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Empirical Research on Vulnerability Assessment of Supply Chain Network Based on Cascading Effect*

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Abstract. The growing complexity of the supply chain brings benefits as well as vulnerability. The research on the reasons of vulnerability of the supply chain and the evaluation method is the premise of implementing effective management measures. Based on cascading effect, complex network theory is applied to model the supply chain network and evaluate the importance of supply chain node enterprises. For an important node, its failure will cause great cascading effect to damage the supply chain, which reveals the vulnerability of the supply chain network. In this paper, the empirical analysis shows that this method can accurately identify the visible critical nodes, and it is also able to find hidden important nodes, which helps offer guidance for the protection of node enterprises, thus to reduce the vulnerability of supply chain.

Introduction

With the increasing complexity of supply chain and the uncertainty of the operating environment, supply chain network is facing various stability challenges and even some micro disturbances may lead to serious problems of the whole supply chain network. Therefore, it is urgent to implement necessary protection measures for supply chain. But before the protection of supply chain network, we need to evaluate the vulnerability of supply chain network and find the key node enterprises in order to achieve the least investment and the best protection.

Currently, there are many scholars engaged in research on the vulnerability of supply chain [1,2]. According to Christopher's theory [3], the vulnerability of the supply chain was defined as the serious interference caused by the exposure of the supply chain networks to the endogenous and exogenous risks. Peck [4] considered that the vulnerability of supply chain is closely related to the risks and vulnerability is the tendency of supply chain to suffer loss and destruction when faced with risks. Ning [5] analyzed supply chain vulnerability and seven main influence factors, such as demand fluctuation, trend of globalization, centralization of production distribution and so on, are determined. He also put forward three management principles to solve the problems of the vulnerability of supply chain. Shi et al. [6] built a theoretical framework of the effect of attitudinal commitment between supply chain cooperative partners on the vulnerability of supply chain. They made statistical test by enter hierarchical regression analysis, and drew a conclusion that loyal commitment between supply chain cooperative partners can significantly reduce the vulnerability of the supply chain. Li et al. [7] analyzed some characteristics of supply chain network, and revealed the generating mechanism of vulnerability of supply chain network and proposed prevention strategies. Chen [8] divided the vulnerability of the food supply chain into two kinds and proposed interventions based on supply chain integration. Based on the process model of system vulnerability, Zhang et al. [9] discussed the node failure mode, edge failure mode and supply chain vulnerability. From the perspective of system and network, Jiang et al. [10] analyzed network topology structure of the system and defined the node load and vulnerability coefficient. Alamoudi et al. [11] proposed a model to assess the vulnerability of supply chain networks to disturbances, based upon topography and interconnectedness of various resources in the networks. Wagner et al.

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[12] discussed and defined the concept of supply chain vulnerability and compare supply chain vulnerability for various categories of firms. Neureuther et al. [13] developed a model of risk, called the risk assessment index, to assess the vulnerability of different supply chain structures.
Most of the study of supply chain vulnerability mentioned above are analyzed by qualitative methods, few of them can quantitatively make direct assessment for the vulnerability of supply chain. This paper considered the complex and dynamic characteristics of supply chain network and made an evaluation and empirical analysis of the supply chain network vulnerability by modelling complex network based on cascading effect. According to the actual situation of the supply chain network, a reasonable and effective evaluation method is proposed to identify the important nodes, which can help managers and decision-makers to understand the dynamic situation of the supply chain network risks, and accurately locate the specific nodes that need to carry out risk management.
The structure of this paper is as follows: Firstly, the theory of cascading effect in the supply chain network is introduced and its effects are analyzed. Next, the evaluation index of the cascading effect in the supply chain network is determined and the procedures of node importance assessment are given. Finally, the validity of the model is verified through a case study.

Problem Description and Model Formulation

Analysis of Cascading Effect in the Supply Chain Network

Supply chain contains material flow, information flow, cash flow and so on, which are called loads. When the supply chain network is under some kind of interferences, functions of some node enterprises in the network may be impaired, then it will cause the change of network conditions. The loads in the network will also change the original running state and find new ways of circulation according to certain guidelines and reallocate. The situation of node enterprises on the load bearing capacity therefore changes. The fixed maximum capacity of node enterprises may lead to unbalanced loads and bearing capacity, which causes adverse reactions of node enterprises. To circulate repeatedly, many node enterprises' functions will be impaired, the network will then show vulnerability, which is called the cascading effect.
It is evident that cascading effect exists widely in the supply chain network, which is the root of the vulnerability. Thus, it can be concluded that, if a node enterprise's loss of efficacy can cause serious cascading effect and has a strong negative impact on supply chain network, it is an important node.

Model Hypotheses

1. The external supply and demand of supply chain network model is stable. It means that there is enough and stable raw material supplies and consumer demands.
2. All node enterprises only pursue the maximization of economic benefits and take no account of the actual load bearing capacity as long as there is a profitable business.
3. No elasticity of supply chain network [14], which means that the supply chain network does not have the ability to repair itself after its functions were impaired.
4. No consumers in the model. Because consumers contain too many irrational factors

Determination of Evaluation Index

When a cascading effect occurs, the most direct expression is the change of the overall efficiency of the network. Network efficiency is a physical quantity used to describe the nodes transfer ability in the complex network. The definition of network efficiency [15] is: supposing V is a set of points, E is a set of edges and the network model is expressed as $G=(V,E)$. Let e_{ij} and d_{ij} are connection efficiency and the shortest path between node i and j, respectively. And the one is inversely proportional to the other, that is $e_{ij}=1/d_{ij}$. If there is no connectivity between node i and j, then d_{ij} tends to infinity and e_{ij} tends to zero. Network efficiency can be expressed by the following formula:

$$E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} e_{ij} \qquad (1)$$

In which, N is the number of nodes in the network. In the actual supply chain network, d_{ij} can be regarded as business costs. Meanwhile, in order to compare the importance of nodes, we can standardize the network efficiency [16] as the following formula:

$$I_i = 1 - E_i / E_0 \qquad (2)$$

In which, I_i is the importance of node i, E_0 is the network efficiency during normal operation and E_i is the network efficiency after the cascading effect caused by node i.

Load and Load Bearing Capacity of Nodes

Most models in scholars' past studies about cascading effect use betweenness to reflect the load of the network topology [16,17]. The concept of the shortest path is fit for the lowest cost concept of supply chain network. Therefore, the functional form of betweenness can be used to represent the node load. The formula is as follows:

$$C_B(i) = \sum_{p \neq q \in V} \sigma_{pq}(i) / \sigma_{pq} \qquad (3)$$

In which, σ_{pq} is the sum of all the shortest paths between node p and q, $\sigma_{pq}(i)$ is the number of shortest paths passing node i between node p and q. Meanwhile, the p and q in the formula (3) can both equal to i [18].

This paper also applies betweenness to reflect the load and the load of each node is defined as:

$$L_i = C_B(i) \qquad (4)$$

If a node enterprise's load bearing capacity is infinite and no matter how much load it bears, the node enterprise can still maintain the same pass efficiency and cost, then the cascading effect will never happen. Obviously, this is only an ideal state in the real supply chain network. Because the node enterprise's load bearing capacity is related to the investments and the investments must be infinite if the node enterprise wants to reach this infinite capacity, which does not conform to the economic law. Each node in the supply chain network has its capacity limitation, and there is a certain proportional relationship between the maximum load bearing capacity and initial load. Therefore, the maximum load bearing capacity can be defined as:

$$C_i = (1 + \alpha) L_i(0) \qquad (5)$$

In which, C_i is the maximum capacity of node i, $L_i(0)$ is the initial load of node i, α is the tolerance factor and $\alpha > 0$.

Procedures of Node Importance Assessment

The assessment process draws on the idea of "importance is proportional to destructiveness". But in the process of simulation of cascading effect, nodes in the network will not be deleted directly.

On one hand, it maintains the integrity of the supply chain network in order to reflect the overall performance; on the other hand, it retains part of the functionality of the ineffective nodes. Moreover, the sum of the shortest paths will stay the same, which can help us compare before and after state of the network.

According to the three states in the process of supply chain network cascading effect, changes of node state can be divided into three stages. The first stage is from normal to overloaded. In this stage, no node lose efficacy, but some of the nodes overloaded. The network will eventually be balanced. The second stage is from overloaded to partial failure. In this stage, some of the nodes lose efficacy and the network is in a cascading failure status and will eventually form a new equilibrium, too. But the status of nodes which lose efficacy are unchanged. The third stage is from partial failure to complete failure. All the nodes lose efficacy and the network is in a state of collapse.

Cascading failure process expresses through the change of edge weights which are connected to the nodes. Linear overloaded function F_i can indicate the change of edge weights caused by the change of the load state of nodes. Linear overloaded function formula is as follows:

$$F_i(t) = \begin{cases} F_i(t-1) & L_i(t) \leq \max\{L_i(t-1),...,L_i(0)\} \\ Q_0 + \dfrac{L_i(t) - L_i(0)}{C_i - L_i(0)}(M - Q_0) & \max\{L_i(t-1),...,L_i(0)\} < L_i(t) < C_i \\ M & L_i(t) \geq C_i \end{cases} \quad (6)$$

In which, F_i is the edge weight that starts or ends with node i, Q_0 is the initial weights of the corresponding edges in the model and $F_i(0) = Q_0$ and M is an arbitrary dimensionless number, which means that the biggest cost that passes through the node.

Procedures of node importance assessment are as follows:

1. Choose research object. This paper chooses a typical supply chain network model.
2. Determine the edge weights according to the length of the edges between nodes and form a network with directions and weights.
3. Lists the adjacency matrix of the network structure model as A_0. If node i and j are not directly connected, then let $a_{ij} = inf$.
4. According to the formula (3),(4),(5), calculate the betweenness $C_B(i)$, initial load $L_i(0)$ and node capacity C_i of each node in the network,
5. Floyd algorithm is an algorithm to find the shortest path between multiple source nodes in a given graph. So, Floyd algorithm is applied to operate on the adjacency matrix and the matrix D_0 of the shortest distance between each node can be got. Then calculate the normal network efficiency E_0 according to the formula (1).
6. Let a node V_k lose efficacy, then the weight of the edges connected to node V_k become M and a new network with directions and weights is formed.
7. Recalculate the remaining nodes' load $L_i(t)$ in the network according to the new network with directions and weights. Then according to formula (6), recalculate the weight of each edge, is forming a new network with directions and weights.
8. Repeat step 7 until $F_i(t) = F_i(t-1)$. That is each weight of node remains unchanged.
9. Calculate the network efficiency E_k, then calculate the node importance I_k according to formula (2).
10. Repeat steps 6 to 9 until get all the node importance, then sort them.

Case Study

There are two milk sources of Mengniu Dairy. One is from ranches, the other is from dairy farmers who feed cows around ranches. The production processes are shown in figure 1.

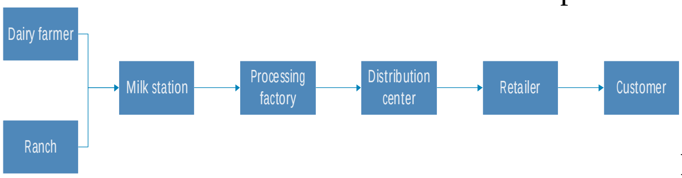

Figure 1: Production Flow Chart of Mengniu Dairy

The supply chain of Mengniu Dairy can be abstracted into a network model as figure 2:

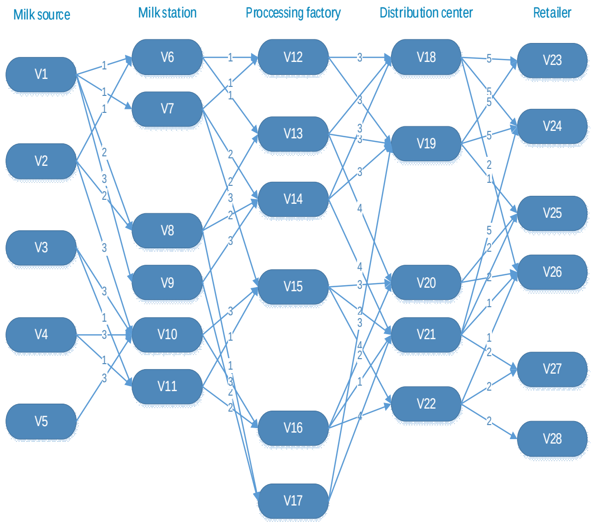

Figure 2: The Supply Chain Network Model Diagram of Mengniu Dairy

The network structure in figure 2 can be divided into five layers, from left to right in the order: milk source(dairy farmer V_1, V_2; ranches V_3, V_4, V_5), milk station($V_6, V_7, V_8, V_9, V_{10}, V_{11}$), processing factory($V_{12}, V_{13}, V_{14}, V_{15}, V_{16}, V_{17}$), distribution center($V_{18}, V_{19}, V_{20}, V_{21}, V_{22}$) and retailer($V_{23}, V_{24}, V_{25}, V_{26}, V_{27}, V_{28}$).

Suppose $\alpha = 0.2, M = 10$, assessment results of the Mengniu Dairy based on the method in section 2.5 is shown in table 1.

Table 1: Results of Node Importance Assessment

Node	Cascading Effect Method			Betweenness Method	
	Cascading Effect Process	Importance	Rank	Betweenness	Rank
V_1	1-8-17-9-13-14-15-18-20-22	0.4168	17	20	8
V_2	2-14-15-18-20-22-8-9-17	0.3502	19	20	9
V_3	None	0.0464	22	12	20
V_4	None	0.0464	23	12	21
V_5	None	0.0141	27	11	23
V_6	6-7-8-17-9-10-14-16-18-22	0.5161	6	19.33	12
V_7	7-8-14-9-10-20-22-16	0.4548	12	12.17	19
V_8	8-9-14-12-15-19-20-22-7	0.4551	11	9.5	25
V_9	9-14-19-20-8-12-22-13	0.4656	8	3	28
V_{10}	10-9-14-12-19-20-16-22	0.4429	13	21	6
V_{11}	11-10-16-15-9-14-12-19-20	0.6009	1	24	5
V_{12}	12-13-14-8-16-17-20-22	0.4208	16	19.33	13
V_{13}	13-12-8-14-15-17-18	0.4576	9	17.42	16
V_{14}	14-8-12-20-7-10-16-22-18	0.4345	14	7.5	26
V_{15}	15-8-14-16-9-13-19-7	0.5710	2	33.75	2
V_{16}	16-15-9-14-18-8	0.5463	4	30	3
V_{17}	17-14-7-12-15-20-22	0.4121	18	19	14
V_{18}	18-19-20-9-14-16-22-8	0.4561	10	18.75	15
V_{19}	19-14-18-19-20-8-16-17-22	0.5131	7	30	4
V_{20}	20-8-14-16-13-19-22	0.4236	15	5	27
V_{21}	21-14-20-22-7-9-13-16	0.5516	3	47.25	1
V_{22}	None	0.0581	21	15	18
V_{23}	None	0.0107	28	12	22
V_{24}	None	0.0182	25	20	10
V_{25}	None	0.0693	20	20	11
V_{26}	26-8-17-20-13-22	0.5299	5	21	7
V_{27}	None	0.0385	24	16	17
V_{28}	None	0.0177	26	11	24

By analyzing the above assessment results, it is evident that most important node enterprises are processing factories and distribution centers, accounting for the top 10 important node enterprises about more than 50%. Most of those enterprises are in the middle reaches of supply chain, which contact more with upstream and downstream enterprises. Their businesses are more frequent and they are more sensitive to the changes of load. In addition, milk station V_{11} and retailer V_{26} have great influence on the supply chain. Comparing with the betweenness assessment methods, the method based on cascading effect can identify the important nodes which are relatively obvious, such as V_{15}, V_{16}, V_{21}. Furthermore, it can also find the hidden important nodes, such as V_{9}, V_{14}, V_{20}. The betweenness of those nodes are not high, but their loss of efficacy will trigger a serious cascading failure effect, leading to a serious impact on the network and reducing network operational efficiency. Hence, for the important nodes, more protection should be taken in order to reduce the vulnerability of the whole supply chain.

Conclusion

The assessment method based on cascading effect considers the dynamic nature of supply chain network and the principle of cost minimization, which is more consistent with the actual conditions of supply chain network. Meanwhile, this method can comprehensively consider the whole network and find some hidden impotent node enterprises. The empirical analysis based on Mengniu Dairy further reflects the superiority of this method. By evaluating the importance of node enterprises in the supply chain can provide effective recommendations for the prevention of node failure, promote the process of protection for important nodes and reduce the vulnerability of the supply chain network effectively thus reducing risk and economic losses.

The research of this paper also has some limitations. Although the selection of production enterprise as the representative object of case study, but the supply chain structure and pattern of different industries may be different. In addition, this paper has not studied the recovery ability of the supply chain after suffered cascading effect. The simulation method can be applied to study the mechanism. To sum up, the above deficiencies can be further improved in the follow-up study.

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