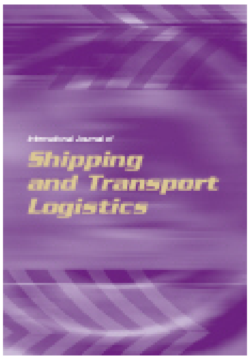

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Vulnerability analysis of Maritime Silk Road shipping network under port emergencies

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Abstract: The shipping network faces natural or man-made port emergencies, and the failure of port affects the network connectivity and efficiency. In view of this, we first construct Maritime Silk Road shipping network and analyse its characteristics. Then we select four indexes to measure its vulnerability. Random and deliberate attacks are simulated and the order of deliberate attacks is based on the importance obtained by PageRank algorithm. The importance also divides ports into four categories. Finally, the vulnerability is further analysed under the substitution effect of adjacent ports. The results demonstrate that the Maritime Silk Road shipping network is relatively weak under deliberate attack. When both core and regional hub ports are attacked, the network still has a certain local connectivity. Furthermore, when considering the substitution effect of adjacent ports, the failure of Singapore, Colombo, Jeddah, Shenzhen, Jebel Ali, Piraeus and Busan still has a high impact on the network vulnerability.

Keywords: emergency; Maritime Silk Road; MSR; shipping network; vulnerability; substitution.

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1 Introduction

In 2013, China proposed the Belt and Road Initiative which aims at building a connectivity network by strengthening partnerships among countries along the belt and road. The Maritime Silk Road (MSR) aims at building common interests, with ports as its fulcrum connecting the whole world in the form of maritime transport. It plays a crucial driving role in regional economic development (Huang et al., 2021). The status of ports has highly improved due to the integration of global economy and liberalisation of foreign trade. Consequently, it becomes an important carrier and key node of global transportation. In terms of total volume, more than 80% of goods are transported by sea, which accounts for 70% of the total international trade (Kosowska-Stamirowska, 2020).

At present, the trade between ports along the MSR has become very frequent. In addition, a relatively complete shipping network has been developed. However, because of the complexity of the countries and regions along the MSR, political, religious, cultural and economic problems exist, and therefore the ports are vulnerable to terrorist attacks and sabotage (Yang et al., 2013; Yang and Liu, 2022). Moreover, natural disasters such as earthquakes, tsunamis and typhoons sometimes pose fatal threats to the ports, thus affecting their normal operation (Doll et al., 2014; Lai et al., 2020; Zhang et al., 2020). In the case where the core ports are not able to normally operate because of some emergencies, the shipping network efficiency is reduced and most of the trade is affected or interrupted, which affects the trade between the countries and regions along the MSR. The shipping network has also its own vulnerability.

For instance, in 2011, an 8.9 magnitude earthquake on the coast of Northeastern Japan triggered a huge tsunami which shuts down ports in Northeastern Japan. In August 2015, the massive explosion at Tianjin Port suspended most of the transport missions. In August 2020, the explosion at Beirut port suspended the trade and caused huge economic losses. In December 2021, Port Kelang faced severe floods, which highly affected its operation. In addition, several ports were also affected by port service suspension and delay due to worker strikes. Different types and extents of emergencies have different impacts on the ports. Few emergencies affect multiple ports, while most of them affect a single port.

Due to the political instability and frequent natural disasters in some regions along the MSR, it is important to study the vulnerability of the MSR shipping network, determine its weak nodes and develop the security strategies aiming at ensuring the connectivity, stability and reliability of the network and promoting the trade cooperation among countries. Therefore, this paper constructs the MSR shipping network and analyses its vulnerability to emergencies. Considering the substitution effect of the adjacent ports when a certain port fails, the ports that need to focus on retaining the port functions and improving the robustness are further selected. Finally, the corresponding countermeasures and suggestions are formulated.

The remainder of this paper is organised as follows. Section 2 presents the literature review. Section 3 details the constructed MSR shipping network and the analysis of its characteristics. The vulnerability measurement index of the MSR shipping network is performed in Section 4. In Section 5, the vulnerability of the MSR shipping network to emergencies is analysed while considering the substitution effect of the adjacent ports. Finally, the conclusions and perspectives are provided in Section 6.

2 Literature review

2.1 MSR shipping network

The shipping network is a complex network composed of ports, routes, ships and other elements (Jiang et al., 2019). The existing studies are based on a complex network theory, in order to transform the real shipping system into an abstract complex network and analyse the network topology including the node degrees, cluster coefficient, average path length, node strength, etc. These topologies allow to better understand the maritime network. The degree distribution reveals the scale-free characteristics of the maritime network (Liu et al., 2017). Few ports have a high node degree, while others have a low node degree, obeying power law distribution. The smaller average shortest path length and larger clustering coefficient also illustrate the shipping network small-world characteristics and accessibility (Guo et al., 2017; Ducruet, 2020).

The centrality is a crucial reflection of the port nodes position in the network. It plays an important role in revealing the spatial structure characteristics of the shipping networks. Liu et al. (2018b) use weighted ego network analysis to explore the hierarchical structure of the global shipping network and found all centrality indices exhibited scale-free properties with obvious power-law distributions. Tovar et al. (2015) use the degree, betweenness and port accessibility index to analyse the ports connectivity in The Canary Islands. Wan et al. (2021) evaluate the ports importance along the MSR, including the degree, betweenness and closeness centralities.

Other studies also combine the space-time characteristics of the shipping network in order to determine some rules. For instance, Xu et al. (2015) study the centrality characteristics of the global maritime transport network from 2001 to 2012, and analyse the regional unbalanced evolution process, which demonstrates that the shipping network is spatially and structurally heterogeneous (Liu et al., 2018a). Due to the different economic backgrounds of various regions, the evolution process of the global shipping network is also unstable (Alvarez et al., 2021). Ducruet and Notteboom (2012) study several ports in China, Japan, South Korea and Russia. They construct the Northeast Asia liner network so as to explain the close relationship between the local port policies and the evolution of the shipping network design, and analyse the impact of the port regional spatial changes according to the evolution trend of the container shipping network.

The 21st century MSR initiative, proposed by China, is an important regional cooperation project for the world. There are also some studies from the perspective of shipping network. For example, Mou et al. (2018) explore the spatial pattern and current situation of regional trade associations of the MSR shipping network. Jiang et al. (2019) determine the network type by constructing the network feature set, demonstrate that the shipping network of the MSR belongs to the scale network, and analyse its topological characteristics. Zhao et al. (2021) explore the evolution of the MSR shipping network motivated by the need for sustainable development. Yang et al. (2022) propose an integrated local propagation and global centrality (LPGC) method to identify the key ports based on the MSR shipping network.

2.2 Shipping network vulnerability

The network vulnerability has also been widely studied in complex networks. The concept of vulnerability was first introduced in the natural disasters field, where it is used to express the possibility and degree of system damage when affected by adverse factors such as disasters, for example. In the transport field, Berdica (2002) first proposes a clear definition of road network vulnerability. More precisely, he considers that vulnerability reflects the sensitivity of the transportation network to emergencies, and defines it as the sensitivity coefficient of the transportation network service level, after the occurrence of extreme events. Taylor et al. (2005) consider the vulnerability of the transportation network as the relative change of accessibility, after the occurrence of emergencies. Bell et al. (2008) further consider the functionality of the transportation network, and measure the vulnerability to the relative changes of traffic after the occurrence of emergencies.

The vulnerability of the shipping network mainly represents the degree of influence on the network connectivity when the network is attacked or partially failed, while focusing on the impact on the whole system when some elements (such as nodes or links) fail or show disturbance (Pan et al., 2021). Wang et al. (2016) propose a quantitative method to study the change rate of the network vulnerability, while selecting the route data of 2004 and 2014. They deduce that the vulnerability of the global container shipping network to deliberate attacks tends to weaken in the past ten years. Lhomme (2016) evaluates the vulnerability of the global maritime network to the failure of a single node or a group of nodes. He deduces that, although the global shipping network is relatively resilient, it is vulnerable to the damage of the most important ports, especially those located in Asia. This also demonstrates that the vulnerability to the disruption of shipping transport services varies with respect to the role of the ports/countries in the network (Calatayud et al., 2017). In order to study the impact of edge failure on the vulnerability of the global container shipping network, Viljoen and Joubert (2016) sort the network edges according to their importance, and delete edges according to their order. The results show that the impact of edge failure on the connectivity of the container shipping network is smaller than that of node failure. Guo et al. (2017) analyse the vulnerability of the shipping network among China, Japan and South Korea using the blocking flow theory, hub port interruption and deletion. Yu et al. (2020) propose a quantitative method of network survivability in order to assess the vulnerability.

Moreover, the links in the shipping network pass through several places with high incidence of emergencies, such as the Strait of Malacca, Suez Canal, Strait of Hormuz and Panama Canal, for example. Their interruption highly affects the connectivity of the global shipping network (Ducruet, 2016). Wu et al. (2019) study the impact of the channel interruption on the container shipping network. They analyse the network vulnerability using the total transport capacity and average minimum transport time.

However, few studies on the vulnerability of the MSR shipping network exist. Furthermore, the substitution effect of adjacent ports in the case of port failure, which is of great significance for the re-judgment of network vulnerability and the layout planning of ports and routes along the MSR, is not considered in the vulnerability analysis. Therefore, this paper builds the MSR shipping network using route data, and analyses the characteristics of the complex network. The port importance is then calculated using the Pagerank algorithm, which is considered as the basis of the deliberate attack, and the ports are classified according to their importance. Afterwards, the network vulnerability to random and deliberate attacks is analysed. Finally, considering the substitution effect of adjacent ports, the ports strengthening the emergency response capacity are excavated, in order to ensure the network transportation efficiency, while improving the network connectivity and stability.

3 Network construction and analysis

3.1 MSR shipping network construction

The MSR focuses on the route from China's coastal ports to Europe and Africa through the South China Sea and Indian Ocean, as well as the route from China's coastal ports to the South China Sea and South Pacific. Its scope mainly includes East Asia, Southeast Asia, South Asia, West Asia, East Africa, Oceania, the Mediterranean, Europe and other regions, covering the main part of the east-west route.

The current studies on the shipping network are mainly performed using the space L and space P model. In the space L model, each port is directly connected according to the route. This can intuitively reflect the spatial characteristics of the route and the topological structure of the shipping network. It is decent to analyse the key nodes in the network and extract the characteristics of the shipping network, which is more coherent with the research objectives of this paper. Therefore, this paper uses the space L model to construct an undirected and unweighted MSR shipping network, which considers the ports as network nodes and the routes as connecting edges. The route data is derived from the Container Forecaster of Drewry in 2019. After screening, 179 ports and 1,424 non-duplicate port pairs are finally considered.

3.2 Network topology analysis

The average node degree of the MSR shipping network is 7.955, among which 99 port nodes have a degree value less than 5, accounting for 55% of all the nodes, and 16 port nodes have a degree value greater than 20, accounting for 8.9% of all the nodes. It can be seen from Figure 1 that the node degree distribution of this network is coherent with the power-law distribution, and belongs to the scale-free network.

In order to analyse the small-world characteristics of the MSR shipping network, the average path length and clustering coefficient of the network and random network of the same size are calculated. The obtained results are presented in Table 1.

Figure 1 Distribution of the port's node degrees in the MSR shipping network (see online version for colours)

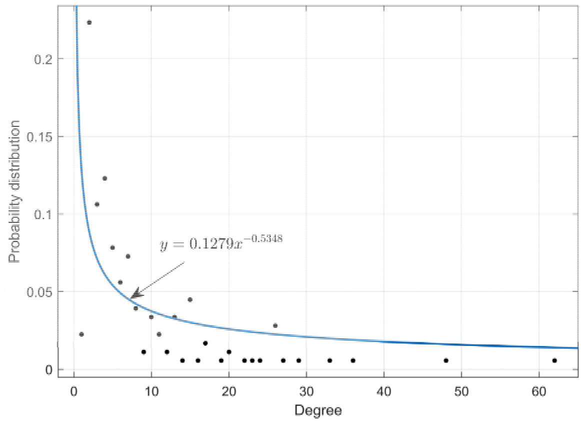


Table 1 Topological comparison between the MSR shipping network and the random network of the same size

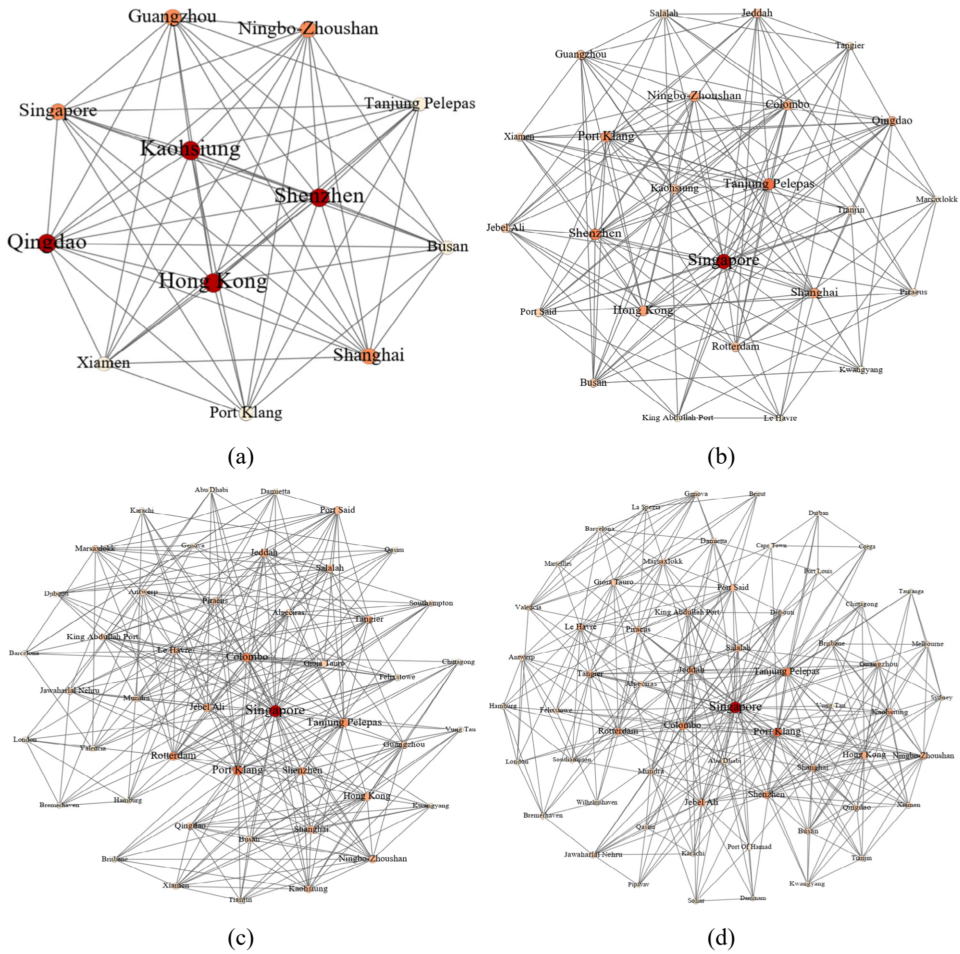
Network	*Number of nodes*	*Average degree*	*Average path length*	*Clustering coefficient*
MSR shipping network	179	7.955	2.915	0.4899
Random network	179	7.943	2.721	0.0436

The calculation results demonstrate that the average path length of the MSR shipping network is 2.915 and its clustering coefficient is 0.4899, while the average path length of the random network is 2.721 and its clustering coefficient is 0.0436, and therefore it has the characteristics of a small-world network. The average path length computation consists in considering two transshipments on average, from the starting port to the destination port within the scope of the MSR. In addition, it is deduced that the average path length of the MSR shipping network is slightly higher than that of the random network. This is due to the fact that the shipping is limited by several factors such as the Marine geography and channel distribution to a certain extent. Therefore, the ships cannot freely sail, and most of the trans-regional shipping routes need to pass through some straits or canals for transportation.

3.3 Network hierarchy analysis

The K-shell algorithm divides the network nodes into multi-layer structures according to the importance of the network location, which is a coarse-grained measurement method (Jia et al., 2020). The K-shell algorithm can be used to layer the MSR shipping network. The specific calculation process is as follows: at first, calculate the degree values of all nodes in the network, and delete the nodes whose degree values are 1 and their edges from the network. After deletion, new nodes whose degree values are 1 will appear in the network, then delete these new nodes and their edges. Repeat the above operations until there are no new nodes whose degree values are 1. At this time, all deleted nodes form the first layer, i.e., 1-shell, and the K value of the node is equal to 1. In the remaining network, the degree value of each node is at least 2. Continue to repeat the above deletion operation to get the second layer with K value equal to 2, that is, 2-shell. And so on, until all nodes in the network are given K value. The larger the K value, the more important the position of the sub-network and the stronger the centrality of its ports. Figure 2 presents the hierarchical structure of the MSR shipping network.

Figure 2 Different hierarchical shipping networks of MSR, based on K-shell, (a) 9-shell network (b) 8, 9-shell network (c) 7, 8, 9-shell network (d) 6, 7, 8, 9-shell network (see online version for colours)



The 9-shell network is mainly composed of the Shenzhen, Hong Kong, Qingdao and Kaohsiung ports of China, Busan port of South Korea, Singapore and Kelang ports of Southeast Asia. The 8, 9-shell network adds important hub ports such as Colombo, King Abdullah and Jeddah ports, as well as Port Said along the China-Europe route. It also adds European transit hub ports such as Piraeus, Rotterdam and Le Havre ports, for example. The 7, 8, 9-shell network further adds some hub ports in the Middle East, South Asia and Oceania. The 6, 7, 8, 9-shell network expands its scope to Eastern and Southern Africa, forming the main line and important branch lines of the MSR. This shows that the hierarchy of the MSR shipping network structure consists of the Northeast Asia –

Southeast Asia sub-network, Northeast Asia – Southeast Asia – Europe sub-network, Northeast Asia – Southeast Asia – South Asia – West Asia – North Africa – Europe – Oceania sub-network, and Northeast Asia – Southeast Asia – South Asia – West Asia – North Africa – Europe – Oceania – Eastern and Southern Africa sub-network.

4 Measurement index of vulnerability

Potential risks of port paralysis, congestion and shipping delay are caused by the port and route failure in the MSR shipping network. When faced with emergencies, the potential risk is exposed, which results in reducing the network connectivity and transport efficiency, and therefore the network will be more loosely. Consequently, this paper develops four network vulnerability measurement indexes computed as follows (Zhang et al., 2016; Ma et al., 2020):

4.1 Change rate of network connectivity

The number of ports in the maximal connected subgraph reflects the network connectivity after the failure of the port under attack. The ratio of the number of ports in the maximal connected subgraph to the number of ports in the initial network, is used to measure the overall connectivity of the network:

$$C = \frac{n_{\max}}{N} \tag{1}$$

where N is the total number of ports in the initial network and $n_{\max}$ is the number of ports contained in the maximal connected subgraph.

The change rate of network connectivity of the MSR shipping network is then expressed as:

$$C_i' = \frac{C - C_i}{C} \tag{2}$$

where C represents the initial network connectivity, C_i denotes the network connectivity after the failure of port i, and C_i' is the change rate of the network connectivity after the failure of port i.

4.2 Change rate of network efficiency

The network efficiency is usually used to reflect the connection between the ports in the whole network. The transport efficiency between any two port nodes i and j, can be expressed by the reciprocal of the shortest path length. The average value of the network efficiency between all the port pairs is the efficiency of the whole network, given by:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}} \tag{3}$$

where d_{ij} is the shortest path length between ports i and j.

Afterwards, the change rate of network efficiency of the MSR shipping network is expressed as:

$$E_i' = \frac{E - E_i}{E} \tag{4}$$

where E represents the initial network efficiency, E_i denotes the network efficiency after the failure of port i, and E_i' is the change rate of the network efficiency after the failure of port i.

4.3 Change rate of network density

The network density reflects the closeness of the connection between the ports. It is expressed by the ratio of the actual number of connected edges to the maximum number of connected edges in the network:

$$D = \frac{2M}{N(N-1)} \tag{5}$$

The change rate of network density of the MSR shipping network is then expressed as:

$$D_i' = \frac{D - D_i}{D} \tag{6}$$

where D represents the initial network density, D_i denotes the network density after the failure of port i, and D_i' is the change rate of the network density after the failure of port i.

4.4 Change rate of network clustering coefficient

The network clustering coefficient represents the average probability of interconnection between two ports connected to the same port in the network, reflecting the tightness of port aggregation:

$$CC = \frac{1}{N}\sum_{i=1}^{N}\frac{2M_i}{k_i(k_i - 1)} \tag{7}$$

where M_i is the number of connected edges between the ports that are connected with port i, and k_i is the degree value of port i.

The change rate of network clustering coefficient of the MSR shipping network is then computed as:

$$CC_i' = \frac{CC - CC_i}{CC} \tag{8}$$

where CC represents the initial network clustering coefficient, CC_i denotes the network clustering coefficient after the failure of port i, and CC_i' is the change rate of the network clustering coefficient after the failure of port i.

5 Vulnerability analysis

5.1 Network attack mode

The port emergencies can be classified into two types. The first type includes the typhoons, earthquakes, rainstorms, floods, explosions and other disasters that occur at random locations and frequencies, and they are referred to as random emergencies. The second type consists of the events caused by human factors such as terrorist attacks and public activities, and they are referred to as purposeful emergencies. These two types of emergencies respectively correspond to random and deliberate attacks in complex network theory. The vulnerability of the port nodes to the shipping network under different types of emergencies, is simulated based on these two attack strategies.

The random attack consists in randomly attacking any port node and its connected edge in the network, with any probability. In the deliberate attack, the network port nodes are sorted by the importance index, while the nodes of high importance and their connected edges are first removed. In most of the current studies, indexes such as the degree centrality and betweenness centrality are often used as measurement methods of node importance. However, in the actual shipping network, there are often cases where the degree centrality and betweenness centrality of multiple ports are equal, and the importance between them cannot be accurately ordered. The PageRank algorithm is a variant of the eigenvector centrality algorithms, which sorts web pages according to their link structure (Ullah et al., 2021; Wang et al., 2021). The importance of a web page depends on the number and importance of the other pages that are linked to it. For the MSR shipping network, if a port node has a large number of links with other port nodes, then this port node will also be very important. At the same time, the port node with high importance will use links to transfer more weight to other port nodes, so the port node linked with the port node with high importance will also be more important. It can better reflect the global centrality of nodes. Therefore, this paper uses the PageRank algorithm as importance measurement method of port nodes:

$$PR_i = \theta \sum_{j \in F(i)} \frac{PR_j}{L_j^{out}} + 1 - \theta \tag{9}$$

where PR_i is the PageRank value of port i, $F(i)$ represents the collection of all the linked ports of port i, L_j^{out} denotes the total number of the linked ports of port j, N is the total number of ports, and θ is the damping coefficient (usually equal to 0.85) which is used to deal with the calculation difficulty due to the convergence failure (Flores et al., 2020).

The importance of each port is then evaluated using the PageRank algorithm, and the rank of each port is obtained and further used as the attack order of the deliberate attack.

In order to facilitate the evaluation of the subsequent simulation results, the ports importance in the MSR shipping network is first analysed. The probability distribution is obtained based on the importance value, as shown in Figure 3. It can be seen that the importance of port nodes highly differs, and shows uneven distribution.

The K-means clustering algorithm is used to classify the ports, according to the importance value. The number of categories to be clustered is set to 4. After multiple iterations, the obtained numbers of ports of different types are 4, 14, 37 and 124. In addition, these four categories of ports are respectively defined as core hub ports, regional hub ports, local hub ports and general ports. The ports included in the first three categories are presented in Table 2.

Figure 3 Probability distribution of the importance of port nodes (see online version for colours)

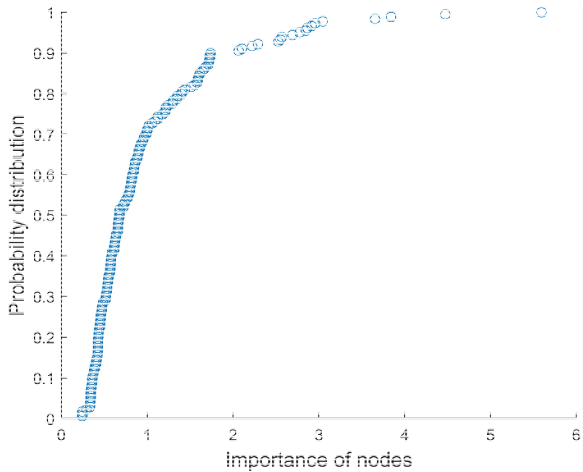


Table 2 Ports classification along the MSR, using the K-means clustering algorithm

Category	*Port*
Core hub port	Singapore, Port Kelang, Tanjung Pelepas, and Colombo
Regional hub port	Jeddah, Hong Kong, Ningbo-Zhoushan, Rotterdam, Port Said, Shenzhen, Jebel Ali, Shanghai, Piraeus, Busan, Ambarli, Qingdao, Kaohsiung, and Le Havre
Local hub port	Bremerhaven, Tangier, Brisbane, Tauranga, Salalah, Algeciras, Jawaharlal Nehru, King Abdullah Port, Damietta, Antwerp, Melbourne, Mundra, Guangzhou, Gioia Tauro, Marsaxlokk, Tianjin, Valencia, Genova, Sydney, Durban, Auckland, Hamburg, Xiamen, Dammam, Djibouti, Abu Dhabi, Felixstowe, Hamad, Tanjung Priok, Barcelona, Southampton, London, Kwangyang, Lyttelton, Cape Town, Dar Es Salaam, and Fremantle

5.2 Analysis of the attacked results

The connectivity, efficiency, density and clustering coefficient of the MSR shipping network are first calculated in the initial state without interference. The obtained values are 1, 0.3878, 0.0447 and 0.4899, respectively. The failure of each port is then simulated one by one, according to the node importance obtained using the PageRank algorithm. In terms of topology, the failed port and its connected edge are deleted. At this stage, all the measurement index values of vulnerability are calculated by combining the initial index values: the change rate of network connectivity, network efficiency, network density and network clustering coefficient. Table 3 presents the vulnerability index of the core hub ports and regional hub ports, after their respective failure.

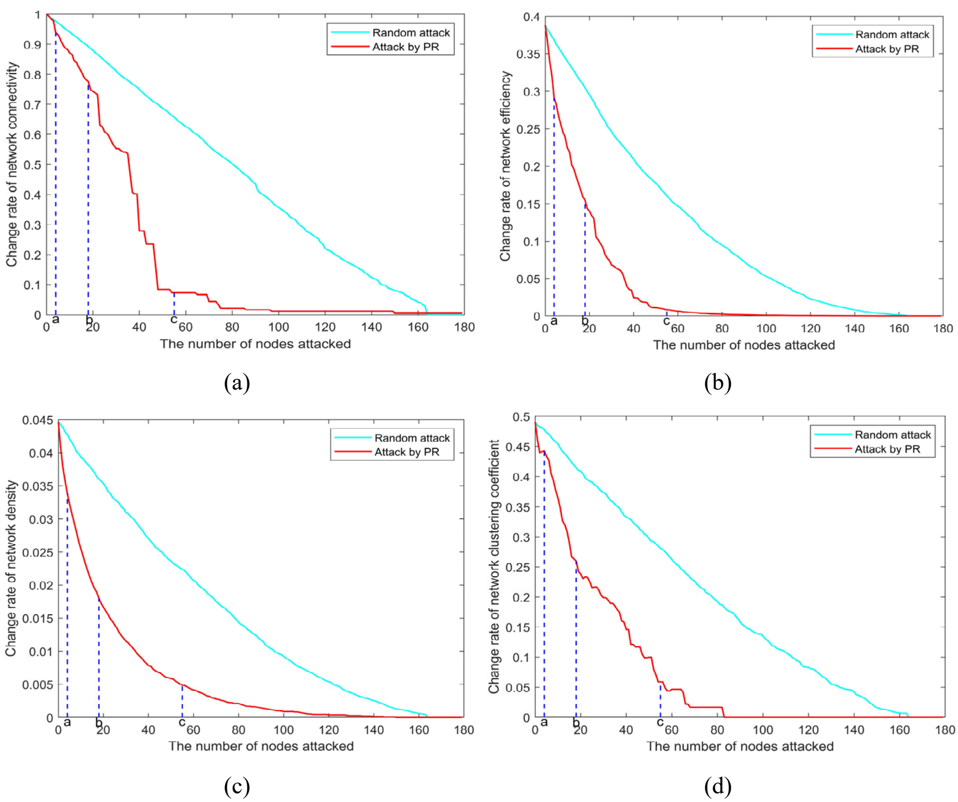
Table 3 Vulnerability indexes in the case where the core hub ports and regional hub ports fail alone

Port	*Network connectivity*	*Change rate of network connectivity*	*Network efficiency*	*Change rate of network efficiency*	*Network density*	*Change rate of network density*	*Network clustering coefficient*	*Change rate of network clustering coefficient*
Singapore	0.9944	0.56%	0.3665	5.47%	0.0408	8.71%	0.4615	5.77%
Port Kelang	0.9944	0.56%	0.3705	4.45%	0.0417	6.74%	0.4623	5.61%
Tanjung Pelepas	0.9944	0.56%	0.3740	3.55%	0.0424	5.06%	0.4893	0.11%
Colombo	0.9832	1.68%	0.3778	2.57%	0.0426	4.63%	0.4861	0.75%
Jeddah	0.9944	0.56%	0.3793	2.17%	0.0429	4.07%	0.4803	1.94%
Hong Kong	0.9944	0.56%	0.3803	1.92%	0.0431	3.65%	0.4751	3.00%
Ningbo-Zhoushan	0.9944	0.56%	0.3808	1.80%	0.0431	3.65%	0.4744	3.13%
Rotterdam	0.9888	1.12%	0.3761	3.01%	0.0431	3.65%	0.4783	2.35%
Port Said	0.9944	0.56%	0.3804	1.89%	0.043	3.79%	0.4763	2.76%
Shenzhen	0.9944	0.56%	0.3808	1.80%	0.0431	3.65%	0.4825	1.50%
Jebel Ali	0.9944	0.56%	0.3813	1.66%	0.0431	3.65%	0.4820	1.60%
Shanghai	0.9944	0.56%	0.3817	1.56%	0.0432	3.37%	0.4865	0.68%
Piraeus	0.9944	0.56%	0.3786	2.37%	0.0432	3.23%	0.4826	1.48%
Busan	0.9944	0.56%	0.3813	1.66%	0.0433	3.09%	0.4773	2.56%
Ambarli	0.9944	0.56%	0.3813	1.65%	0.0436	2.39%	0.4660	4.87%
Qingdao	0.9944	0.56%	0.3822	1.44%	0.0434	2.81%	0.4758	2.87%
Kaohsiung	0.9944	0.56%	0.3816	1.59%	0.0435	2.67%	0.4797	2.06%
Le Havre	0.9944	0.56%	0.3819	1.51%	0.0434	2.81%	0.4873	0.50%

In general, the separate failure of the core hub ports has a greater impact on the network than that of the regional hub ports, which is coherent with the importance order obtained using the PageRank algorithm. Simultaneously, the variation of the vulnerability index value of each port in the case where it fails alone, also shows that the statuses and roles are different. The Singapore port and Port Kelang have a great impact on both global and local efficiency of the MSR shipping network. The Tanjung Pelepas port and Colombo port have a great impact on the global efficiency of the network. However, the clustering coefficient of the MSR shipping network slightly changes when they fail alone, which indicates that these two ports play an important role as a bridge in the whole MSR shipping network. However, they contribute less to the aggregation of the network.

In terms of network connectivity, the failure of each port alone has a small influence on the connectivity of the MSR shipping network. In the case of separate failure of the Colombo port and Rotterdam port, some neighbouring ports become isolated nodes, and the separate failure of other ports affects the connectivity of the shipping network. This is due to the fact that each port has shipping contacts with many ports, and does not rely on few important ports. In summary, the failure of core and regional hub ports has a great impact on the network, and therefore the protection of these ports should be strengthened.

Figure 4 Vulnerability index under random and deliberate attacks, (a) represents the change rate of network connectivity (b) represents the change rate of network efficiency (c) represents the change rate of network density (d) represents the change rate of network clustering coefficient (see online version for colours)



Afterwards, based on the importance sorting of all the port nodes, the nodes with the highest importance in the network are continuously deleted until all the nodes are deleted, and the vulnerability index of each step is calculated. In addition, the vulnerability indexes of the network under random and deliberate attacks are compared, based on the average value of 1,000 simulations (cf. Figure 4). On the abscissa of Figures 4(a), 4(b) and 4(c) are the boundary points of core hub port, regional hub port and local hub port respectively, that is, ports numbered 0 to a are core hub ports, ports numbered $a + 1$ to b are regional hub ports, ports numbered $b + 1$ to c are local hub ports.

It can be seen that the MSR shipping network can still maintain a good connectivity, agglomeration and efficiency when dealing with random attacks, while in the case of deliberate attacks, the failure of few ports leads to the rapid decline of network connectivity, agglomeration and efficiency. This shows that the shipping network is robust to random attacks and vulnerable to deliberate attacks. More precisely, a random event such as typhoon, tsunami and earthquake, will not have a great impact on the connectivity and efficiency of the whole network. However, if the main hub ports are damaged by deliberate events such as terrorist attacks or military blockades, the network connectivity will be highly affected. Therefore, the operation safety of these ports should be protected.

Moreover, compared with the network efficiency, the decline rate of network connectivity and network clustering coefficient is slightly slower when the first 18 ports fail. This indicates that the ports after ranking 18 have a strong local connectivity. These port nodes are also the previously defined local hub ports. This is due to the fact that after the failure of the core hub ports and regional hub ports, other ports still maintain the route connection with the local hub ports, so that certain local connectivity of the network can still be maintained.

5.3 Vulnerability analysis considering the substitution effect of adjacent ports

A substitution effect exists between the ports. That is, when a port node fails, the adjacent ports can replace it in order to complete the transportation or loading and unloading tasks. For instance, a serious explosion accident occurred at Tianjin port in 2015, which interrupted the port service. However, this did not affect the trade in northern China, since the Qingdao and Dalian ports around the Bohai Sea quickly shared and performed the transportation tasks of the Tianjin port. When the distance between the ports is too long, the substitution effect cannot be performed. For instance, if the Colombo port in Sri Lanka is disturbed, the Shanghai port in China cannot replace it and share the transportation task.

In addition to meeting its own transportation demand, ports also have certain redundant capacity. When a port fails, the adjacent ports will undertake the transportation task through their redundant capacity. Therefore, this paper proposes the substitution rate and defines it as the ratio of the operation capacity that can be provided by the adjacent ports to the transportation demand of failed port. Then assume that transportation demand of a port is positively correlated with its weighted degree, and its redundancy capacity is positively correlated with the transportation demand, this ratio is set to a. In addition, distance will also affect the substitution rate. Assuming that container ships sail at an economic speed of 18 knots, when a port fails, the adjacent ports that can be arrived in 10–12 hours are the primary choice to undertake the transportation tasks of failed port, and their substitution rate is not affected by distance. The adjacent ports that can be arrived in one day are also good choices, but their substitution rate will be affected by distance. When the distance between the adjacent port and the failed port exceeds one day's voyage, then the adjacent port will not be able to undertake the transportation tasks of failed port. For the convenience of calculation, these two boundary points are set at 200 and 400 nautical miles respectively.

Then the substitution rate SR_{ij} of port i to port j can be calculated as:

$$SR_{ij} = \begin{cases} \dfrac{a \cdot k_i}{k_j}, & 0 < SD_{ij} < 200 \\ \dfrac{200 \cdot a \cdot k_i}{SD_{ij} \cdot k_j}, & 200 \le SD_{ij} \le 400 \end{cases} \tag{10}$$

where k_i is the weighted degree value of port i, SD_{ij} is the actual sailing distance from port i to j, a is the ratio of the port's redundant capacity to its transportation demand.

The actual sailing distance between the ports is obtained using the Netpas distance software. Assume that a is 0.2 and we can get the substitution rate of the adjacent ports of each port. Additionally, the total substitution rate of the adjacent ports to a port, is the sum of the substitution rates of the adjacent ports. Table 4 presents the substitution rate of the adjacent ports when the core hub ports and regional hub ports fail.

Table 4 Number and substitution rate of adjacent ports, when the core hub ports and regional hub ports fail

Port	*Number of ports within 200 nautical miles*	*Number of ports within 201–400 nautical miles*	*Port with maximal substitution rate*	*Total substitution rate of adjacent ports*
Singapore	1	2	Port Kelang	14.22%
Port Kelang	2	1	Singapore	56.69%
Tanjung Pelepas	1	2	Singapore	100.51%
Colombo	1	1	Cochin	1.25%
Jeddah	1	0	King Abdullah port	9.39%
Hong Kong	3	5	Shenzhen	84.66%
Ningbo-Zhoushan	1	3	Shanghai	22.58%
Rotterdam	5	6	Antwerp	52.48%
Port Said	5	5	Damietta	32.82%
Shenzhen	2	2	Hong Kong	13.02%
Jebel Ali	4	5	Abu Dhabi	13.38%
Shanghai	1	2	Ningbo-Zhoushan	22.86%
Piraeus	0	6	Ambarli	14.15%
Busan	2	3	Kwangyang	4.87%
Ambarli	4	6	Piraeus	52.09%
Qingdao	1	3	Shanghai	29.14%
Kaohsiung	2	5	Xiamen	43.82%
Le Havre	4	4	Rotterdam	87.67%

It can be seen from Table 4 that for each failing port, the ports having the maximal substitution rate are all the nearby hub ports that can quickly replace it in order to complete the work. These ports form port groups within a certain range such as the Singapore port, Port Kelang and Tanjung Pelepas port, the Shanghai port and Ningbo-Zhoushan port, the Shenzhen port and Hong Kong port, the Rotterdam port and Antwerp port.

The total substitution rate of adjacent ports indicates the percentage of transportation tasks that can be undertaken by adjacent ports when the port fails. For example, when Singapore port is completely paralysed and loses all operational capacity, its adjacent ports can only undertake 14.22% of its transportation demand. Among the core hub ports and regional hub ports, total substitution rates of adjacent ports of Singapore, Colombo, Jeddah, Shenzhen, Jebel Ali, Piraeus, Busan ports are all less than 20%. When 20% of their operational capacity is affected by emergencies, it is difficult to make up for the transportation or loading and unloading tasks, then other ports in the network will also be affected. In particular, the impact caused by the failure of Colombo port and Busan port are more serious. Therefore, it is necessary to build a port emergency repair mechanism in order to improve the resilience of these ports.

Based on this analysis, more port groups (especially around the core ports) should be established in order to ensure the interconnection of the MSR shipping network, and the structure of the shipping network should be optimised by adding adjacent hub ports, so as to increase the network resistance to external disturbances.

In addition, more robust systems should be developed in order to increase the network resilience. All the ports should first formulate contingency plans to deal with natural disasters, bad weather and other emergencies. An efficient management system should also be developed in order to avoid the ports damage by accidents to the maximum extent, so as to ensure the normal operation of the ports. In addition, each country should enhance the cooperative relations with the other countries and regions along the MSR. A maritime alliance could be established to jointly ensure the safe operation of the MSR shipping network, so as to prevent ships and routes from terrorist attacks in the controlled sea areas. Finally, the port management should provide an efficient emergency repair system for port construction according to different events, while formulating a sound scheme. Simultaneously, the port information should be released in time in order to ensure that the cargo owner can make rapid response, so as to avoid more problems such as congestion due to lack of information circulation, for example.

6 Conclusions

This paper studies the network characteristics and vulnerability of the MSR shipping network using complex network theory, based on the global route data extracted from the Container Forecaster of Drewry in 2019. It puts forward the substitution rate index of the adjacent ports, so as to further explore the ports that need to focus on and strengthen the emergency response capacity. The main conclusions of this paper are summarised as follows:

- The MSR shipping network has scale-free and small-world characteristics. The hierarchical structure of the MSR shipping network is deduced according to the hierarchical analysis of the K-shell network. It is concluded that the hierarchy of the

MSR shipping network structure consists of the Northeast Asia – Southeast Asia sub-network, Northeast Asia – Southeast Asia – Europe sub-network, Northeast Asia – Southeast Asia – South Asia – West Asia – North Africa – Europe – Oceania sub-network, and Northeast Asia – Southeast Asia – South Asia – West Asia – North Africa – Europe – Oceania – Eastern and Southern Africa sub-network.

- Using the PageRank algorithm to calculate the importance of ports, the ports are divided into four categories: core hub, regional hub, local hub and general ports. Considering the ranking as the basis of the deliberate attack, it is deduced that the MSR shipping network is strong under random attack and very fragile under deliberate attack. Therefore, the operation safety of the core hub ports and regional hub ports should be enhanced.
- When the core hub port and regional hub port are all attacked, the network still has a certain local connectivity since the general ports still maintain the route connection with local hub ports.
- Considering the substitution effect of adjacent ports, it is deduced that the ports along the MSR form port groups within a certain range, such as the Singapore port, Port Kelang and Tanjung Pelepas port, the Shanghai port and Ningbo-Zhoushan port, the Shenzhen port and Hong Kong port, the Rotterdam port and Antwerp port. Among the core and regional hub ports, the failure of Singapore, Colombo, Jeddah, Shenzhen, Jebel Ali, Piraeus and Busan still have a great impact on the network vulnerability. All the countries should strengthen the security management of these ports, improve the port emergency plan and strengthen the cooperation between the ports.

This paper analyses the vulnerability of the MSR shipping network. The results can provide a valuable reference for protecting key ports in emergency situations, and improving the safety and efficiency of the global maritime transportation. However, some deficiencies still exist. In practice, the port has a certain emergency capacity and self-recovery ability in case of emergencies. In addition, the port function is not completely ineffective. These factors should be considered in future work.

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