

Research Article

Cascade Failure Model in Multimodal Transport Network Risk Propagation

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The cascade failure theory is introduced into the risk propagation problem of the multimodal transport network in order to study the inherent law of risk propagation and provide theoretical support for the safety management of multimodal transport networks. Firstly, this paper analyses the characteristics of the multimodal transport network and concludes that the risk of the multimodal transport network belongs to failure risk. Secondly, the applicability of cascade failure theory is expounded. Based on cascade failure theory, a risk propagation model of the multimodal transport network is established. Through simulation experiments, the risk propagation of the multimodal transport network is analyzed from the differences of node distribution and node type. The process is analyzed, and the results show that different node distributions and different types of risk source nodes will have an impact on the risk propagation process. The influence of four types of node distributions on the risk propagation effect is in the following order: increasing type > concave-convex type \approx balanced type > decreasing type. The influence of four types of source nodes on the risk propagation effect is in the following order: transportation type > transporting type > storage type > assistant type.

1. Introduction

Multimodal transport is a mode of transport that China is focusing on. It plays an important role in the development of the country. Multimodal transport refers to the effective connection of two or more modes of transport to provide the whole process of integrated organization of cargo transport services. Multimodal transport network is a complex network involving transport nodes, transport connecting edges, transshipment nodes, and transshipment connecting edges. Each node contains different safety risks, which together constitute the safety risk system of the multimodal transport network. In the safety risk system, the phenomenon of risk propagation is widespread. With the increase of network complexity, the degree of association between nodes becomes stronger. Once a node fails, the risk will spread rapidly to the associated nodes, which will cause multiple node failures in the multimodal transport network, causing network paralysis, affecting the speed and quality of cargo transport, and affecting the normal operation of social economy. Therefore, the study of the risk propagation law of

the multimodal transport network can understand the speed and direction of risk propagation in the multimodal transport network, which is conducive to the control of security risk of multimodal transport, the reduction of network node inefficiency after failure, and the effective management of multimodal transport networks.

For the study of multimodal transport, scholars mainly focus on the optimization of the transport organization mode of multimodal transport [1–6], the layout of facilities and stations [7, 8], policies, laws, and regulations [9–12], and related technical applications [13–16]. At present, the cascade failure problem of the multimodal transport network is still blank, but there are plenty of studies on urban transport networks. Zhong and Shuai [17] established a cascade failure model of the dangerous goods transportation network under serial attack and took the node survival rate and relative secondary cascade failure as the evaluation factors. Liu et al. [18] proposed a cascade failure model of the urban traffic network under emergencies, and the initial load was determined by the incremental loading method under multipath probability. Peng [19] constructed a cascade model of

the urban road traffic network based on the disaster propagation dynamics, with the number of collapsed nodes and the node repair rate as the evaluation factors. Zhang et al. [20] analyzed the influence of different factors on the network and obtained the importance of different factors affecting the cascade failure process in the traffic network. Qian et al. [21] studied the effects of time delay and self-healing on cascade failure in traffic congestion. In a multimodal transport network, nodes no longer refer to the intersection of roads but the intersection of different modes of transport. Compared with urban transport networks, multimodal transport networks have poorer connectivity and stronger correlation between nodes. After the node fails, the effect of the failure will be more intense. Therefore, it is of great practical significance to study the cascade failure of the multimodal transport network.

In terms of methods, for the study of cascade failure theory, Wang and Rong [22] studied the impact of the initial load strength of different nodes on the network under the two attack modes of the US grid. Cao et al. [23] compared the effects of three link-adding strategies to improve network robustness in the network structure, and the results show that the low-polarization linking strategy is most effective. Jiang and Ma [24] believed that the key for improving network robustness against cascading failures is to maximally defend cascade propagation with minimum total extracapacity of all nodes and discussed three general extracapacity distributions including degree-based distribution (DD), average distribution (AD), and random distribution (RD). They proposed a novel SC-based local load redistribution mechanism to improve the cascade defense ability of the network and confirmed the effectiveness of the SC local load redistribution method. Jiang et al. [25] proposed two extracapacity distributions including degree-based distribution and average distribution and compared the effects of four heuristic algorithms to discover key sets of nodes in the network, including the high-degree-first (HDF) algorithm, low-degree-first (LDF) algorithm, random algorithm (RA), and greedy algorithm (GA). The results show that the greedy algorithm can efficiently find the set of key nodes in both scale-free and random networks. The existing research results are based on the consistency of nodes in the network, and the initial load strength and node distribution rules of the network are studied. However, in the multimodal transport network, there are several different types of nodes corresponding to different attributes, which can cause different cascading failure effects when a node fails. The authors believe that the node attribute is similar to the initial load strength and node distribution rules, and it is the key factor affecting the cascading failure effect in the network. Therefore, it is a new research idea to study the impact of different attributes of nodes on the network.

2. Risk Characteristic Analysis of Multimodal Transport Networks

In the process of risk propagation in the network, different network topology structures will bring significant difference to the propagation process. Only when the power of risk

propagation exceeds the threshold of the network, it can spread in the network [26]. According to the conclusion of Lei [27], the multimodal transport network can be approximated to the scale-free network. Because of the low propagation threshold in the scale-free network, network risk will be easier to spread.

According to a different nature of risk propagation, network risk can be divided into two types: infectious risk and failure risk [28]. Infectious risk refers to the risk that will spread between adjacent nodes with a certain probability and eventually lead to the infection of the whole network, such as food quality risk. Failure risk refers to that when the nodes in the network are affected by internal or external factors, the load on the failed nodes will transfer to the associated adjacent nodes, and the adjacent nodes may fail beyond their maximum load, which will lead to cascade failure so that the risk has an impact on the whole network, such as traffic congestion risk.

The multimodal transport network is a complex network composed of different transport agents, including multiple nodes, edges, and transshipment nodes. When the risk in the network affects the node, the node will absorb certain risk by its resistance. When it exceeds the safety threshold of the node, the node will fail. And the load on the failed node will transfer to the associated adjacent node. The adjacent node may fail because of the increase of the load and exceed the maximum load, and then the risk will be propagated downward, which makes the risk affect the whole network. Therefore, it can be considered that the risk characteristics of the multimodal transport network are similar to those of failure type and belong to failure risk.

3. Applicability Analysis of Cascade Failure Theory

In this paper, the load-capacity model in cascade failure theory is adopted, which includes the node failure model [29], edge failure model, and node-edge hybrid failure model. It represents cascade failure phenomena caused by different failure sources and can quantify failure risk propagation phenomena in multimodal transport networks comprehensively. This paper uses the node failure model to study.

The characteristics of the multimodal transport network are compared with those of cascade failure theory, as shown in Table 1.

From this table, we can see that the characteristics of the multimodal transport network and cascade failure theory have obvious consistency. Therefore, cascade failure theory can be applied to the risk propagation of multimodal transport networks.

4. Establishment of Risk Dissemination Model

4.1. Model Hypothesis

- (i) Each node in the multimodal transport network has a certain safety threshold, and the influence of internal and external environments within the safety threshold can be digested by the node itself. If the

TABLE 1: Feature comparison.

—	Composition	Risk types	Propagation process	Propagation subject	Risk resistance
Multimodal transport network	Nodes, edges, and transshipment nodes	Failure risk	Adjacent nodes/edges	Cargo	Yes
Cascade failure theory	Nodes and edges	Failure risk	Adjacent nodes/edges	Load	Yes

safety threshold is exceeded, the failure risk will be brought.

- (ii) Each node has a certain self-repairing ability. When affected by the risk, the node can resolve the risk through self-repairing.
- (iii) According to a different nature of node operation, it can be divided into the transport node, storage node, auxiliary node, and transshipment node.
- (iv) In the process of risk propagation, the self-repairing function of nodes is not considered.

4.2. Model Establishment. In the multimodal transport network $G = (V, E)$, the set of nodes $V = \{v_1, v_2, \dots, v_n\}$, the set of edges $E = \{e_1, e_2, \dots, e_m\}$, the safety threshold of the node i is S_i , and different types of nodes have different safety thresholds. When $t = 0$, the initial load of the node i is L_i and the maximum load is C_i . The following formula can be obtained according to the ML model, in which β is the variable parameter:

$$C_i(0) = (1 + \beta)L_i(0). \quad (1)$$

Generally, the states of nodes can be divided into "normal," "overload," and "failure" [30]. When the node v_i is affected by the internal and external factors, the difficulty of load passing through the node will change because of the change of the node state. In this paper, overload function $F_i(t)$ is used to express the difficulty of load passing through nodes:

$$F_i(t) = \begin{cases} 1, & L_i(t) \leq L_i(0), \\ 1 + \frac{L_i(t) - L_i(0)}{C_i - L_i(0)}(N - 1), & L_i(0) \leq L_i(t) \leq C_i, \\ N, & L_i(t) > C_i, \\ N^2, & \text{failure.} \end{cases} \quad (2)$$

In multimodal transport networks, different states of nodes lead to different load allocation modes. When the node v_i fails because of a fault, all loads on the node need to be redistributed and distributed to adjacent nodes according to the proportion of edge weights. Let ω_{ij} be the weight of the edge between v_i and v_j :

$$L_j(t + 1) = L_j(t) + \frac{\omega_{ij}L_i(t)}{\sum_{k=1}^{k_i} \omega_{ik}}. \quad (3)$$

When the node v_i is overloaded, the part of the node that exceeds the maximum load needs to be reallocated:

$$L_j(t + 1) = L_j(t) + \frac{\omega_{ij}(L_i(t) - C_i)}{\sum_{j=1}^{k_i} \omega_{ij}}. \quad (4)$$

When the load exceeds the maximum load C_j of the node v_j , the excess part will continue to propagate to the adjacent nodes until the load of all nodes in the network is within the maximum load, and the cascade failure ends.

In this paper, the proportion of abnormal nodes and average network efficiency are used to measure the effect of risk propagation in multimodal transport networks.

4.2.1. Proportion of Abnormal Nodes. Let the total number of nodes in the multimodal transport network be N , in which the total number of abnormal nodes is N_f and the proportion of abnormal nodes is R_f . The higher the proportion, the stronger the risk propaganda in the multimodal transport network or otherwise the weaker the risk propaganda in the multimodal transport network:

$$R_f = \frac{N_f}{N}. \quad (5)$$

4.2.2. Average Network Efficiency. Average network efficiency E is used to measure the connectivity of multimodal transport networks. When the nodes are in the abnormal state, the higher the average network efficiency is, the weaker the dissemination of risk in the network is or otherwise the stronger the risk propagation is. d_{ij} represents the path with the highest load trafficability between node v_i and node v_j , and $P(i, j)$ represents the set of all paths between node v_i and node v_j .

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{d_{ij}}, \quad (6)$$

$$d_{ij} = \min \left\{ \sum_P F_p(t), \quad p \in P(i, j) \right\}.$$

5. Risk Propagation Simulation

5.1. Simulation Process. In this paper, the effect of risk propagation in multimodal transport networks is analyzed from the difference of node distribution and node type, and the node types include transshipment, storage, auxiliary, and transportation. Different types of nodes have different

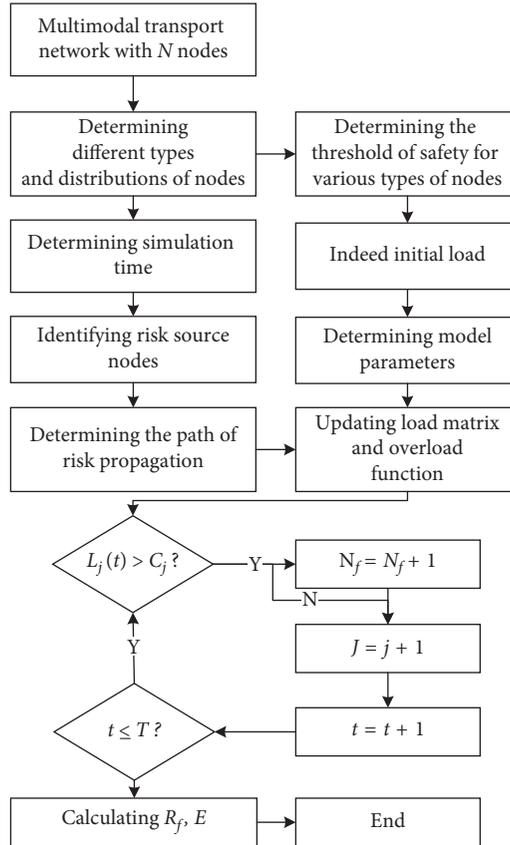


FIGURE 1: Simulation process.

TABLE 2: Node parameter considerations.

Node type	Effects	Facilities and equipment	Redundancy	Expansion measures
Auxiliary node	Used for loading, unloading, handling, distribution processing, and information processing of goods in multimodal transport networks	Software and hardware facilities such as forklifts, work vehicles, conveyors, and information admission systems	Little	Accelerating operational efficiency
Storage node	Used for the storage of goods	Hardware facilities for pallets and shelves	Normal	Utilization of temporary storage areas
Transshipment node	Used for loading, unloading, handling, etc. of goods at the intersection of two modes of transportation	Hardware facilities for cranes and conveyors	Much	Infrastructure equipment between different modes of transport can be used with each other
Transport node	Transport operation for goods	Transport vehicles	More	Meeting the transportation demand by adjusting the number of transport vehicles

maximum load values. The node states include normal, overload, and failure. The simulation process of risk propagation in multimodal transport networks is shown in Figure 1.

5.2. Analysis of Simulation Results. In this paper, the total number $N = 500$ of multimodal transport network nodes is set. Based on the field investigation and questionnaire survey of multimodal transport stations, the parameters of different types of nodes can be set according to the factors shown in Table 2.

Considering the factors in Table 2, we can get that the parameters β of auxiliary, storage, transshipment, and

transport nodes are 0.1, 0.3, 0.5, and 0.7, respectively. Different proportions of failure nodes are set up to simulate the multimodal transport network under different conditions, and the risk propagation law in the multimodal transport network can be studied from many aspects and perspectives.

5.2.1. Analysis of Risk Dissemination Effects under Different Node Distributions. In multimodal transport networks, different functional preferences can lead to a diverse distribution of node types. The initial load values of auxiliary, storage, transshipment, and transport nodes are the same

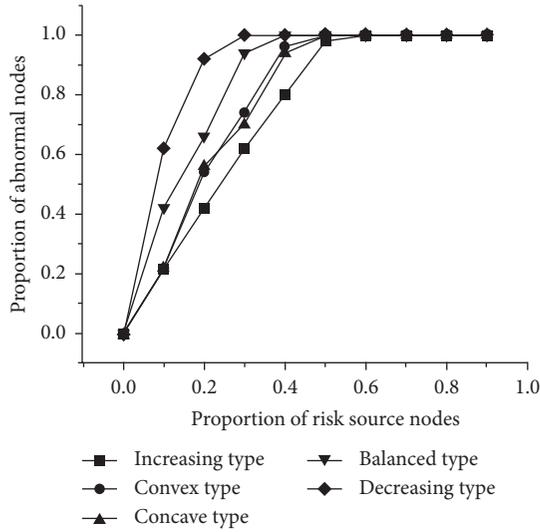


FIGURE 2: Proportion of abnormal node states with different node distributions.

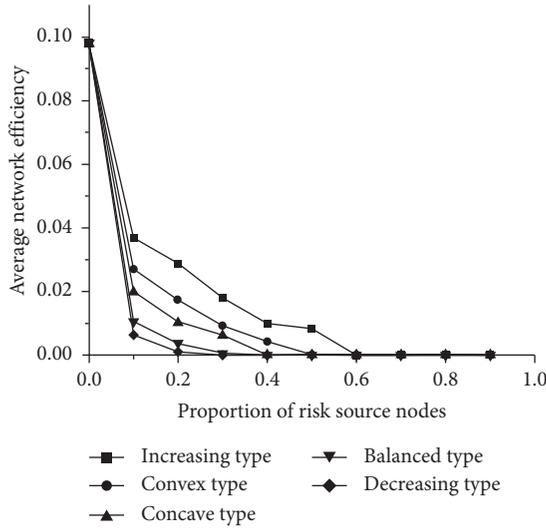


FIGURE 3: Average network efficiency with different node distributions.

under the stable state of the network. According to different proportions of nodes in the multimodal transport network, the distribution of nodes can be expressed as the balanced type (auxiliary node:storage node:transshipment node:transport node=1:1:1:1), increasing type (1:2:3:4), decreasing type (4:3:2:1), convex type (1:2:2:1), and concave type (2:1:1:2).

From Figures 2 and 3, it can be seen that the multimodal transport network with different node distributions presents different proportions of abnormal nodes and average network efficiency. When the proportion of risk source nodes is more than 60%, the multimodal transport network presents a complete failure state. At this time, the nodes of the whole network fail or are overloaded, and the average network efficiency is almost 0. When the proportion of risk source nodes is less than 60%, the order of the proportion of abnormal nodes from large to small is increasing

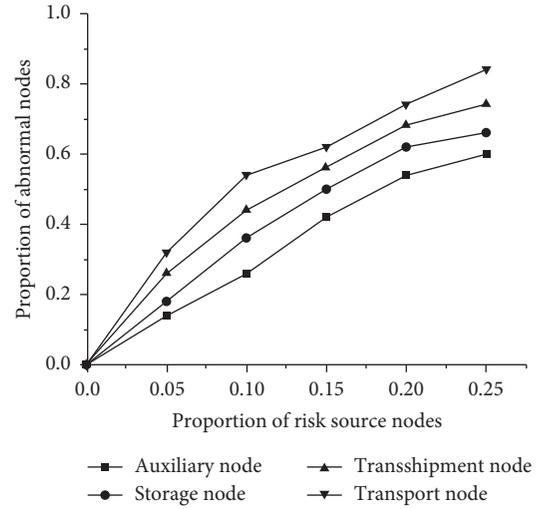


FIGURE 4: Proportion of abnormal node states with different node types.

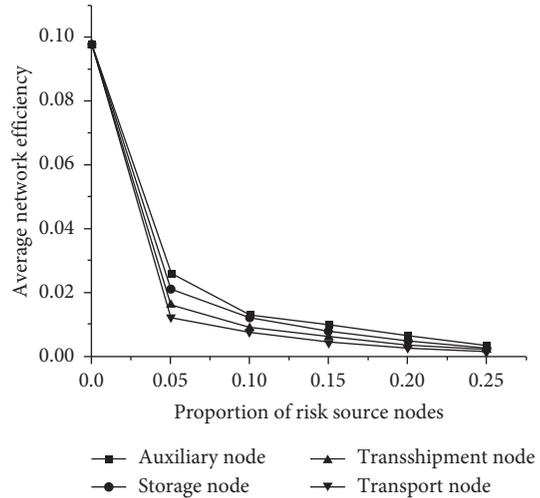


FIGURE 5: Average network efficiency with different node types.

type > concave type > convex type > balanced type > decreasing type. Meanwhile, the order of average network efficiency is the same as that of abnormal nodes. Therefore, in the multimodal transport network, the risk spreading range of the increasing network node distribution is smaller, and the risk spreading range of the diminishing network node distribution is larger. It can be considered that the increasing network node distribution has higher stability, while the diminishing network node distribution has the opposite.

5.2.2. *Effect Analysis of Risk Propagation under Different Types of Risk Source Nodes.* Different types of risk source nodes will also affect the risk propagation effect in multimodal transport networks. Under the condition of balanced network node distribution, if the risk source is set as a single similar node, the proportion of abnormal nodes and the average network efficiency can be obtained, as shown in Figures 4 and 5.

Under the distribution of balanced network nodes, the proportion of each type of the risk source node varies from 0 to 0.25. From Figures 4 and 5, when other conditions are the same, different types of risk source nodes will bring different risk propagation effects. It can be seen that the order of the proportion of abnormal state nodes is transport type > transshipment type > storage type > auxiliary type, and the order of average network efficiency is the same. It shows that different types of risk source nodes will affect the risk transmission effect of the multimodal transport network and only its change range, but will not change its trend. In the multimodal transport network, the state change of the transport node has the greatest impact on the risk propagation in the whole network, and the auxiliary node has the least impact.

6. Conclusion

In this paper, the cascade failure model is applied to the multimodal transport network, and risk propagation in the multimodal transport network is studied. By establishing a mathematical model, the effect of risk propagation is evaluated by the proportion of abnormal nodes and the average network efficiency. The simulation results show the following:

- (1) Different node distributions will affect the risk propagation effect of multimodal transport networks. When the proportion of risk source nodes is more than 60%, all the nodes in the multimodal transport network are in a state of failure or overload. The average network efficiency is almost 0, and the network completely fails. When the proportion of risk source nodes is less than 60%, the stability of the increasing network is the highest, and the diminishing network is the most unstable. The impact on the effect of risk propagation from large to small is increasing > concave > convex > balanced > diminishing.

Different types of risk source nodes will also affect the risk propagation effect of multimodal transport networks. When the network fails completely, the failure of the transport node will cause a wider risk propagation in the same proportion of risk source nodes, while the failure of the auxiliary node will have the smallest impact, and the impact on the effect of risk propagation from large to small is transport > transshipment > storage > auxiliary.

Data Availability

All data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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