations, challenges, and opportunities", *Ocean and Coastal Management*, Vol. 264, 107636, doi: [10.1016/j.ocecoaman.2025.107636](https://doi.org/10.1016/j.ocecoaman.2025.107636).
- Wan, G., Yang, L., Hao, Y. and Geng, Y. (2025), "Assessing the impacts of digital economy on urban green development efficiency", *Sustainable Futures*, Vol. 10, 100910, doi: [10.1016/j.sftr.2025.100910](https://doi.org/10.1016/j.sftr.2025.100910).

-
- Wang, L., Zhou, Z., Yang, Y. and Wu, J. (2020), "Green efficiency evaluation and improvement of Chinese ports: a cross-efficiency model", *Transportation Research Part D: Transport and Environment*, Vol. 88, 102590, doi: [10.1016/j.trd.2020.102590](https://doi.org/10.1016/j.trd.2020.102590).
- Wang, X.T., Liu, H., Lv, Z.F., Deng, F.Y., Xu, H.L., Qi, L.J., He, K.B., Zhao, J.C., Zheng, S.X. and Man, H.Y. (2021), "Trade-linked shipping CO2 emissions", *Nature Climate Change*, Vol. 11 No. 11, pp. 945-951, doi: [10.1038/s41558-021-01176-6](https://doi.org/10.1038/s41558-021-01176-6).
- Wang, J., Mo, L. and Ma, Z. (2023), "Evaluation of port competitiveness along China's 'Belt and Road' based on the entropy-TOPSIS method", *Scientific Reports*, Vol. 13 No. 1, 15717, doi: [10.1038/s41598-023-42755-1](https://doi.org/10.1038/s41598-023-42755-1).
- Wang, L., Yang, Y., Mei, Q. and Song, R. (2025), "Generational evolution and spatial distribution characteristics of ports along the belt and road initiative", *Journal of Transport Geography*, Vol. 128, 104343, doi: [10.1016/j.jtrangeo.2025.104343](https://doi.org/10.1016/j.jtrangeo.2025.104343).
- Xiao, R., Liu, S., Wu, L., Luo, M., Ma, R. and Li, J. (2025), "Regional classification and competitiveness of port cluster: a case study of China's coastal ports", *International Journal of Logistics Research and Applications*, Vol. 28 No. 7, pp. 745-762, doi: [10.1080/13675567.2023.2189693](https://doi.org/10.1080/13675567.2023.2189693).
- Yang, L., Zhang, Q., Lv, Z., Zhang, Y., Yang, Z., Fu, F., Lv, J., Wu, L. and Mao, H. (2022), "Efficiency of DECA on ship emission and urban air quality: a case study of China port", *Journal of Cleaner Production*, Vol. 362, 132556, doi: [10.1016/j.jclepro.2022.132556](https://doi.org/10.1016/j.jclepro.2022.132556).
- Yang, S., Shen, J., Deng, X., Lu, K., Liu, Z. and Cheng, B. (2024), "Digital economy revolutionizing green total factor productivity in construction industry", *Technological Forecasting and Social Change*, Vol. 206, 123564, doi: [10.1016/j.techfore.2024.123564](https://doi.org/10.1016/j.techfore.2024.123564).

Corresponding author

Lin Yang can be contacted at: yanglin0631@sdu.edu.cn