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Identifying Important Ports in Maritime Container Shipping Networks Along the Maritime Silk Road

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Abstract: Ports, as the main components of global maritime transportation, have attracted attention from both industry and academia in relation to their safety management. Identifying the important ports of a maritime shipping network is necessary and significant for the recovery of ports when encountering severe disasters, especially with limited emergency resources. This paper proposes a new method to evaluate the importance of ports by incorporating centrality measures of networks into the TOPSIS framework. Three types of centrality measures were used in an integrated manner to provide a more comprehensive evaluation of the port importance. Some economic factors such as the throughput of ports and GDP of the cities port are also considered in combination with the entropy weight method to determine the weight of each criterion in the proposed model. Furthermore, a case study of the ports along the (MSR) shipping network is conducted to demonstrate the feasibility and effectiveness of the proposed method in identifying essential ports.

1 Introduction

Maritime transportation is the invisible backbone of the global economy, without which international seaborne trade could not occur. According to the International Maritime Organization, around 90% of the world's trade is carried by sea, and maritime transportation is more significant in developing countries (Wan et al., 2019a). In China, about 40% of the energy supplies and 85% of the foreign trade are transported by sea. Being the hubs of maritime transportation, ports play an increasingly important role in promoting international trade and regional economic development. Nowadays, the role that ports play in the maritime transport system is a stage of cargo loading and unloading and an indispensable part of the whole supply chain (Chen et al., 2019a, 2019b). The loss of ports will seriously affect both the upstream and downstream of the supply chains (Wan et al., 2019b). For example, the 2002 strike on 29 ports along the west coast of the United States caused billions of dollars in losses every day and caused massive losses to transportation and sea shipping firms. The port plays a vital role in the development of both urban and regional economies. According to statistics, 31 of the world's 35 international cities are developed because of ports, and 50% of the world's wealth is concentrated in coastal port cities. Among the different components in global supply chains, ports are crucial in maintaining the continuous flow of cargo between supply chain entities. Their role has changed from a traditional regional gateway to where important value adds and complex logistics-related activities occur (Loh et al., 2014). Hence, the research on the importance of ports has attracted extensive attention from all over the world. Song et al. (2004) used AHP to identify the competitiveness of container ports in China from an outsiders' perspective. In another research, Song and Panayides (2008) developed measures for port integration in the supply chain and empirically tested the influence of portal integration in the supply chain on port competitiveness. Puig et al. (2017) applied a computer-based tool to identify ports' performance indicators from an environmental and Sustainable development perspective. More recently, Brandão et al. (2020) analysed the importance of Brazilian ports based on the flow of non-containerized cargo, considering both national and foreign trades.

Previous research has shown that the value of a port can be quantified using various centrality measures, depending on the specific requirements. Ducruet (2010) used the between centrality to examine the shifting location of hub ports in Northeast Asia, revealing the region's changing shipping routes trends. From a geographical perspective, Li (2015) divided the global shipping network into 25 regions and analyzed the position of each shipping region in the global shipping network based on the proposed multi-centrality indicators. In another study, Gonzalez et al. (2012) measured the importance of ports in the global shipping network using degree centrality, according to which the shipping network was divided into different hierarchies. Besides, the spatial characteristics of the maritime shipping network can directly reflect its evolution direction and thus provide a reference for the shipping route planning and port construction. Although the centrality-based indicators have been widely used in evaluating and identifying port importance, the usage of centrality measures individually reflects only one aspect of the role that a port plays in the shipping network.

To provide more comprehensive evaluation of the port importance, this paper considers three centrality measures (degree centrality, betweenness centrality, and closeness centrality) into TOPSIS, one of the most widely applied multi-criteria decision-making models. The importance of a port in the shipping network can be reflected from different angles. This research mainly contributes to the knowledge of multi-criteria decision-making by extending the traditional TOPSIS method with ideas from the complex network theory. The results obtained from this research offer helpful insights into identifying influential ports in shipping networks considering both the spatial structure and business condition of maritime shipping. Moreover, this research can provide a good reference for stakeholders and management authorities to protect key ports under emergencies and optimize shipping routes according to the role of different ports in global maritime transportation.

The rest of the paper is organized as follows. Section 2 reviews the research related to centrality measures and TOPSIS framework in maritime transportation, respectively. In Section 3, the methods used in this research, including centrality measures, TOPSIS, entropy weight method, and the proposed methods, are introduced. Section 4 demonstrates the proposed method with a case study of ports along with the MSR shipping network, and this study is concluded in Section 5.

2 Literature review

2.1 Centrality measures in maritime transportation

Centrality was introduced to the waterway transport area to measure the importance of nodes in shipping networks as early as the 1990s (Fleming, 1994). As an essential tool in network analysis, centrality has been widely studied and applied in recent years from different aspects. Besides, Li et al. (2018) selected 34 major container ports in the targeted region and constructed a new orientation based on the service information of the top 20 shipping companies in the world, based on the core area of the 21st MSR shipping network. Five indicators were selected to analyze the central position of ports in the MSR container shipping network. The results showed that the Port of Hong Kong, Shenzhen, Dalian, Singapore, and Shanghai held relatively more important hubs in the network. Yang et al. (2018) analyzed the characteristics of the shipping network and the connectivity between China and the rest of the shipping network based on indicators including degree distribution, degree, and closeness centrality.

Furthermore, the extent of destruction of the shipping network caused by node and edge failures was studied respectively through simulation to reveal the vulnerability of the shipping network under disasters. Wang et al. (2016) extended the application of the three basic centrality measures (i.e., degree centrality, betweenness centrality, and closeness centrality) in a directional and weighted container shipping network. The authors considered the cargo flow and the carrying capacity to reflect the actual situation's characteristics better. They evaluated the impact of the market coverage of the port hinterland through an adjusting coefficient attached to the three centrality measures. Some representative studies related to the importance of ports in maritime shipping networks based on centrality measures are summarized in Table 1.

Table 1 Research on the importance of ports

Year	Author(s)	Measure of centrality	Data sources
2012	Ducruet and Zaidi	Degree and betweenness centralities	AIS information
2012	Low, et al.	Newly developed centrality index	Lloyd’s database
2013	Ducruet	Degree, and betweenness centralities	AIS information
2014	Ducruet, et al.	Degree centricity	AIS information

2015	Tovar, et al.	Degree, and betweenness centralities	Liner shipping company
2016	Fraser, et al.	Betweenness centrality	Lloyd's database
2016	Li, et al.	Degree, betweenness, and closeness centralities	Alphaliner database
2018	Ducruet and Wang	Degree centricity	Lloyd's database
2018	Ducruet, et al.	Degree and betweenness centralities	Lloyd's database
2019	Wu, et al.	Degree, betweenness, and closeness centralities	Shipping company
2019	Jeon, et al.	Degree and betweenness centrality	Shipping company
2020	Cheung, et al.	Eigenvector centrality	Shipping lines

2.2 TOPSIS methods in maritime transportation

TOPSIS is one of the most commonly used methods in addressing multi-attribute decision-making (MCDM) problems (Hwang and Yoon, 1981). It has been studied for several decades and has been widely applied in different aspects of maritime transportation due to its advantages of being intuitive, easy to understand and implement. Yan et al. (2017) used the fuzzy-TOPSIS method to evaluate the waterway congestion in the Yangtze River under dynamic risk conditions. Zhang et al. (2018) used a TOPSIS method based on entropy weight to analyze 27 different gauges in different regions across the country Modular ports for military transport capacity assessment. Cao (2019) established a combination model based on data envelopment analysis (DEA) and TOPSIS method to calculate the comprehensive efficiency, pure technical efficiency, and scale efficiency of ports. Other applications of TOPSIS in port transport can be found in Wang and Peng (2015) and Morteza et al. (2016).

2.3 Research gap analysis

In previous studies, most of the research used one or some of the centrality-based indicators when evaluating the importance of ports. Moreover, these centrality measures were used separately, reflecting a specific aspect of the ports' importance in the shipping network. To deal with the above-mentioned limitations, this paper combines the selected centrality measures into one integrated model based on the TOPSIS framework so that different centrality measures can work in a complementary manner. Besides, two more economic indexes, which are port throughput and GDP (gross domestic product) of the port city, provide a more comprehensive evaluation of the port importance.

3 Methodology

3.1 Centrality measures

(1) Degree Centrality

Degree centrality is the simplest centrality index in network analysis, defined as the number of links directly connected to the target node (Wan et al., 2020). It symbolizes the importance of a node based on the idea that essential nodes have the largest number of links to other nodes in the network (Freeman, 1979). The degree centrality of a node is defined as:

$$DC\ (i) = \sum_{j=1}^{n} a_{ij} \tag{1}$$

where $C_D\ (i)$ indicates the degree centrality of node i, n represents the total number of nodes in the network, and a_{ij} is the number of links between two nodes i and j.

(2) Closeness Centrality

Closeness centrality measures the extent to which a node is near to all other nodes along the shortest path. It indicates how central a node is in the network. It can be calculated using Eq. (2).

$$CC(i) = \frac{n-1}{\sum_{i \neq j \in n} d_{ij}} \tag{2}$$

where d_{ij} represents the geodesic distance between two nodes i and j.

(3) Betweenness Centrality

Betweenness centrality measures the extent to which a node falls between pairs of nodes on the shortest paths connecting them in a network. It indicates the strength of connectivity between the nodes in the network. The betweenness of a node i is defined as:

$$BC(i) = \sum_{j \neq i \neq k \in N} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{3}$$

where σ_{jk} denotes the sum of all shortest paths between two nodes j and k, and $\sigma_{jk}(i)$ is the number of these shortest paths that pass through port v_i.

3.2 TOPSIS method

TOPSIS is a method for identifying solutions from a finite set of alternatives. The fundamental principle of TOPSIS is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution (Nelson and Grubesic, 2021). The implementation of the TOPSIS consists of the following steps.

Step 1. Construct the decision matrix

Assuming that there are n alternatives, and m criteria (attributes), the decision matrix can be constructed as:

$$D = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \tag{4}$$

where each variable x_{ij} describes the performance of each alternative with respect to the criterion.

Step 2. Normalize the decision matrix.

The normalised value r_{ij} of each variable x_{ij} is calculated through Eq. (5).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}} \tag{5}$$

Step 3. Construct a weighted normalized decision matrix.

The weighted normalised decision matrix (V_{ij}) can be obtained by multiplying the normalised decision matrix by its associated weights with Eq. (6).

$$v_{ij} = w_j \cdot r_{ij},\ i = 1, 2, ..., n,\ j = 1, 2, ..., m \tag{6}$$

where w_j is the weight of the jth criterion.

Step 4. Determine the positive ideal solutions (PIS) and negative ideal solutions (NIS)

Assuming that the criteria are beneficial ones, the PIS (Z^{+}) and NIS (Z^{-}) can be calculated as follows.

$$Z^{+} = (max\{z_{11}, z_{21}, \cdots, z_{n1}\}, max\{z_{12}, z_{22}, \cdots, z_{n2}\}, \cdots, max\{z_{1m}, z_{2m}, \cdots, z_{nm}\}) \tag{7}$$

$$Z^{-} = (min\{z_{11}, z_{21}, \cdots, z_{n1}\}, min\{z_{12}, z_{22}, \cdots, z_{n2}\}, \cdots, min\{z_{1m}, z_{2m}, \cdots, z_{nm}\}) \tag{8}$$

where z_{nm} indicates the nth feasible solutions in terms of mth criterion.

For cost criteria, the PIS and NIS are calculated oppositely.

Step 5. Calculate the Euclidean distances

The Euclidean distances from the PIS and the NIS of each alternative can be calculated using Eq. (9) and (10).

$$d_i^+ = \sqrt{\sum_{j=1}^{m}\left(Z_j^+ - z_{ij}\right)^2} \tag{9}$$

$$d_i^- = \sqrt{\sum_{j=1}^{m}\left(Z_j^- - z_{ij}\right)^2} \tag{10}$$

where, d_i^+ and d_i^- are the Euclidean distances of ith alternative to the PIS and the NIS, respectively.

Step 6. Rank the alternatives according to their relative closeness C_i:

$$c_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{11}$$

where $0 \leqslant C_i \leqslant 1$.

The alternative can be ranked according to their relative closeness. The larger value of C_i represents, the better alternative that is close to the positive ideal and far from the negative ideal solution.

3.3 Entropy weight method

The entropy weight method belongs to objective fixed weight methods. According to entropy characteristics, an event's randomness and disorder degree can be determined by calculating the entropy values. These values also indicate the dispersion degree of an index, and the greater the dispersion degree of an index, the greater the weight it holds. The steps of applying the entropy weight method are as follows.

Step 1. Normalizing the indicators.

There are two kinds of indexes in the entropy weight method, and the calculation for positive indicators can be achieved using Eq. (12).

$$x_{ij}^{'} = \frac{x_{ij} - min\{x_{ij}, \ldots, x_{nj}\}}{max\{x_{ij}, \ldots, x_{nj}\} - min\{x_{ij}, \ldots, x_{nj}\}}, i = 1, \ldots, n; j = 1, \ldots, m \tag{12}$$

The negative indicators can be calculated using Eq. (13).

$$x_{ij}^{'} = \frac{max\{x_{ij}, \ldots, x_{nj}\} - x_{ij}}{max\{x_{ij}, \ldots, x_{nj}\} - min\{x_{ij}, \ldots, x_{nj}\}}, i = 1, \ldots, n; j = 1, \ldots, m \tag{13}$$

where x_{ij}' is the normalised value, and x_{ij} is the indicator.

Step 2. Calculating the information entropy

The entropy information can be computed using Eq. (14) and (15).

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \ , i = 1, \dots, n; j = 1, \dots, m \quad (14)$$

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \ , j = 1, \dots, m \quad (15)$$

where, p_{ij} is the proportion of the ith sample value in jth indicator, and e_j is the information entropy.

Step 3. Calculating the weight of each indicator:

Finally, the weight of each indicator can be obtained using Eq. (16).

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_{j})} \ , j = 1, \dots, m \quad (16)$$

where w_j is the weight of jth criterion.

3.4 The proposed model for evaluating port importance

In the proposed method, the centrality measures are considered as the criteria, and the ports are alternatives. A decision matrix on the comparison of port importance can then be constructed based on the idea of TOPSIS. However, centrality measures mainly reflect the importance of ports in a shipping network from the topological perspective, with the operational situation of ports being ignored. Therefore, two economic indicators are further considered in this research: port throughput and the GDP of the port city. Throughput is the total amount of cargo handled by a port annually, reflecting the scale and development of a port, while the GPD is the embodiment of the comprehensive economic capacity of the port city. After determining the weight of the five selected criteria using the entropy weight method, the relative closeness of each port can be calculated. Then, the ports are ranked according to the relative closeness values. The flowchart of the proposed method is shown in Figure 1.

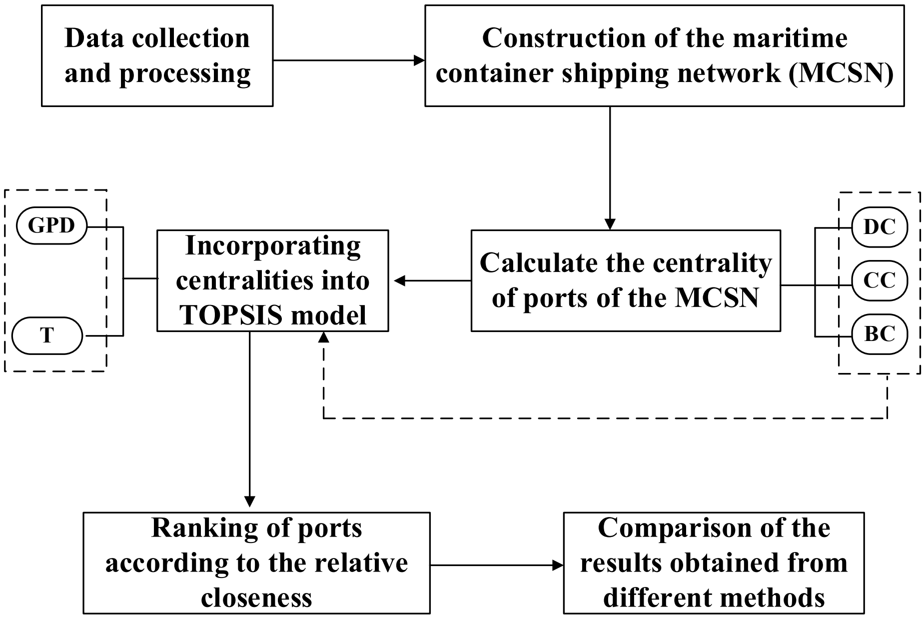


Figure 1 Flowchart of the proposed method

The detailed research steps are presented as follows.

Step 1. Constructing decision matrix

$$D = \begin{bmatrix} BC_{11} & CC_{12} & DC_{13} & T_{14} & GDP_{15} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ BC_{k1} & CC_{k2} & DC_{k3} & T_{k4} & GDP_{k5} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ BC_{n1} & CC_{n2} & DC_{n3} & T_{n4} & GDP_{n5} \end{bmatrix} \tag{17}$$

where D represents the decision matrix, T is the throughput of a port, and GDP is the Gross Domestic Product of the port city.

Step 2. Calculating the weight of criteria using the entropy weight method

In this research, it is assumed that two types of indicators are of the same importance, which means that the centrality indexes and economic indexes share the same weight. The weight of five sub-indicators, including degree centrality, betweenness centrality, closeness centrality, and port throughput and GDP of port cities, are evaluated within the centrality index and economic index groups.

Step 2.1. Normalize the indicators:

$$x_{ij}^{'} = \frac{x_{ij} - min\{x_{ij}, \ldots, x_{nj}\}}{max\{x_{ij}, \ldots, x_{nj}\} - min\{x_{ij}, \ldots, x_{nj}\}}, i = 1, \ldots, n; j = 1, \ldots, m \tag{18}$$

Step 2.2. Calculate information entropy

$$p_{ij} = \frac{x_{ij}^{'}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{'}}}; \; i = 1,\ldots,n; \; j = 1,\ldots,m \tag{19}$$

$$e_j = -\frac{1}{\mathrm{In}n}\sum_{i=1}^{n} p_{ij}\,\mathrm{In}\,(p_{ij}), \; j = 1,\ldots,m \tag{20}$$

Step 2.3. Calculating the weight of each indicator

Typically, the weight of the centrality indicator group and economic indicator group can be calculated according to Eq. (16). For the demonstration purpose in this study, it is assumed that these two groups shared the same weight, that is, 0.5 of each. Then, the weight of sub-indicators of each group can be calculated using Eqs. (21) and (22), respectively.

$$w(c)_j = 0.5 * \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \;, j = 1,2,3 \tag{21}$$

$$w(e)_j = 0.5 * \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \;, j = 4,5 \tag{22}$$

Step 3. Constructing the standardized matrix

The decision matrix is normalize using Eq. (23), and the standardized matrix can then be developed using Eq. (24).

$$Z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}} \tag{23}$$

$$D = \begin{bmatrix} BC_{11}^{'} & CC_{12}^{'} & DC_{13}^{'} & T_{14}^{'} & GDP_{15}^{'} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ BC_{k1}^{'} & CC_{k2}^{'} & DC_{k3}^{'} & T_{k4}^{'} & GDP_{k5}^{'} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ BC_{n1}^{'} & CC_{n2}^{'} & DC_{n3}^{'} & T_{n4}^{'} & GDP_{n5}^{'} \end{bmatrix} \tag{24}$$

where Z is the standardized matrix.

Step 4. Determining the position of the highest and the lowest importance

Based on Eq. (7) and (8), the set of positions of the highest and the lowest importance of ports can be determined as follows.

$$Z^{+} = \left(max\{BC_{11},\ldots,BC_{n1}\}, max\{CC_{12},\ldots,CC_{n2}\},\ldots, max\{GDP_{1m},\ldots,GDP_{nm}\}\right) \tag{25}$$

$$Z^{-} = \left(\min\{BC_{11}, \ldots, BC_{n1}\}, \min\{CC_{12}, \ldots, CC_{n2}\}, \ldots, \min\{GDP_{1m}, \ldots, GDP_{nm}\} \right) \tag{26}$$

Step 5. Rank the ports according to the relative closeness

Calculate each port's Euclidean distance to the highest and the lowest importance using Eq. (27) and (28).

$$D_i^{+} = \sqrt{\sum_{j=1}^{m} w_j \left(Z_j^{+} - z_{ij}\right)^2} \tag{27}$$

$$D_i^{-} = \sqrt{\sum_{j=1}^{m} w_j \left(Z_j^{-} - z_{ij}\right)^2} \tag{28}$$

Then, the relative closeness of each port ($C_{(p)i}$) to the position of highest importance can be calculated using Eq. (29).

$$C_{(p)i} = \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \tag{29}$$

The relative closeness indicates the importance of ports. The larger value of $C_{(p)i}$, the more important position a port holds in the investigated maritime shipping network.

Step 6. Validating the results

The importance evaluation results of ports obtained are compared with those obtained from other well-established methods to validate the rationality and feasibility of the proposed method.

4 Case study of the MSR

The 21st Century MSR was proposed by China in October 2013 to deepen and strengthen contacts and cooperation between countries and regions globally, which has promoted the development of the global maritime shipping industry in the past seven years. The MSR enriches the shipping network, promotes cooperation, and improves competitiveness within the shipping network (Chen et al., 2019c). In this study, the ports along the MSR shipping network are considered to conduct the case study to demonstrate the proposed method.

4.1 Data collection and processing

In this study, some world-leading shipping companies' official published service information was collected to construct the MSR shipping network. Basic information of a specific shipping route consists of departure port, destination port, ports of call, time schedule, and ship fleet. In this research, the schedule information from 6th March to 7th May in 2017 of the top 16 liner shipping companies was considered for the case study. According to the transport capacity information provided by Alphaliner (https://www.alphaliner.com/#top100), the top 16 container shipping companies in the world accounted for 88% of the total global container shipping capacity in 2018, which is believed to be representative. Besides, service information from the three largest Chinese container shipping companies was considered a supplement to the sample data since they mainly provided service for the MSR areas. Finally, the service information of 1249 shipping routes connecting 254 ports was collected. In the case study of this research, official documents and published data were accessed to collect port throughput information and city GDP in 2018.

4.2 Construction of the MSR shipping network

Generally, there are two ways to construct a shipping network: Space L and the Space P models (Wu et al., 2019). In a Space L model, each port is directly connected continuously, while in the Space P model, any two ports within the same shipping routes are considered to be connected, either directly or indirectly. Although Space L is simple, Space P could better illustrate the dominant position of the hub port and the transit relationship of ports in the shipping network. Therefore, this paper chooses the Space P to build the MSR shipping network, the topology shown in Figure 2. For better readability, only the top 10 most connected ports are marked in the figure.

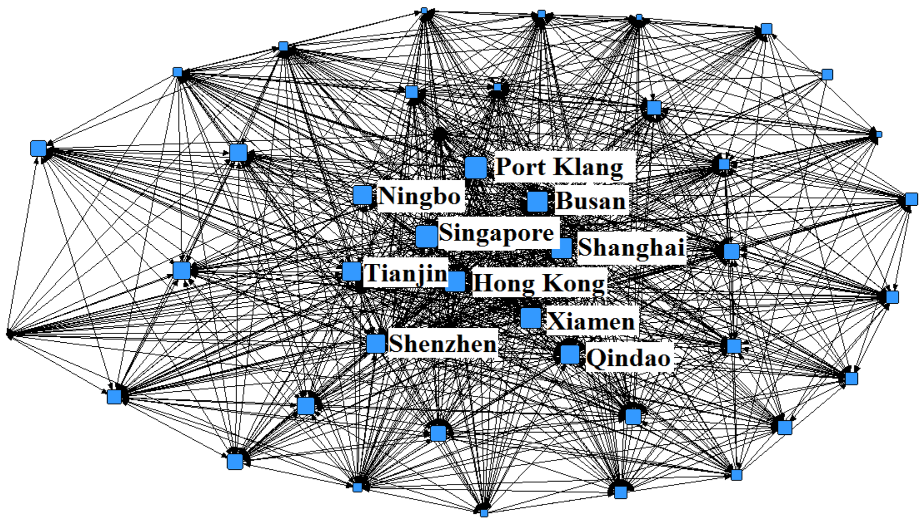


Figure 2. The container shipping network of the MSR

It is noted that among the 254 ports involved in this case study, there are 169 ports along the MSR, in which more than 80% of them are from Asian countries.

4.3 Evaluation of ports in terms of different criteria

(1) Centrality indicator group

Based on Equation (1) to (3), the degree centrality, closeness centrality, and betweenness centrality of each port within the MSR shipping network can be calculated. The top 10 ports in terms of centrality measures are summarised in Table 2.

Table 2 Centrality of ports along with the MSR shipping network

Rank	**Port**	**Degree Centrality**	**Port**	**Closeness Centrality**	**Port**	**Betweenness Centrality**
1	Hong Kong	273	Hong Kong	354.600	Singapore	19.062
2	Singapore	261	Singapore	353.967	Hong Kong	8.860
3	Shanghai	246	Shenzhen	335.633	Port Klang	5.975
4	Ningbo	244	Shanghai	334.717	Busan	5.178
5	Shenzhen	234	Ningbo	334.300	Shenzhen	4.919
6	Port Klang	206	Port Klang	322.434	Laem Chabang	4.230
7	Busan	202	Busan	316.267	Colombo	3.979
8	Qingdao	192	Xiamen	310.217	Lome	3.765
9	Xiamen	190	Kaohsiung	303.970	Xiamen	3.439
10	Tianjin	181	Qingdao	299.633	Kaohsiung	3.238

(2) Economic indicator group

We have collected the throughput of the sample ports and the corresponding GDP of port cities. The information of the top ten ports by container throughput in 2018 (iContainers, 2020) is summarized in Table 3.

Table 3. The information of the top ten ports by container throughput in 2018

No.	**Port**	**GDP (billion USD)**	**Throughput (million TEU)**
1	Shanghai	537.49	42.01
2	Singapore	373.22	36.60
3	Shenzhen	361.52	27.74
4	Ningbo-Zhoushan	160.14	26.35
5	Guangzhou	340.68	21.87
6	Busan	70.43	21.66
7	Hong Kong	361.69	19.60
8	Qingdao	178.86	18.26
9	Tianjin	199.45	16.01
10	Jebel Ali	108.39	14.95

Based on the performance of all ports for each criterion (from both centrality and economic indicator groups), the decision matrix can be constructed by using Eq. (17), as shown below.

$$D = \begin{array}{c} \\ \text{Hong Kong} \\ \vdots \\ \text{Singapore} \\ \vdots \\ \text{Busan} \end{array} \begin{array}{c} \begin{array}{ccccc} BC & CC & DC & T & GDP \end{array} \\ \begin{bmatrix} 8.86 & 354.6 & 273 & 19.6 & 361.69 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 9.06 & 354.0 & 261 & 36.6 & 373.22 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 5.18 & 316.3 & 202 & 21.66 & 70.43 \end{bmatrix} \end{array}$$

4.4 Calculation of the weight of criteria

The entropy weight method is used to calculate the local weight of degree centrality, closeness centrality, and betweenness centrality of the centrality indicator group, port throughput, and the GDP of the port city of the economic indicator group. Taking the betweenness centrality of an example, firstly, the indicator is normalized using Eq. (18).

$$x_{11} = \frac{2.043 - 0}{19.062 - 0} = 0.107$$

The information entropy redundancy can be calculated by using Eqs. (19) and (20).

$$p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} = \frac{0.107}{6.81707} = -0.0653$$

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln(p_{i1}) = -\frac{1}{\ln 254} * -3.92 = 0.708$$

The weight of each attribute can be calculated by using Eqs. (21) and (22).

$$w_1 = 0.5 \times \frac{1 - 0.708}{0.408} = 0.358$$

Finally, the global weight of each indicator can be obtained, as shown in Table 4.

Table 4. The weight of indicators/criteria

	Centrality indicators (0.5)			**Economic indicators (0.5)**	
	BC	*CC*	*DC*	*T*	*GDP*
weight	0.358	0.034	0.109	0.244	0.256

4.5 Discussion of the results

(1) Ranking the ports according to their importance

The Euclidean distances of each port to the PIS and the NIS can be calculated according to Eq. (27) to (28). Then the relative closeness of each port can be obtained using Eq. (29). The top 10 ports in terms of relative closeness are summarized in Table 5.

Table 5. Top 10 important ports of MSR shipping network

Rank	Port	d^+	d^-	$C_{(p)i}$
1	Singapore	0.158	0.394	0.714
2	Hong Kong	0.190	0.358	0.653
3	Shanghai	0.258	0.312	0.548
4	Shenzhen	0.222	0.266	0.546
5	Port Klang	0.254	0.252	0.498
6	Jeddah	0.323	0.284	0.468
7	Busan	0.304	0.224	0.424
8	Ningbo	0.335	0.185	0.355
9	Guangzhou	0.354	0.171	0.326
10	Tanjung Pelepas	0.343	0.152	0.307

Based on the above results, the top 10 ports can roughly be divided into three levels. Port of Singapore and Port of Hong Kong belong to the first level, with a relative closeness above 0.65, showing their dominant position in the MSR shipping network. This is mainly because of their good performance with respect to degree, betweenness, closeness centrality, and the city GDP. Port of Shanghai, Shenzhen, Port Klang, and Jeddah belong to the second level, with a relative closeness value between 0.45 and 0.65. The third level consists of the last four ports: Port of Busan, Ningbo, Guangzhou, and Tanjung Pelepas.

(2) Comparative analysis of the results

To verify the rationality of the proposed method, the ranking results obtained from the method are compared with those obtained from other well-established methods; results are depicted in Figure 3. Taking the ranking of container throughput as a baseline, the results of the comparative analysis indicate that the rankings obtained from different methods are basically in a consistent manner. The Port of Shanghai ranked first in container throughput, ranked third in the proposed model, and ranked eighth in a multi-centrality model (Wu et al., 2019). The Port of Singapore ranked second in terms of container throughput and multi-centrality model and ranked first in the proposed model. The Port of Shenzhen ranked third in container throughput and multi-centrality models and ranked fourth in the proposed model. The Port of Ningbo ranked fourth in container throughput, ranked eighth in the proposed model, and ranked seventh in the multi-centrality model. The ranking results obtained in this research show a similar variation trend compared to that obtained from Wu et al. (2019) research.

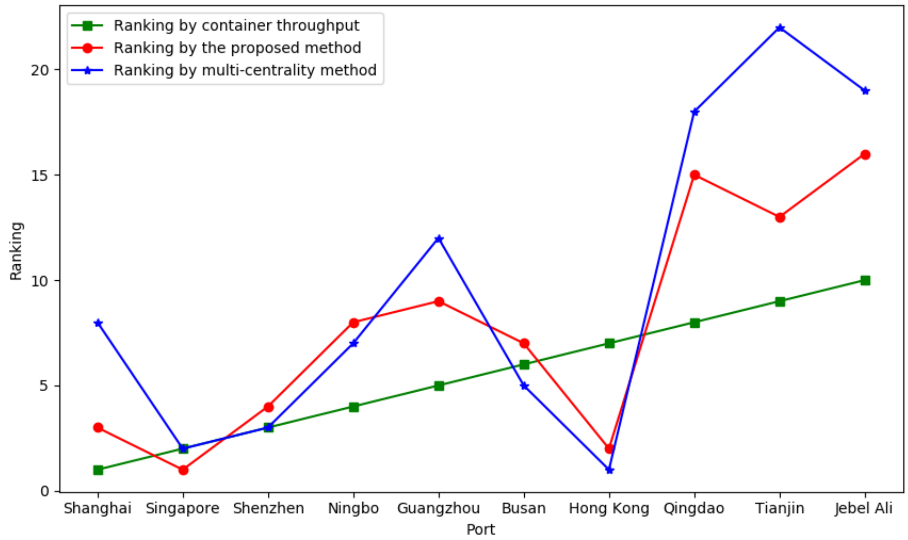


Figure 3. Comparison of port ranking by different methods

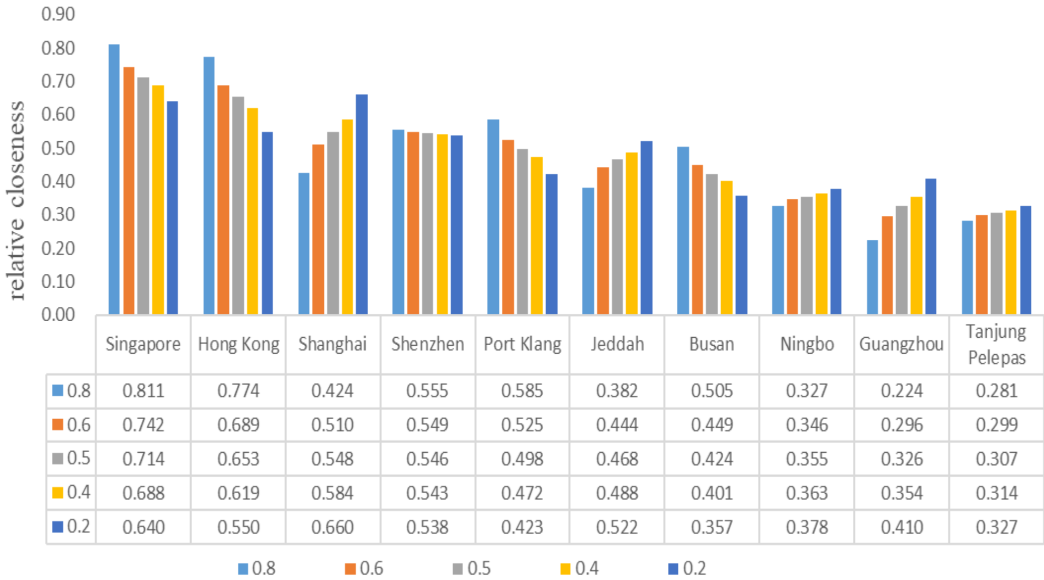
4.6 Sensitivity analysis

This section examines the sensitively analysis of MSR port importance evaluation results of the shipping network. The initial weights of centricity indicator- and economic indicator- groups in the case study are set as 0.5 and 0.5, which indicates the same preference of both topological and economic indicators when assessing the importance of ports. However, this ratio may vary under different scenarios. To further test the robustness of the proposed model, other scenarios are set as follows. Assuming that the ratio of the weight of the centricity indicator group to the economic indicator group is 8/2, 6/4, 4/6, and 2/8, respectively, then the weight of each criterion under different scenarios can be calculated and presented in Table 6.

Table 6. The weights of criteria under different scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Weight of centricity indicators		0.8	0.6	0.4	0.2
Weight of economic indicators		0.2	0.4	0.6	0.8
Centricity indicators	*BC*	0.573	0.429	0.286	0.143
	CC	0.054	0.040	0.027	0.013
	DC	0.174	0.130	0.087	0.043
Economic indicators	*T*	0.102	0.205	0.307	0.410
	GDP	0.098	0.195	0.293	0.390

According to the method proposed in 3.4, the relative closeness of ports under different scenarios is calculated, as shown in Figure 4. The figure shows the changing trend of the relative closeness of the top 10 ports.



	Singapore	Hong Kong	Shanghai	Shenzhen	Port Klang	Jeddah	Busan	Ningbo	Guangzhou	Tanjung Pelepas
0.8	0.811	0.774	0.424	0.555	0.585	0.382	0.505	0.327	0.224	0.281
0.6	0.742	0.689	0.510	0.549	0.525	0.444	0.449	0.346	0.296	0.299
0.5	0.714	0.653	0.548	0.546	0.498	0.468	0.424	0.355	0.326	0.307
0.4	0.688	0.619	0.584	0.543	0.472	0.488	0.401	0.363	0.354	0.314
0.2	0.640	0.550	0.660	0.538	0.423	0.522	0.357	0.378	0.410	0.327

Figure 4 The relative closeness of the top 10 ports under different scenarios

According to Figure 4, it can be seen that the relative closeness of Singapore, Hong Kong, Klang, and Busan Port show an obvious downward trend with the decrease of the proportion of centrality indicators. It means that the topological indicators have a more significant impact on the importance of these four ports. In contrast, the relative closeness of Shanghai, Jeddah, and Guangzhou Port show an obvious upward trend, which means that these ports depend more on economic factors. The fluctuations of the relative closeness of the rest ports are relatively small. The consistency in the direction of change of the relative closeness indicates that the proposed model is rational and robust.

5 Conclusions

This paper proposes a novel model for the comprehensive evaluation of port importance based on centrality measures and the TOPSIS method. The degree centrality, betweenness centrality, closeness centrality, port throughput, and the GDP of the port cities are combined in an integrated way. The proposed method is demonstrated with a case study of ports along with the MSR shipping network. Some conclusions are listed as follows.

1) The evaluation results revealed that five are from China among the top ten important ports of the MSR shipping network. The top three most important ports are the Port of Singapore, Hong Kong, and Shanghai.
2) The comparative analysis of different methods indicated that the results obtained from the proposed method are consistent with those from other

methods, validating the proposed method to some extent.

Besides, this research provides a theoretical basis for identifying influential ports in complex maritime transportation networks. The results obtained from this research can also provide a valuable reference for stakeholders in protecting key ports in the face of emergencies and improving the safety and efficiency of global maritime transportation. It is noted that the centrality and economic indicator groups are assumed of the same importance when constructing the decision matrix, which, however, may vary according to the specific situation under investigation in real life. Therefore, dynamic weights of the criteria are suggested to be investigated in future research to offer more flexible results. Furthermore, the influence of weights of criteria on the evaluation results is also worthy of study.

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References

Brandão, L. C., Del-Vecchio, R. R., Mello, J. C. C. B. S. D., & Francisco, C. N. (2020). Evaluating the importance of Brazilian ports using graph centrality measures. *Pesquisa Operacional*, 40.

Cao, L. (2019). Research on Green Port Efficiency Evaluation Based on DEA and TOPSIS. *International Core Journal of Engineering*, *5*(11), 106-119.

Chen, J., Zheng, T., Garg, A., Xu, L., Li, S., & Fei, Y. (2019a). Alternative Maritime Power application as a green port strategy: Barriers in China. *Journal of Cleaner Production*, 213, 825-837.

Chen, J., Zhang, W., Wan, Z., Li,S., Huang, T. & Fei, Y.(2019b). Oil spills from global tankers: Status review and future governance. *Journal of Cleaner Production*, 227, 20-32.

Chen, J., Fei, Y., Lee, P. T. W., & Tao, X. (2019c). Overseas port investment policy for China's central and local governments in the Belt and Road Initiative. *Journal of Contemporary China*, 28(116), 196-215.

Cheung, K. F., Bell, M. G., Pan, J. J., & Perera, S. (2020). An eigenvector centrality analysis of world container shipping network connectivity. *Transportation Research Part E: Logistics and Transportation Review*, 140, 101991.

Ducruet, C. (2013). Network diversity and maritime flows. *Journal of Transport Geography*, 30, 77-88.

Ducruet, C., Cuyala, S., & El Hosni, A. (2018). Maritime networks as systems of cities: The long-term interdependencies between global shipping flows and urban development (1890–2010). *Journal of Transport Geography*, 66, 340-355.

Ducruet, C., Lee, S. W., & Ng, A. K. (2010). Centrality and vulnerability in liner shipping networks: revisiting the Northeast Asian port hierarchy. *Maritime Policy & Management*, 37(1), 17-36.

Ducruet, C., & Wang, L. (2018). China's global shipping connectivity: Internal and external dynamics in the contemporary era (1890–2016). *Chinese geographical science*, 28(2), 202-216.

Ducruet, C., & Zaidi, F. (2012). Maritime constellations: A complex network approach to shipping and ports. *Maritime Policy & Management*, 39(2), 151-168.

Du, Y., Gao, C., Hu, Y., Mahadevan, S., & Deng, Y. (2014). A new method of identifying influential nodes in complex networks based on TOPSIS. *Physica A: Statistical Mechanics and its Applications*, *399*, 57-69.

Fleming, D. K., & Hayuth, Y. (1994). Spatial characteristics of transportation hubs: centrality and intermediacy. *Journal of Transport Geography*, 2(1), 3-18.

Fraser, D. R., Notteboom, T., & Ducruet, C. (2016). Peripherality in the global container shipping network: The case of the Southern African container port system. *GeoJournal*, 81(1), 139-151.

Hwang, C. L. & K. Yoon (1981). *Multiple Attribute Decision Making: Methods and Applications*. Springer-Verlag, New York.

iContainers (2020), *Top 20 ports in the world*. https://www.icontainers.com/top-20-ports-in-the-world/. Accessed on 14th Oct., 2020.

Jeon, J. W., Duru, O., & Yeo, G. T. (2019). Cruise port centrality and spatial patterns of cruise shipping in the Asian market. *Maritime Policy & Management*, *46*(3), 257-276.

Loh, H. S., & Thai, V. V. (2014). Managing port-related supply chain disruptions: a conceptual paper. *Asian Journal of Shipping & Logistics*, 30(1), 97-116.

Laxe, F. G., Seoane, M. J. F., & Montes, C. P. (2012). Maritime degree, centrality and vulnerability: port hierarchies and emerging areas in containerized transport (2008–2010). *Journal of Transport Geography*, 24, 33-44.

Li Z., Shi Y., Xu M. et al. (2016) Global Liner Network Status of Asian Container Port.

Economic Geography, 36 (3), 91-98.

Li, Z., Li, W. Y., & Xu, M. (2018). Centrality of container shipping network of the new Maritime Silk Road. *China Maritime*, 41(03):126-131+137.

Li, Z., Xu, M., & Shi, Y. (2015). Centrality in global shipping network basing on worldwide shipping areas. *GeoJournal*, 80(1), 47-60.

Li, Z. F., Shi, Y. L., Xu, M. Q., Zhang X. L., & Jiang S.F. (2016). Hierarchical structure in the global liner shipping network. *Systems Engineering - Theory & Practice*, 36(4): 981-988.

Low, J. M., & Tang, L. C. (2012). Network effects in the East Asia container ports industry. *Maritime Policy & Management*, 39(4), 369-386.

Morteza, Z., Reza, F. M., Seddiq, M. M., Sharareh, P., & Jamal, G. (2016). Selection of the optimal tourism site using the ANP and fuzzy TOPSIS in the framework of integrated coastal zone management: a case of Qeshm Island. *Ocean & Coastal Management*, 130, 179-187.

Nelson, J. R., & Grubesic, T. H. (2021). A spatiotemporal analysis of oil spill severity using a multi-criteria decision framework. *Ocean & Coastal Management*, 199, 105410.

Puig, M., Pla, A., Seguí, X., & Darbra, R. M. (2017). Tool for the identification and implementation of Environmental Indicators in Ports (TEIP). *Ocean & Coastal Management*, 140, 34-45.

Song, D. W., & Yeo, K. T. (2004). A competitive analysis of Chinese container ports using the analytic hierarchy process. *Maritime Economics & Logistics*, 6(1), 34-52.

Song, D. W., & Panayides, P. M. (2008). Global supply chain and port/terminal: integration and competitiveness. *Maritime Policy & Management*, 35(1), 73-87.

Tovar, B., Hernández, R., & Rodríguez-Déniz, H. (2015). Container port competitiveness and connectivity: The Canary Islands main ports case. *Transport Policy*, 38, 40-51.

Wan, C., Tao, J. L., Wu, L., & Zhang, D. (2020). An analysis of influences of the COVID-19 on the spatial structure of the China's global shipping network. *Journal of Transport Information and Safety*, 38(02), 129-135.

Wan, C., Yan, X., Zhang, D., & Yang Z. (2019a). Analysis of risk factors influencing the safety of maritime container supply chains. *International Journal of Shipping and Transport Logistics*, 11(6), 476-507

Wan, C., Yan, X., Zhang, D. Qu, Z., & Yang, Z. (2019b). An advanced fuzzy Bayesian-based FMEA approach for assessing maritime supply chain risks. *Transportation Research Part E: Logistics and Transportation Review*, 125, 222-240.

Wang, X., & Peng, B. (2015). Determining the value of the port transport waters: based on improved TOPSIS model by multiple regression weighting. *Ocean & Coastal*

Management, 107, 37-45.

Wang, Y., & Cullinane, K. (2016). Determinants of port centrality in maritime container transportation. *Transportation Research Part E: Logistics and Transportation Review*, 95, 326-340.

Wu, J., Zhang, D., Wan, C., Zhang, J., & Zhang, M. (2019). Novel approach for comprehensive centrality assessment of ports along the Maritime Silk Road. *Transportation Research Record*, 2673(9), 461-470.

Yan, X., Wan, C., Zhang, D., & Yang, Z. (2017). Safety management of waterway congestions under dynamic risk conditions - a case study of the Yangtze River. *Applied Soft Computing*, 59, 115-128.

Yang, C. X., Zong, K., & Hu, Z.H. (2018). Analysis of connectivity between China and the Maritime Silk Road. *Journal of Shanghai University (Natural Science Edition)*, 24(03): 169-176.

Zhang, J., Zhang Z. H., Li, X.D., Sun, Q. & Qiao, W. (2018). Military transport capacity evaluation of ports using entropy weight and TOPSIS. *Journal of Tsinghua University (Science and Technology)*, 58(5), 494-499.