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Inland port ranking analysis considering port efficiency for sustainable port development: A case study

Yanjie Zhou, Xueqian Wang, Chenglin Hu, Tao Li *

School of Management, Zhengzhou University, Zhengzhou, China

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ABSTRACT

Inland ports are important facilities for transferring cargo to the seaport along the New Maritime Silk Road. Inland port ranking will affect the port development decisions. This paper explores the inland port ranking along the Yangtze River considering the port efficiency. Firstly, we adopt the Data Envelopment Analysis (DEA) method to calculate the port efficiency, which is considered one of the seventeen indicators for inland port ranking. Secondly, Analytic Hierarchy Process (AHP) and the entropy method are used to calculate the subjective and objective weights of the indicators for determining their relative importance. Finally, the technique for order preference by similarity to ideal solution (TOPSIS) method is developed to calculate the inland port ranking. This paper did a case study by adopting five major inland ports along the Yangtze River, which are Wuhan, Jiujiang, Yueyang, Yichang, Huangshi, and Jingzhou ports. The evaluation results were analyzed in depth to identify each port's strengths and weaknesses. Based on these analyses, solutions and recommendations are proposed for ports with purely technical inefficiencies, input redundancy and output shortfall, as well as management insights for sustainable port development.

1. Introduction

Under the background of globalization and regional integration, ports as important nodes connecting domestic and foreign markets, have a significant impact on regional economic development in terms of their efficiency and comprehensive competitiveness (Zhen et al., 2022; Feng et al., 2024; Zhong et al., 2024). As an important economic belt in China, the competitiveness of the port cluster in the middle reaches of the Yangtze River is directly related to the prosperity and development of the regional economy. Therefore, evaluating the comprehensive competitiveness of port clusters in the middle reaches of the Yangtze River not only helps to improve the operational efficiency of ports but also promotes the coordinated development of the regional economy.

Inland port efficiency is an important factor for evaluating operational performance, which affects the turnaround time of the vessel. Inland port efficiency is not considered by previous inland port ranking methods (Zhou et al., 2024). To make a comprehensive competitiveness of inland ports, this paper studies the inland port ranking considering inland port efficiency. The contributions of this paper are summarized as follows.

Inland port efficiency is an important index for evaluating the comprehensive competitiveness of ports. The previous inland port ranking method only considered facilities, such as the number of berths, which has limitations for directly using these parameters. To calculate inland port efficiency, this paper adopts the DEA model by considering multiple factors. We take the comprehensive efficiency of each port obtained from the DEA model, which is also the port efficiency in the evaluation index.

The comprehensive competitiveness evaluation index system of major ports in the middle reaches of the Yangtze River is further constructed. To ensure the scientific and fairness of the evaluation, we combine the AHP and entropy methods to assign subjective and objective combinations to the indicators in the evaluation index system. Then, we adopt the TOPSIS method to rank the comprehensive competitiveness of ports by calculating the distance of each port from the ideal solution and the negative ideal solution to find out the advantages as well as the disadvantages of each port to evaluate the comprehensive competitiveness of each port in the middle reaches of the Yangtze River.

For methodology, previous studies often use DEA or AHP, entropy, and other methods alone or two methods for investigation. Differently, we integrate DEA, AHP, entropy, and TOPSIS methods, which can fully utilize the advantages of each method and make up for the limitations of

* Corresponding author.
E-mail address: taoli@zzu.edu.cn (T. Li).

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a single method. In other words, DEA can evaluate the efficiency of ports in the middle reaches of the Yangtze River, AHP can be used to assign subjective weights to the evaluation indexes, entropy can be used to assign objective weights to reduce the subjective bias and make the weight distribution more reasonable, and TOPSIS can be used for the comprehensive ranking and decision-making, which improves the accuracy and reliability of the evaluation results.

In terms of application, this study applies this comprehensive evaluation model to the ports in the middle reaches of the Yangtze River to supplement the existing research. The middle reaches of the Yangtze River are an important part of the Yangtze River Economic Belt, which carries the east to the west, connects the south to the north, and is the bridge and link connecting the resource-rich regions of eastern China and the west, it has a very important status, but its competitiveness research is comparatively less (Wu and Wang, 2022; Ye et al., 2020). This paper reveals the advantages and disadvantages of the competitiveness of the region's ports through an in-depth analysis of the region's ports, providing strong support for port managers to formulate targeted development strategies, helping the ports to improve their operational efficiency and competitiveness, thus promoting the sustainable development of the region's ports and the prosperity of the regional economy.

The remainder of this paper is organized as follows: Section 2 presents the literature review. Section 3 introduces the port efficiency evaluation methods. Section 4 introduces the proposed evaluation method. Section 5 shows the case study. Finally, the conclusions are given.

2. Literature review

Cullinane et al. (2005) used the data envelopment analysis-Banker Charnes Cooper (BCC) model to evaluate the efficiency of the world's major ports regarding port coastline length and other input indicators. Wang et al. (2020) use three DEA models to assess port environmental efficiency under different control conditions. Innovations involve environmental parameters, non-proportional changes, and port preferences. Analysis of 11 Chinese ports reveals higher efficiency in eastern ports, benefits of cooperation, and consistent output loss trends. Stephen et al. (2020) used a DEA approach to investigate the effect of relative size on technical efficiency in the Irish and Spanish port systems during the period from 2000 to 2015, and the results showed that there is a positive correlation between size and technical efficiency among ports in marginal areas. Hsu et al. (2023) conducted an empirical study using the port operator of Kaohsiung Port in Taiwan as a case study to calculate the operational efficiency of the port by the DEA model, which provides a methodological framework for port operators to assess the operational efficiency within the port.

Min et al. (2022) and Yeo et al. (2008) investigated the relevant factors affecting the inland port ranking. Tseng and Yip (2021) used a fuzzy analytic hierarchy process to assess the key criteria and sub-criteria affecting the development of the four major cruise ports in Taiwan. The study found that port infrastructure and facilities were most important, followed by port city development plans, port geography and climate, and port regulations and services. Wang. (2024) through literature research and expert consultation, selected five factors that affect port competitiveness to construct an evaluation index system for ranking ports in the Bohai Rim area. The study used the AHP for subjective weighting and the entropy method for objective weighting. The final weights were calculated using a game theory-based combination weighting formula. Finally, the technique for order of preference by TOPSIS was applied to analyze the rankings of the ports in the Bohai River. Liu et al. (2020) used the fuzzy AHP-TOPSIS method to establish a port attractiveness evaluation model to determine the six evaluation dimensions and 24 important attractiveness criteria for carriers to choose a port and validated the model through simulation to provide a basis for carrier decision-making. Wang et al. (2023) constructed a port competitiveness evaluation model based on Porter's diamond model using the entropy-TOPSIS method to assess the competitiveness of 15 seaports along the "Belt and Road" in China, and came up with a comprehensive ranking, pointing out the strengths and weaknesses of each port, which will provide a reference for the long-term development of ports.

To sum up, in the previous research, scholars only used DEA to analyze the port effect or used TOPSIS to evaluate the comprehensive competitiveness of the port alone, then in this paper's research, we combine them to evaluate the comprehensive competitiveness of the port in an all-rounded way to give full play to their respective advantages, and to provide a comprehensive, objective and practical needs of the research of this paper's evaluation system.

First of all, this paper selects multiple input and output indicators. It treats each port as a DMU to evaluate the efficiency of major mid-Yangtze River ports. DEA is chosen precisely because of its unique advantages and applicability to this study, because DEA can deal with the complexity of multiple inputs and multiple outputs, and because of the nonparametric nature of not needing to make assumptions about the function as well as objectively determining the weights. Most importantly, DEA is particularly suitable for assessing the relative efficiency of decision-making units.

Secondly, this paper takes the comprehensive efficiency obtained by DEA as an indicator for evaluating port competitiveness. Then it selects other indicators to evaluate the comprehensive competitiveness of ports from different dimensions. Firstly, AHP is used to fully reflect the preferences and experiences of decision makers through its subjective weighting and its hierarchical structure analysis helps to decompose and understand the complex decision-making problems; the entropy method is used to determine the weights based on data information with objectivity, providing an objective evaluation perspective that is not affected by subjective factors. The entropy method, with its objectivity, can determine the weights based on the data information, providing an objective evaluation perspective that is not influenced by subjective factors. Moreover, this paper calculates the comprehensive ranking of the ports by using the TOPSIS after the subjective and objective weights are integrated and assigned the weights, which comprehensively analyzes the comprehensive competitiveness and development potential of the ports in multiple dimensions, providing richer reference information for the management and decision-making of the ports. Table 1. summarizes the previous studies related to this paper.

3. Inland port efficiency evaluation

DEA, which is capable of assessing the relative efficiencies of multiple inputs and outputs without the need to preset the specific form of the production function (Hong Yuan, 2021), is a nonparametric method to measure productive efficiency. The BCC model is a variant of the DEA model for assessing scale efficiency based on the assumption of the realized variable return to scale. It can simultaneously reflect the technical efficiency and scale efficiency of the decision-making unit (DMU), which is more reflective of the actual operation situation of inland ports. This paper adopts the BCC model to calculate the inland port efficiency. This paper evaluates the efficiency of major inland ports from 2018 to 2022, considering each port as a DMU.

3.1. Indicators

In the BCC model, there are two types of indicators, including input and output indicators, which are used to determine the inland port efficiency. Cargo and container throughput, which correspond to bulk port and container port, are the primary output indicators used to measure port efficiency by many previous studies (Li et al., 2022; Wu and Wang, 2022). Cargo/container throughput is mainly affected by the berths. More berths mean a large capability for loading and unloading on/from vessels, which affects cargo/container throughput. There are two types of berths: continuous and discrete berths. Thus, this paper adopts the

Table 1
Summary of previous studies related to this paper.

Papers	Factors				Method			
	Length of productive berths	Number of productive berths	Container throughput	Cargo throughput	DEA	AHP	Entropy Method	Topsis
Cullinane et al. (2005)	√		√		√			
Wang et al. (2020)	√	√			√			
Stephen et al. (2020)					√			
Hsu et al. (2023)	√		√	√	√			
Tseng and Yip (2021)						√		
Wang. (2024)						√	√	
Liu et al. (2020)						√		√
Wang et al. (2023)							√	√
This paper	√	√	√	√	√	√	√	√

number and length of berths as the input indicators corresponding to continuous and discrete berths. Table 2. shows the port efficiency indicators. The mathematical notations are introduced in the next subsection.

3.2. BCC model

Before introducing the BCC model, the parameters used in the model are introduced in Table 3.

It constructs the BCC model to analyze and assess the efficiency of inland ports. M denotes the set of inland ports and N denotes the set of length and number of berths. S denotes the set of throughput.

$$P_k \min\left(\theta_k - \varepsilon\left(\sum_{i\in N} x_i^- + \sum_{r\in S} y_r^+\right)\right) \quad \forall k \in M \tag{1}$$

$$s.t. \sum_{j=1}^{m} B_{ij}\lambda_j + x_i^- = \theta_k b_{ik} \forall i \in N, \forall k \in M \tag{2}$$

$$\sum_{j=1}^{m} C_{rj}\lambda_j + y_r^+ = c_{rk} \forall r \in S, \forall k \in M \tag{3}$$

$$\sum_{j=1}^{m} \lambda_j = 1 \tag{4}$$

$$\lambda_j \geq 0 \forall j \in M \tag{5}$$

$$x_i^- \geq 0 \forall i \in N \tag{6}$$

$$y_r^+ \geq 0 \forall r \in S \tag{7}$$

$$\theta_k \in [0, 1] \tag{8}$$

Eq. (1) minimizes the efficiency score of a single DMU. Constraint (2) represents that the sum of the inputs of the DMU equals the expected input amount, indicating that the port needs to adjust the quantity of x_i^- in a timely manner to optimize port efficiency. Constraint (3) represents that the sum of the outputs of the DMU equals the desired output level, indicating that the port needs to adjust the quantity of y_r^+ in a timely manner to optimize port efficiency; Constraint (4) represents that the sum of all decision variables weights equals 1. Constraints (5)-(8) are decision variables.

Table 2
Port efficiency indicators.

Indicator properties	Indicator	Unit
Input indicators B_{ij}	The length of productive berths B_{1j}	Meter
	The Number of productive berths B_{2j}	
Output indicators c_{rj}	Container throughput c_{1j}	Ten thousand TEU
	Cargo throughput c_{2j}	Hundred million tons

Note: TEU denotes the Twenty-feet Equivalent Unit.

Table 3
Description of symbols in the BCC model.

Set	
M	The set of ports
N	The set of the length and number of berths
S	The set of throughput
Index	
i	Index of the length and number of productive berths
j, k	Index of ports
r	Index of container throughput and cargo throughput
Parameters	
B_{ij}	The i^{th} input of the j^{th} port, $\forall i \in N$
b_{ik}	Input i of the evaluated port $k, \forall k \in M$
c_{rj}	The r^{th} output of the j^{th} port, $\forall r \in S$
c_{ik}	Output i of the evaluated port $k, \forall k \in M$
ε	Archimedean infinitesimal
Decision variables	
θ_k	Port integrated efficiency value
x_i^-	Input redundancy in length and number of productive berths
y_r^+	Output shortfalls in container throughput and cargo throughput
λ_j	Weight of port j

3.3. Variable analysis

B_{ij} denotes the i^{th} input indicator of the j^{th} port $(i \in N)$, when $i = 1$ meaning that the input is the length of productive berths. When $i = 2$, the input is the number of productive berths, and c_{rj} denotes the r^{th} output of the j^{th} port (r ∈ S). When $r = 1$, the output is the container throughput. When $r = 2$, the output is the cargo throughput. $x_i^-(i \in N)$, $i = 1$ is the input redundancy of the length of productive berths and $i = 2$ is the input redundancy of the number of productive berths, respectively. $y_r^+(r \in S)$, $r = 1$ is the output shortfall of container throughput and $r = 2$ is the output shortfall of cargo throughput. ε is a non-Archimedean infinitesimal. If the optimal value of the model, $\theta_k = 1, x_i^- = 0, y_r^+ = 0$, then the current evaluation of the efficiency of the DMU is DEA effective, that is, the integrated efficiency value of 1, and the current port is the most efficient. If the optimal value of the model, $\theta = 1$ and $x_i^- \neq 0$, $y_r^+ \neq 0$, then the current evaluation of the efficiency of the DMU is weakly DEA effective, for the original inputs can be reduced by x_i^- while keeping the original output unchanged, or in the case of unchanged inputs can be increased by y_r^+ output. If $\theta_k < 1$, then the current evaluation of the efficiency of the decision unit is DEA ineffective.

4. A hybrid evaluation model

For inland port k, we can obtain θ_k for solving the corresponding model P_k. In the following content, the port efficiency d_{23} is one of the indicators for evaluating inland port ranking, which equals θ_k.

4.1. Selection of factors

Based on the principles of scientificity, comprehensiveness, availability, and comparability, we construct the evaluation index system from five different domains including port infrastructure capacity, port operational capacity, hinterland capacity, port development, and natural condition, which are presented as follows.

(1) Port infrastructure capacity is evaluated by the length of productive berths, the number of productive berths, the container throughput capacity, and the cargo throughput capacity, and these indicators are crucial for improving the operational efficiency of port infrastructure (Deng et al., 2022).
(2) Port operational capacity is assessed by container throughput, cargo throughput, and port efficiency, which are key indicators of operational efficiency and market competitiveness, and then port operational capacity can be evaluated (Wan et al., 2022; Wang et al., 2023; Peide et al., 2023).
(3) Hinterland capacity is assessed by the hinterland GDP and the hinterland import and export trade volume, which is one of the important criteria for assessing its competitiveness. The economic vitality of the hinterland directly affects the industrial development of a port and the generation and absorption capacity of shipping cargo sources, thus promoting the growth of the port economy (Park., 2021).
(4) Port development is assessed by container throughput growth rate, cargo throughput growth rate, hinterland GDP growth rate, and hinterland foreign trade growth rate, which are growth indicators indicating the recent development dynamics of the port and hinterland, and are also directly associated with the position of a port in the competition (Deng et al., 2022; Zhou et al., 2024).
(5) Natural condition is assessed by the standard water depth of the channel, distance to the seaport, the total mileage of the channel network, and the port water quality to assess the port water quality scoring using a percentage system method: Class I water for 100 points, Class II water 80 points, Class III water 60 points, Class IV water 40 points, Class V water 20 points, inferior Class V water 0 points (Yeo et al., 2008). These indicators have an important impact on the accessibility and sustainable development of the harbor.

In summary, this paper constructs a comprehensive competitiveness evaluation system for inland ports. The specific evaluation index system is shown in Table 4.

Table 4
Evaluation index system of comprehensive competitiveness of inland ports.

First level indicator	The secondary indicators	Unit
Logistics infrastructure capacity D_1	The length of productive berths d_{11}	Meter
	The Number of productive berths d_{12}	
	Container throughput capacity d_{13}	Ten thousand TEU
	Cargo throughput capacity d_{14}	Hundred million tons
Port operations capacity D_2	Container throughput d_{21}	Ten thousand TEU
	Cargo throughput d_{22}	Hundred million tons
	Port efficiency d_{23}	
Hinterland support capacity D_3	Hinterland GDP d_{31}	100 million RMB
	Hinterland import and export trade volume d_{32}	100 million RMB
Port development potential D_4	Container throughput growth rate d_{41}	%
	Cargo throughput growth rate d_{42}	%
	Hinterland GDP growth rate d_{43}	%
	Hinterland foreign trade growth rate d_{44}	%
Port natural conditions capacity D_5	Standard water depth of the channel d_{51}	Meter
	Distance to the seaport d_{52}	Kilo meter
	Total mileage of the channel network d_{53}	Kilo meter
	Port water quality d_{54}	

4.2. Proposed framework

To show more intuitively the construction process of the comprehensive competitiveness evaluation model of inland ports, the flowchart of inland port ranking evaluation is shown in Fig. 1.

To evaluate the comprehensive competitiveness of inland ports, we use a combination of the AHP and entropy methods to assign weights to each indicator. This method integrates subjective and objective judgments to ensure that each indicator is given appropriate weights. After determining the weights of each indicator, we further apply the TOPSIS method to evaluate the comprehensive competitiveness of each port. Through this evaluation model, we can analyze the competitiveness of each port in-depth, reveal their respective advantages and shortcomings, and provide a scientific basis for the development planning and competitiveness enhancement of the ports.

4.3. Ranking scores calculation

This paper applies the TOPSIS method to the calculation of the comprehensive competitiveness score. The TOPSIS method determines the distance of the evaluated ports' evaluation indexes relative to the positive and negative ideal solutions. The following is a detailed introduction to the TOPSIS process.

Firstly, 17 s-level indicators are constructed into the original matrix d, where d_{ij} denotes the j^{th} second-level evaluation indicator of the i^{th} port.

$$d = \begin{pmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{pmatrix} \tag{9}$$

To make the second-level indicators of each port can be changed into positive indicators, it is necessary to normalize each second-level indicator affecting the comprehensive competitiveness of the port.$\min(d_{1j}, d_{2j}, ..., d_{ij})$ is the minimum value of the indicator in the j^{th} column and $\max(d_{1j}, d_{2j}, ..., d_{ij})$ is the maximum value of the indicator in the j^{th} column, respectively.

$$d'_{ij} = \frac{d_{ij} - \min(d_{1j}, d_{2j}, \ldots, d_{ij})}{\max(d_{1j}, d_{2j}, \ldots, d_{ij}) - \min(d_{1j}, d_{2j}, \ldots, d_{ij})}, i = 1, 2, \ldots, m; j = 1, 2, \ldots n \tag{10}$$

The processed normalized matrix is R:

$$R = \begin{bmatrix} d'_{11} & \cdots & d'_{1n} \\ \vdots & \ddots & \vdots \\ d'_{m1} & \cdots & d'_{mn} \end{bmatrix} \tag{11}$$

After the standardization of Eqs. (10) and (11) carried out above, the matrix of evaluation indicators after the standardization is multiplied with the final weights of the combination weighting obtained from Eq. (13) to calculate the weighting matrix, as shown in Eq. (12):

$$V = R \times W_j = \begin{bmatrix} v_{11} & \cdots & v_{1n} \\ \vdots & \ddots & \vdots \\ v_{m1} & \cdots & v_{mn} \end{bmatrix} \tag{12}$$

Where W_j represents the final weight, which is defined as follows.

$$W_j = \sigma W_j^1 + (1 - \sigma) W_j^2 \tag{13}$$

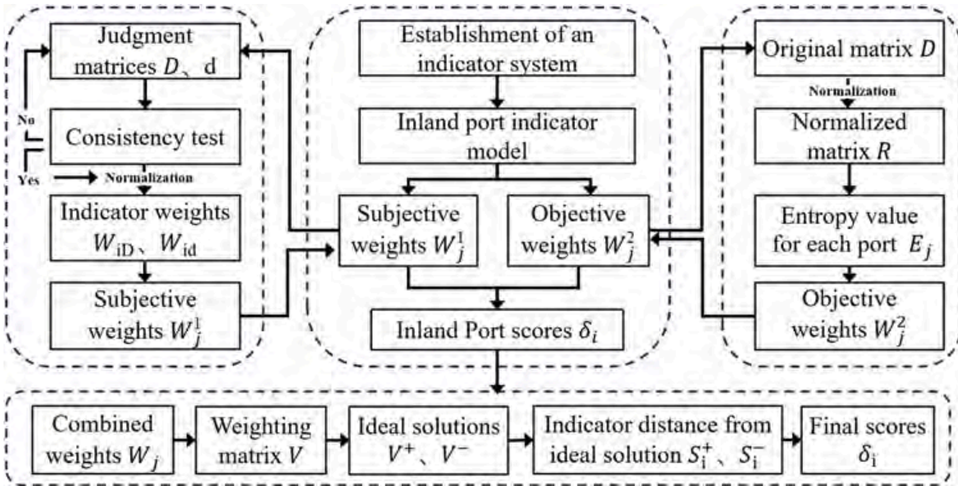

Fig. 1. Flowchart of inland port ranking evaluation.

W_j^1 represents the subjective weights of each indicator obtained by AHP, W_j^2 represents the objective weights of each indicator obtained by the entropy method. σ represents how much weight is taken by each of the two methods, with reference to previous literature and in the study of this paper, it is set that $\sigma = 0.5$. Sections 4.4 and 4.5 will provide a detailed description of the acquisition of subjective and objective weights.

As shown in Eqs. (14) and (15), V^+ represents a positive ideal solution consisting of the maximum values of the 17 evaluation indicators and V^- represents a negative ideal solution consisting of the minimum values of the 17 indicators.

$$V^+ = \left(v_1^+, v_2^+, \ldots, v_n^+\right) = \left\{\max v_{ij} | j \in 1\ldots\ldots n|\right\} \tag{14}$$

$$V^- = \left(v_1^-, v_2^-, \ldots, v_n^-\right) = \left\{\min v_{ij} | j \in 1\ldots\ldots n|\right\} \tag{15}$$

Next, the distance of each port indicator from the positive and negative ideal solutions is calculated as shown in Eqs. (16) and (17).

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2} \tag{16}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2} \tag{17}$$

Calculating the score of the port as shown in Eq. (18) is to assess the final score of the port. It can be clearly seen that the score and the larger mean that the port is closer to the optimal value. That is, the larger the score, the better the overall competitiveness of the port.

$$\delta_i = \frac{S_i^-}{S_i^+ + S_i^-}, i = 1, 2, \ldots, m \tag{18}$$

4.4. *Subjective weighting* $\mathbf{W_j^1}$

The method used in this paper for the subjective assignment of indicators is the AHP. The first step is to construct a judgment matrix and then find the weight of each indicator. According to the port comprehensive competitiveness evaluation index table, we used $D = \left(D_{ij}\right)_{n\times n}$ denotes the first-level indicator set and $d = \left(d_{kl}\right)_{m\times m}$ denotes the second-level indicator set. n and m are the number of first and second-level indicators, D_{ij} represents the relative importance of indicator i to indicator j, d_{kl} represents the relative importance of indicator k to indicator l. The first-level indicator and second-level indicator matrix judgment matrix are shown in Table 5. and Table 6., respectively.

In the judgment matrix $\left(D_{ij}\right)_{n\times n}$ of the first-level indicators, for example, when $i = 1, j = 1$, the value of the indicator is 1 meaning that logistics infrastructure capacity and logistics infrastructure capacity are equally important. When $i = 2, j = 1$, the value of the indicator is 3 meaning that the port operation capacity is slightly more important than the logistics infrastructure capacity, and so on. The level of importance among the indicators is described below.

The degree of importance between indicators in the matrix uses a scale of 1–9, with the specific element $\left(D_{ij}\right)_{n\times n}$ and the principles for assessment of $\left(d_{kl}\right)_{m\times m}$ shown in Table 7.

In the actual evaluation of port competitiveness, the scoring of experts is likely not a consistency matrix. If the deviation is too large, it is not conducive to the determination of the weight of the evaluation indicators. Therefore, it is necessary to calculate the size of the *CR* value to determine whether the experts' scores for each evaluation index of the port are reasonable. If the $CR < 1$, it means that the consistency test is

Table 5
Judgment matrix for first-level indicator.

First-level indicator	D_1	···	D_n
D_1	D_{11}	···	D_{1j}
⋮	⋮	···	⋮
D_n	D_{i1}	···	D_{ij}

Table 6
Judgment matrix for second-level indicators.

Second-level indicator	d_1	···	d_m
d_1	d_{11}	···	d_{1l}
⋮	⋮	···	⋮
d_m	d_{k1}	···	d_{kl}

Table 7
Scale of the importance of indicators.

Quantitative indicators	Implication
1	$i(k)$ evaluation indicator and $j(l)$ evaluation indicator are equally important
3	$i(k)$ evaluation indicator is slightly more important than $j(l)$ evaluation indicator
5	$i(k)$ evaluation indicator is obviously more important than $j(l)$ evaluation indicator
7	$i(k)$ evaluation indicator is intensively more important than $j(l)$ evaluation indicator
9	$i(k)$ evaluation indicator is extremely more important than $j(l)$ evaluation indicator
2, 4, 6, 8	Importance is between quota bases

passed and the expert scoring is reasonable, and the process can continue.

The size of $CR = CI/RI$, $CI = \lambda_{\max} - n/n - 1$, RI can be obtained according to Table 8., and the size of RI value is only determined by the number of evaluation indicators of the judgment matrix being evaluated.

Next, the judgment matrix obtained according to the expert's scoring is normalized. Then, each row in the matrix after normalization is added and divided by the number of comprehensive competitiveness evaluation indexes to obtain the index weights of each first-level indicator and second-level indicator index. The specific formulas are as shown in the following Eqs. (19) and (20), respectively.

$$w_{id} = \frac{\sum_{j=1}^{n} \frac{d_{ij}}{\sum_{i=1}^{n} d_{ij}}}{n}, i,j = 1,2,\ldots,n \tag{19}$$

$$w_{iD} = \frac{\sum_{j=1}^{n} \frac{D_{ij}}{\sum_{i=1}^{n} D_{ij}}}{n}, i,j = 1,2,\ldots,n \tag{20}$$

The final weights of the indicators are obtained by multiplying the obtained weights of the primary indicators by the weights of the secondary indicators, as shown in the following Eq. (21).

$$W_j^1 = w_{id} \times w_{iD} \tag{21}$$

4.5. Objective weighting W_j^2

This paper uses the entropy method to assign weights to the indicators objectively, which gives corresponding weights to the indicators. This can reflect the information size of the indicators. In this paper, 17 s-level indicators.

Using the results of the normalization process above, the weight of the indicator of the j^{th} port under the second-level evaluation indicator is calculated, and the entropy value E_j of the second-level indicator of each port can be obtained from Eq. (22).

$$E_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} \ln p_{ij}, i = 1,2,\ldots,m; j = 1,2,\ldots n \tag{22}$$

Where p_{ij} is defined as follows.

$$p_{ij} = \frac{d'_{ij}}{\sum_{i=1}^{m} d'_{ij}}, i = 1,2,\ldots,m; j = 1,2,\ldots n \tag{23}$$

Finally, the entropy weights of the second-level indicators of the evaluated ports are obtained for each year of the evaluation of the comprehensive competitiveness of ports, which are calculated as shown in Eq. (24):

$$W_j^2 = \frac{1 - E_j}{\sum_{j=1}^{n} 1 - E_j}, j = 1,2,\ldots n \tag{24}$$

5. Case study

This paper conducts a case study. The detail of the case study is presented as follows.

5.1. Inland port along the Yangtze river

In this paper, six inland ports, which are Yichang Port, Jingzhou Port, Yueyang Port, Wuhan Port, Huangshi Port, and Jiujiang Port in the middle reaches of the Yangtze River are adopted as a case study. The data is obtained from "Annual Waterway Plan Depth of the Yangtze River Waterway Bureau", "China Port Yearbook", "Yichang Statistical Yearbook", "Jingzhou Statistical Yearbook", "Wuhan Statistical Yearbook", "Yueyang Statistical Yearbook", "Jiujiang Statistical Yearbook", "Report on the Quality of Surface Water" by the Ministry of Ecology and Environment of the People's Republic of China, the database of the National Bureau of Statistics, and the China Economic and Social Big Data Statistical Platform of China Knowledge Network. We collected five year's data from 2018 to 2022. The five-year data of the inland ports are shown in Appendix A.

Table 8
RI values corresponding to different *n*.

n	1	2	3	4	5	6
RI	0	0	0.52	0.89	1.12	1.26

5.2. Port efficiency analysis

By using the source data shown in Appendix A, we solved the model P_k for each inland port k. The following contents analyze the inland port efficiency by using the results obtained by model P_k.

5.2.1. Efficiency analysis

Table 9. shows the results obtained by the BCC model. "irs" indicates increasing scale effects, "-" indicates constant scale effects, and "drs" indicates decreasing scale effects.PTE denotes Pure Technical Efficiency. SE represents Scale Efficiency. TE denotes Technical Efficiency and RS means Return to Scale.

Yueyang and Wuhan Port both have an individual efficiency of 1, which is relatively optimal, indicating that these two ports have certain advantages in both management and technology. Moreover, their scale compensation coefficients equal 1 and the port scale has also reached the optimal state, indicating that the ability to adjust the port scale according to the demand of the hinterland is also very excellent. The technical efficiency and pure technical efficiency of the Yichang port are the lowest among all inland ports. However, its scale efficiency is better, which indicates that Yichang Port is not good at management and technology. However, it has done a better job of controlling its scale, and it should strengthen its internal management and technology level to improve the input-output ratio. Jingzhou Port, Huangshi Port and Jiujiang Port have better technical efficiency, but their scale efficiency and pure technical efficiency are lower for five consecutive years. There is a lack of scale adjustment and there should be an appropriate increase in the number of productive berths and the length of productive berths to increase the output efficiency of the port significantly. Jiujiang Port's coefficient of return to scale is greater than 1 for five consecutive years, which suggests that its expansion has not resulted in increased output and that measures need to be taken to attract more sources of goods or to reduce the size appropriately.

The average value of pure technical efficiency, scale efficiency, and technical efficiency of each port were made into a radar chart for analysis, which is shown in Fig. 2.

5.2.2. Analysis of input-output results

The input redundancy rate and output shortfall rate of each indicator for six ports in the middle reaches of the Yangtze River for the five years from 2018 to 2022 are analyzed, in which the input redundancy rate refers to the ratio of excessive inputs to current inputs. The input redundancy rate equals (current inputs - optimal inputs)/current inputs. When the current inputs are smaller than the optimal inputs, the input redundancy rate is noted as 0. The output shortfall rate refers to the ratio of output shortfall to current output. The output shortfall rate equals (optimal output - current output)/current output. When the current output is greater than the optimal output, the output shortfall rate is 0. The specific results are shown in Table 10.

The ports of Wuhan and Yueyang have zero redundancy in both length and number of productive berth inputs, which are consistent with their high efficiency. Yichang Port, Jingzhou Port, and Huangshi Port have some redundancy in the length of berths but not in the number of berths. Moreover, from the previous analysis, it is concluded that they

Table 9
Analysis of port efficiency in the middle reaches of the Yangtze river.

Year	Attributes	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
2018	PTE	0.28	1.00	1.00	1.00	0.87	1.00
	SE	0.66	0.44	1.00	1.00	0.40	0.50
	TE	0.19	0.44	1.00	1.00	0.35	0.50
	RS	irs	irs	-	-	irs	drs
2019	PTE	0.34	0.88	1.00	1.00	1.00	1.00
	SE	1.00	0.61	1.00	1.00	1.00	0.84
	TE	0.34	0.54	1.00	1.00	1.00	0.84
	RS	irs	irs	-	-	irs	drs
2020	PTE	0.41	1.00	1.00	1.00	1.00	1.00
	SE	0.91	0.59	1.00	1.00	0.75	0.91
	TE	0.37	0.59	1.00	1.00	0.75	0.91
	RS	irs	irs	-	-	irs	drs
2021	PTE	0.36	0.89	1.00	1.00	1.00	1.00
	SE	0.97	0.44	1.00	1.00	0.61	0.60
	TE	0.35	0.39	1.00	1.00	0.61	0.60
	RS	irs	irs	-	-	irs	drs
2022	PTE	0.33	0.67	1.00	1.00	1.00	1.00
	SE	0.96	0.66	1.00	1.00	0.72	0.43
	TE	0.32	0.44	1.00	1.00	0.72	0.43
	RS	irs	irs	-	-	irs	drs
AVG	PTE	0.34	0.89	1.00	1.00	0.97	1.00
	SE	0.90	0.55	1.00	1.00	0.69	0.66
	TE	0.31	0.48	1.00	1.00	0.68	0.66
	RS	irs	irs	-	-	irs	drs

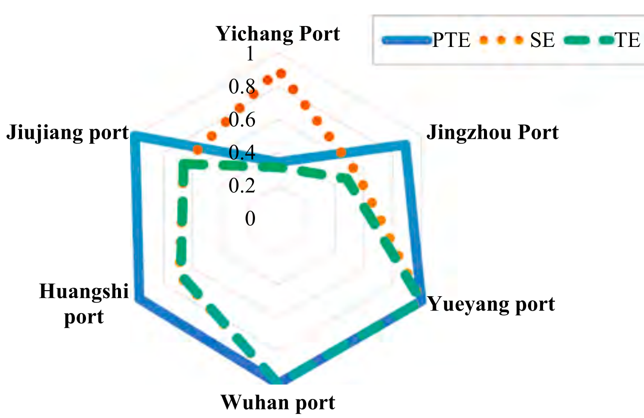

Fig. 2. Radar chart of average values for each efficiency.

are still in the stage of incremental scale payoffs and the ports should make an appropriate increase in the number of berths to enhance efficiency. Jiujiang Port has redundancy in the length and number of berths. In the previous analysis. Jiujiang Port is in the stage of diminishing returns to scale, which means that it needs to reduce the inputs or increase the sources of cargo to improve efficiency. Wuhan and Yueyang Ports have no output shortfalls in container and cargo throughput. In contrast, Yichang, Huangshi, Jingzhou, and Jiujiang Ports have output shortfalls in container throughput, especially Yichang and Huangshi Ports, which have output shortfalls averaging 2.24 and 3.64, respectively. This suggests that they need to upgrade their container-handling capacity. They may need to increase export orders and improve loading and unloading efficiencies to achieve this.

5.3. Inland port ranking analysis

5.3.1. Subjective weighting calculation

Based on the AHP, the problem of evaluating the comprehensive competitiveness of the ports is decomposed into first-level and second-level indicators. Experts in the field are invited to fill in the judgment matrices for the five first-level and each second-level indicators. The judgment matrices of each expert are calculated according to Eqs. (19) and (20) to get the corresponding weights of the indicators. The consistency test is carried out. If the CR< 0.1, it means that the experts' scores on the subjective weights of the indicators pass the consistency test. Table 11. shows the obtained subjective weights of the indicators and the CR value.

From Table 10, we can see that all the CR< 0.1, which means that each judgment matrix is reasonable and the indicator weights are available. The weight of each second-level indicator is multiplied by the weight of the first-level indicator to get the final subjective weight of the hierarchical analysis method. The results are shown in Table 12.

5.3.2. Objective weighting calculation

After the AHP finds the subjective weights of the evaluation index system of the ports in the middle reaches of the Yangtze River, the objective weights of the evaluation index system of the ports are found according to the entropy method. The obtained results are shown in Table 13.

5.3.3. Calculation of W_j

Eq. (21) is used to calculate the combined weights of the subjective and objective weights. The subjective weights derived from the AHP and the objective weights from the entropy method are averaged after summing up the weights at a ratio of 50 % each, which is shown in Table 14.

As shown in Table 14., it can be found that the difference between the indicator weights derived from the AHP and the entropy method is not significant, indicating that the robustness of the indicator weights is good. The final weights are analyzed for the importance of the indicator weights, as shown in Fig. 3.

From Fig. 3, it can be found that the indicator with the highest weight is hinterland import and export trade volume, with a weight of 12.91 %, followed by five other indicators that basically reach more than 8 %, namely, port efficiency, container throughput, cargo throughput, GDP of the hinterland and cargo throughput. If we want to improve the comprehensive competitiveness of the port, we should focus on the improvement of these indicators.

5.3.4. Inland port ranking

According to the TOPSIS method, the comprehensive competitiveness scores of the six major inland ports in the middle reaches of the Yangtze River for 2018–2022 are obtained. The comprehensive competitiveness rankings are made based on the scores, which are

Table 10
Input-output results.

Attributes	Indicators	Year	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
Input redundancy rate(%) x_i^-	The length of productive berths x_1^-	2018	0.01	0.08	0.00	0.00	0.00	0.05
		2019	0.05	0.06	0.00	0.00	0.26	0.05
		2020	0.06	0.07	0.00	0.00	0.18	0.06
		2021	0.06	0.04	0.00	0.00	0.16	0.00
		2022	0.11	0.05	0.00	0.00	0.04	0.00
		AVG	0.06	0.06	0.00	0.00	0.13	0.03
	The number of productive berths x_2^-	2018	0.00	0.00	0.00	0.00	0.02	0.00
		2019	0.00	0.00	0.00	0.00	0.00	0.00
		2020	0.00	0.00	0.00	0.00	0.00	0.00
		2021	0.00	0.00	0.00	0.00	0.00	0.35
		2022	0.00	0.00	0.00	0.00	0.00	0.17
		AVG	0.00	0.00	0.00	0.00	0.00	0.10
Output shortfall rate(%) y_r^+	Container throughput y_1^+	2018	1.05	0.33	0.00	0.00	2.82	0.24
		2019	0.98	0.28	0.00	0.00	1.52	0.31
		2020	1.84	0.41	0.00	0.00	3.17	0.10
		2021	2.70	0.41	0.00	0.00	5.04	0.27
		2022	4.64	1.74	0.00	0.00	5.65	0.71
		AVG	2.24	0.63	0.00	0.00	3.64	0.32
	Cargo throughput y_2^+	2018	0.00	0.00	0.00	0.00	0.00	0.00
		2019	0.00	0.00	0.00	0.00	0.00	0.00
		2020	0.00	0.00	0.00	0.00	0.00	0.00
		2021	0.00	0.00	0.00	0.00	0.00	0.00
		2022	0.00	0.00	0.00	0.00	0.00	0.00
		AVG	0.00	0.00	0.00	0.00	0.00	0.00

Table 11
Indicator weights and CR values.

Indicator name		Weight(%)	CR value
First level indicator	Logistics infrastructure capacity D_1	22.1	0.020
	Port operations capacity D_2	33.9	
	Hinterland support capacity D_3	22.1	
	Port development potential D_4	13.7	
	Port natural conditions capacity D_5	8.10	
Logistics infrastructure capacity D_1	The length of productive berths d_{11}	15.4	0.008
	The Number of productive berthsd_{12}	8.10	
	Container throughput capacity d_{13}	28.8	
	Cargo throughput capacity d_{14}	47.6	
Port operations capacity D_2	Container throughput d_{21}	26.1	0.052
	Cargo throughput d_{22}	32.8	
	Port efficiency d_{23}	41.1	
Hinterland support capacity D_3	Hinterland GDP d_{31}	33.3	0
	Hinterland import and export trade volume d_{32}	66.7	
Port development potential D_4	Container throughput growth rated_{41}	27.7	0.012
	Cargo throughput growth rate d_{42}	46.6	
	Hinterland GDP growth rate d_{43}	1.00	
	Hinterland foreign trade growth rate d_{44}	16.1	
Port natural conditions capacity D_5	Standard water depth of the channel d_{51}	16.1	0.012
	Distance to the sea port d_{52}	46.6	
	Total mileage of the channel network d_{53}	27.7	
	Port water quality d_{54}	9.60	

shown in Table 15.

To better analyze each port's positive and negative aspects, we also calculate and rank its scores in the first-level indicators: logistics infrastructure capacity, port operations capacity, hinterland support capacity, port development potential, and port natural conditions capacity, as shown in Table 16.

According to Table 16, we analyze each port's comprehensive competitiveness, find out the positive and negative of each port, and provide a basis for proposing port development suggestions.

5.4. Management insights

The comprehensive competitiveness of Yichang Port ranks fourth among the ports, and its rankings in all level indicators are backward, with no obvious strong points. Even though the length and number of productive berths are ranked high, the port efficiency is only 0.31, which is the lowest in the whole port. This results in general container and cargo throughput capacity and general logistics infrastructure capacity. So, it is necessary to focus on improving the port efficiency.

The comprehensive competitiveness of Jingzhou Port ranks sixth among the ports, and except for the port development potential, which ranks first, all other first-level indexes are in a relatively low position. This shows that the development potential of Jingzhou Port is very great. However, the scale of the port itself is small. It is known from the previous article that Jingzhou Port is the port with a significant incremental effect on scale efficiency. Therefore, to improve the comprehensive competitiveness of Jingzhou Port, the focus should be on improving the logistics infrastructure capacity, port operation capacity, and hinterland support capacity.

The comprehensive competitiveness of Yueyang Port is firmly ranked third, with balanced performance and high rankings in all its first-level indicator capacities. Even though the length and number of productive berths are ranked fifth, the logistics infrastructure capacity performs well due to the strong container and cargo throughput capacity, which

Table 12
Analytic hierarchy process final weighting.

First level indicator	Weight (%)	Second level indicator	Weight(%) Relative	Final
Logistics infrastructure capacity D_1	22.14	The length of productive berths d_{11}	15.44	3.42
		The Number of productive berths d_{12}	8.13	1.80
		Container throughput capacity d_{13}	28.84	6.39
		Cargo throughput capacity d_{14}	47.58	10.53
Port operations capacity D_2	33.94	Container throughput d_{21}	26.11	8.86
		Cargo throughput d_{22}	32.78	11.13
		Port efficiency d_{23}	41.11	13.95
Hinterland support capacity D_3	22.14	Hinterland GDP d_{31}	33.33	7.38
		Hinterland import and export trade volume d_{32}	66.67	14.76
Port development potential D_4	13.67	Container throughput growth rate d_{41}	27.71	3.79
		Cargo throughput growth rate d_{42}	46.58	6.37
		Hinterland GDP growth rate d_{43}	9.60	1.31
		Hinterland foreign trade growth rate d_{44}	16.11	2.20
Port natural conditions capacityD_5	8.11	Standard water depth of the channel d_{51}	16.11	1.31
		Distance to the sea port d_{52}	46.58	3.78
		Total mileage of the channel network d_{53}	27.71	2.25
		Port water quality d_{54}	9.60	0.78

Table 13
Final weights of the entropy method.

Indicator	Weight(%) 2018	2019	2020	2021	2022	Average
The length of productive berths d_{11}	7.79	5.19	6.36	6.76	5.40	6.30
The Number of productive berths d_{12}	5.68	4.24	5.30	7.00	6.28	5.70
Container throughput capacity d_{13}	9.31	8.33	5.97	7.21	6.25	7.42
Cargo throughput capacity d_{14}	5.16	6.09	5.71	7.21	7.65	6.36
Container throughput d_{21}	8.23	8.42	9.31	8.80	8.16	8.58
Cargo throughput d_{22}	4.83	4.36	5.17	4.52	4.83	4.74
Port efficiency d_{23}	4.60	2.96	3.15	5.14	4.70	4.11
Hinterland GDP d_{31}	9.69	8.90	9.03	8.42	8.02	8.81
Hinterland import and export trade volume d_{32}	12.77	12.00	11.83	9.98	8.73	11.06
Container throughput growth rate d_{41}	3.51	4.66	4.01	2.39	7.55	4.42
Cargo throughput growth rate d_{42}	2.84	5.21	7.06	10.76	7.38	6.65
Hinterland GDP growth rate d_{43}	2.30	10.83	4.91	2.72	3.97	4.95
Hinterland foreign trade growth rate d_{44}	6.83	3.84	5.13	3.18	3.10	4.42
Standard water depth of the channel d_{51}	3.82	3.61	3.96	3.69	3.55	3.73
Distance to the sea port d_{52}	5.75	5.44	5.96	5.56	3.72	5.28
Total mileage of the channel network d_{53}	2.89	2.16	3.00	2.80	5.35	3.24
Port water quality d_{54}	4.00	3.79	4.15	3.87	5.35	4.23

Table 14
Final weights for combination weighting.

Indicator	Weight(%) AHP method	Entropy method	Final
The length of productive berths d_{11}	3.42	6.30	4.86
The Number of productive berths d_{12}	1.80	5.70	3.75
Container throughput capacity d_{13}	6.39	7.42	6.90
Cargo throughput capacity d_{14}	10.53	6.36	8.45
Container throughput d_{21}	8.86	8.58	8.72
Cargo throughput d_{22}	11.13	4.74	7.93
Port efficiency d_{23}	13.95	4.11	9.03
Hinterland GDP d_{31}	7.38	8.81	8.10
Hinterland import and export trade volume d_{32}	14.76	11.06	12.91
Container throughput growth rate d_{41}	3.79	4.42	4.10
Cargo throughput growth rate d_{42}	6.37	6.65	6.51
Hinterland GDP growth rate d_{43}	1.31	4.95	3.13
Hinterland foreign trade growth rate d_{44}	2.20	4.42	3.31
Standard water depth of the channel d_{51}	1.31	3.73	2.52
Distance to the sea port d_{52}	3.78	5.28	4.53
Total mileage of the channel network d_{53}	2.25	3.24	2.74
Port water quality d_{54}	0.78	4.23	2.51

belongs to the port's strong management and technical capacity. The standard water depth of Yueyang Harbor Channel is only 3.8 m, ranking fifth. Therefore, to enhance the comprehensive competitiveness of Yueyang Port, the focus should be on improving the berth construction and deepening the standard water depth of the channel.

The overall competitiveness of the Wuhan Port is first and far ahead of all six ports, ranking first in terms of logistics infrastructure capacity, port operation capacity, and hinterland support capacity, which comes from the strong support of the Wuhan economy, especially Wuhan's leading GDP and import and export trade volume. Even though the port development potential is ranked lower because the port's current size and output are already high, resulting in lower growth rates for each, the absolute value of the increase is not low. Furthermore, its natural condition capability is weak, mainly affected by the water quality of Wuhan harbor. Therefore, the improvement of the comprehensive competitiveness of Wuhan Port should focus on improving the water quality of the port above.

The comprehensive competitiveness of Huangshi Port ranks fifth, which is at a weak level. Even though the development potential and natural conditions rank second, indicating a huge development potential, the operation capacity ranks fourth, and the logistics infrastructure capacity and hinterland infrastructure capacity rank fifth, reflecting the small scale of export itself, and the influence of geographically close to the Wuhan Port. Its source of cargo has been absorbed too much, so the enhancement of the comprehensive competitiveness of Jingzhou Port should be focused on the differentiation of the development of the port of Wuhan and its gradual growth.

The comprehensive competitiveness of Jiujiang Port is ranked second, and its overall comprehensive competitiveness is strong. Even though the port operation capacity is weak, the cargo and container throughput rank third and first, respectively, so the reason for the weak port operation capacity is the low efficiency of the port; the average value of the efficiency is 0.66, ranked fourth of all ports. Jiujiang Port indicates decreasing scale effects, so the enhancement of the comprehensive competitiveness of the Jiujiang Port should be focused on the improvement of the efficiency of the port and the reduction of the size of the port.

6. Conclusions

This paper studied the ranking of inland ports considering their efficiency. Furthermore, a case study on five inland ports was conducted, including Yichang Port, Jingzhou Port, Yueyang Port, Wuhan Port, Huangshi Port, and Jiujiang Port, which are along the Yangtze River.

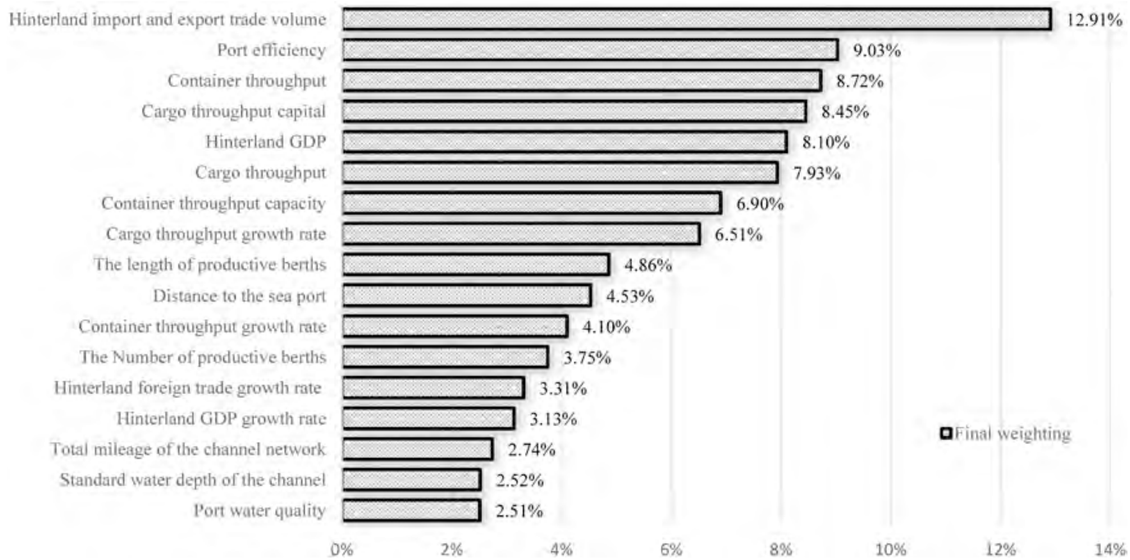

Fig. 3. Ranking of final indicator weights.

Table 15
Comprehensive competitiveness score and ranking.

	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score
2018	0.33	4	0.32	6	0.46	3	0.68	1	0.32	5	0.49	2
2019	0.36	4	0.22	6	0.46	3	0.61	1	0.35	5	0.52	2
2020	0.30	5	0.31	4	0.48	3	0.70	1	0.26	6	0.54	2
2021	0.41	4	0.24	5	0.43	3	0.62	1	0.24	6	0.49	2
2022	0.30	6	0.32	5	0.44	3	0.57	1	0.32	4	0.48	2
AVG	0.34	4	0.28	6	0.46	3	0.63	1	0.30	5	0.50	2

The contributions are summarized as follows.

(1) This paper proposed a framework to evaluate the inland port ranking considering the port efficiency. To calculate the port efficiency, this paper adopted the DEA to calculate the technical efficiency, scale efficiency, and pure technical efficiency of inland ports. From the data analysis, this paper found that most of the pure technical efficiencies of the ports could not reach the optimum. There are some ports suffering input redundancy and output shortfall.

(2) By using the port efficiency obtained by the DEA model, this paper adopted 17 indicators, which are divided into two levels. We employed the AHP integrated with the entropy method to obtain the weights of each indicator. The developed approach allowed us to evaluate the relative importance of each factor in determining the ports' performance. Finally, we utilized the TOPSIS method to rank the ports' comprehensive competitiveness. The ranking results provide an in-depth analysis of the competitiveness of ports in different domains, revealing the performance of ports in terms of logistics infrastructure capacity, port operations, hinterland support, development potential, and natural conditions. It promotes the improvement of ports' efficiency and comprehensive competitiveness.

(3) From above analysis, it can be summarized why the purely technical efficiency of ports is not optimal because port efficiency is limited by poor operation and management, infrastructure shortcomings, and insufficient regional synergies. Yichang Port has low efficiency due to operation and management problems, Jingzhou port is constrained by its small scale and weak infrastructure, Yueyang Port is affected by the lack of channel depth, Wuhan Port is economically strong but its potential is hampered by ecological and environmental problems, Huangshi port's operational capacity is limited due to the competition for cargo sources with Wuhan Port and its own small scale, and Jiujiang Port is inefficient due to the irrationality of its operation, management, and allocation of resources. These results show that to enhance the comprehensive competitiveness of ports, it is necessary to optimize operation and management, make up for the shortcomings of infrastructure, and strengthen regional synergistic development, to help ports break through the bottleneck of efficiency and achieve efficient synergy of the port group in the middle reaches of the Yangtze River as well as prosperous development of the regional economy.

(4) Yichang Port, Jingzhou Port and Huangshi Port production berth length redundancy, the number of moderate, reflecting the berth planning is unreasonable, the scale of expansion strategy is inappropriate, reflecting the strategic planning is not scientific, the market demand forecast is not allowed and other systemic issues; Jiujiang Port berth number of redundancy, the scale of the payoff diminishing, suggesting that the allocation of resources is unreasonable, and the infrastructure of the blind expansion, cost control is not effective, and so on. In terms of output, the container throughput of each port is insufficient, but the cargo throughput is normal, reflecting the bottleneck of container business development, which is closely related to external factors such as the single regional industrial structure, the low efficiency of port operation, and the poor transportation between the port and the hinterland restricting the efficiency of container delivery. Therefore, to enhance the competitiveness of our ports, we need to optimize planning, strengthen industrial synergy, improve the logistics system, actively respond to changes in the external environment, and achieve efficient and sustainable development.

Table 16
Scores and ranking of ports on first-level indicators.

D_1	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
2018	0.50	3	0.06	6	0.47	4	0.56	1	0.09	5	0.52	2
2019	0.49	4	0.07	5	0.51	3	0.58	1	0.01	6	0.56	2
2020	0.50	4	0.08	5	0.52	3	0.66	1	0.04	6	0.61	2
2021	0.40	4	0.07	5	0.46	3	0.56	2	0.24	6	0.49	2
2022	0.41	4	0.10	5	0.46	3	0.51	2	0.01	6	0.61	1
AVG	0.46	4	0.08	6	0.49	3	0.57	1	0.08	5	0.56	2
D_2	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
2018	0.20	4	0.17	5	0.66	2	0.91	1	0.12	6	0.52	3
2019	0.20	5	0.17	6	0.61	3	0.75	1	0.43	4	0.62	2
2020	0.18	6	0.19	5	0.60	3	0.79	1	0.30	4	0.65	2
2021	0.27	4	0.05	6	0.59	2	0.79	1	0.22	5	0.52	3
2022	0.24	5	0.11	6	0.63	2	0.78	1	0.29	4	0.47	3
AVG	0.22	5	0.14	6	0.62	2	0.80	1	0.27	4	0.56	3
D_3	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
2018	0.11	2	0.03	6	0.08	4	1.00	1	0.05	5	0.11	3
2019	0.12	2	0.03	5	0.11	3	1.00	1	0.02	6	0.10	4
2020	0.12	4	0.03	6	0.14	2	1.00	1	0.04	5	0.13	3
2021	0.13	4	0.03	6	0.15	2	1.00	1	0.04	5	0.14	3
2022	0.13	4	0.04	6	0.16	3	1.00	1	0.04	5	0.19	2
AVG	0.12	4	0.03	6	0.13	3	1.00	1	0.04	5	0.13	2
D_4	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
2018	0.34	6	0.70	1	0.45	5	0.57	3	0.66	2	0.52	4
2019	0.46	3	0.11	6	0.52	2	0.21	5	0.44	4	0.53	1
2020	0.12	6	0.58	2	0.53	4	0.62	1	0.37	5	0.54	3
2021	0.93	1	0.41	4	0.38	5	0.42	3	0.28	6	0.43	2
2022	0.30	5	0.66	2	0.37	3	0.07	6	0.69	1	0.35	4
AVG	0.43	6	0.49	1	0.45	4	0.38	5	0.49	2	0.47	3
D_5	Yichang		Jingzhou		Yueyang		Wuhan		Huangshi		Jiujiang	
Year	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
2018	0.33	6	0.42	5	0.44	3	0.48	2	0.43	4	0.74	1
2019	0.43	5	0.49	4	0.36	6	0.55	3	0.56	2	0.74	1
2020	0.33	6	0.42	5	0.44	3	0.44	3	0.43	4	0.74	1
2021	0.33	6	0.42	4	0.44	3	0.41	5	0.49	2	0.74	1
2022	0.33	6	0.42	4	0.44	2	0.41	5	0.43	3	0.74	1
AVG	0.35	6	0.44	4	0.42	5	0.46	3	0.47	2	0.74	1

This study provides an in-depth understanding of the efficiency and competitiveness of ports in the middle reaches of the Yangtze River. It also provides strategic recommendations for their future development, thus promoting their sustainable development and competitiveness.

There are many factors that affect inland port ranking. Besides that, the inland port ranking methods also affect inland port ranking. Future studies could be considered to develop a universal inland port ranking method by using large language models.

Ethical and informed consent for data used

This research does not involve human participants and animals. This paper does not contain any data with human participants performed by any of the authors.

Author statement

We would like to declare that all or part of the work described in the manuscript is original research, which has not been published elsewhere and is not prepared for publication elsewhere.

CRediT authorship contribution statement

Wang Xueqian: Investigation, Formal analysis, Data curation. **Hu Chenglin:** Investigation, Formal analysis, Data curation. **Li Tao:** Writing – review & editing, Writing – original draft. **Zhou Yanjie:** Writing – original draft, Validation, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

There is no conflict of interest exiting in the manuscript which is approved by all authors for publication.

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Declaration of competing interest

The authors declare that they have no competing interests.

Appendix A. source data

Table A1
Raw data of inland port efficiency evaluation index in 2018–2022

Year	Inland port	The length of productive berths (Meter)	The number of productive berths	Container throughput(Ten thousand TEU)	Cargo throughput (Hundred million tons)
2018	Yichang	23175	231	15.20	0.687
	Jingzhou	6441	55	13.00	0.380
	Yueyang	6652	70	50.46	1.112
	Wuhan	14114	135	157.40	1.030
	Huangshi	7463	83	5.11	0.430
	Jiujiang	15311	146	42.93	1.169
2019	Yichang	22685	184	18.00	0.797
	Jingzhou	5856	50	12.00	0.345
	Yueyang	9128	88	50.66	1.135
	Wuhan	13906	134	170.00	0.918
	Huangshi	4904	35	8.00	0.451
	Jiujiang	15600	141	52.14	1.527
2020	Yichang	22924	185	12.55	0.812
	Jingzhou	7028	60	13.00	0.417
	Yueyang	10269	99	50.90	1.160
	Wuhan	18078	163	196.40	1.050
	Huangshi	7336	54	5.00	0.475
	Jiujiang	15963	144	61.04	1.530
2021	Yichang	22609	182	15.00	1.147
	Jingzhou	7263	62	15.00	0.438
	Yueyang	7054	68	60.10	1.242
	Wuhan	19695	177	248.00	1.168
	Huangshi	6310	45	4.00	0.499
	Jiujiang	16204	375	65.10	1.710
2022	Yichang	29633	191	16.00	1.239
	Jingzhou	8548	74	17.70	0.666
	Yueyang	7054	68	100.96	1.387
	Wuhan	18037	144	270.00	1.300
	Huangshi	5145	47	7.50	0.685
	Jiujiang	21400	339	76.90	1.806

Table A2
Raw data of inland port indicators in 2018

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
The length of productive berths(Meter)	23175	6441	6652	14114	7463	15311
The Number of productive berths	231	55	70	135	83	146
Container throughput capacity(Ten thousand TEU)	50	55	120	350	20	33.5
Cargo throughput capacity(Hundred million tons)	0.97	0.43	2.24	1.05	0.63	2.08
Container throughput(Ten thousand TEU)	15.20	13.00	50.46	157.40	5.11	42.93
Cargo throughput(Hundred million tons)	0.69	0.38	1.11	1.03	0.43	1.17
Port efficiency	0.19	0.44	1.00	1.00	0.35	0.50
Hinterland GDP(100 million RMB)	4039.29	2310.60	3173.67	14928.72	1610.97	2860.07
Hinterland import and export trade volume(100 million RMB)	202.20	120.00	206.51	2146.00	238.08	357.70
Container throughput growth rate(%)	10.59 %	21.61 %	19.32 %	15.99 %	70.05 %	28.26 %
Cargo throughput growth rate(%)	16.86 %	9.17 %	−6.81 %	2.81 %	6.46 %	−0.24 %
Hinterland GDP growth rate(%)	14.19 %	11.08 %	−2.59 %	14.04 %	12.67 %	12.36 %
Hinterland foreign trade growth rate(%)	9.77 %	24.61 %	34.56 %	10.86 %	4.54 %	3.58 %
Standard water depth of the channel(Meter)	4.5	3.5	3.8	4.2	4.1	5
Distance to the sea port(Kilo meter)	1751	1621	1356	1125	1005	856
Total mileage of the channel network(Kilo meter)	678.4	1744.4	1200	555.3	443.5	888
Port water quality	80	80	80	80	60	100

Table A3
Raw data of inland port indicators in 2019

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
The length of productive berths(Meter)	22685	5856	9128	13906	4904	15600
The Number of productive berths	184	50	88	134	35	141
Container throughput capacity(Ten thousand TEU)	50	52	120	350	15.5	33.5
Cargo throughput capacity(Hundred million tons)	0.97	0.43	2.24	1.05	0.48	2.46
Container throughput(Ten thousand TEU)	18.00	12.00	50.66	170.00	8.00	52.14
Cargo throughput(Hundred million tons)	0.80	0.35	1.13	0.92	0.45	1.53

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Table A3 (*continued*)

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
Port efficiency	0.34	0.54	1.00	1.00	1.00	0.84
Hinterland GDP(100 million RMB)	4460.82	2516.48	3778.10	16223.21	1767.19	3123.06
Hinterland import and export trade volume(100 million RMB)	220.60	115.80	329.95	2441.40	178.40	349.71
Container throughput growth rate(%)	18.42 %	−7.69 %	0.40 %	8.01 %	56.71 %	21.45 %
Cargo throughput growth rate(%)	16.06 %	−9.09 %	2.06 %	−10.90 %	4.86 %	30.67 %
Hinterland GDP growth rate(%)	10.44 %	8.91 %	19.04 %	8.67 %	9.70 %	9.19 %
Hinterland foreign trade growth rate(%)	9.10 %	−3.50 %	59.77 %	13.77 %	−25.07 %	−2.23 %
Standard water depth of the channel(Meter)	4.5	3.5	3.8	4.2	4.1	5
Distance to the sea port(Kilo meter)	1751	1621	1356	1125	1005	856
Total mileage of the channel network(Kilo meter)	678.4	1744.4	1200	555.3	443.5	888
Port water quality	80	80	60	80	80	80

Table A4
Raw data of inland port indicators in 2020

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
The length of productive berths(Meter)	22924	7028	10269	18078	7336	15963
The Number of productive berths	185	60	99	163	54	144
Container throughput capacity(Ten thousand TEU)	65.8	67.5	150	325	20.6	98.5
Cargo throughput capacity(Hundred million tons)	0.97	0.43	2.24	1.23	0.57	2.46
Container throughput(Ten thousand TEU)	12.55	13.00	50.90	196.40	5.00	61.04
Cargo throughput(Hundred million tons)	0.81	0.42	1.16	1.05	0.48	1.53
Port efficiency	0.37	0.59	1.00	1.00	0.75	0.91
Hinterland GDP(100 million RMB)	4184.56	2361.00	4001.04	15516.07	1597.84	3235.02
Hinterland import and export trade volume(100 million RMB)	206.20	110.12	419.84	2704.30	238.50	448.69
Container throughput growth rate(%)	30.28 %	8.33 %	0.48 %	15.53 %	−37.50 %	17.07 %
Cargo throughput growth rate(%)	1.86 %	20.65 %	2.25 %	14.42 %	5.43 %	0.17 %
Hinterland GDP growth rate(%)	−6.19 %	−6.18 %	5.90 %	−4.36 %	−9.58 %	3.58 %
Hinterland foreign trade growth rate(%)	−6.53 %	−4.91 %	27.24 %	10.77 %	33.69 %	28.30 %
Standard water depth of the channel(Meter)	4.5	3.5	3.8	4.2	4.1	5
Distance to the sea port(Kilo meter)	1751	1621	1356	1125	1005	856
Total mileage of the channel network(Kilo meter)	678.4	1744.4	1200	555.3	443.5	888
Port water quality	80	80	80	80	60	100

Table A5
Raw data of inland port indicators in 2021

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
The length of productive berths(Meter)	22609	7263	7054	19695	6310	16204
The Number of productive berths	182	62	68	177	45	375
Container throughput capacity(Ten thousand TEU)	65.8	67.5	90	325	33.8	101
Cargo throughput capacity(Hundred million tons)	0.94	0.40	4.43	1.23	0.56	3.57
Container throughput(Ten thousand TEU)	15.00	15.00	60.10	248.00	4.00	65.10
Cargo throughput(Hundred million tons)	1.15	0.44	1.24	1.17	0.50	1.71
Port efficiency	0.35	0.39	1.00	1.00	0.61	0.60
Hinterland GDP(100 million RMB)	5044.87	2733.93	4384.05	17688.03	1873.86	3753.68
Hinterland import and export trade volume(100 million RMB)	338.50	157.40	612.06	3359.40	323.80	651.57
Container throughput growth rate(%)	19.52 %	15.38 %	18.07 %	26.27 %	−20.00 %	6.65 %
Cargo throughput growth rate(%)	41.27 %	5.04 %	7.00 %	11.23 %	5.01 %	11.76 %
Hinterland GDP growth rate(%)	20.56 %	15.80 %	9.57 %	14.00 %	17.27 %	16.03 %
Hinterland foreign trade growth rate(%)	64.16 %	42.94 %	45.78 %	24.22 %	35.77 %	45.21 %
Standard water depth of the channel(Meter)	4.5	3.5	3.8	4.2	4.1	5
Distance to the sea port(Kilo meter)	1751	1621	1356	1125	1005	856
Total mileage of the channel network(Kilo meter)	678.4	1744.4	1200	555.3	443.5	888
Port water quality	80	80	80	60	80	100

Table A6
Raw data of inland port indicators in 2022

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
The length of productive berths(Meter)	29633	8548	7054	18037	5145	21400
The Number of productive berths	191	74	68	144	47	339
Container throughput capacity(Ten thousand TEU)	65.8	67.5	90	402	9.8	101
Cargo throughput capacity(Hundred million tons)	1.16	0.60	4.44	1.31	0.63	3.83
Container throughput(Ten thousand TEU)	16.00	17.70	100.96	270.00	7.50	76.90

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Table A6 (*continued*)

Indicator	Yichang	Jingzhou	Yueyang	Wuhan	Huangshi	Jiujiang
Cargo throughput(Hundred million tons)	1.24	0.67	1.39	1.30	0.69	1.81
Port efficiency	0.32	0.44	1.00	1.00	0.72	0.43
Hinterland GDP(100 million RMB)	5502.69	3008.61	4710.67	18866.43	2041.51	4026.60
Hinterland import and export trade volume(100 million RMB)	414.70	221.74	736.57	3532.20	412.00	972.34
Container throughput growth rate(%)	6.67 %	18.00 %	67.99 %	8.87 %	87.50 %	18.13 %
Cargo throughput growth rate(%)	8.02 %	52.23 %	11.66 %	11.31 %	37.22 %	5.62 %
Hinterland GDP growth rate(%)	9.07 %	10.05 %	7.45 %	6.66 %	8.95 %	7.27 %
Hinterland foreign trade growth rate(%)	22.51 %	40.88 %	20.34 %	5.14 %	27.24 %	49.23 %
Standard water depth of the channel(Meter)	4.5	3.5	3.8	4.2	4.1	5
Distance to the sea port(Kilo meter)	1751	1621	1356	1125	1005	856
Total mileage of the channel network(Kilo meter)	678.4	1744.4	1200	555.3	443.5	888
Port water quality	80	80	80	60	60	100

Data availability statement

Data of this study can be obtained by request.

References

Cullinane, K., Ji, P., Wang, T., 2005. The relationship between privatization and DEA estimates of efficiency in the container port industry. J. Econ. Bus. 57, 433–462. https://doi.org/10.1016/j.jeconbus.2005.02.007.

Deng, C., Li, T., Jia, W., 2022. Research on the construction of comprehensive evaluation index system of influencing factors of port industry based on data analysis. Int. J. Front. Eng. Technol. 7. https://doi.org/10.25236/IJFET.2022.040701.

Feng, X., Liu, M., Zhang, W., Yin, W., Chao, Y., 2024. The impacts of pilotage planning on green maritime logistics. Reg. Stud. Mar. Sci., 103989 https://doi.org/10.1016/j.rsma.2024.103989.

Hong Yuan, C., 2021. Efficiency evaluation of main ports in Jiangsu province based on DEA model. IOP Conf. Ser. Earth Environ. Sci. 1. https://doi.org/10.1088/1755-1315/831/1/012048.

Hsu, W.K.K., Huang, S.H.S., Huynh, N.T., 2023. An assessment of operating efficiency for container terminals in a port-an empirical study in Kaohsiung port using data envelopment analysis. Res. Transp. Bus. Manag. 3, 100823. https://doi.org/10.1016/j.rtbm.2022.100823.

Li, H., Jiang, L., Liu, J., et al., 2022. Research on the evaluation of logistics efficiency in Chinese coastal ports based on the four-stage DEA model. J. Mar. Sci. Eng. 10 (8), 1147. https://doi.org/10.3390/jmse10081147.

Liu, D.C., Ding, J.F., Liang, G.S., Ye, K.D., 2020. Use of the fuzzy AHP-TOPSIS method to select the most attractive container port. J. Mar. Sci. Technol. 28 (2), 3. https://doi.org/10.6119/JMST.202004_28(2).0003.

Min, W., Haibo, K., Yue, Y., et al., 2022. Evaluation of the competitiveness of the container multimodal port hub. Sci. Rep. 12. https://doi.org/10.1038/S41598-022-23845-Y, 19334-19334.

Park, C.H., 2021. A Study on the Policy priorities for the enhancement of the trans-shipment competitiveness of the port of Busan. J. Korean Stud. 45, 75–86. https://doi.org/10.5394/KINPR.2021.45.2.075.

Peide, L.I.U., Qian, P.A.N., Baoying, Z.H.U., et al., 2023. Evaluation of comprehensive competitiveness of coastal ports: an extended MABAC method based on cloud model and game weight. Oper. Res. Manag. Sci. 32 (3), 50–55. https://doi.org/10.1038/S41598-022-23845-Y.

Stephen, H., Ingrid, M., Eamonn, O., et al., 2020. Relative size and technical efficiency in peripheral port markets: evidence from Irish and North Atlantic Spanish ports. Marit. Econ. Logist. 22, 383–402. https://doi.org/10.1057/s41278-019-00119-5.

Tseng, P.H., Yip, T.L., 2021. An evaluation model of cruise ports using fuzzy analytic hierarchy process. Marit. Bus. Rev. 6 (1), 22–48. https://doi.org/10.1108/MABR-01-2020-0004.

Wan, M., Kuang, H., Yu, Y., et al., 2022. Evaluation of the competitiveness of the container multimodal port hub. Sci. Rep. 12 (1), 19334. https://doi.org/10.3390/jmse10070870.

Wang, H., 2024. Combination weighting-competitiveness evaluation of TOPSIS model-based on Bohai rim ports. Forum Res. Innov. Manag. 2. https://doi.org/10.18686/FRIM.V2I2.4006.

Wang, J., Mo, L., Ma, Z., 2023. Evaluation of port competitiveness along China's "Belt and Road based" on the entropy-TOPSIS method. Sci. Rep. 13 (1), 15717. https://doi.org/10.1038/S41598-023-42755-1.

Wang, Z., Wu, X., Guo, J., et al., 2020. Efficiency evaluation and PM emission reallocation of China ports based on improved DEA models. Transp. Res. Part D 82. https://doi.org/10.1016/j.trd.2020.102317, 102317-102317.

Wu, L., Wang, C., 2022. Evaluating shipping efficiency in Chinese port cities: four-stage bootstrap DEA model. J. Mar. Sci. Eng. 10 (7), 870. https://doi.org/10.3390/jmse10070870.

Ye, S., Qi, X., Xu, Y., 2020. Analyzing the relative efficiency of China's Yangtze River port system. Marit. Econ. Logist. 22 (4), 1–21. https://doi.org/10.1057/s41278-020-00148-5.

Yeo, G., Roe, M., Dinwoodie, J., 2008. Evaluating the competitiveness of container ports in Korea and China. Transp. Res. Part A 42, 910–921. https://doi.org/10.1016/j.tra.2008.01.014.

Zhen, W., Su-Han, W., Po-Lin, L., et al., 2022. The economic impact of inland ports on regional development: evidence from the Yangtze River region. Transp. Policy 12780–12791. https://doi.org/10.1016/j.tranpol.2022.08.012.

Zhong, Z., Jin, H., Sun, Y., Zhou, Y., 2024. Two incentive policies for green shore power system considering multiple objectives. Comput. Ind. Eng. 194, 110338. https://doi.org/10.1016/j.cie.2024.110338.

Zhou, Y., Luo, L., Zhao, Q.Q., Chen, H., Qian, Z., Leng, S., 2024. Influence index analysis of inland waterway ports along the Yangtze River. Eur. J. Ind. Eng. https://doi.org/10.1504/EJIE.2025.10066546.