

Cascading Failure Analysis of Container Shipping Network for Maritime Silk Road

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Abstract: Related to the realization of the 21st century Maritime Silk Road Initiative (MSRI), container shipping network needs to have strong survivability. The research of this paper can provide guidance for the construction of shipping network as well as the improvement of network survivability. This paper constructs a cascade failure model and designs network survivability from three aspects. Finally, simulation analysis is used to study the survivability of Maritime Silk Road (MSR) container shipping network based on cascade failure. The results show that the network has the worst survivability under the maximum load failure. Besides, the strategy of load redistribution based on the remaining capacity as well as the adding edge, etc. can effectively improve the network survivability.

1. Introduction

The 21st century MSR is one of the two most important components of the Belt and Road Initiative. As a necessary condition of container liner shipping, container shipping network is the basic condition and main carrier for the formation and development of the MSR. The ports along the MSR are the basis for the construction of container shipping networks. On the one hand, due to economic and political factors, it is difficult to achieve communication and cooperation of all ports in a short period of time, besides it is hard to establish a reasonable and stable shipping network. Once a cascading failure occurs, it may cause serious consequences and cause huge economic losses. On the other hand, due to the large number of ports along the MSR, meanwhile most of the routes have passed through the key node ports of the MSR. Once these ports are affected by unexpected events, it is more likely to cause cascade failure which can even cause more serious consequences on them. Therefore, it is vital to study the cascade failure survivability of container shipping network for MSR, which can be conducive to the realization of MSRI by probing into an operational mechanism within the network and digging problems on deeper levels.

2. Literature Review

At present, relevant scholars have various conducted researches on the survivability of complex networks based on cascade failure. Chen et al.[1] have studied how to improve the network cascading failure survivability by optimizing node capacity. Ruj and Pal[2] have analyzed the cascading failure phenomena of smart grid under random and deliberate attacks. According to the

simulation method to study the cascading failure of road transportation network, Liu and Yin[3]reasonably determined the load and capacity and considered the load and length of adjacent sections to distribute the load reasonably while making macro measurement of traffic congestion within the network. In addition, Liu et al.[4] proposed a model framework for identifying and analyzing the relevant survivability in the supply chain, and proved the adaptability of the proposed framework through a case of Maersk Line in the Asia-Europe route. What's more, Wang et al.[5]studied the time robustness of global container shipping networks. Besides, Yin et al.[6] analyzed the influence of node capacity on cascading failure and studied the impact of non-scale random network structure parameters on the survivability of network by establishing a node-based scale-free random network model based on cascading failure.

To sum up, there are few researches on the survivability of container shipping networks, and previous studies have mainly focused on static survivability rather than on dynamic survivability. Besides, the dynamic survivability is closer to reality and has a greater impact on container shipping network, so it requires further research. On the basis of previous studies, this paper first applies the theory of survivability based on cascading failure to the study of container shipping network and studies the dynamic survivability of MSR container shipping network.

3. The Cascading Failure Model

This paper establishes an undirected weighted network and in order to describe the cascading failure process of container shipping network, the following assumptions are made by this paper:

- (1) Assume that the container cargo flow in the container shipping network is transported along the shortest path, which means that the number of flights passing through is the least;
- (2) When the port is destroyed due to an emergency or the container handling capacity exceeds its maximum limit, the port is assumed to be invalid and the side connected to it is deleted;
- (3) Assume that during the study period, the port does not have resilience after failure, which means that it does not consider the recovery of the port.

3.1. The Cascading Failure Model of Container Shipping Network

Considering the actual operating regularity and characteristics of the container shipping network, a cascading failure model of container shipping network is established from three aspects: load, capacity and load redistribution. The specific contents of the model are as follows:

1) Load

The port load represents the container handling capacity of the port. In this paper, the port load is defined as:

$$L_i = O_i + D_i + B_i \quad (1)$$

In this formula, L_i represents the load of the port i , O_i denotes the container handling capacity generated from the failed port i ; D_i denotes the container handling capacity attracted from the failed port i , and B_i represents the transshipped container handling capacity of the port i .

Before the container shipping network has no emergencies, the network function is normal, and each port has an initial load. However, when cascading failure occurs, the port load changes accordingly.

2) Capacity

Port capacity represents the port's largest container operating capacity. Constrained by cost, the capacity of the nodes in the actual network cannot be infinite. Like the container shipping network,

the port capacity in the network is limited, and the port capacity is the maximum load that the port can bear. This paper will adopt the following capacity model:

$$C_i = L_{i0} + \beta L_{i0}^\alpha \quad (2)$$

In this formula, C_i is the capacity of port i , L_{i0} is the initial load of port i , β is the capacity factor, and α is the adjustable factor and $\beta \geq 0, \alpha \geq 0$. When $\alpha = 1$, the model degenerates into a capacity model in the ML model; when $\alpha \neq 1$, it is a nonlinear model.

In the cascading failure process, if $L_i > C_i$, the cascading failure continues to spread, otherwise the cascading failure is terminated and the container shipping network tends to be stable.

3) Load redistribution strategy

There are two general ideas for the load redistribution strategy after the node fails. One is to distribute the load to the neighbor nodes of the failed node according to certain rules. The other is to distribute the load globally according to the routing policy of the shortest path. The load of the port is composed of three parts, the characteristic of each port should be considered while different load redistribution strategies are being designed, so the two ideas need to be considered in this article. It can be seen that the redistribution of the container handling capacity that is generated and attracted is applicable to the first distribution idea. Therefore, the two parts of the load assigned to the adjacent ports of the failed port are:

$$\Delta L_{j \leftarrow i} = (O_i + D_i) \times \frac{k_j}{\sum_{j \in J} k_j} \quad (3)$$

In this formula, $\Delta L_{j \leftarrow i}$ denotes the load assigned to the adjacent port j by the failed port i ; O_i denotes the container handling capacity generated from the failed port i ; D_i denotes the container handling capacity attracted from the failed port i ; and k_j represents the load distribution weight of the adjacent port B , which is generally weighted by port. In addition, J represents the collection of ports which is adjacent to the failed port i .

However, for the distribution of the transshipped container handling capacity of the invalid port, the second idea should be considered. When the transship function of a port is lost, the transshipped container handling capacity of the invalid port will be assigned to the new transship port in accordance with the global allocation the shortest path strategy.

3.2. Survivability Evaluation Indexes of Container Shipping Network Based on Cascading Failure

This part has developed two indexes so as to describe the survivability of container shipping network in terms of connectivity and transportation efficiency.

(1) Connectivity change index

According to the relevant knowledge of the graph theory, the larger the maximum connected sub-graph, the better the connectivity of the network. Therefore, the maximum connected sub-graph is used as an index to describe the change of the connectivity of the container shipping network. The formula is as follows:

$$g = \frac{N'}{N} \quad (4)$$

In the formula, N and N' represent the maximum connected sub-graphs of the container shipping network before and after the cascading failure respectively, g represent the change of connectivity of the network. Besides, when $g \approx 1$, it shows that the connectivity of container shipping network is almost unchanged after cascading failure, and the network survivability is very strong, and when $g \approx 0$, it shows that the container shipping network completely collapses after the cascading failure and the survivability of network is very weak.

(2) The change indexes of transportation efficiency

Referring to the definition of complex network transportation efficiency, this paper regards it as the transportation efficiency of container shipping network. The specific formula is as follows:

$$E = \frac{1}{n(n-1)} \sum_{i=1}^n \sum_{j=1}^n \frac{1}{d_{ij}} \quad (5)$$

In the formula, n is the number of ports in the container shipping network, and d_{ij} is the shortest path length between ports i and j . Accordingly, the index of container shipping network transportation efficiency is worked out as follows:

$$f = \frac{E'}{E} \quad (6)$$

In this formula, f is used to describe the change of the transportation efficiency of the container shipping network, and E and E' respectively represent the transportation efficiency of the container shipping network before and after the cascading failure.

When $f \approx 1$, it indicates that after the cascading failure, the container shipping network can still complete the transportation task very well, and the network basically maintains the original function. When $f \approx 0$, it shows that the efficiency of container shipping network is almost zero, and the network transportation function is completely lost. It can be seen that this index can clearly reflect the change of container shipping network transportation efficiency before and after cascading failure.

4. Survivability Simulation Design

In this part, the research approach is designed from three aspects based on two types of failure modes and simulated by MATLAB to study survivability of container shipping network based on cascading failure.

4.1. Simulation Design of the Effect of Failure Mode on Survivability

In order to simulate various types of emergencies that may be encountered in the container shipping network, this paper intends to adopt three failure modes: random failure, maximum betweenness failure and maximum load failure. According to the different failure modes, this paper will randomly remove a port first, and then the port with the largest number of ports as well as the port with the largest load respectively, so as to study the effect of different failure modes on the survivability of container shipping network under the influence of cascading failure.

4.2. Simulation Design of the Effect of Load Redistribution Strategy on Survivability

In the load redistribution strategy, the redistribution of the container handling capacity generated and attracted from the invalid port is carried out according to formula (3). In this formula, there are many methods to determine the load distribution weight of the adjacent ports of the failed port, such as the load distribution weight is determined according to the size of the port degree, the larger the distribution of the port degree is, the more container handling capacity is generated and attracted. In addition, there are distributions by port remaining capacity, distribution by the betweenness, and so on. According to the previous research results, this paper mainly compares the effects of the degree distribution strategy and the remaining capacity distribution strategy on the survivability of container shipping network based on cascade failure.

4.3. Emulation Design of the Influence of Adding Edge on Survivability

Considering the limitation of the cost, the measure of adding edge in this part is mainly implemented in the adjacent ports of the failed port. The measures of adding edge include adding edge by degree, adding edge by capacity and adding edge by betweenness, which is equal to increase the edge between the neighboring ports of the failed port according to the degree, capacity and betweenness respectively. And the greater the corresponding value of the two neighboring ports, the greater the possibility of adding edge. At the same time, it is stipulated that the number of added edges shall not be greater than the number of failed port sides. Finally, the influence of the measures on the survivability of container shipping network based on cascading failure is obtained through comparing the way of no adding edges.

5. The Analysis and Discussion of Simulation Results

5.1. Analysis of MSR Container Shipping Network

Taking the top 42 countries or regions in the trade volume of import and export of goods along the MSR as the initial data, the initial load of the ports along the MSR can be obtained through processing the data in this paper. In addition, betweenness of ports belonging to the top 30 in the container shipping network of the MSR are selected to reflect the relative size of the transshipped container handling capacity so that the data can be normalized. Furthermore, the effects that factors of four aspects: failure mode, adjustable coefficient, load redistribution strategy and adding edge will cause on the survivability of MSR container shipping network based on cascading failure can be studied thoroughly.

5.2. Simulation Analysis of the Impact of Failure Mode on Survivability

In the simulation, when the adjustable coefficient $\alpha=1$, the capacity coefficient β changes from 0 to 1, the container handling capacity which is generated and attracted from the invalid port is distributed to the adjacent ports based on the degree distribution, and the random failure takes the average result of 10 tests. Finally, the effects of random failure, maximum betweenness failure and maximum load failure on survivability of the MSR container shipping network based on cascading failure are shown in Figure 1.

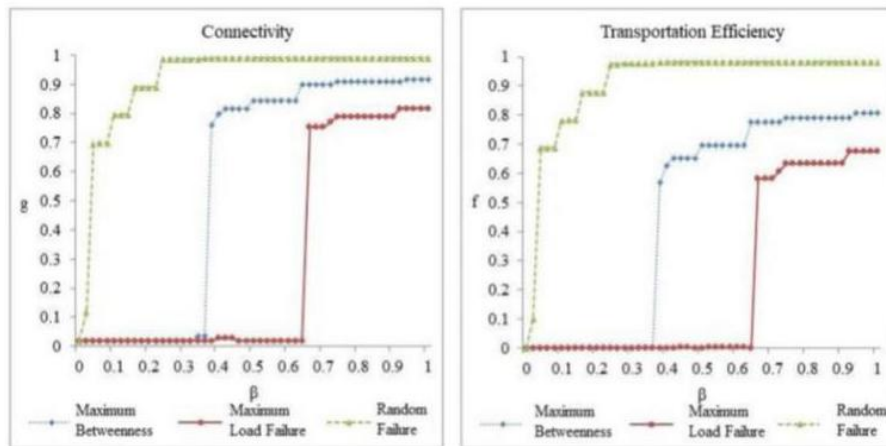


Figure 1: The results of failure mode to survivability.

It can be seen from Figure 1 that under the same failure mode, the curve of the connectivity and transportation efficiency of the MSR container shipping network is the same. The capacity coefficient β has a significant step-by-step inhibition on the cascading failure. Initially, with the increase of the capacity coefficient, the index value is always maintained at a very low level. The cascading failure has great damage to the network survivability and the network almost collapses. In terms of different failure modes, the effects brought by the cascading failures are quite different. The capacity factor of the maximum load failure step is 0.66, at last, g is stable at 0.817, f is stable at 0.675. The maximum betweenness failure occurs with a capacity factor of 0.38, at last, g is stable at 0.917, f is stable at 0.807. The capacity factor of the random failure step is 0.04, and the index value is finally close to 1. It can be seen that considering the cascading failure, the maximum load failure has the greatest impact on the survivability of the MSR container shipping network, followed by the maximum betweenness failure, and the random failure has the least impact.

Therefore, considering the characteristics of the ports along the MSR, the capacity of the ports which are important hubs, passed through by large number of routes, or geographically important such as Shanghai port, Singapore port and Rotterdam port should be adequately enlarged, because survivability has greater impacts on these ports.

5.3. Simulation Analysis of the Impact of Failure Mode on Survivability

When studying the impact of the load redistribution strategy on the survivability based on cascading failure, the failure mode selects the maximum load failure and the maximum betweenness failure respectively. When the adjustable coefficient $\alpha = 1$, the capacity coefficient β changes from 0~1, and the final simulation result is shown in Figure 2 (a-b).

It can be seen from Figure 2 (a) that the steep change of the capacity coefficient based on the remaining capacity distribution strategy is 0.46, the index value of the final steady-state is larger, while the capacity coefficient of the strategy based on the degree distribution is 0.66, and the index value of the final steady state is smaller. This shows that if the ports with heavy load in the MSR container shipping network fail, the survivability of the network can be improved significantly by using the remaining capacity distribution strategy than the degree distribution strategy. In Figure 2(b), the two curves formed by the two allocation strategies are close to each other, which indicate that if the port with the maximum betweenness in the MSR container shipping network fails, the two allocation strategies have little change on the network survivability. But overall, the distribution strategy based on remaining capacity is still more effective.

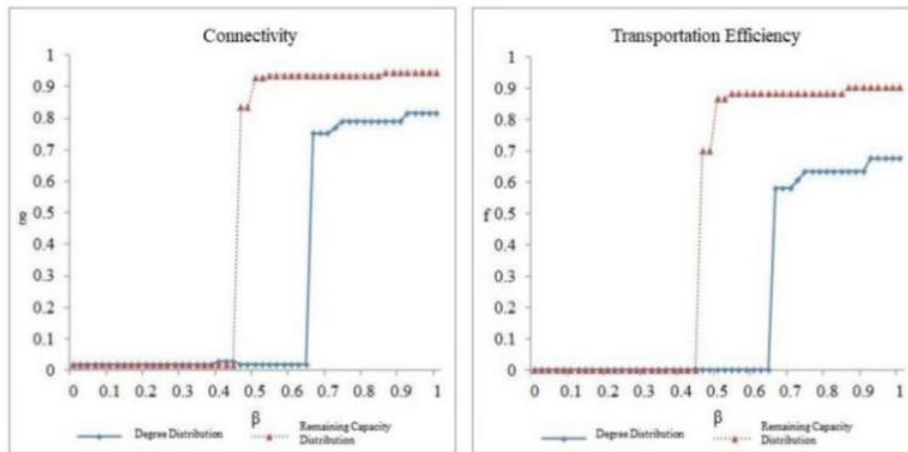


Figure 2(a): The results of load redistribution strategy to survivability under Maximum load failure.

5.4.Simulation Analysis of the Influence of Adding Edge on Survivability

The initial conditions of the simulation are: adjustable coefficient $\alpha = 1$, the capacity coefficient β changes from 0~1, the failure mode is the maximum load failure or maximum betweenness failure, and the container handling capacity which is generated and attracted from the invalid port is allocated to the adjacent ports based on the degree distribution strategy. Finally, the effect of adding edge on the survivability is shown in Figure 3 (a-b).

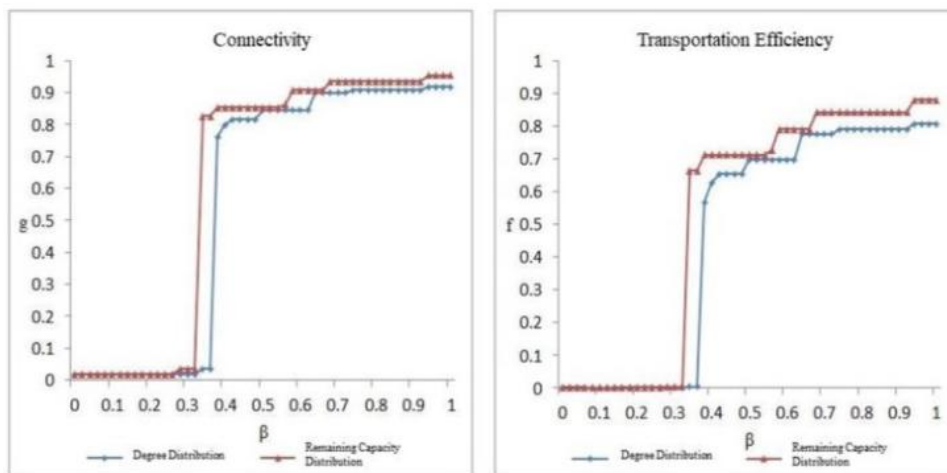


Figure 2(b): The results of load redistribution strategy to survivability under maximum betweenness failure

Figure 2: The results of load redistribution strategy to survivability.

It can be seen from Figure 3(a-b) that the adding edge measures can significantly improve the survivability of the MSR container shipping network regardless of the failure mode. At the same time, it can be found that different adding edge measures have different effects on improving network survivability under different failure modes. For instance, under the maximum load failure, the increase in the survivability of the network caused by the adding edge by betweenness is most obvious, followed by the adding edge by degree. And the survivability based on cascading failure caused by adding edge by capacity has certain volatility. In the case of the maximum betweenness

failures, the most obvious improvement on the survivability of the network is caused not by adding the edge by betweenness, but by adding the edge by degree. Therefore, as for the MSR container shipping network, when the ports in the network fail, it is necessary to adopt corresponding adding edge measures for different failure modes. That is to strengthen cooperation between ports along the MSR and increase the number of routes between ports so as to resist the cascading failure more effectively as well as maximize the network survivability.

Based on the above research, this paper proposes some measures to enhance the survivability of the MSR container shipping network, including prevention and remediation. The preventive measures that can be taken are as follows: 1) Optimize the network structure and coordinate the balance between economy and survivability. 2) Strengthen key ports to reduce the risk of maximum load failure or maximum betweenness failure. 3) Appropriately improve the container throughput capacity of adjacent ports and share the load of key ports. The remedies that can be taken are as follows: 1) Establish an emergency recovery mechanism for the failed port and quickly restore the port function. 2) Improve the existing information release mechanism, effectively guide the container cargo flow level, and update the information of each route and each port in a timely manner. 3) Appropriately adjust the container liner route, so that the side of the adjacent port increases, which will replace some functions of the failed port. By doing so, it can resist the cascading failure and enhance the network survivability.

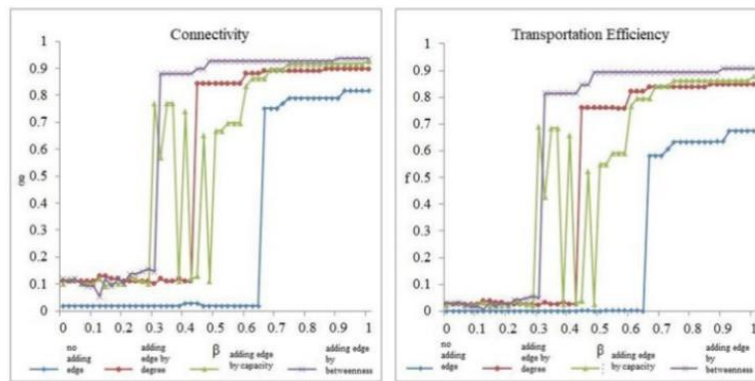


Figure 3(a): The results of adding edge to survivability under maximum load failure.

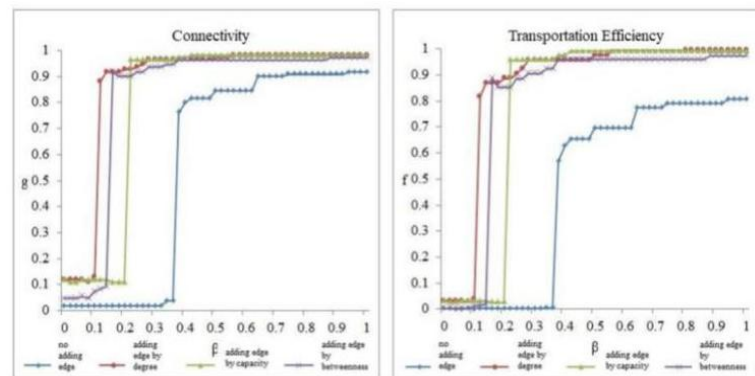


Figure 3(b): The results of adding edge to survivability under maximum betweenness failure.

Figure 3: The results of adding edge to survivability.

6. Conclusions

Establishing a cascading failure model according with the actual characteristics of container shipping network, this paper designs a simulation scheme for the study of survivability based on this model, and analyzes the survivability of container shipping network along the MSR based on cascading failure and the feasibility of the model is verified.

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