The Research of Single_NODE Risk Spread in Supply Chain Complex Network Based on Fixed Risk Values

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Abstract

Complex networks cannot only describe the complicated, asynchronous system, but also can be used to model and analyze network topological properties. Sophisticated methods for network construction and analysis exist in other fields. But until recently, researchers have few focused on the risk spread of a supply chain network. In this paper, a supply chain risk network based on single_node risk spread is modeled and the static network statistics are analyzed, including degree distribution, risk distribution, average path length and clustering coefficient. The simulation results indicate that supply chain complex network is a small-world network with short average path length and high degree of clustering, and its degree distribution and risk distribution follow a double power law. In addition, the average risk tends to decrease with the total number of risk node increase in supply chain risk spread network.

Keyword

Supply Chain; Complex Network; Single_node Risk Spread; Modelling and Simulation

Introduction

Supply chain is an integrated network where suppliers, sellers and customers are highly interconnected through material/product flows, information flows, and financial flows. In supply chain, it has many tiers which provide goods or services to the next similar level tier. Moreover, each tier may have multiple components or members, and the flow of goods is linear.

With the rapid development of economic globalization, various factors of uncertainties create risks which can impact the proper functioning of the enterprise such as procurement risk, production risk, financial risk, marketing risk and outsourcing risk. As a kind of effective mode in the market competition, the supply chain has already been accepted by a lot of enterprises. Due to its structural characteristics, there exists great risk. As a potential threat, supply chain risk may take advantage of its vulnerability to destruct the supply chain system, and finally bring damage and loss for the entire supply chain upstream and downstream enterprises. Therefore, risk is the main problem of supply chain enterprises.

Complex network describes a wide range of systems in nature and society. It is an important tool to describe and analyze the changes between each factor. The relationship of supply chain members provides a channel to transmit the risk variations of suppliers and customers and therefore the liquidity risks are rampant along supply chains. A lot is infected if one object in it is infected. To describe this phenomenon, we employ computer software to analyse the laws of risk spread evolution based on single_node risk.

The rest of this paper is organized as follows: In the next section, there is a brief literature review relating supply chain risk and complex network risk research. In Section 3, we design a supply chain risk network and describe the risk spread based on single_node risk and its connection mechanism. In section 4, some basic concepts of the complex network are introduced in this paper, such as degree distribution, risk distribution, average path length, and clustering coefficient. In Section 5, a simulate experiment of single_node risk spread to observe indicators changes is showed. Finally, we offer some concluding remarks in Section 6.
Literature Review

Supply Chain Risk

Supply chain is an integrated network wherein a number of various business entities work together in an effort to acquire raw materials, convert into final products, and deliver them to customers. As a complex system, it is especially vulnerable to a variety of risks. Risk sometimes interpreted as the probability of loss due to danger, damage, loss, injury or any other unreliable and uncertain consequences. In view of its great significance, there has been increased attention focused on supply chain risk from various directions.


However, the risk is random, independent, and spread along the upstream to downstream node enterprise. Recently, many researches pay more attention to the spread in supply chain.

Fabrizio Natalea et al build a movement network to simulate epidemic spread. They analyze degree, in-degree and out-degree distribution of the nodes and show average number of infected nodes. Monique A. van der Gaaga Fred Vosa design a detailed stochastic state transition model and analyze its characteristics. Mathilde Paula et al focus on the spread process of HPAI H5N1 and provide a stochastic state-transition simulation model which described the spread of Salmonella from multiplying through slaughter. Houyuan Ye point out that the risk spread are divided into five types: bubble burst, elements scarce, collapse of structure, tsunami and chain reaction. Guoping Cheng and Qin Liu research on the occurred conditions of close coupling and the changes in the amount of risk caused by close coupling.

In summary, the research of the risk spread is still little. Most scholars focused on the risk spread of supply chain in a certain respect. It is an undeniable fact that it has a certain reference value to the similar enterprises, but the application range is parochialism. In this paper, we analyse the rules of risk spread evolution in the entire supply chain, through a definite transmission routes.

Complex Network Risk

Networks provide a new angle of view to express relationships between constituent elements how to change. Graphs can be used to create a visual image of network interior movements.

Disease remained an overarching concern for all scientists. To use complex network is one of the effective methods to study the spread of disease. The two most common models are SIR and SIS in a wide variety of disease transmission model. However, each of these has particular features, so corresponding extended models arise.

Mathieu Moslonka-Lefebvrea, Marco Pautassoc and Mike J. Jegerec establish in directed networks at four levels of competence in six network structures (local, small-world, random, one-way, uncorrelated, and two-way scale-free networks). Mario Ventresca and Dionne Aleman estimate contagion spread using social network characteristics. They study the effect of the six mitigation strategies on the degree distribution and local clustering coefficients. D. Mayera, J. Reiczigela and F. Rubela simulate the airborne spread of foot-and-mouth disease virus using Lagrangian particle model which take into account the realistic orographic and meteorological conditions.

Like the disease spread, the information spread is the object of researchers’ focus either, especially in the epoch of information. M. Nekoveea and Y. Morenob et al. introduce a general stochastic model for the spread of rumors, and use some equations to analyze the threshold behavior and dynamics of the model on several models. Laijun Zhao, Hongxin Cui et al redesign a flow chart of the rumor spreading process with the SIR model, and simulate the process of rumor spread in the new media age. Laijun Zhao, Qin Wang et al study a rumor spreading model called Livejourna which provide a more detailed and realistic description of rumor spreading process with combination of forgetting mechanism and the SIR model of epidemics.

The network conceptual framework and graph-theory-analytic framework have been very useful for the description and analysis of the disease and rumour spread. This approach could be applied in many directions. Such the mature approach provides
reference experience for the spread of supply chain risk.

The Supply Chain Risk Model

Basic Element
The network conceptual framework has been very useful for the description and analysis of the risk of transmission. Now, we will present the basic definitions of the components of risk network:

i) Risk source: risk source is the node enterprise which generates risk. The origin of risk by classification can be divided into external risks which caused by external environment and internal risk which caused by internal operations.

ii) Risk nodes: in supply chain network, each risk enterprise can be called as risk node. According to the difference of risk source, risk nodes can be divided into conduction node and risk receiver.

iii) Risk carriers: risk carriers are “mediums” or “bridges” which can transmit risk from one node to another. For different properties of risk carriers and risk source attribute, risks have had transmitted dependent on different medium.

iv) Conduction pathways: it can be defined as the logical distance of risk transmitted from one node to another. The supply chain risk conduction path is based on “Supplier --- Manufacturer --- Dealers --- Consumers”.

v) Risk threshold: the risk threshold is a value that determines whether the node enterprises can normally transmit material/product, information and finance. In the supply chain network, each enterprise itself has a constant risk threshold value regardless of how much it received risk.

The Risk Supply Chain Network Model

1) Supply Chain Network
To observe the rules of risk spread in a network, a network is generated randomly. A weighted network is represented as a graph \( A=(V,E) \) with a set \( V \) of \( n \) node enterprises connected by \( M \) edges which are randomly chosen from the \( n(n-1)/2 \) possible edges. New nodes, which connected to \( m \) existing nodes with a certain probability, are added sequentially until the network reaches the required size.

It is worthy of note that the risks are spread along with the material/product flows, information flows, and financial flows. That means there are business relationships among each node enterprise. One risk node enterprise will establish business relation with others. One randomly chosen node was initially designated as a source risk. At each time step, each node was considered in a fixed order. The spread of risks begins in suppliers, passing sellers and finally deliver to customers. If exceed risk threshold, the node could potentially infect any or all of its neighbours, with a given probability. Once infected risk, a part of risk node enterprise will control them, and others continue to repeat the process.

2) Definition of Node
In the supply chain network, each node is assumed to be a risk enterprise, and each edge was assumed to be a method of spread of the risk from one risk node enterprise to another. Each business entity is represented by a node. The node of supply chain complex network is defined as \( \text{v}=(\text{ID}, \text{Category}, \text{Level}) \); ID is the number of node in supply chain. Category is the label of node; the nodes are divided into three categories as suppliers, sellers and customers. The level of node shows the business order in supply chain, the customer’s level is bigger than seller’s and the seller’s level is bigger than the supplier’s.

Generation Process

1) The Selection of Local World
According to the categories and level of nodes, there are three ways to select:

a) When the new added node is supplier, it will establish business relation with other suppliers or sellers, so all the suppliers and sellers are selected as its local world.

b) When the new added node is seller, it will establish business relation with suppliers; customers or other sellers, so all nodes of the network are selected as its local world.

c) When the new added node is customer, it will establish business relation with sellers, so all the sellers are selected as its local world.

2) Connection Mechanism
At each step of the evolution, generate a number of edges and connect them together by adding new node, or, to put it another way, a new added node can establish business relation with \( k \) nodes by
The Degree Statistic Characteristics for the network.

In this paper, one must take into consideration that the node’s risk value may affect its probability proportional of node connection. A new node connects to existed node within its local world by

\[
p(k) = \frac{\prod_{l \in A} r(l)^{r(k)}}{(m-1)^{\prod_{l \in A} r(l)}}.
\]

Here, \(m\) is the total number of risk nodes, \(r(k)\) is the risk value of new node, \(r(l)\) is the risk value of all its associated node. \(A\) is the ultimate supply chain network.

**Modelling Process**

The supply chain network model based on risk connection is generated by the following algorithm:

1) Start with a small number \(m_0\) of nodes and confirm the risk of node, the edges, direction and its risk spread probability.

2) A new coming node enters into the supply chain network, select its local world from the existing network.

3) The new coming nodes connected with existed nodes by probability \(p(k)\).

4) Repeat 2), 3) until the number of nodes in the network reaches to \(N\).

**Statistical Characteristics for the Parameters**

**Degree**

The degree which be described by \(k\) is one of the most important topology attributes of complex network. \(k\) is the number of nearest neighbours a node. It has two components: in-degree \(k_{in}\) (the number of incoming edges) and out-degree \(k_{out}\) (the number of outgoing edges). In supply chain risk network, \(k_{in}\) means the supply channel and \(k_{out}\) means the sale channel.

The distribution function \(P(k)\) is the probability that a node has degree \(k\). It describes the network’s topology properties and consequently can expound the mechanisms of structure’s evolution. \(P(k)_{in}\) is the probability that a node has \(k\) incoming edges directed to itself (probability of supply chain from \(k\) supply channel), \(P(k)_{out}\) is the probability that a node has a total of \(k\) edges to other nodes (probability of supply chain to \(k\) sale channel). Most networks have degree distributions, which have a power law tail \(P(k) \sim k^{-\alpha}\).

**Risk**

Risk sometimes also known as vulnerability, disruptions or disturbances. All those can have negative impacts. Risk probability interpreted as a chance of risk emerging. It is a measurement data.

The change of risk probability obeys three distributions: normal distribution, triangular distribution and \(\beta\) distribution. The difference between the three applications is the variable property. Normal distribution represents the variation of general economic variables, the change of random variable is described by \(\beta\) distribution and triangular distribution can indicate any of them.

Any type of risk is uncertain. Before analyze them, we should make a general judgment to significance and the most intuitive approach is to compare the size of risk probability. According to the change of risk personality, variation tendency can be seen on the whole network.

**Average Path Length**

The average effective path length \(L_s\) of the network represents the minimum distance between a lowest-level supplier and a customer. It’s defined to be the average value:

\[
L_s = \frac{1}{c} \sum_{i,j} d_{ij}
\]

Here, \(d_{ij}\) is the average shortest effective path length from lowest-level supplier \((k=0)\) to customer, \(c\) is the number of links between them.

From the above formula, it can be seen clearly that with \(c\) decrease \(L_s\) increase. \(L_s\) indicates the network’s performance. The smaller \(L_s\) is, the shortest reaction time there are. In supply chain risk network, the flow of product, information or financial will be interrupted under the influence of risk. They may not have an opportunity to pass down and then choose another path. Therefore, its shortest path length is changed. In this paper, the average path length is actually minimum distance in sub-supply chain.

**Clustering Coefficient**

In supply chain network, a positive clustering coefficient indicates that nodes with similar degrees tend to be connected with each other closer. On average, the likelihood of a node being infected by risk increased with a positive clustering coefficient.

The Clustering coefficient \(C_i\) is defined as the
proportion of number of links shared by the neighbor node, which is adjacent to each other.

\[ C_i = \frac{1}{k_i-1} \sum_{j,k} \frac{w_{ij} + w_{jk}}{2} \left( a_{ij} + a_{jk} \right) \]

Where \( k_i \) is the degree of node i; \( w \) is the weight of edges between two nodes, including \( \omega_{ij} \) and \( w_{ij} \); \( a_{ij} = a_{jk} \) respect there is an edge between nodes i, j and k. The default value is 1 if there is a connection between two nodes, otherwise it is 0.

Average clustering coefficient \( C \) measures the prevalence of local connections in supply chain risk network. It is defined by:

\[ C = \frac{1}{N} \sum C_i \]

Under the influence of the risk, the effective clustering coefficient will wave violently, and the value of average clustering coefficient perhaps not by much.

Simulation Experiment of Single_Node Risk Spread

Preferences

The enactment of parameters in supply chain risk network model is generated by the following algorithms:

a) Set up 30 nodes in the initial network, and the number of suppliers, sellers and customers’ edge is set as 3, 5, 3, respectively;

b) Set up a threshold for every node at random;

c) Suddenly increase the risk value of a single node over 50%;

d) Perform the simulation with the Initial Parameters. Each experiment is performed 50 times and took the average;

Specific parameters will be described in TABLE 1.

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<th>Experiment number</th>
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Degree Distribution

FIG. 1 is the double logarithmic distribution graphs of supply chain risk network node degree. We can see that most of node enterprises degree is relatively small, yet a minority of the degree of node enterprises is very big.

![Degree Distribution](image)

FIG. 1 THE DEGREE DISTRIBUTION OF SUPPLY CHAIN NETWORK BASED SINGLE_NODE RISK

In FIG. 1, we find that the degree distribution of supply chain network follows a power law distribution. The power-law exponent of all nodes degree distribution \( \gamma_{\text{degree}} = -1.41 \pm 0.05 \). That means the most business entities have relatively less business relation with other entities, but few have a large number of business relation with other entities.

In supply chain risk network, the degree of a node defined to show its ability and prominence. The larger degree, as a supplier, means it has power supply capacity; as a seller, means it has more supply channel and sales leads; as a customer, means it has more purchase funnels and stronger purchase capital. Above all, the larger the degree of a node and the closer it connect with others. The node with larger degree has more opportunity to build business relation with new added enterprise and finally become “core enterprise”.

Risk Distribution

We can see that the node enterprise risk distribution obeys the power-law distribution which manifest in FIG. 2. It shows that the distribution of the “risk” of the nodes of risk movement network is heavy-tailed. Most of node enterprises degree is relatively small.

In FIG. 2, we find that the risk distribution of supply chain network also follows a power law distribution. The power-law exponent of all nodes risk distribution \( \gamma_{\text{risk}} = -1.44 \pm 0.05 \). That means the most business
entities have relatively lower risk, but few have a large risk. The node with large risk will cause the unstable of supply chain.

![Graph showing the risk distribution of supply chain network based on single node risk](image)

**FIG. 2** THE RISK DISTRIBUTION OF SUPPLY CHAIN NETWORK BASED SINGLE_NODE RISK

![Graph showing the relationship between degree and risk](image)

**FIG. 3** THE RELATIONSHIP BETWEEN DEGREE AND RISK

From FIG. 3, we can find that there is no distinctive linear relationship between degree and risk. It reflects two sides: (1) the most business entities have relatively lower risk and its risk value trend fluctuates above and below 40, but few have a large risk; (2) the most business entities have relatively lower degree (k<20), but few have a large degree (k>20). That means the degree and risk distribution follow a power law distribution.

**The Scale of Node Risk**

From FIG. 3, we can find that the number of risk nodes is increasing, and the total numbers of risk nodes are of small proportion from 0.14% to 7.9%. That means risk will travel along conduction carriers to other enterprise nodes.

From the FIG. 4, we can easily come to the conclusion that the number of risk nodes is increasing first, then decreasing and finally remain unchanged in the same time period.

At the beginning of the risk spread of supply chain, most of the associated risk nodes are especially vulnerable to the single risk node. A supply chain network with a small scale will exhibit fast risk spread. However, each node enterprise has a certain risk thresholds. The growing risk nodes cannot be increased without limitation. At each step, a proportion of risk will be control until they complete be dissolved. So overall, the total numbers of risk nodes are increasing and finally tended to be stable.

![Graph showing the number of risk node and its percentage based single node risk](image)

**FIG. 4** THE NUMBER OF RISK NODE AND ITS PERCENTAGE BASED SINGLE_NODE RISK

**Average Risk**

FIG. 5 shows the tendency of average risk. Average risk increases with time and its slope performs increasing previously and decreasing later.

![Graph showing the average risk in supply chain network based single node risk](image)

**FIG. 5** THE AVERAGE RISK IN SUPPLY CHAIN NETWORK BASED SINGLE_NODE RISK

From FIG. 5, we can find that the size of average risk is...
decreased from 40.24 to 40.69. That means a part of risk will be control by them, and others continue to attack their associated risk nodes. The invasive risk will cause the unstable of supply chain.

**Average Path Length**

The path length indicates the typical number of intermediate links between any two randomly chosen vertices. From TABLE 2, we can find the average supply chain path length is nearly to 4.2541 with scale of supply chain increasing. We can see that while the network scale grows larger, the average effective path length tend to become smaller, which means that the risk node enterprises have faster reflect and shorter response time.

**Average Clustering Coefficient**

Clustering has been shown to be a network feature relevant to risk spread. From the network structure, different scales of supply chain have different average clustering coefficient. With the scale of supply chain increased, the average clustering coefficient C is nearly to 0.0015. The result show the supply chain has a low average clustering coefficient C which manifest TABLE 3.

**Conclusions**

Networks are not only relevant for many current issues but have found application in a variety of supply chain systems. In this paper, we used a computer model to simulate the risk spread based on single_node risk in supply chain network. By means of analytical statistic characteristics and numerical results, we show that: (1) Degree distribution and risk distribution has the same variation rule that all of them follow a double power law; (2) There is a positive correlation between the number of risk node and average risk. (3) This supply chain risk network is a small-world network which characterized by a short average path length and high average clustering. The interaction between the statistical properties of the network and the results of risk spread is of certain reference value for similar network.

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