The Assessment of Vulnerability of the Global Container Shipping Network Based on MATLAB Software

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Keywords: Network Disconnection, Vulnerability, Layered Weighted Network Efficiency, Complex Network, Maritime.

Abstract: Extreme Events seriously affect the normal flow of goods on routes and exacerbate the vulnerability of the global container shipping network. To assess the impact of extreme events on the vulnerability of the global container shipping network, the global container shipping network was constructed based on the route data of the top seven liner shipping companies in the world against the backdrop of the COVID-19. Based on the network disintegration theory and the layered weighted network efficiency metric, routes suffering from different levels and degrees of disconnection are simulated. The results show that the disconnection of each segment has a wide impact on the vulnerability of the global container shipping network, the disconnection between Singapore Port and Santos Port will have the greatest impact on the shipping network, which reduce the efficiency of the shipping network by 2%. The reduction of layered weighted network efficiency is consistent with the degree of segments disconnection. The global container shipping network has strong anti-interference resistance to international segments partial disconnection, and presents great vulnerability to international segments complete disconnection. While the number of international segments remains at 10%, the performance of the maritime network can still reach 48.4% of the original network. However, if the international segments are completely disconnected, the performance of the maritime network will drop to 8.2% of the original network. This paper further improves the understanding of the global container shipping network under extreme events, and provides a useful reference for studying the vulnerability of the global shipping network under interference in the future.

1 INTRODUCTION

Ships carry more than 80% of global trade, and emergencies seriously affect the normal operation of shipping companies, thus affecting the normal operation of world trade. Therefore, the simulation of different levels and degrees of routes disconnection and the assessment of vulnerability of the global container shipping network under emergencies can help the decision-makers of various countries to formulate reasonable policies, optimize the shipping network and formulate emergency plans after accidents.

At present, scholars' research results on the vulnerability of global container shipping network have been rich. The research results of maritime network from the point of port disconnection are systematic and perfect. LIU used complex network theory to see the topology characteristics of shipping network, and studied the vulnerability of global container shipping network under two attack methods: random interference and intentional attack (Liu Chanjuan, 2016). WANG et al. studied the impact of random interference and intentional attack of Sino-US container shipping network (Wang Liehui, 2020). HE et al. studied the impact of port disconnection on the vulnerability of the shipping network of China's coastal container ports (He Yao, 2022). JIANG et al. evaluated port vulnerability from the perspective of supply chain (Jiang M, 2021). Xu et al. proposed a new cascade model to quantify the impact of port disconnection on network vulnerability by reducing connectivity and network efficiency (Xu X, 2022).

In the process of studying the vulnerability of global container shipping network, scholars have found that when global emergencies occur, the probability of route changes is greater, so route disconnection has gradually become a new research hotspot. VILJOEN et al. studied the vulnerability of global container transport network under the disconnection of target connection, and proposed a new possibility of network disconnection, namely, route connection disconnection (Viljoen N M, 2016).

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DIRZKA et al. used the ship schedule cancellations released by liner companies to quantify the initial degree and dynamics of the COVID-19 pandemic's disconnection to the shipping network (Dirzka C, 2022).

To sum up, the research on the vulnerability of global container shipping network is mainly aimed at the disconnection of port nodes, and few research on route disconnection, and there is no study on the level and degree of route disconnection. The layered weighted network efficiency metric can better describe these problems. Therefore, this paper simulates different levels and degrees of route disconnection and introduces layered weighted network efficiency metric to calculate the vulnerability changes of the global container shipping network, providing reference for relevant maritime managers.

2 CONSTRUCTION OF VULNERABILITY ASSESSMENT MODEL OF GLOBAL CONTAINER SHIPPING NETWORK UNDER EMERGENCIES

2.1 Problem Description

Maritime network vulnerability refers to the degree to which the connectivity and efficiency of the maritime network are disturbed when external factors affect the network (Jin L, 2022). Based on the process, nature and mechanism, emergencies are divided into four types: accident disasters, natural disasters, public health incidents and social security incidents. According to the third type of specific scenario, this paper selects the COVID-19 as research background. The COVID-19 has posed enormous challenges to countries and societies and disrupted the global economy (Tuti R W, McKibbin W). The Clarkson report pointed out that the COVID-19 has had a significant impact on the container shipping industry, and the impact has become a major determinant of market trends, leading to major operational disconnections across the industry, in the first half of 2020, the global container trade volume dropped sharply, only 93.2% in the same period last year.

As for route disconnection level, this paper studies two levels: segment disconnection and international segment disconnection. Segment disconnection refers to the disconnection of the segment between any two directly connected ports in the shipping network, simulating the decline of connectivity between ports due to the impact of the pandemic. International segment disconnection refers to the disconnection of a segment between any two directly connected ports in the shipping network that are not in the same country. It simulates the decline in port connectivity between countries due to certain isolation policies adopted by all countries under the pandemic. The degree of route disconnection refers to the degree of reduction in the number of segments between two directly connected ports.

The layered weighted network efficiency metric can measure the vulnerability change of shipping network when the route is interrupted. The layered weighted network efficiency metric can better measure the vulnerability change of shipping network when the route is interrupted. Firstly, the global container shipping network is divided into several sub-networks, which will change due to route interruption. Then calculate the network efficiency of all sub-networks, get the layered weighted network efficiency, and then quantitatively measure the vulnerability of the whole network.

2.2 MATLAB Software Introduction

MATLAB is a comprehensive mathematical and technical calculation software. It uses a high-level programming language containing hundreds of built-in instructions to carry out mathematical calculations. It includes a complete library of built-in algorithms to meet the needs of more advanced users (Bonakdari H, 2022). MATLAB software is widely used in transportation research and can solve modeling problems well.

2.3 Construction of Global Container Shipping Network Model

The global container shipping network consists of canals, ports and other nodes and the sides (segments) between nodes. V is the set of nodes in the network, E is the set of edges, then the global container shipping network is $G = (V, E)$. Among them, $E = \{(v_i, v_j) | v_i, v_j \in V\}$; The sequence (v_i, v_j) indicates that node i and node j are connected, node i and node j are the two ports of call adjacent to any route. The connection relationship between any two nodes in the network can be represented by the adjacency matrix of $A = (a_{ij})_{m \times m}$ of order $m \times m$.

$$a_{ij} = \begin{cases} 1, & (v_i, v_j) \in E, v_i, v_j \in V \\ 0, & others \end{cases} \quad (1)$$

2.4 Construction of Vulnerability Measurement Model of Global Container Shipping Network

Network efficiency measurement is one of network structure measurement methods, which is derived from the concept of average shortest path length. The measurement of network efficiency is not limited by the weight, connectivity and sparsity of the system, and can better measure the efficiency of network information transmission and achieve accurate quantitative analysis of weighted and unweighted networks (Latora V, 2001). Therefore, in the relevant research of shipping network, network efficiency measurement is widely used to describe the change of the transportation efficiency of the entire network when the network is attacked, and measure the connectivity of network. The network efficiency measure can be expressed as

$$E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in R} \frac{1}{d_{ij}} \quad (2)$$

In formula (2), $E(G)$ is the network efficiency of the shipping network; N is the total number of nodes in the shipping network G; d_{ij} is the shortest path length between node i and node j.

The global container shipping network is a weighted network, and weight is an important part of it. This paper takes the number of segments between two ports as weight. During the COVID-19 pandemic, faced with uncertain cargo demand and continuous market fluctuations, liner companies rescheduled or canceled route services, resulting in disconnection of container shipping network links and decreased connectivity (Pan J J, 2022). Therefore, this paper aims to study how the vulnerability of the maritime network is affected by the removal of a large number of segments. The layered weighted network efficiency can better describe this process. It can accurately identify the impact of addition or deletion of segments and increase or decrease of the number of segments on the efficiency of the maritime network, which is helpful to study the impact of route disconnection on the overall network efficiency. Using the idea of network disintegration, the shipping network is regarded as a multi-layer network, and the number of layers on each side is determined by the number of segments. The weighted network is decomposed into several unweighted subnetworks by deleting all the directly connected edge segments from the remaining network and forming a subnet with these deleted segments in each step (Zhou Y, 2021). Then, the network efficiency of each sub-network is calculated using formula (2). The layered weighted network efficiency of the original network is obtained by summing the network efficiency of all subnetworks.

Any change in the route will change the structure of the shipping network, and then change the network efficiency of several subnets, which will then be reflected in the efficiency calculation results of the original network. Therefore, the layered weighted network efficiency metric can well measure the disconnection of the container shipping network caused by the COVID-19 pandemic. Therefore, this study uses this index to measure the importance of segment and the vulnerability of the maritime network. In this paper, MATLAB software is used to calculate the efficiency index of the layered weighted network through the above steps, so as to measure the vulnerability of the global container shipping network under global interference.

3 EMPIRICAL ANALYSIS

3.1 Data Selection and Procession

The data of the global container shipping network constructed in this paper comes from the websites of the top seven liner companies in terms of global shipping capacity collected by Alphaliner. The total capacity of these seven shipping companies is 76.4% worldwide, this is highly representative. As shown in Table 1. The total service network of these seven liner companies covers six continents in the world, involving the world's most basic maritime ports. Based on the shipping schedule on the website of each shipping company, all the ports where liners call on each route are tracked and obtained respectively, and the tracking time is from April 2022 to June 2022. Repeated routes were processed, resulting in 544 ports and 2,464 routes involving 138 countries. The global container shipping network is abstracted as a complex network $G = (V, E)$, consisting of 544 nodes and 2464 edges, as shown in Figure 1.

Table 1. Capacity and market share of the top 7 liner shipping companies.

Rank	Company	Capacity/teu	Share
1	MSC	4949720	18.5%
2	Maersk	4132026	15.5%
3	GMA-CGM	3449314	12.9%
4	COSCO	2890349	10.8%
5	Hapag-Lloyd	1795909	6.7%
6	Evergreen	1664330	6.2%
7	ONE	1553956	5.8%
	Total	20435604	76.40%

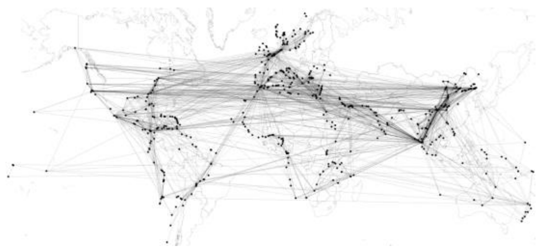

Figure 1. Global container shipping network.

Among them, the direct link between Shanghai port and Ningbo Port has the greatest weight, there are 339 segments between the two ports, 10% of the port pairs are connected through one segment. The layered weighted network efficiency of the global container shipping network is 0.8641, while the unweighted efficiency is only 0.332. To sum up, the weight distribution of the global container shipping network is not uniform.

3.2 Results and Results Analysis

1) The Impact of Segment Disconnection on Maritime Network Vulnerability

The vulnerability of the global container shipping network to segment disconnection can be evaluated by calculating the change of the layered weighted network efficiency during segment disconnection. The results of the impact of disconnection of each segment on the vulnerability of the global container shipping network were calculated. The top 20 segments ranked by the percentage of decreased network efficiency by stratified weighting are shown in Table 2. Columns 2 and 3 represent the two ports at either end of each segment. In the global container shipping network constructed in this paper, the two ports with the greatest weight are Shanghai Port and Ningbo Port, and the number of segments is 339. However, it is calculated that the impact of disconnection of this segment on the vulnerability of the shipping network ranks 29th. The reason may be because that the factors affecting the vulnerability of the maritime network caused by the disconnection of flight segments do not only depend on the number of flight segments, other factors may be the geographical location of the two ports, the country to which they belong and the connection with other ports.

It can be seen from Table 2 that the ports at both ends of the segment that most affect the vulnerability of the shipping network are Singapore Port and Santos Port, and the number of segments between the two ports is 16. If this segment is disconnected, the layered weighted network efficiency will decrease by 2.01928%. Singapore Port is adjacent to the southeast side of Malacca Strait in the west and the north side of Singapore Strait in the south. It is the main port node connecting the Pacific Ocean and the Indian Ocean. There are 124 ports directly connected to port of Singapore. Santos Port, more than 60 kilometers northwest of Sao Paulo and 210 kilometers northeast of Rio de Janeiro, is a free port in Brazil and the largest port in Latin America. Ports directly connected to port of Santos include port of Singapore, port of Rotterdam, port of Antwerp, and 15 small Latin American ports. These 15 small ports are relatively isolated from the rest of the world, and the disconnection of the segment between port of Santos and port of Singapore virtually cuts them off from the global container shipping network. As a result, this segment is the most vulnerable in the global container shipping network.

Table 2. Top 20 vulnerable segments in the global container shipping network.

Rank	Port 1	Port 2	Segments number	Percentage of efficiency decrease
1	Singapore	Santos	16	2.01928%
2	Busan	Manzanillo	13	1.54472%
3	Shanghai	Nansha New	9	0.52626%
4	Manzanillo	Balboa	13	0.47735%
5	Santos	Rio de Janeiro	19	0.47124%
6	Dakar	Tangier Mediterranee	8	0.46858%
7	Jeddah	Tangier Mediterranee	23	0.44481%
8	Singapore	Piraeus	8	0.44446%
9	Balboa	Buenaventura	12	0.43423%
10	Tuticorin	Colombo	5	0.39210%
11	Bangkok	Laem Chabang	17	0.38986%
12	Singapore	Tangier Mediterranee	12	0.38920%
13	Manzanillo	Guaranao	2	0.38190%
14	Kingston	Au Prince	5	0.35371%
15	Manzanillo	Cartagena	27	0.34751%
16	Pasir Gudang	Singapore	10	0.33221%
17	Pointe Des Galets	Louis	5	0.32899%
18	Kobe	Osaka	13	0.32607%
19	Jeddah	Aden	2	0.32141%
20	San Juan	Caucedo	6	0.31618%

Figure 2 shows the local network between port of Singapore and port of Santos and ports directly connected to them. Among them, the black dot represents the port node, and the width of the line is proportional to the number of segments. It can be seen that there are five indirectly connected routes between port of Santos and port of Singapore, but the weight of these five routes is relatively small, unable to bear the existing volume of Asia-Pacific-Latin American cargo transported through port of Santos to port of Singapore, so the disconnection of this segment will lead to a certain stagnation of global cargo transport, seriously affecting the connectivity of the global container shipping network.

2) The Impact of Segment Disconnection Degree on the Vulnerability of Maritime Network

The purpose of this section is to study the changes in the vulnerability of the maritime network when four levels of disconnection occur. Table 3 shows the degradation of the layered weighted network efficiency of the maritime network when four levels of disconnection occur in the top 20 most vulnerable segments. In general, the decrease of the efficiency of the layered weighted network is consistent with the degree of segment disconnection, that is, the higher the degree of segment disconnection, the more the efficiency of the layered weighted network of the maritime network will decline. However, the impact of different degree of disconnection on the global container shipping network is not the same. For example, when calculating the ports of Singapore and Piraeus, port of Singapore and port Tangier Mediterranee, Kobe and Osaka ports, the percentage decline in the efficiency of the layered weighted network is approximately linear with the degree of reduction in the number of segments, and the degree of decline in the layered weighted network efficiency approximately increases proportionally as the degree of disconnection deepens. Busan and Manzanillo ports, Manzanillo and Balboa ports, Dakar and port Tangier Mediterranee, Jeddah and port Tangier Mediterranee are convex. The ports of Shanghai and Nansha New Port, Tuticorin port and Colombo port, Bangkok port and Laem Chabang port, Kingston port and Port Au Prince are concave.

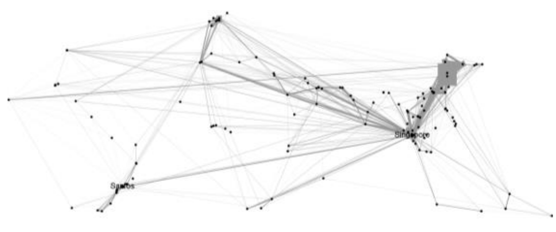

Figure 2. Port of Singapore and Port of Santos.

Table 3. Layered weighted network efficiency to different degrees of disconnection.

Rank	Port 1	Port 2	Percentage decline in efficiency			
			25%	50%	75%	100%
1	Singapore	Santos	0.16243%	0.62682%	1.70263%	2.01928%
2	Busan	Manzanillo	0.34793%	1.03851%	1.51822%	1.54472%
3	Shanghai	Nansha New	0.05700%	0.13182%	0.23689%	0.52626%
4	Manzanillo	Balboa	0.14018%	0.43339%	0.46974%	0.47735%
5	Santos	Rio de Janeiro	0.01616%	0.09683%	0.34281%	0.47124%
6	Dakar	Tangier Mediterranee	0.24566%	0.45537%	0.45961%	0.46858%
7	Jeddah	Tangier Mediterranee	0.04429%	0.37130%	0.40982%	0.44481%
8	Singapore	Piraeus	0.03942%	0.14619%	0.31405%	0.44446%
9	Balboa	Buenaventura	0.13127%	0.42514%	0.43116%	0.43423%
10	Tuticorin	Colombo	0.04952%	0.10627%	0.17456%	0.39210%
11	Bangkok	Laem Chabang	0.03991%	0.10540%	0.22669%	0.38986%
12	Singapore	Tangier Mediterranee	0.07880%	0.18161%	0.30035%	0.38920%
13	Manzanillo	Guaranao	0.00226%	0.15374%	0.15374%	0.38190%
14	Kingston	Au Prince	0.04346%	0.09191%	0.15308%	0.35371%
15	Manzanillo	Cartagena	0.00928%	0.02269%	0.29218%	0.34751%
16	Pasir Gudang	Singapore	0.05642%	0.17859%	0.30368%	0.33221%
17	Pointe Des Galets	Louis	0.03744%	0.07977%	0.32716%	0.32899%
18	Kobe	Osaka	0.02545%	0.08887%	0.20675%	0.32607%
19	Jeddah	Aden	0.00226%	0.09141%	0.09141%	0.32141%
20	San Juan	Caucedo	0.02867%	0.17076%	0.28686%	0.31618%

By analysing the proportion of the number of segments to the total number of routes, the relationship between the reduction of the efficiency of the layered weighted network and the reduction of the number of segments is obtained. Taking the segment of Dakar port and port Tangier Mediterranee as an example, there are 17 routes passing through port Tangier Mediterranee, and a total of 8 routes between Dakar port and port Tangier Mediterranee. This means that the segment between Dakar port and port Tangier Mediterranee is essentially to serve port Tangier Mediterranee. Therefore, when part of the border is interrupted, the cargo transported between Dakar port and port Tangier Mediterranee is the most affected, and the route with the port Tangier Mediterranee as a transit port is almost unaffected. But when this border is completely interrupted, cargo using port Tangier Mediterranee as a transit port will be diverted, and the shipping network will be severely disrupted. Another example is the segment of Shanghai port and Nansha New port. Shanghai port is the largest international container port, there are 420 routes through Shanghai port, there are 106 routes through Nansha New port, and there are only 9 routes between the two ports, which indicates that these two ports are important ports for goods to pass through. As a result, a partial disconnection of this segment would seriously affect the normal movement of global cargo, thereby affecting the connectivity of the maritime network and increasing its vulnerability.

3) The Impact of International Segment Disconnection on the Vulnerability of Maritime Networks

During the COVID-19 pandemic, countries have formulated various pandemic prevention policies, and airline companies have adjusted their routes, seriously affecting international transportation. Therefore, the purpose of this section is to examine the impact of varying degrees of disconnection in the international segment on the global container shipping network. In the global container shipping network constructed in this paper, the number of all international segments is reduced to a certain level at the same time, and the layered weighted network efficiency of the remaining network is calculated. In Figure 3, horizontal coordinate represents the proportional reduction of the number of international segments, vertical coordinate represents the layered weighted network efficiency of the remaining network as a proportion of the original network efficiency. It can be seen that the global container shipping network has a strong impact resistance to the reduction in the number of international segments. Even if all countries cancelled 40 percent of their international segments, the maritime network would still maintain 82 percent of its performance. However, if all international segments are eliminated, the efficiency of the maritime network will drop to 8.2% of the original network. The reason is that when the international segment is partially interrupted, although the transportation efficiency between ports has declined, the global container shipping network is still a complete network, and the global cargo can basically achieve circulation. However, if all international segments are cancelled, the global container shipping network will become an isolated subnet, and international transportation will be greatly affected. As a result, the global container shipping network is highly vulnerable to complete disconnection of international segments.

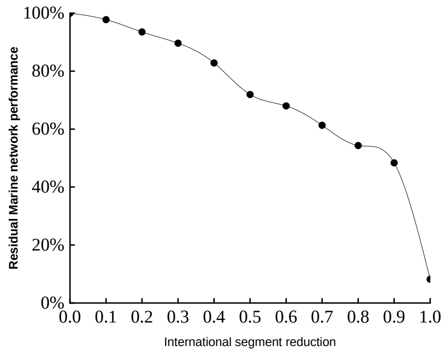

Figure 3. The impact of international segments disconnection on the vulnerability of shipping network.

4 CONCLUSION

In this paper, a layered weighted network efficiency method was introduced to build a global container shipping network based on the route data of the top seven liner companies in the world in terms of shipping capacity against the background of the COVID-19 pandemic. The vulnerability of the global container shipping network was studied by simulating different levels and degrees of disconnection of routes. The results show that the disconnection of different segments has a great difference on the vulnerability of the global container shipping network, and the disconnection of Singapore Port and Santos Port has the greatest impact, which will reduce the efficiency of the shipping network by 2%. When the segments are interrupted to different degrees, the decrease of the efficiency of the layered weighted network is consistent with the variation trend of the segments interrupted degree. The global container shipping network has strong anti-interference to the partial disconnection of the international segment and great vulnerability to the complete disconnection of the international segment. As long as the number of international segments in the maritime network is maintained at 10% of the original, the maritime network can still achieve 48.4% of the pre-disconnection performance; However, if the international segment is completely disconnected, the efficiency of the shipping network will drop to 8.2% of the pre-disconnection level. This paper deepens the understanding of the global container shipping network under extreme events, provides a reference for the study of the vulnerability of the shipping network under global disturbance, and provides management enlightenment for relevant government departments and private enterprises.

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