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Robustness Analysis of Cold-Chain Logistics Emergency Materials Storage and Transportation Network under Emergency Scenes

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Abstract:

In the process of dealing with all kinds of emergencies, such as natural disasters, it is particularly important for emergency materials to reach the disaster areas in time and in full. During the COVID-19 epidemic, designated emergency material transfer points had been set up in Wuhan City, Hubei Province or Xi'an City and Shaanxi Province to help get through the transportation channels and ensure the social life and material supply in the affected areas. Under this background, cold-chain logistics, as one of the important means to protect people's livelihood materials, has received extensive attention. In this paper, Hubei Province where emergency materials transit points had been set up during the COVID-19 epidemic is taken as the example. The robust optimization analysis is made for the emergency transit cold storage. By collecting the location data of retail nodes in Hubei Province, the Hubei emergency material transportation network is depicted, and its network characteristics and cascading failure robustness are analyzed to summarize the experience and practice of regional disaster emergency materials support in China, and provide some reference for improving various emergency response mechanisms.

Keywords*: Emergency,Cold-chain logistics, Emergency material support,Robustness.*

I. INTRODUCTION

In recent years, many emergencies and disasters, including the COVID-19 epidemic, have brought huge losses to the society, and they also bring severe challenges to cold-chain logistics. Accelerating the improvement of the cold-chain logistics emergency support system is the key to enhance China's emergency handling capacity. The construction of cold chain emergency support system has become a hot issue for scholars at home and abroad. In the construction of emergency cold chain supply chain, Li Xuegong and Li Fang used the analytic hierarchy process (AHP) and sequence parameter method to evaluate the coordination level of emergency cold chain supply chain [1]; Chaiwuttisak et al. studied the location and distribution of blood products storage and transportation facilities based on the transportation characteristics of cold-chain medical materials of blood products [2]; Zhu Shufan and Gui Ping discussed the decision-making problem of cold chain emergency logistics collaborative distribution from the perspective of evolutionary game [3]; Ni Weihonget al., discussed the role of blockchain technology in building the cold chain supply chain system of medical epidemic prevention emergency materials, and based on this, built a cooperative operation mechanism [4]. In addition, emergencies and disasters have brought challenges to the circulation of agricultural products. How to solve the problem of emergency support for agricultural products is a test for urban agricultural products supply chain system.

Based on this, this paper takes Hubei Province's initiative of setting up emergency material transit points during the COVID-19 epidemic (February, 2020) as a case study, analyzing the robustness of its emergency material transportation network by using cascading failure method, with the aim of providingnew ideas and suggestions for improving China's cold-chain logistics emergency support system.

II. RESEARCH METHODS AND ANALYSIS

Through investigation, we can find: due to the severe COVID-19 epidemic, there was a serious shortage of living materials in Wuhan City, and there were a large number of outstanding problems such as poor logistics, disconnection between wholesale and retail, shortage of personnel, shopping queue. To deal with these problems, the Ministry of Commerce of China and the Development and Reform Commission jointly set up the Working Group of Wuhan Living Materials Support, and established a joint guarantee and supply mechanism based on nine provinces to coordinate the rapid response of nine neighboring provinces such as Anhui Province and Jiangxi Province and organize the allocate and transport of materials in short supply in Wuhan City at the first time.

At the same time, to ensure the smooth road transportation channels connecting other provinces and Hubei Province to effectively safeguardthe timely delivery of all kinds of materials for epidemic prevention and control in Hubei Province, the Hubei headquarters for prevention and control of COVID-19 identified five logistics parks in Wuhan City, EzhouCity and Xiangyang City, including Jieli Logistics Park in Dongxihu District of Wuhan City, Wuhu Cuiyuan Cold Chain Food Logistics Park in HuangpiDistrict of Wuhan City, Baowan Logistics Park in Hannan District of Wuhan City, Hubei EzhouChiwanDongfang Logistics Co., Ltd. and XiangyangGuangcai International Logistics Base, as transit stations for road transportation of emergency materials from other provinces to Hubei Province.

In terms of internal supply network, before the lockdown of Wuhan City, nearly 400 farmers' markets were the main channels of vegetable retail, accounting for 70%-80%. After the medical isolation, the farmers' markets in the central city were all closed, and the retail sales were mainly supplied by there major superstores, namely Wushang, Zhongnan Commercial and Zhongbai.

Therefore, in this paper, combined with the above-mentioned practical cases, the location node data of five emergency materials transfer stations and 266 major retailers' superstores in Hubei Province are selected to construct the emergency materials storage and transportation support network in Hubei Province during the epidemic, and the emergency materials support network is analyzed. The information of retail superstores comes from Baidu Map, and the location data of retailers' superstores comes from the coordinate pickup system of Baidu Map.

2.1 Network Construction

One of the difficulties in studying the transportation network of emergency materials in Hubei Province during the epidemic is the complexity of the relationship between transportation lines and transportation nodes. Firstly, this paper calculates the distance between nodes according to the latitude and longitude coordinate information of 271 nodes. In the actual operation process, the transportation relationship (i.e. connection) between different nodes is highly complicated, so this paper simplifies the network construction. Considering that there are a large number of connection relationships among five emergency transit stations, which conform to the scale-free network characteristics, the network is generated and weighted according to the scale-free network characteristics, as shown in Fig 1.

To study the weighted network, we must first determine the way to give weight. At present, there are two ways to express weight in weighted network: similarity weight and dissimilarity weight. The similarity weight indicates the degree of closeness between nodes. The greater the weight, the closer the relationship, and the smaller the distance between two points.The dissimilarity weight is similar to the distance between two nodes. The larger the weight, the more distant the relationship, the smaller the weight, and the closer the relationship. Therefore, the reciprocal of the actual distance between two nodes is taken as the weight of the connecting edge, and the weight in the modeling process is uniformly considered as the similarity weight. On this basis, we consider expressing the weight of each edge with similarity weight, and constructing the network with Space-L method. Each serial number represents a warehouse station, as shown in Fig 2.

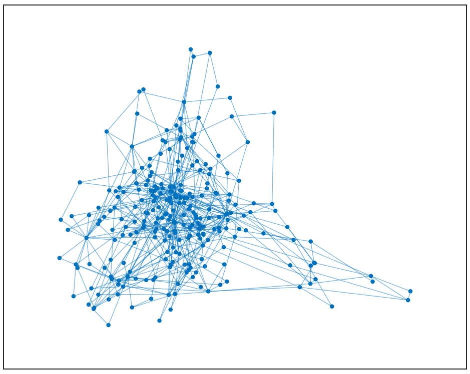

Fig 1: Emergency material transportation node network

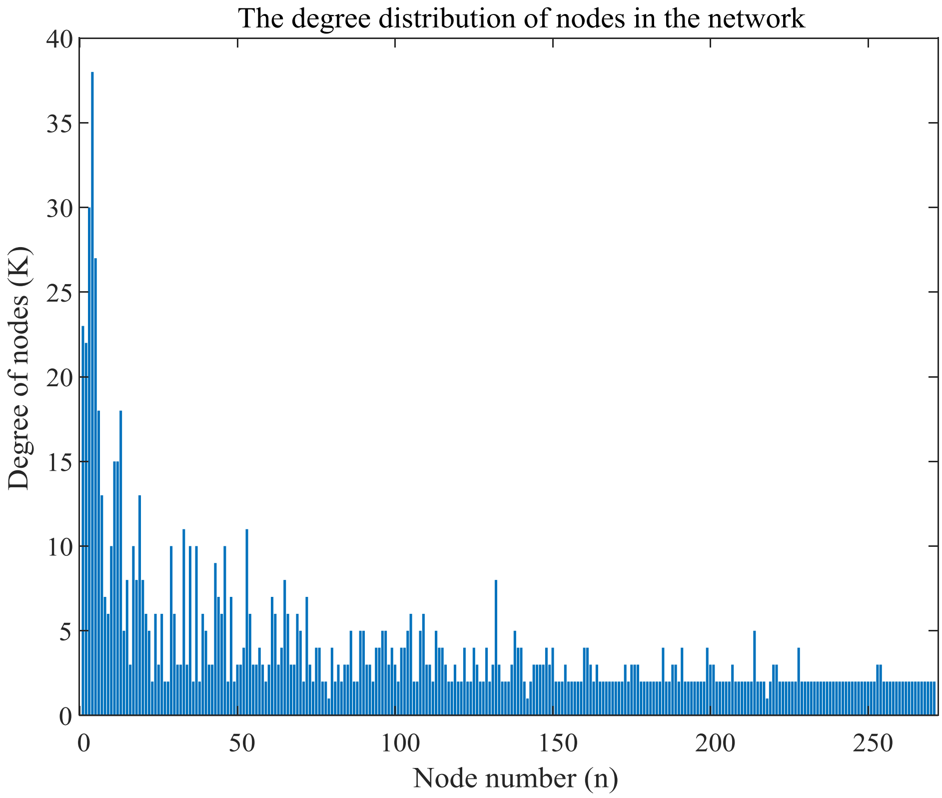

Fig 2: Degree distribution diagram of emergency material transportation network nodes

2.2 Network Characteristic Index Calculation

(1) Point weight and distribution of point weight

In the weighted network, the point weight is also called the point strength, and the size of the point weight indicates the importance of the node. The point weight V_i of node V_i is defined as the sum of its associated edge weights, which is defined as:

$$\mathrm{S_i} = \sum_{\mathrm{V_j \in N_i}} \mathrm{w_{ij}}$$

Wherein,N_i is the set of neighboring nodes of node V_i; W_{ij} is the weight of the connection edge between node V_i and node V_j. $\mathrm{P(k)}$ is defined as the proportion of nodes with the node weight of k in the whole network. That is, the probability of randomly picking nodes with the node weight of k in the network is $\mathrm{P(k)}$, and the distribution of the node weight of all nodes in the whole network can be obtained by $\mathrm{P(k)}$. The cumulative point weight distribution is fitted by power law, and the fitting equation is shown in Figure 3.

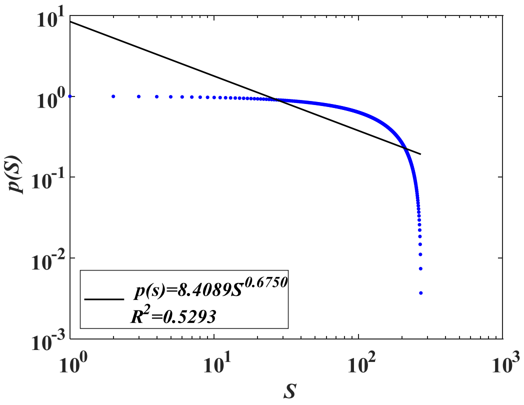

Figure 3 Fitting function of cumulative point weight distribution of emergency material transportation network

In the fitting function, based on double logarithmic coordinates, the distribution probability of the cumulative degree of the emergency material transportation network obeys the power law distribution, and the fitting coefficient is $R^2 = 0.5293$, indicating a good fitting effect. It meets the characteristics of scale-free network proposed by Barabási and Albert that few nodes in the network have larger degrees and most nodes have smaller degrees, and that the distribution probability of the cumulative degree of network stations obeys the power law distribution. Therefore, the stations on the logistics warehouse network conform to the characteristics of scale-free network in L space.

(2) Weighted average path length

The path with relatively large average path length has better robustness. Assuming that stations i and j are connected by two edges with weights w_{ik} and w_{kj}. The harmonic average of node spacing is:

$$\mathrm{d_{ij}} = \mathrm{w_{ik}} \mathrm{w_{kj}} / (\mathrm{w_{ik}} + \mathrm{w_{kj}})$$

The average distance of the weighted complex network is:

$$\mathrm{L} = \frac{1}{\mathrm{N(N-1)}} \sum_{i \neq j} \frac{1}{d_{ij}}$$

(3) Weighted network efficiency

According to Latora et al., network efficiency can measure the efficiency of network information exchange, which is defined as:

$$\mathrm{E_{glob}} = \frac{1}{\mathrm{N(N-1)}} \sum_{\mathrm{i \neq j}} \frac{1}{\mathrm{d_{ij}}}$$

(4) Basic network indexes

Based on the above evaluation indexes, the basic indexes of emergency material transportation network are shown in Table I:

TABLE I. Basic indexes of emergency material transportation network

Network	Number of nodes	Edge number	Average path length	Average point weight	Maximum path length	Network efficiency
Weight	271	538	0.0431	0.2341	0.3550	36.3081

2.3 Comprehensive Evaluation Index

According to the node degree and the betweenness, the betweenness centrality index and the degree centrality index of nodes are calculated. Based on the above indexes, the comprehensive evaluation indexes of station importance are given, namely:

$$C_B(i) = B_i / \frac{N(N-1)}{2}$$

$$C_D(i) = \frac{K_i}{N-1}$$

$$F_i = \lambda C_B(i) + \mu C_D(i)$$

In the above formula, F_i is the comprehensive evaluation index of i importance of the node. λ and μ are weight coefficients, and $\lambda + \mu = 1$ is satisfied.

To comprehensively measure the importance of stations in the network, it is necessary to select an optimal combination of weight coefficients. By setting different values of λ and μ ($\lambda, \mu \in [0,1]$), the importance of stations is ranked. According to the ranking results, the attack experiment is carried out on the top 5% of the stations in the network by deliberate attack. Under the combination of λ and μ, the values of network efficiency E and maximum connectivity subgraph size S are recorded and analyzed, and the corresponding values of λ and μ when E and S have the largest change are selected as the weight coefficients of the evaluation index. The weight combination obtained at this time can measure the importance of the stations in the network to the greatest extent.

TABLE II. Determination of the best parameters in the importance method

μ	λ	**E Network efficiency E**	**S Maximum connectivity S**
0	1	13.2925	247
0.1	0.9	13.2925	247
0.2	0.8	13.2925	247
0.3	0.7	13.2925	247
0.4	0.6	13.2925	247
0.5	0.5	13.2925	247
0.6	0.4	13.2925	247
0.7	0.3	13.2925	247
0.8	0.2	12.9543	243
0.9	0.1	14.7465	239
1	0	27.9401	252

According to the comprehensive evaluation indexes of station importance proposed earlier, the calculation results of network performance under different weight coefficient combinations are shown in Table II: when $\mu = 0.8$ and $\lambda = 0.2$, the network efficiency value is 12.9543, and the maximum connected subgraph is 243. The network performance change rate is the largest. Therefore, this group of weight combinations is selected as the weight coefficient of the importance evaluation indexes of logistics warehousing network stations.

According to the comprehensive evaluation indexes, the stations with top 5% importance of the logistics warehousing network are as shown in Table III. These stations play an important role in the network. Once a fault occurs, it may cause serious damage to the logistics warehousing network, resulting in a significant reduction in the operation efficiency and connectivity of the whole network. Therefore, it is necessary to strengthen the protection of these stations, optimize the infrastructure configuration and reduce their failure rate to ensure the normal operation of the network.

TABLEIII. Evaluation results of important stations

Ranking	**Station**
5	XiangyangGuangcai International Logistics Base
4	Wuhu Cuiyuan Cold Chain Food Logistics Park in Huangpi District of Wuhan City
2	Baowan Logistics Park in Hannan District of Wuhan City
3	EzhouChiwanDongfang Logistics Co., Ltd.
43	Wushang Supermarket (No.16 Jinlong Road, Shashi District, Jingzhou City)
1	Jieli Logistics Park in Dongxihu District of Wuhan City
29	Wushang Supermarket (No.90 Ping'an Road, Wuchang District, Wuhan City)
17	Wushang MALL (No.690 Jiefang Avenue, Jianghan District, Wuhan

	City)
200	Zhongbai Supermarket (No.75 FengxiangAvenue,Laifeng County, EnshiTujia and Miao Autonomous Prefecture)
11	Wushang Supermarket (No.888, Minzu Avenue, Guandong Street, Donghu New Technology Development Zone, Jiangxia District, Wuhan City)
19	Wushang Supermarket (No.23 No.10 Village, Tianshunyuan, Fengshun Road, Qiaokou District, Wuhan City)
6	Wushang MALL (No.688 Jiefang Avenue, Jianghan District, Wuhan City)
44	Wushang Supermarket (No.307 Jiangjin West Road, Shashi District, Jingzhou City)
53	Wushang Supermarket (No.4 Qianjin Road, Fancheng District, Xiangyang City)

2.4 Cascade Failure Analysis

When a station in the emergency transportation network fails due to various emergencies, the impact is not limited to the failed station, but also radiates to its neighboring stations and even the whole network. When a certain station breaks down, the original load flow and the load flow that has not yet reached the station will be distributed to its neighboring stations, which will cause the load of neighboring stations to change. If the load of the neighboring station exceeds its maximum carrying capacity, a new failed station will be generated, causing a new round of station load redistribution. After several rounds of station load redistribution, the whole network may be partially or completely paralyzed. The schematic diagram of cascading failure process is shown in Figure 4.

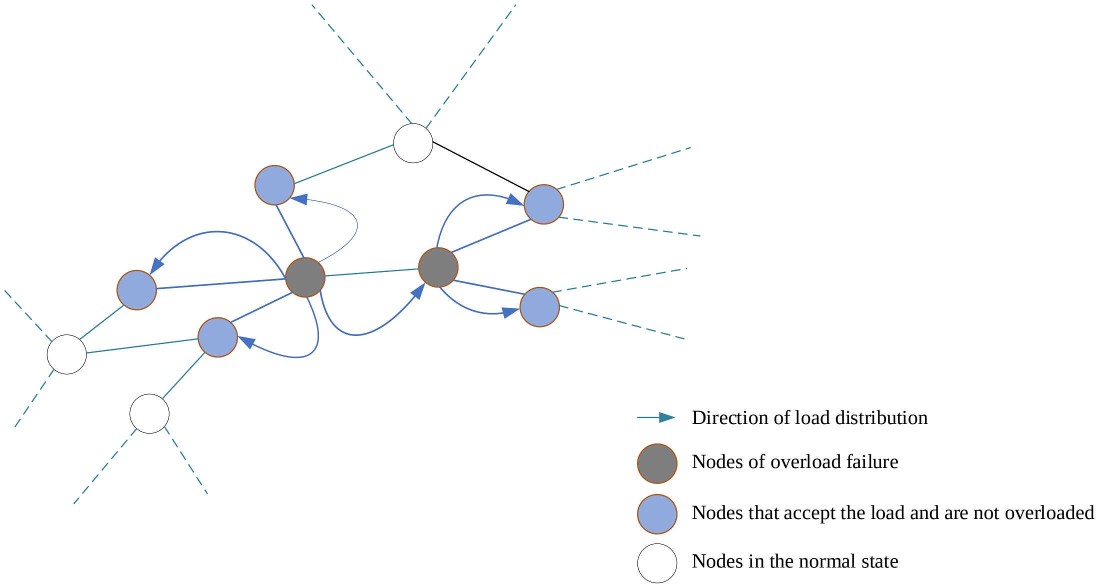

Fig 4: Schematic diagram of cascade failure process

(1) Initial station flow and capacity

The station betweenness can reflect the load situation of the station, so the station betweenness is taken as the quantitative index of the initial load. For the network with N stations in total:

$$Q_i(0) = B_i$$

In the above formula, $Q_i(0)$ represents the initial load of station i, and B_i is the node number of station i. It is assumed that all stations in the emergency material transportation network have the capacity to bear the load. According to Motter-Lai model, the capacity of the station is positively correlated with its initial load and related to the spare capacity coefficient. The calculation formula of node capacity is as follows:

$$C_i = (1 + a)Q_i(0)$$

In the above formula, C_i is the capacity of station V_i; a is the standby capacity coefficient, which is used to measure the processing capacity of the station when it exceeds the initial load.

(2) The principle of load redistribution

When the load of the station exceeds its capacity, the load redistribution process will be carried out. Assuming that there is a failed station V_i in the network, as the capacity of the station is positively correlated with the number of stations, the load of the failed station V_i distributed to any neighboring station V_j is as follows:

$$\Delta Q_j = K_j Q_i = \frac{B_j}{\sum_{V_j \in \theta_M} B_M} Q_i$$

In the above formula, ΔQ_j is the load increment of station V_j; K_j is the load distribution ratio of neighboring stations; B_j is the betweenness of station V_j, and θ_M is the set of neighboring stations of failed station V_i.

(3) Cascade failure propagation process

When the station is in normal operation, the cargo flow of the station is less than its capacity at t, which is defined as the normal state in this paper. At this time, the relationship between the cargo flow and capacity of the node is as follows:

$$L_i(t) < C_i$$

Wherein, C_i is the capacity of node i, and $L_i(t)$ is the actual cargo flow of node i at time t.

When the station is in the aging state, at the time of operation t, when the operation of the station is interrupted due to an emergency or when the cargo flow of the station exceeds its limit capacity, the state of the node is defined as the failure state. When the actual load Q of the node is greater than the limit capacity C_{max}, the node fails, and its actual load is distributed according to the load distribution strategy mentioned above; when the actual load Q of the node is greater than the capacity C but less than the limit capacity C_{max}, the node is in the state of overload but not failure. The overloaded part (that is, the actual load Q minus the capacity C) is also distributed according to the load distribution strategy mentioned above, and distributed to its neighboring nodes in the normal state; when the actual load Q of the node is less than the capacity C, the node is in a normal state. When the difference between the limit capacity C_{max} and the capacity C increases, that is, when the freight demand of the logistics station increases, its anti-explosion capacity becomes stronger. The difference between C_{max} and C can also be used to reflect the demand of local material transportation during the epidemic.

(4) Cascade failure algorithm

The cascading failure algorithm designed in this paper is as follows:

Step 1 Establish an emergency material transportation network. Abstract warehouses and retail outlets as network nodes, and abstract lines as network connections to form an undirected and unauthorized network;

Step 2 Initialize the standby capacity coefficient a of the network, calculate the node betweenness B_i, and determine the initial load $Q_i(0)$ and capacity C_i of each node;

Step 3 Choose an attack strategy (random attack or deliberate attack) to simulate the rising demand of materials storage and transportation caused by the outbreak of regional emergencies, remove the failed nodes in the network and update the network status;

Step 4 Redistribute the load of the failed node to its neighboring nodes, and update the network state;

Step 5 Judge the node state, and judge whether the load of each neighboring node θ_M of the failed node exceeds its node capacity. If not, end the cascading failure process, and turn to Step 6; if exceeded, carry out a new round of cascading failure process, and remove the failed nodes from the network. Then turn to Step 4;

Step 6 After the cascading failure process ends, calculate the network efficiency E and the maximum connected subgraph ratio S to evaluate the invulnerability of the network.

(5) Cascade failure analysis of emergency material transportation network

Considering that the frequent epidemic situation causes the regional demand for emergency materials to fluctuate greatly, this paper uses a variety of attack strategies such as random attack, point weight attack, betweenness attack and importance attack to simulate and analyze. The supply result under normal attack and cascade failure is shown in Figure 5, where $\alpha = 0.5, \beta = 1.6$ is taken.

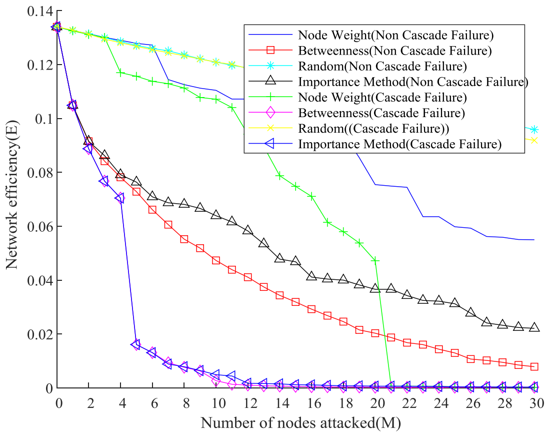

Fig 5: Changes of network efficiency under different attack modes

Fig 5 shows the change of network efficiency of logistics warehousing network under different attack strategies in the case of non-cascading failure and cascading failure. By observing the above results, we can find that: the first six nodes can influence the robustness of the network to the greatest extent.

It can be seen that under the non-cascading failure random attack, the network efficiency drops slowly, which indicates that the random failure has little effect on the overall operation of the networkin a small range, but it will also have a greater impact on the network with the expansion of the failure scale. When the number of removed nodes reaches 30, the network efficiency is only 71.6% of the initial efficiency. However, in the case of cascading failure, the random attack strategy is adopted, and there is little difference between the decline of network efficiency and the trend of non-cascading failure. In the face of deliberate attacks, the network efficiency drops rapidly. In the case of non-cascading, when the number of removed nodes is 10, the network efficiency under the betweenness attack and the importance attack drops to 2.24% and 3.73% of the initial efficiency, respectively, and the network efficiency drops suddenly. This can be explained that these attacks remove important stations in the network, thus triggering multiple rounds of load redistribution process, causing multiple stations to fail, which has a great impact on the network efficiency and leads to the network. This phenomenon also shows that these attacked stations are particularly critical in the network, and play a key role in connecting the logistics and warehousing network, and that the failure of nodes with high importance will bring more serious consequences to the whole network. In the case of cascading failure, attacking the top five important stations will reduce the network efficiency to 11.94% of the initial network efficiency, while attacking the top 12 important stations will reduce the network efficiency to 1.27% of the initial efficiency. Betweenness attack and degree attack will also cause great damage to the network. When the number of attackedstations reaches 20, the network efficiency will decrease to 0.75% of the initial efficiency, and the network will be devastated and unable to operate normally.

The scale change of the maximum connectivity subgraph of the emergency transportation network under different attack strategies is shown in Fig 6. Under the random attack strategy, the downward trend of the maximum connected subgraph is slow. But when the number of removed stations reaches a certain number, once the key stations fail and there is cascading failure, most of the remaining stations in the network will fail and become isolated stations, resulting in a sharp drop in the proportion of the maximum connected subgraph. Under the attack strategies including degree attack, betweennessattack and importance attack, the proportion of the maximum connected subgraph changes significantly. In the case of cascading failure, when the number of removed stations is 15, the maximum connection proportion of the network drops to 1.39%, 98.16% and 96.68% respectively, and the network connectivity is greatly affected;in the case of non-cascading failure, when faced with three attack strategies, the connection proportion of the maximum subgraph of the network decreases rapidly in the early stage, then changes little and decreases steadily as a whole.

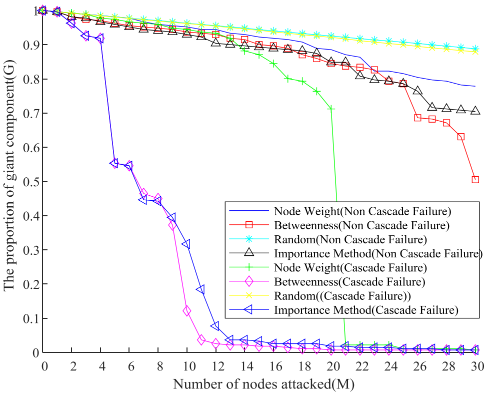

Fig 6: Relative sizes of maximal connected subgraphs under different attack modes

In addition, the tolerance coefficient α and the limit coefficient β will have an impact on the cascading failure robustness of the network. Fig 7 and Fig 8 respectively shows the influence of the number of removed stations on the proportion of the maximum connected subgraph in the emergency materials transportation network when A and B take different values. It can be seen that with the increase of A and B, the decreasing trend of the proportion of the largest connected subgraph in the network slows down. This is because with the increase of tolerance coefficient and limit coefficient, the limit capacity of storage stations will increase, and the probability of cascading failure of emergency materials transportation network will decrease. The impact of station failure on the network will decrease, and the robustness of cascading failure of the network will be enhanced. When the storage and transportation demand in a certain place increase and the limit capacity is limited, it is reflected that the gap between sum is relatively reduced, which will lead to the increased probability of cascading failure of the network. Therefore, when rebuilding and expanding logistics storage stations, for key stations, capacity should be appropriately increased to a certain extent on the basis of meeting the daily storage flow demand, so as to reduce the influence range of cascade failure of stations, enhance the invulnerability of logistics storage network and ensure the reasonable operation of logistics storage network.

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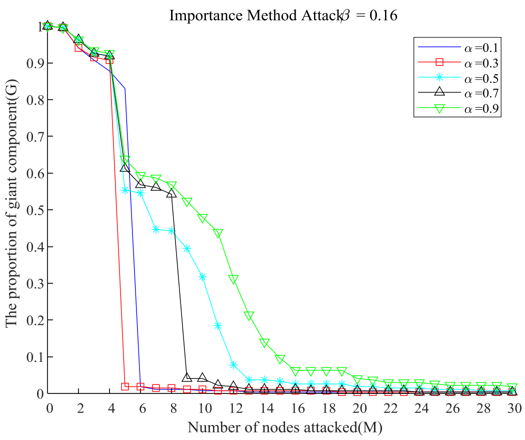

Fig 7: Scale change of maximum connected subgraph under different tolerance coefficients

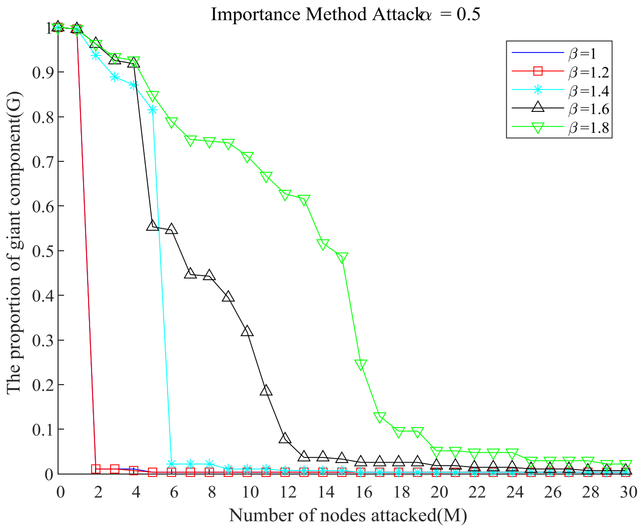

Fig 8: Scale change of maximum connected subgraph under different limit coefficients

From the above analysis, it can be seen that the emergency material transportation network shows certain robustness under random attack, but it has strong vulnerability under deliberate attack. And the vulnerability is more obvious when considering cascading failure. This shows that the emergency material transportation network can basically maintain operation in the face of random attacks such as equipment failure, natural disasters and emergencies. But the network will completely collapse under deliberate sabotage such as terrorist attacks. Therefore, we must carry out the security protection of important sites to ensure the safe operation of the logistics storage network.

III. CONCLUSIONS AND PROSPECTS

Based on the complex network theory, this paper constructs the topological structure of the emergency materials storage and transportation network in Hubei Province by using the Space-L method, puts forward the comprehensive evaluation indexes of station importance by combining degree centrality and betweenness centrality, excavates the important stations of the emergency materials storage and transportation network, establishes the cascading failure model of the emergency materials storage and transportation network, and empirically analyzes the complex characteristics and cascading failure robustness of the emergency materials storage and transportation network in Hubei Province.

The results show that: 1) The average shortest path of the emergency material transportation network is short and the emergency material transportation is convenient, but the clustering coefficient is low and the network fault tolerance is poor. Once the node fails, there will be fewer alternative lines, which will have a great impact on the operation of the whole emergency material transportation network. 2) In L-space, the cumulative degree distribution of emergency material transportation network nodes obeys the power law distribution, which has the characteristics of scale-free network; 3) The emergency material transportation network is robust under random supply, but vulnerable under deliberate supply. The vulnerability is more obvious when considering cascading failure, so it is necessary to strengthen the daily maintenance and safety protection of key stations; 4) During the reconstruction and expansion of the transportation network of emergency materials, for key stations, capacity should be appropriately increased to a certain extent on the basis of meeting the demand of daily shipments. The standby capacity of storage stations should be improved to ensure the safe operation of the storage and transportation network of emergency materials under emergencies.

In this study, the topological characteristics of the network and the cascading failure process are analyzed from the physical level, and the transportation network of emergency materials under the prevention and control of COVID-19 is abstractly analyzed, with the aim of summarizing the valuable experience of emergency materials storage and transportation support in China, and at the same time giving full play to the important role of cold-chain logistics infrastructure in the emergency materials support system. However, this study still has the following limitations: 1) The transportation network between different nodes has been simplified, and the complex transportation relationship between different nodes in reality has not been fully displayed; 2) The actual transportation cost and actual road conditions are not considered. Therefore, in the follow-up research work, further in-depth research should be conducted in combination with the actual investigation, so as to truly combine complex scenes with theories.

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