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Research on Supply Chain Network Risk Management Based on Multi-layer Complex Network Model

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Abstract: As necessities in people's lives, the stability and quality safety of the production and circulation of agricultural products are widely of concern to the whole society. With the development of economic globalization, networking and informatization, the structure and dynamic behaviour of the agricultural product supply chain are becoming increasingly complex. A concept increasingly central to supply chain theory is sustainability. As the frontier of network science, complex network theory provides a new method to study complex real networks. This paper adopts the complex network theory to explore the formation and evolution mechanism of the agricultural product supply chain network and the risk propagation mechanism on the supply chain network through modelling and simulation. On this basis, it proposes the control strategy of risk propagation. The research in this paper can enrich the results of complex network theory in the field of supply chain based on ecological theory. The network model construction can reveal the formation and evolution mechanism of the agricultural product supply chain network. The analysis of risk dynamics can provide a theoretical basis and practical guidance for controlling risk propagation of agricultural product supply chain networks.

Keywords: Multi-layered, complex network, supply chain, network risk, control strategy

1. Introduction

China is a nation with a large populations, and agriculture is the basic industry. As a necessity of the daily life of residents, the production and circulation of agricultural products are related to both rural income and development as well as people's livelihood and price level (Wang et al. 2008, Fu & Liu 2011, Lv et al. 2013). With rapid developments of the economy and improvements in people's living standards, new periodical changes are occurring to the lifestyles and consumption structures of urban and rural residents, and significant and deep changes are happening in the consumption demands of people on agricultural products. Changes in market demands and agricultural production techniques bring relevant changes to agricultural product production, circulation and management (Yang & Zhang 2013).

A concept increasingly central to supply chain theory is sustainability. Calls to create more sustainable supply chain practices have led to significant theoretical advancements across supply chain management, business ethics, and related fields (Xu et al. 2016, Sheng et al. 2016, Shen 2017, Zhang et al. 2017). Moreover, a variety of firm-driven sustainability efforts have been produced from these advancements, such as the design of eco-friendly products (You & Grossmann 2016), product life extensions (Yan et al. 2016), environmental life cycle inventory and assessment (Bilir et al. 2017), and closed-loop supply chains (Basole et al. 2017). Nevertheless, important theoretical strides must be made if scholars are to direct research and practice toward creating sustainable supply chains that operate within the carrying capacity of their supporting natural ecosystems. Such theoretical strides are particularly important for increasingly globalized companies. In this context, it is crucial to mitigate or altogether avoid issues such as the exploitation of cross-country differences in environmental regulations, large environmental footprints, and compliance issues arising from implementing codes of conduct (Fattahi et al. 2017).

To lead the way toward creating sustainable supply chains, we develop a theory of socio-ecological intergradation. In the context of supply chains, socio-ecological intergradation recognizes the link between the supply chain and the natural systems. Socio-ecological intergradation is the merger of the organizational and environmental dimensions. Socio-ecological intergradation is built on accepting organizations as an integral part of ecosystems and invokes nature as a source of new ideas for designing more sustainable operational processes. We employ "intergradation" rather than "integration" to capture the gradual merging of the social and ecological dimensions to result in a more harmonious, interdependent and sustainable relationship. We borrow the term from zoology and related fields, which refers to how species can gradually share characteristics and merge (Ledwoch et al. 2018). During the intergradation process, a sharing of characteristics (overlap) precedes the merging of the social and ecological dimensions, as in the merging of economics and ecological principles occurring in the emerging field of ecological economics (Pavlov et al. 2018).

Consumption demands of agricultural products are converting to functionalization, diversification, branding and greenization, and demands of markets in agricultural, processed and high-end products are increasingly growing. Developments of agricultural technologies and logistics industries increasingly enrich varieties of agricultural products and provide more choices to consumers, and product diversification also promotes consumption demands. From 1995 to 2015, the population gross of China constantly kept rising with a small amplitude, while total demands for basic agricultural products like grains and vegetables, etc., declined; comparably, demands for nutritious products like fresh fruits, meats, eggs and dairy products, etc. keep growing, which indicates that demands of national residents on agricultural products have been transforming from basic products to functional ones. Another prominent change is that concerns of the whole society on food safety in recent years have reached an unprecedented level; thus agricultural quality safety has become an important influence factor during product circulation and sales processes, and branded and green agricultural products have become a developing trend for agricultural products (Kumar et al. 2017).

Modeling and simulation are tried in this thesis based on features of agricultural supply chains through complicated network theories to discuss the inner mechanisms of the formation and evolution of agricultural product networks and analyze structural features of networks of agricultural product supply chains. Based on this, transmission dynamic mechanisms of various risks in networks of agricultural product supply chains are further researched in this thesis, threshold values and important nodes of risk communications are analyzed, and relevant risk control countermeasures and suggestions are put forward. The research meanings of this thesis contain theoretical and practical meanings.

This paper adopts the complex network theory to explore the formation and evolution mechanism of the agricultural product supply chain network and the risk propagation mechanism of the supply chain network through modelling and simulation.

2. Materials and Methods

2.1. Significance Evaluation Model of Supply Chain Enterprises

Model Description. The core thought of a multi-index strategy evaluation model based on TOS is to see each enterprise as a strategy and to see the multiple indexes in evaluations of enterprise significance as properties of each strategy, then map significant degrees of enterprises through comparison between optimal strategies and worst strategies of an enterprise.

First, a significance index matrix for enterprises in supply chain networks must be established. Assume that there are N enterprises in supply chain networks and s enterprise significance evaluation indexes, through which a strategy set $E=\{E_I;\cdots;E_N\}$ and a strategy index set $F=\{F_1;\cdots;F_s\}$ can be formed through respective correspondence. Record the j^{th} significance index of the i^{th} enterprise as $E_i(F_j)$, which constitutes a significant index matrix of enterprises in supply chain networks.

$$G=\begin{bmatrix} E_1(F_1) & \cdots & E_1(F_s) \\ \vdots & \ddots & \vdots \\ E_N(F_1) & \cdots & E_N(F_s) \end{bmatrix} \tag{1}$$

Due to different index dimensions, standardization disposals need to be done, and detailed processes are as follows:

$$e_{ij}=E_i(F_j)/\sum_{i=1}^{N}E_i(F_j) \tag{2}$$

A standardized significant index matrix is recorded as $G^*=(e_{ij})_{N^*}$.

Secondly, confirm the optimal strategy index set H^+ and worst strategy index set H^- based on standardized Matrix G:

$$\begin{cases} H^+=\{\max(e_{11},\cdots,e_{N1}),\cdots,\max(e_{1s},\cdots,e_{Ns})\}=\{e_1^{\max},\cdots,e_s^{\max}\} \\ H^-=\{\min(e_{11},\cdots,e_{N1}),\cdots,\min(e_{1s},\cdots,e_{Ns})\}=\{e_1^{\min},\cdots,e_s^{\min}\} \end{cases} \tag{3}$$

Thirdly, calculate the differences between each strategy and the optimal and worst strategies:

$$\begin{cases} L_i^+ = \sum_{j=1}^{s} \left| e_{ij} - e_j^{\max} \right| \\ L_i^- = \sum_{j=1}^{s} \left| e_{ij} - e_j^{\min} \right| \end{cases} \tag{4}$$

Finally, calculate close degree T_i with optimal strategy and measure significance degrees of enterprises according to the value of T_i, to realize quantitative comprehensive evaluations on enterprise significance:

$$T_i = L_i^- / \left(L_i^- + L_i^+ \right) \tag{5}$$

The larger the value of T_i is, the closer the strategy is with optimal strategy, and the higher the mapped enterprise significance degree will be. The smaller the value of T_i is, the farther the strategy is with optimal strategy, and the lower the mapped enterprise significance degree will be.

Cross-layer Evaluation on Risks in Supply Chain Networks. Influence factor information in supply chain risk systems is a kind of grey information; in practices of risk evaluations, the occurrence rate and risk degree of several events are impossible to describe accurately. As a kind of method integrated with qualitative and quantitative analysis, comprehensive fuzzy evaluation can reflect the risk degrees of different factors in detail and make more comprehensive and objective evaluations of supply chain networks affected by multiple factors.

Based on the above comprehensive evaluations of the significance of enterprises, the enterprise significance index is taken as an important parameter of risk evaluations for supply chain networks, through which a comprehensive evaluation model of risks in supply chain networks is established based on fuzzy theory. Based on multilayer comprehensive fuzzy evaluation theory, the risk factor set that causes abnormal events for Enterprise i is defined as $U_i = \{u_{i,1}, u_{i,2}, \ldots, u_{i,n}\}$, to confirm uniformity of judgments, evaluation ranks of all node enterprises are kept in conformity, which are set as $V = \{v_1, v_2, \ldots, v_m\}$. For each risk factor in *U*, a fuzzy evaluation is conducted by an expert panel consisting of several experts integrated with grade indexes of judgment set, and a judgment matrix *n* x *m* aimed at Enterprise i is acquired:

$$R_i = \begin{bmatrix} r_{i,11} & r_{i,12} & \cdots & r_{i,1m} \\ r_{i,21} & r_{i,22} & \cdots & r_{i,2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i,n1} & r_{i,n1} & \cdots & r_{i,nm} \end{bmatrix} \tag{6}$$

Of which $r_{i,xy}$ is the proportion of experts who think that risk factor $\mathrm{U}_{i,\mathbf{x}}$ causes Grade v_y, which refers to membership of $\mathrm{U}_{i,\mathbf{x}}$ towards $\mathrm{U}_{i,\mathbf{x}}$. Meanwhile, an expert panel should score for the significance of all risk factors and form a risk prime weight matrix $P_i = \{p_{i,1}, p_{i,2}, \ldots, p_{i,n}\}$ of 1×*n,* and the reliability evaluation result of Enterprise Z_i can be acquired through the judgment matrix R_i and weight matrix P_i:

$$Z_i = P_i \cdot R_i \tag{7}$$

Evaluation grades of all node enterprises (total number is *N*) form a risk judgment matrix R^* of $N \times m$ aimed at risks in supply chain networks:

$$R^* = [Z_1; Z_2; \ldots; Z_i; \ldots; Z_N] \tag{8}$$

Then solve the weight coefficient q_i of all node enterprises based on Formula (8) and acquire the weight matrix Q^* of enterprises in supply chain networks.

$$\begin{cases} q_i = T_i / \sum_{i=1}^{N} T_i \\ Q^* = \{q_1, q_2, \ldots, q_N\} \end{cases} \tag{9}$$

Finally, acquire evaluation results of comprehensive risks in supply chain networks:

$$Z^* = Q^* \cdot R^* \tag{10}$$

According to the maximum membership principle, the reliability grade corresponding to the maximum value of Z^* is reliability judgment result of a supply chain network.

2.2. Scale-free Characteristics of Supply Chain Networks

Algorithm Structure. A scale-free network is one in which degrees of network nodes are heterogeneous, that is, there are few hubs in most nodes, which contain large sums of connections, linking numbers of nodes in networks show a serious unbalance, only a few hub nodes play a leading role in network operations, and scale-free networks manifested a robustness towards random impacts and a vulnerability towards specific hub impacts. Degree distribution of scale-free network nodes meets:

$$\log \mathrm{P(k)} \propto -\lambda \log \mathrm{k} \tag{11}$$

Of which *P(k)* is a probability distribution in supply chain networks with a node degree of *k*, and *λ* is a fixed coefficient for a certain supply chain network.

A supply chain network is a typical scale-free network whose scale-free characteristics can greatly reduce risks caused by infections and the system when the supply chain system is suffering external attacks. In contrast, external impacts aimed at hub nodes in supply chain networks will cause even more losses. The main aspect of risks is the influence of hub nodes in supply chain networks (supply chain organizations) on stability of supply chain system.

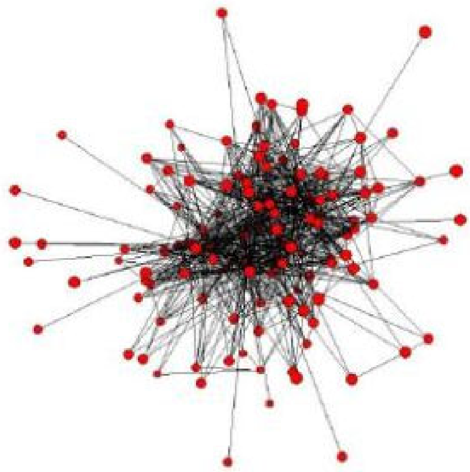

Fig. 1. Supply chain network

Figure 1 shows the Japanese inter-bank sales data network researched by Inaoka et al. in 2004, proving to be a scale-free network. Nodes with different colours in Figure 1 represent different kinds of supply chain organizations, the darkness of connecting colours represents the frequency of sales and transactions, it can be seen that large quantities of supply chain organizations only have a few connections, while a few nodes in the centre of the network have a large number of connections. A similar structure also occurred in inter-bank supply chains constituted by 125 banks in Brazil in 2007, which Rama con et al. researched in 2010. No matter seen from aspects of supply or sales, generally, supply chain organizations with a larger scale in supply chain networks will be thought more stable, as management in large supply chain organizations is more standardized, and seen from the moral aspect, governments will not close down large supply chain organizations due to reasons of supply chain risks, all of which tend to transact with large supply chain organizations; thus large supply chain organizations usually have large sums of supply chain network connections, while small ones only have a few supply chain network connections, which is also a main reason that leads to formation of scale-free networks. Figure 1 shows the Japanese inter-bank sales network structures in 2004 and the Brazil supply chain network in 2007.

2.3. PageRank Algorithm

PageRank Algorithm is the basis of the DebtRank algorithm, which is an algorithm based on the importance ranking of webpages on the internets. With webpages on the internets as nodes, a complicated network is formed with connections among webpages as sides, which was researched by Sergey Brin and Lawrence Page, doctoral candidates of Stanford University PageRank Algorithm was then put forward, and the prototype system was established. PageRank Algorithm calculates the importance of webpages of internets (PageRank value of webpages), which is the initial ranking algorithm used by Google, the internet search engine. PageRank Algorithm is based on 3 hypotheses, one is that if several webpages quote a webpage, these webpages must be importance; the second is that id a webpage is quoted by an importance webpage, then this webpage must be importance; the third is that if a user randomly visit a webpage in webpage collection without consideration backspacing functions of webpages, then product of probability for the next webpage to be connected with links of this webpage and PageRank value of it will be the PageRank value transmitted to the scanned webpages.

If there are n webpage nodes p_i, it is initially assumed by PageRank Algorithm that each webpage has equal PageRank value, which is $1/n$, calculates the new PageRank value of each webpage according to page sequence, present PageRank value of p_i, the i^{th} webpage, is $PR(p_i)$, M (i) represents webpage collection of p_i, the i^{th} webpage, $L(j)$ represents quantity of links on p_i, the j^{th} webpage, and d refers to probability for the user to continue scanning when coming to a certain webpage (it is set as 0.85 in google search engine), then compute mode is:

$$PR(p_i) = \frac{1-d}{n} + d \sum_{p_j \in M(i)} \frac{PR(p_j)}{L(j)} \tag{12}$$

Continue to execute the 2nd round of recursive computation after the 1st round is finished until the calculation result is completely convergent. W represents the adjacent matrix after the line is normalized, whose compute mode is:

$$p_i = dWp_{i-1} + \frac{1-d}{n} \tag{13}$$

2.4. Infection Algorithm based on Adjacent Matrix

Infections based on influence models think that infectious influences of a node on other nodes are conducted through an adjacent matrix. The first step in the computation of the influence model or infection model is to construct an adjacent matrix, and a propagation of network node influence is a matrix multiplication.

Assume that the owners' equity vector of each supply chain organization is $E = (E_1, E_2, \cdots, E_n)$, the infection matrix (adjacent matrix) of construction is A if no organization closes down due to infections, then losses caused for each organization through an infection is EA; if no organization closes down, losses caused for each organization through the n^{th} infection is $E(A)^n$. After the n^{th} infection, if no organization closes down, vector constituted by owner's equity of all organizations is $E(I - A - \cdots - A^n)$, of which I is a unit matrix.

The key point of the infection algorithm based on an adjacent matrix is to design a reasonable infection matrix, which can be launched in 2 ways; one is to acquire relationship among owner's equities of all organizations through calculating actual losses after the first infection, and then calculate infection matrix; the second is to analyze the relationship between infection losses and factors and acquire infection matrix, and then calculate infections caused by bank organizations.

2.5. Data sources

All data comes from on-site research, literature reviews of enterprises and industries, and software simulation.

3. Results and Discussion

The simulation parameter setting is the same as that of the powerless network, which is divided into 2 conditions: the one in which fitness obeys normal distribution and the one in which fitness obeys power-law distribution. Simulations are made on networks with a total scale of N = 500, 1000, 2000, 5000 and 8000, respectively, through which a weighting network planning of agricultural product supply chains is generated, and analysis on features of its topological structure is made to avoid disturbances of random errors, each scale is repeated for 10 times, and the average value is taken as the result of simulation experiment.

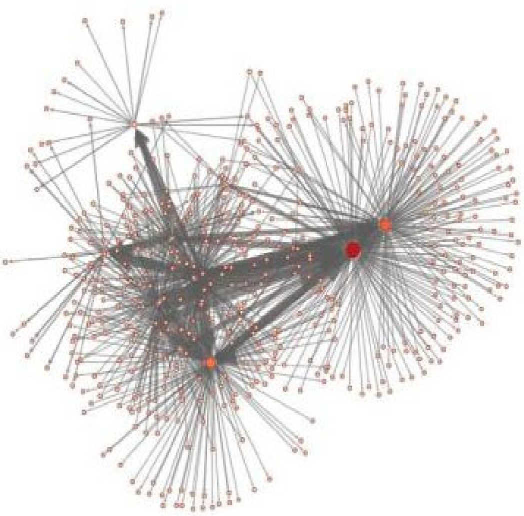

Fig. 2. Node fitness obeys normal distribution

Figure 2 shows the network simulation planning when $N = 500$ (Matlab simulation is adopted, visualization is done on Dephi), it can be seen that this is a directed weighting network, in which the thickness of lines represents the edge weight of networks, and the obvious scale-free characteristic is manifested in this network.

4. Conclusion

A concept increasingly central to supply chain theory is sustainability. This paper considers the directionality and balance of transactions in networks based on the evolution model of dual-local-world evolving network of fitness, through which a directed weighting network model of agricultural product supply chains is established. Edge weights in the model represent business volumes among nodes, node intensity represents business volumes of nodes, and construction of the model is done based on the co-ordination of supply and demand. The construction of weighting network models is more beneficial for describing features of agricultural product supply chains. Theoretical analysis is made on edge weight, node intensity, and degree distributions of weighting networks through mean-field theory. Meanwhile, data simulation, analysis, and verification of all kinds of topological structural features of networks are also done. Theoretical analysis and simulation results indicate that edge weight, node intensity and degree distributions of agricultural product weighting networks obey generalized power-law distribution, of which power exponent is decided by distribution of fitness, node proportions of different categories and selection of local world, compared with supply chain hierarchies, mean route lengths of both networks and supply chains are long, which indicates that agricultural product supply chain networks are of low efficiencies; network clustering coefficients are small, which indicates that clustering phenomenon seldom occurs to networks, which is not beneficial for cooperation among network nodes and stability of networks.

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