Research on Supply Chain Evolutionary Patterns Considering Behavioral Characteristics of Different Nodes (Postprint)

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Abstract

With the development of economic globalization, the evolution of supply chain networks has become increasingly complex. To investigate the actual evolutionary patterns of supply chains, this paper proposes a supply chain network evolution model based on the multi-local-world model from complex network theory, which incorporates both local and global nodes and reflects various behavioral elements of supply chains. The model verifies that under natural evolution, real-world supply chain networks exhibit certain power-law characteristics; through comparative analysis of computational examples, it is demonstrated that this model can better simulate real-world supply chain networks compared to evolutionary networks in existing literature. Research shows that during the natural evolution of supply chains, network connectivity and transmission efficiency continuously increase; however, as new node enterprises tend to cooperate with larger-scale enterprises while neglecting others, the closeness between nodes decreases. The closeness between enterprises and the supply chain network gradually develops to a certain extent and then stabilizes; the development speed of large-scale enterprises first increases and then slows down, while the development speed of nodes of various scales remains stable in the middle and later stages.

Full Text

Study on Evolution Law of Supply Chain Considering Characteristics of Behavior Factors of Different Nodes

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Abstract: With the development of economic globalization, supply chain networks have become increasingly complex. To investigate the actual evolution laws of supply chains, this paper proposes a supply chain network evolution model based on the multi-local world model from complex network theory. The model incorporates both local and global nodes while reflecting multiple supply chain behavioral factors. Through mean-field theory and simulation experiments, the model verifies that real supply chain networks exhibit power-law characteristics under natural evolution. Comparative analysis demonstrates that this model better simulates real-world supply chain networks than existing models in the literature. The research reveals that during natural supply chain evolution, network connectivity and transmission efficiency continuously strengthen. However, as new node enterprises tend to cooperate with larger-scale enterprises while neglecting others, the closeness between nodes decreases. The tightness between enterprises and the supply chain network gradually develops to a certain extent and then stabilizes. The development speed of large-scale enterprises first increases and then slows down, while the development speed of nodes at various scales remains stable in the middle and later stages.

Keywords: supply chain evolution law; complex network; multi-local world model; mean-field theory; simulation

Introduction

A supply chain is a functional network structure that revolves around a core enterprise, controlling material flow, capital flow, and information flow from beginning to end, connecting suppliers, manufacturers, distributors, retailers, and ultimately end users into an integrated whole. In recent years, with the rise of "distributed networked manufacturing" and the development of economic globalization, phenomena such as global procurement and transnational factory establishment have become widespread, making enterprise supply chain network structures more complex and their evolution laws more variable. This increasing complexity in supply chain network evolution has created tremendous pressure for enterprise supply chain management and coordination, making it a key focus in academic research to study supply chain evolution processes, predict supply chain trends, and reveal supply chain network evolution laws through relevant models.

Currently, domestic and international scholars have primarily used collaborative development theory, evolutionary game theory, and complex network theory to study supply chain evolution laws. Among these, complex network theory, with its powerful capabilities for analyzing network structures and evolution laws, has been widely applied to network research in various fields since Watts et al. proposed the WS small-world network model revealing the small-world characteristics of real networks, and Barabási et al. proposed the famous BA scale-free network model with "Matthew effect" revealing the scale-free characteristics of actual complex networks. In applying complex network theory to supply chain evolution research, Barrat et al. proposed a fitness model that defines each node' s fitness to reflect node characteristics in supply chain networks. Li et al. proposed a local-world evolving network model, arguing that preferential attachment of nodes occurs within a local world. Tian Si et al. proposed a novel multi-local world network model that reflects local properties and connection strengths, applying it to simulate real Internet networks. Sun Junyan et al. constructed a manufacturer-core, five-level network evolution model based on the BA model and multi-level local world model, analyzing its topological properties. Zhang Jihui et al. studied adaptive supply chains by introducing position parameters combined with node degree as the basis for inter-node selection. Liu Hong et al. proposed a layered supply chain evolution model that considers the importance of nodes at different levels and uses importance as the basis for partner selection. Cao Wenbin et al. used node degree and edge benefit as indicators for preferential attachment to construct a local-world supply chain model, providing economic explanations for supply chain network evolution at different stages. Zhang Xu et al. proposed a weighted improved node contraction method to study node importance in coal supply chain networks during evolution.

However, most existing literature on supply chain evolution laws has only considered node preferential attachment rules and fitness issues of different node types, without deeply investigating the real-world local-world properties and the influence of different node behavioral factors on supply chain evolution laws. Consequently, these studies have difficulty reflecting the impact of different node enterprises when simulating real supply chains.

Since supply chain networks are self-organizing systems with both complexity and dynamics, where nodes on the chain interact and evolve over time, and considering that in real environments there exist barriers such as geography, language, and corporate culture, enterprises cannot always select partners globally. Therefore, this paper builds upon the multi-local world network evolution model, incorporating real supply chain characteristics and evolutionary behaviors into the network model. We propose dividing network nodes into local nodes and global nodes and classifying supply chain network behavioral elements into seven categories to simulate how regional and global enterprises in real supply chain networks select partners and how behaviors may occur during supply chain development. Through theoretical analysis of the model, we verify the power-law characteristics of supply chain networks, thereby reflecting the evolution laws of real supply chain networks.

1.1 Model Description and Assumptions

Current global supply chain development trends indicate that the network nodes of large multinational enterprises continuously extend to countries worldwide, with multinational corporations and international procurement organizations becoming increasingly active and frequent in global market procurement activities. More and more large enterprises can select partners globally. However, it should also be recognized that many enterprises with weaker business scale and capabilities have smaller radiation ranges and find it difficult to cross geographical, linguistic, and other boundaries to select partners on a larger scale.

Based on this observation, this paper considers supply chain network characteristics with different types of local and global nodes on the foundation of the multi-local world network. The relevant concepts are defined as follows:

a) **Local node**: A node that can only develop within its own local world, meaning it can only select partners within a local region. This reflects the development status of some small and medium-sized enterprises in real supply chain networks.

b) **Global node**: A large node that can select partners both within its local world and globally. This reflects the ability of global nodes to establish relationships with high-fitness enterprises already existing in the supply chain.

Through research on the development history of real supply chains and analysis of supply chain node enterprise behaviors, this paper introduces the following behavioral elements into the supply chain network evolution model:

a) **New node network joining**: Enterprise groups or small supply chains with certain network structures join the supply chain network, specifically manifested as strategic cooperation between groups.

b) **New local node joining**: A small or medium-sized enterprise in the industry joins the supply chain network, and this node can only select partners within its local world.

c) **New global node joining**: A large enterprise in the industry joins the supply chain network, and this node can select partners in all local worlds within the supply chain network.

d) **New relationships within local worlds**: Two node enterprises in the same local world develop cooperation, trade, or other relationships.

e) **New relationships between local worlds**: Two node enterprises in different local worlds develop cooperation, trade, or other relationships.

f) **Node exit**: Node enterprises exit the supply chain network due to strategy or development direction changes.

g) **Old relationship disappearance**: The original cooperation, trade, or other relationships between two node enterprises disappear.

To simplify calculations, the model makes the following assumptions:

a) In the supply chain evolution model, only the above seven categories of behavioral elements are considered, and the occurrence of each behavioral element is assumed to be independent.

b) Local nodes and global nodes are assumed to have the same number of edges when joining the supply chain network.

c) All edges in the model are undirected edges.

d) The average degree in each local world of the model is $\langle MATH_0 \rangle$.

1.2 Supply Chain Network Evolution Model

1) Model Setup

The supply chain network model established in this paper is represented by $\langle MATH_1 \rangle$, mainly containing three elements: $\langle MATH_2 \rangle$ represents nodes in the network, where $\langle MATH_3 \rangle$ indicates the number of all node enterprises in the network; $\langle MATH_4 \rangle$ represents associations between enterprises, where $\langle MATH_5 \rangle$ indicates that node i and node j have an association, and $\langle MATH_6 \rangle$ indicates that node i and node j have no association; $\langle MATH_7 \rangle$ represents the node fitness coefficient. The model uses $\langle MATH_8 \rangle$ to represent the local world, and $\langle MATH_9 \rangle$ to represent a specific local world, where $\langle MATH_1 0 \rangle$, and $\langle MATH_1 1 \rangle$ is the total number of local worlds in the network.

In the model, nodes represent independently operating, self-financing enterprises in real supply chain networks; edges represent associations between enterprises in real supply chain networks, such as trade, information, and service connections.

2) Model Parameters

The network topology parameters of this model include:

a) **Network average degree** $\langle MATH_1 2 \rangle$.

b) **Node degree** $\langle MATH_1 3 \rangle$: Represents the number of enterprises associated with enterprise i; network average degree $\langle MATH_1 4 \rangle$ represents the average level of node degrees in the network, reflecting the basic situation of nodes and edges in the network. In real supply chain networks, this represents the average value of the closeness of each enterprise' s association with the entire network.

c) **Clustering coefficient** $\langle MATH_1 5 \rangle$: Describes the connection situation among nodes directly connected to a node, i.e., the clustering degree of nodes in the network. In real supply chain networks, this represents the relationships among enterprises directly associated with a given enterprise.

d) **Average path length** $\langle MATH_1 6\rangle$: Refers to the average value of the shortest distances from a node in the network to any other node, reflecting the connectivity and transmission efficiency of the supply chain network.

e) **Power-law coefficient** $\langle MATH_1 7\rangle$: Reflects the strength of the power-law property of the network. A larger $\langle MATH_1 8\rangle$ value indicates stronger power-law characteristics. In real supply chains, this reflects the distribution of enterprises of various scales. A larger power-law coefficient means that the proportion of larger-scale enterprises in the entire network is smaller.

3) Model Evolution Rules

The evolution rules of the supply chain network evolution model studied in this paper are:

a) **Initialization**: The network initially has $\langle MATH_1 9\rangle$ mutually disconnected local worlds. Each local world $\langle MATH_2 0\rangle$ is a network with $\langle MATH_2 1\rangle$ nodes and $\langle MATH_2 2\rangle$ edges. We assign weight $\langle MATH_2 3\rangle$ to point i in the network, record node degree $\langle MATH_2 4\rangle$, and define edges between nodes as undirected edges.

b) **Evolution Process**:

With probability $\langle MATH_2 5\rangle$, add a new local world $\langle MATH_2 6\rangle$ to the network.

With probability $\langle MATH_2 7\rangle$, add a local node with $\langle MATH_2 8\rangle$ edges to local world $\langle MATH_2 9\rangle$. The probability of connecting to node i in this local world is $\langle MATH_3 0\rangle$.

With probability $\langle MATH_3 1\rangle$, add a global node with $\langle MATH_3 2\rangle$ edges to local world $\langle MATH_3 3\rangle$, establishing $\langle MATH_3 4\rangle$ edges within its local network and $\langle MATH_3 5\rangle$ edges with other networks. The probability of connecting to nodes in the local world follows Equation (1).

With probability $\langle MATH_3 6\rangle$, add $\langle MATH_3 7\rangle$ edges in local world $\langle MATH_3 8\rangle$. First, randomly select a point, then select the point to connect to using Equation (1), and repeat $\langle MATH_3 9\rangle$ times.

With probability $\langle MATH_4 0\rangle$, add $\langle MATH_4 1\rangle$ edges between local world $\langle MATH_4 2\rangle$ and local world $\langle MATH_4 3\rangle$, with nodes in each local world selected according to Equation (1).

With probability $\langle MATH_4 4\rangle$, delete a node and all its edges in local world $\langle MATH_4 5\rangle$, with the node selected according to probability $\langle MATH_4 6\rangle$.

With probability $\langle MATH_4 7\rangle$, delete $\langle MATH_4 8\rangle$ edges in local world $\langle MATH_4 9\rangle$, where one end is randomly selected and the other end is selected with probability $\langle MATH_5 0\rangle$.

According to the assumptions, $\langle MATH_5 1\rangle$.

c) **Termination Condition**: Specify $\langle MATH_52\rangle$ as needed. When the network scale $\langle MATH_53\rangle$ reaches the specified $\langle MATH_54\rangle$, output the network.

1.3 Theoretical Analysis

This paper employs mean-field theory to analyze the supply chain evolution model. Mean-field theory collectively processes environmental effects on objects, replacing the summation of individual effects with average effects, and demonstrates good performance in handling high-order, high-dimensional complex problems.

From the above model, we can derive that after evolution time t, the average degree of any local world $\langle MATH_55\rangle$ in the network is $\langle MATH_56\rangle$ (assuming the average degree of any point in each local world $\langle MATH_57\rangle$ is $\langle MATH_58\rangle$, and the average number of nodes in each local world $\langle MATH_59\rangle$ is $\langle MATH_60\rangle$). Based on mean-field theory, assuming $\langle MATH_61\rangle$ is a continuous variable with time t, the derivation of the degree change rate $\langle MATH_62\rangle$ is as follows. For the evolution process within each time step, the corresponding dynamic formula is $\langle MATH_63\rangle$. Summarizing these yields:

$\langle MATH_64\rangle$

Since $\langle MATH_65\rangle$ when a node first enters, we define the probability density of $\langle MATH_66\rangle$ as $\langle MATH_67\rangle$. It can be seen that the degree distribution of this model has power-law characteristics. Moreover, when $\langle MATH_68\rangle$, this model can be transformed into the classic BA model, and the power-law coefficient is calculated as $\langle MATH_69\rangle$, further proving the correctness of the derivation process. Therefore, it can be demonstrated that under the assumptions of this paper, the evolution of supply chain networks exhibits certain power-law characteristics.

2.1 Comparative Simulation Analysis

To verify the applicability of the supply chain evolution model, we conduct a comparative analysis with the BA network model and WS small-world network model commonly used in relevant literature to simulate real supply chains, and introduce real supply chain networks for network topology parameter analysis.

[Figure 1: see original paper] shows the main node network structure of China' s ICT industry in recent years, and [Figure 2: see original paper] shows the network relationship diagram of Chinese auto parts enterprises in recent years.

Figure 1 Domestic ICT main node relationship diagram
Figure 2 Auto parts enterprise network

Calculating the topology parameters of the network in Figure 1 yields: network scale $\langle MATH_{7}0\rangle$, average degree $\langle MATH_{7}1\rangle$, power-law coefficient $\langle MATH_{7}2\rangle$, average path length $\langle MATH_{7}3\rangle$, and average clustering coefficient $\langle MATH_{7}4\rangle$. Using the network model in this paper simultaneously with the BA model and WS small-world model to generate networks, the BA model parameters are set as: $\langle MATH_{7}5\rangle$; the WS small-world model parameters are set as: network scale $\langle MATH_{7}6\rangle$, coupling coefficient $\langle MATH_{7}7\rangle$, and rewiring probability $\langle MATH_{7}8\rangle$. Through multiple experimental data runs, the comparison of network topology parameters for each network model is shown in Table 1.

Since the network in Figure 2 contains 9,298 nodes, to simplify calculations, 1,000 nodes are selected as the calculation object. This network has scale $\langle MATH_{7}9\rangle$, average degree $\langle MATH_{8}0\rangle$, average path length $\langle MATH_{8}1\rangle$, power-law coefficient $\langle MATH_{8}2\rangle$, and average clustering coefficient $\langle MATH_{8}3\rangle$. Similarly, using the network model in this paper simultaneously with the BA network model and WS small-world model to generate networks, the network scale is set as $\langle MATH_{8}4\rangle$, with other parameters unchanged. Through multiple experimental data runs, the comparison of network topology parameters for each network model is shown in Table 2.

Table 1 ICT network model simulation parameter comparison
Table 2 Auto parts network model parameter comparison

The numerical values of various topology parameters in Tables 1 and 2 show that under similar network scales, the network evolved from the model in this paper has values very close to real supply chain networks in terms of average degree, average path length, and power-law coefficient, and demonstrates good performance at various stages of supply chain evolution. Therefore, this model can better characterize real supply chain networks compared to the BA network model and WS small-world model, and can well simulate supply chain networks of different scales. This demonstrates that studying the evolution process of this model to reflect and summarize the evolution laws of real supply chain networks is feasible.

2.2 Supply Chain Evolution Analysis

The above comparative analysis demonstrates that this network model can better simulate the evolution of real supply chain networks than existing models. We now use this network model to conduct simulation analysis on the evolution process of real supply chains.

When the supply chain network grows naturally, [Figure 3: see original paper] shows the degree distribution under different network scales, and [Figure 4: see original paper]-[Figure 7: see original paper] show the changes in various parameters as the network scale grows.

Impact of Two Types of Nodes on the Network: By adjusting the probabilities of global nodes and local nodes joining the network, networks of equal scale are generated and their parameters calculated, yielding Table 3. In Network 1, the probability of global nodes joining is higher than that of local nodes, while in Network 2, the probabilities of the two types of nodes joining are exchanged.

Figure 3 Degree distribution map of different network sizes
Figure 4 Average path-network size relationship diagram
Figure 5 [Figure 5: see original paper] Clustering coefficient-network size relationship diagram
Figure 6 [Figure 6: see original paper] Average degree-network size relationship diagram
Figure 7 [Figure 7: see original paper] Power law coefficient-network size relationship diagram

Table 3 Analysis of network parameters of two types of nodes

Figure 3 shows that as the supply chain network scale grows, the overall power-law characteristic of the network becomes more pronounced when $\langle MATH_8 5\rangle$. New node enterprises joining the network tend to prefer large-scale node enterprises in their local world when selecting partners, increasing the importance of core enterprises in the network. Therefore, the stability of the supply chain network when core enterprises encounter risks deteriorates as network scale increases. Connections within each local world are relatively tight, while local worlds are connected through global node enterprises. The behavioral element of new local worlds joining the network has increasingly less impact, so the influence of new small supply chain networks joining the overall network decreases as network scale increases.

From Figures 4-7, we can see that as network scale increases, the overall trends of average path length, average degree, and power-law coefficient are upward, while the clustering coefficient decreases. The values of average path length and clustering coefficient fluctuate to some extent in the early stage of network growth. The fluctuation amplitude of average degree and power-law coefficient is small, and their values stabilize when $\langle MATH_8 6\rangle$. Therefore, during the natural evolution of real supply chain networks, network connectivity and transmission efficiency continuously increase, but the closeness between nodes decreases because new node enterprises mostly cooperate with larger-scale enterprises while neglecting others. The tightness between enterprises and the supply chain network gradually develops to a certain extent and then stabilizes. The development speed of large-scale enterprises first increases and then slows down, while the development speed of nodes at various scales remains stable in the middle and later stages.

Table 3 shows that different nodes have relatively small impact on network average degree. Global nodes can reduce average path length, clustering coefficient, and power-law coefficient. Therefore, global nodes can enhance network connectivity and transmission efficiency, increase the proportion of large-scale node enterprises, and reduce the closeness between nodes to some extent. Global nodes, compared with local nodes, are better able to improve network efficiency and the probability of large-scale enterprise emergence.

Practical Implications

Based on the above evolution laws, this paper draws the following practical implications:

a) According to the degree distribution law in supply chain network evolution, one can calculate the power-law coefficient of a supply chain network and plot its degree distribution to determine whether it is in a stable development period.

b) Based on the fluctuation of certain parameters, core enterprises should carefully consider whether to cooperate with new enterprise alliances in the early stage of supply chain formation, as the addition of new enterprise alliances carries significant risks and may change the status of core enterprises.

c) When a supply chain generates multiple local worlds with poor connectivity, global node enterprises should be introduced to strengthen network connectivity.

d) The research results of this paper have certain reference value for macroscopically predicting changes in supply chain network topology and for supply chain node enterprises to formulate strategies suitable for their own development at different stages of supply chain evolution.

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3 Conclusion

a) Based on the multi-local world network model, this paper designs a supply chain network evolution model that includes both local and global nodes and incorporates seven categories of behavioral elements. Using mean-field theory, we verify that supply chain networks exhibit certain power-law characteristics. Through comparative analysis of two examples, we verify that this network model can better characterize the evolution of real supply chains than existing network models.

b) Simulation results show that supply chain networks have the following topological characteristics during evolution: as network scale increases, the average path length gradually becomes shorter, the power-law characteristic of degree distribution gradually strengthens, and the network maintains high clustering. This also demonstrates that this network model can better characterize the evolution of real supply chains than other network models.

c) Research on supply chain network evolution laws reveals that different supply chain network behavioral elements have different impacts on the supply chain evolution model: as network scale increases, network connectivity and transmission efficiency increase, the tightness between enterprises and the supply chain network tends to stabilize, and the development speed of large-scale enterprises first increases and then slows down.

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Note: Figure translations are in progress. See original paper for figures.