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Analysis of supply chain's resilience in crowd networks

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Abstract

Purpose – The purpose of this paper is to analyze the supply chain's resilience in crowd networks from both static and dynamic perspectives.

Design/methodology/approach – This paper first defines the supply chain's resilience, then proposes a graphical and game-theoretic framework to evaluate the resilience.

Findings – In this framework, an equilibrium with high resilience will be achieved after the iterated prisoner's dilemma in the supply chain. The two-stage update mechanism contributes to higher profits, higher stability and stronger risk resistance capability. The reputation-based tit-for-tat strategy in the second stage helps to realize society cooperation.

Originality/value – This work pays more attention to the dynamic evolution of interactions between organizations in the supply chain. It provides an important theoretical basis for future work such as how to effectively control and guide the evolution of events in the intelligence network and how to stand sudden changes and avoid collapse.

Keywords Resilience, Supply chain, Reputation, Evolutionary game theory

Paper type Research paper

1. Introduction

With the inevitable changes in the world market, each organization is being exposed to different types of risks, which could be a threat to the organization itself as well as the whole supply chain. Take the 2019 novel coronavirus disease (COVID-19) for instance, thousands of companies suffered this pandemic and even went bankrupt, which leads to large-scale economic losses. Therefore, it is of great significance to study the method to define and evaluate the stability of a supply chain. Crowd networks refer to complex and heterogeneous networks that connect small entities such as users, smart devices, companies, organizations and government agencies, and where such smart entities constantly interact with each other, influence each other's decisions and have a significant impact on our society and economy. A supply chain network is a network that supplies products from raw materials to consumers with the help of small entities and is one type of crowd network. They share characteristics as diversity, dynamics, large scale, complexity and vulnerability (Zou *et al.*, 2020). Additionally, new methods and mechanisms are urgent and important for organizations to improve their resilience against risks.



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Researchers had surveyed over 20 different concepts of resilience used in various fields including physics, psychology and ecology. However, in the research of supply chain management, resilience is a relatively undefined concept (Ponomarov and Holcomb, 2009). The Canadian ecologist Holling was one of the first scholars to clarify that resilience determines the ability of systems to absorb changes, and stability is the capability of systems to restore to a new equilibrium state after a sudden disturbance (Holling, 1973). After that, several researchers committed to finding factors that exert influence on supply chain resilience. Scholten's findings identify the importance of cooperation to supply chain resilience. Particularly, they claim cooperation is an antecedent of the constructs of resilience and also consider redundant resources (and the need to balance it with efficiency) as a prerequisite to resilience, as they enable the necessary supply chain processes (Scholten and Schilder, 2015). Additionally, the concept of resilience for the supply chain has proven the potential to improve overall operational performance during periods of dramatic changes and relatively stable ones (Flynn, 2008). Besides, Pettit declares that increased resilience is correlated with improved supply chain performance, whose results showed that the resilience scores of the seven companies evaluated by the SCRAM tool increased by only one percentage, and performance volatility could increase by 26% (Pettit et al., 2013).

Supply chain resilience management aims at optimizing organizational decision-making behavior, based on the measurement of the stability of the organizations and the overall market, thereby improving the ability of the supply chain to respond to risks and ensuring the overall stability of the supply chain. Nevertheless, the lack of empirical work results in a knowledge gap between theory and reality. And heavy reliance on surveys makes the results subjective because organizations themselves may also have an imperfect understanding of their actions and profits. Therefore, to use theoretical frameworks to enhance understanding, Tukamuhabwa and other authors propose Complex Adaptive Systems (CAS) theory as an appropriate method for studying supply chain's resilience because it mirrors various characteristics of a CAS, including adaptation and coevolution, non-linearity and emergence (Tukamuhabwa *et al.*, 2015).

Evolutionary game theory (EGT) is an effective and practical framework studying evolution in different disciplines, from biology to economics (Roca *et al.*, 2009). It is first introduced by Lieberman studying the ability of a mutant gene to overtake a finite structured population in biology (Lieberman *et al.*, 2005). Additionally, one of the most vital extensions of EGT is the game-theoretic application, providing new insight concerning the evolution of cooperation and other game-theoretic concepts in structured population (Shakarian *et al.*, 2012). The structured population is usually model as graphs, from random graphs to more complicated ones such as evolving graphs (Broom *et al.*, 2011). EGT provides researchers with several well-understood basic theoretical issues about the evolutionary dynamics of the model. It also offers a host of techniques for modeling the dynamics of behavior (Sandholm, 2020). Besides, EGT has been used in other fields, for example, economics (Zhou, 2011) and social networks (Jiang *et al.*, 2014).

Supply chain network structure can be modeled as graphs where nodes represent organizations and enterprises while edges represent relationships between nodes, matching the application scenario of EGT. To manage supply chain resilience, we are supposed to study the dynamic evolution of resilience and organizational behavior as well. Thus, EGT is suitable for the analysis of the supply chain's resilience in crowd networks. We borrow the concepts of EGT to the construction and update of the supply chain model.

There are still unaddressed challenges remaining in the research of supply chain resilience management. To start with, although resilience is a widely used concept in different fields, it is not well defined in the research of supply chain management. Besides,

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existing models have made many simplifications, ignoring the dynamic evolution of interactions between organizations. Because of the complexity of parameter settings, most of the existing works are theoretical studies and lack actual experimental results.

Many prior works are studying the resilience of supply chain networks, but they mostly focus on how the factors influence the overall system and heavily rely on surveyed data. In this work, we use models and theories from crowd networks to study the resilience of supply chain networks and focus on the analysis of interactions between smart agents on the dynamic process of supply chain networks. To our knowledge, this is the first work on the dynamic process of agents' interactions in supply chain management. In this paper, we proposed a graphical and game-theoretic framework to model the dynamic process of supply chain transactions. Not only organizations themselves but also their time-varying relationships are included. Moreover, this paper models the dynamic process of the supply chain from the perspective of game theory. A good and healthy supply chain needs various characteristics including connectivity between layers, high profits and stability and robustness against risk. Furthermore, experimental results illustrate that our model can give birth to such a supply chain, and reputation is one of the critical factors to realize society cooperation.

2. Supply chain network

In Section 2, we propose a layered model to describe the network structure of the supply chain and to trace its dynamic variance that interactions and transactions bring about. Furthermore, we propose criteria to measure supply chain resilience in Section 3.

The supply chain model is layered as shown in Figure 1 where nodes represent companies or organizations participating in the supply chain transactions including raw material suppliers, producers, distributors, retailers and consumers. Each role has a specific status in the supply chain, which can be defined as a layer. They are involved in the production and circulation of products and form a dynamically changing network from transactions with upstream and downstream members. Therefore, edges represent transaction relationships between companies or organizations. Various structures of the supply chain are studied in the literature, for example, block-diagonal, scale-free, centralized and diagonal (Kim *et al.*, 2015).

In the above supply chain network, nodes of the same layer have the same role and status in the supply chain, while the roles and status of nodes at different levels are different. Nodes in one layer are in a competitive relationship, thus there is no transaction relationship between them. Nodes in different layers may be in a cooperative relationship, but the relationship can only be established between two adjacent layers. In this network, raw



Figure 1. Layered structure of supply chain

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materials enter the supply chain, and the final products pass through interior layers, reach the end consumers, which is a complete supply chain cycle.

In this work, nodes can be regarded as smart agents. The nodes, representing enterprises or organizations, set goals to maximize their profits in the market. Enterprises and organizations, nodes, modify their strategies based on the changes in the market as well as the changes of competitors' actions. Nodes would get rewards in the game process, such as higher profits and more materials. Nodes continue learning and keep optimizing their strategies. Take the variety of nodes into account, we distinguish ordinary nodes from greedy nodes. Ordinary nodes only emphasize the success or failure of historical transactions, while greedy nodes also pay attention to profits. Greedy nodes wish to get as much profit as possible so they act more aggressively compared with ordinary ones.

3. Supply chain resilience

To study supply chain resilience management, we first introduce several basic concepts. Resilience is originally a term that defines the resistance of an object or material to impact or deformation used in physical sciences (Bodin and Wiman, 2004). Nevertheless, its meaning has been extended to other fields of study such as biology, economics, sociology or ecology (Holling, 1996; Adger, 2000; Masten and Obradović, 2006). More specifically, resilience can be served as the intrinsic property of a complex dynamic system including a supply chain system, reflecting the system's ability to overcome the changes caused by one or more disturbing events and to recover to its initial state or normal operations. In this work, we define various metrics to fully evaluate the resilience of supply chain networks as follows.

3.1 Performance metrics

3.1.1 Statistical characteristics of overall resilience. R(i, t) is a random variable of node *i* and time *t*, which quantifies robustness of node *i* under sudden risks considering both its own ability and the relationship with other nodes in network. We also initialize R(i, t) by Beta distribution, $R(i, 0) = Beta(\alpha_2, \beta_2)$ where α_2, β_2 are parameters.

Each node in the network has its resilience value R. But when comes to evaluate the resilience of the overall network, we get a set of R which is a distribution of random variables. To evaluate the resilience of the overall network, we use statistical characteristics of resilience R including average, variance and percentile instead. The use of appropriate descriptive indicators for continuous data, resilience R, can help us study the facts and laws hidden behind the huge and disorderly data. The three dimensions describing the data refer to the description of the central tendency, the degree of dispersion and the distribution pattern.

The first is the arithmetic mean. We also consider extreme values such as maximum and minimum. The second is variance. The third is percentile.

3.1.2 Measures of the supply chain's ability to overcome the changes. Resilience reflects the supply chain's ability to overcome the changes caused by one or more disturbing events. There are two commonly used measures of the ability. One is the time $T_{recover}$ for the supply chain to recover to its initial state.

$$T_{recover} = T_0 - T_1,$$

where T_0 represents the moment when resilience is restored to its initial value, and T_1 represents the moment when disturbing events happen. The second is the recovery level *d*:

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$$d\% = \frac{R_1}{R_0} \times 100\%,$$

where R_0 represents the final stable resilience value after being disturbed and R_1 represents the resilience value before disturbing events.

3.1.3 Connectivity. In this paper, we model the supply chain as a layered network. Only when raw materials go through from the beginning layer to the end one, from raw materials to products which consumers can use, the supply chain works. Thus, one kind of supply chain collapse is disconnected. Take COVID-19, for example, because of the virus countries and cities block up so that the intermediate products cannot be transported to the destination, resulting in disconnection of the supply chain and further economic losses.

3.2 Important parameters

Several important parameters affect the resilience of the supply chain. Redundancy resources are an indispensable factor in the supply chain's resilience measurement. It is also known as slack resources and refers to the surplus and temporarily idle resources in the enterprise, showing its survival and sustainable development ability. It is believed that redundancy resources have a positive effect because when the enterprise faces changes in the external environment, the redundancy resources can act as a buffer, contributing to more flexibility for the formulation of corporate strategies. However, if there are too many redundancy resources, it may cause waste and inefficiency and hurt the enterprise. Moreover, the network structure may play an important role in quantifying the supply chain's resilience.

3.2.1 Upper limit of redundancy resources. A(i) is the upper limit of redundancy resources of node *i*, which is a fixed value determined by initialization and does not change with iterations because the redundancy resources of an organization serve as an intrinsic property that does not be affected by external factors. The *A* of different nodes in the model obey uniform distribution $A \sim U(A_{min}, A_{max})$.

3.2.2 Value of redundancy resources. V(i, t) is a random variable of node *i* and time *t* denotes value of redundancy resources. We initialize V(i, t) using Beta distribution, $V(i, 0) = A(i) \times Beta(\alpha_1, \beta_1)$, where α_1, β_1 are parameters.

3.2.3 Maximum number of connections. Considering the actual capabilities of nodes, we set the upper limit of the number of cooperative relations that each node can have as N_{max} . In other words, each node in the network has an identical maximum degree.

3.3 Supply chain resilience management

Government or other regulatory authority should establish an information-sharing system based on technology and specific data such as redundancy resources in practice. The information management system has achieved the goal of unobstructed information flow in the entire supply chain system and realized centralized management of information resources. It is conducive to discover potential risks in the supply chain timely, and it can also improve efficiency, which helps organizations or companies to take early measures.

There is an obvious difference between supply chain resilience management and traditional risk management. Risk management focuses on risk minimization while supply chain resilience management pays attention to how to recover from unforeseen interruptions and make a competitive advantage. At the same time, the ultimate goal of the supply chain is still to maximize profits while meeting the reduction of market demand. Therefore, the relationship between cost and benefit should be considered in the process of resilience

IJCS 5,2 optimization. According to the definition of resilience, the supply chain management optimization strategy can be divided into the following three categories:

- (1) Supply chain reconstruction: Break the original connection, reconnect the supply chain structure to establish a new structure with higher resilience.
- (2) Supply chain coordination: The length of the supply chain affects the distribution of risks, and a high degree of coordination, cooperation and division of labor between organizations can reduce risks and improve efficiency. Therefore, creating new partnerships can enhance the resilience of the supply chain.
- (3) Supply chain agility: The market is changing rapidly, and the supply chain is required to be able to coordinate quickly to meet the dynamic changes of market demand. Therefore, improving the quality of the relationship between supply chain members, introducing a reputation mechanism and increasing the degree of information sharing can increase the speed of response, contributing to improving the health of the supply chain.

Enterprises or organizations can take measures based on the supply chain resilience management optimization strategy to achieve pre-prevention and post-remediation and improve the flexibility of the supply chain while ensuring the basic effectiveness of the supply chain.

4. Graphical evolutionary game theoretic modeling of supply chain

Time is divided into two slots for the model update. In the first time slot, agents choose their partners in the adjacent layers of the supply chain, resulting in the disconnection and establishment of edges, thus the network structure changes. The edges denote that the two connected agents have sent cooperation intentions with each other and signed a contract. In the second time slot, only connected agents game and finally decide their actions whether to cooperate or to defect based on the changed network structure. Cooperating means the agent is willing to perform the signed contract while defecting means the agent would betray its partner and break the contract for its goods.

In our work, we assume that the probability for a node to change partners and its resilience are negatively correlated. The lower the resilience, the more likely the node to change partners. More precisely, we define a basis for partners selection called popularity, which takes both resilience and their connected nodes in the previous time slot into consideration.

$$popularity(i) = R_{i1} + \dots + R_{ij} \tag{1}$$

where *popularity(i)* denotes the popularity of node *i* and R_{i1}, \ldots, R_{ij} are the resilience of node *i*'s connected nodes in the adjacent layer on one side. The nodes are sorted by their potential partners, all nodes in the adjacent layers, according to popularity, which means top nodes are more likely to be chose as partners.

If the node decides to change its partners, then it will abandon all its historical connections, reselect nodes to connect according to the popularity of nodes. Besides, the connection can only be established if the upstream and downstream nodes wish to cooperate. If only one node tends to establish a connection, there will be no connection at all.

After reestablishing the supply chain structure, the reward of each node will be calculated. For two nodes with a connection, a two-person binary-choice game is played, while the reward of each node on the connection is obtained. Thus, the total reward of one

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node is accumulated all its reward on connections. The partners' selection and the game process will be illustrated in detail in subsections 4.1 and 4.2.

4.1 Agents' partners selection

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Considering the rationality of the agent's behavior, this paper uses the following process to match the agents' behavior to change the network structure. In practice, it can be considered as signing a contract of intent. Either agent can send an invitation of intent to the other if these two agents are in the adjacent layers, but whether the contract is successfully signed depends on whether both agents are willing to treat each other as partners. The preference of the agents' partners' selection conforms to the hypothesis of rational man, and they all expect to sign a contract and work with agents with higher popularity that means both strong ability and high stability. At the same time, considering the capacity limitations of the agent, we set the maximum number of connections N_{max} , which is the upper limit of the number of cooperative relationships that each agent can have. Take node *i* for instance, the partners' selection process follows the listed steps and the steps would be conducted twice, one for node *i*'s upper layer and the other for node *i*'s next layer.

• First, calculate the node i's probability to change partners P_0 . The agent has a probability P_0 to change its partners, otherwise chooses to maintain the previous relationships. The change probability P_0 is inversely proportional to the agent's resilience R and:

$$P_0 = 1 - \frac{1}{1 + e^{-\sigma R}}.$$

In other words, agents with a larger R tend to maintain the current partners that can achieve satisfying R. When P_0 is greater than a certain threshold T, the agent will change partners; otherwise, the agent keeps its original partners.

• Second, calculate the popularity of all the nodes in node i's adjacent layers. We calculate popularity according to equation (1) and normalize the values in one layer to get each node's probability P_j of being selected by node *i*. Thus, nodes with higher R and more connections rank top and other nodes in the layer tend to imitate the behavior of these top nodes. It is supposed to ensure that other nodes will not completely imitate the behavior of a certain node with the highest popularity because if so we would get a uniformly structured network that lacks trivial. So we introduce a decay rate term β . When a node is selected by multiple nodes in the last round, its probability of being selected in this round decreases. The probability of each node being selected by its potential partners is:

$$P_j = popularity(j)' \times \beta, \ \beta = 1 - k \times \frac{number \ of \ connections \ last \ turn}{maximum \ number \ of \ connections}$$

where P_j is the probability of node *j* to be selected by node *i* and *popularity(j)*' is the node *j*'s normalized popularity.

• Based on the first and second steps, if node *i* chooses to change partners, it will abandon all the original connections, and select its intended connection nodes according to popularity, until the maximum connection number N_{max} is reached. If

node *i* keeps the original connection and the number of the original connection is Supply chain's smaller than the maximum connection number N_{max} , then node *i* continues to select the intention nodes according to popularity until the maximum connection number N_{max} is reached. When all nodes finish selection, the mutual selection relationship between upstream and downstream is counted and recorded to update the network structure. Besides, the edge is established only when two nodes selected each other.

4.2 Game on network to realize society cooperation

After agents' partners' selection, we get a new supply chain network structure. Two nodes with a connection would play a binary-choice game and get a reward, resulting in critical parameters update. There are various typical kinds of binary-choice games in literature such as prisoner's dilemma, hawk-dove game and chicken game (Possajennikov, 2005). Take the Prisoner's Dilemma for instance. If both agents cooperate, which indicates the fact that both agents in the supply chain perform the signed contract, they can obtain high rewards. Besides, if one of the agents defect, that is, the agent in the supply chain breaks the contract, it will get even higher profits, while the betrayed agent will suffer from huge losses relatively. And the third case is that both agents betraved, and both agents' profits will suffer from severe losses.

Thus, the prisoner's dilemma well reflects situations in the actual supply chain market. We conduct experiments based on the iterated prisoner's dilemma model. The prisoner's dilemma is a typical model of non-zero-sum games in game theory, reflecting the best choice of individuals rather than the best choice of the society, but in iterated prisoners' dilemmas, cooperative equilibrium results may appear. In this work, we introduce a reputation mechanism to prevent betraval from being a completely dominant strategy, which indicates that if an agent often breaks contracts, it is also more likely to be betrayed subsequently. In the experiment we hope to increase the cooperation rate in the society, thereby establishing a wide range of group cooperation.

4.2.1 Payoff matrix. We define payoff matrix as Table 1, where T, P, R, S denote temptation, reward, punishment and suckers, respectively, as Table 2 shows. Moreover, to be a prisoner's dilemma game, payoff matrix must follow T > R > P > S, in which R > Pimplies that mutual cooperation is superior to mutual defection, while T > R and P > Simply that defection is the dominant strategy for both agents. In each game agents get payoff and we record cumulative sum of payoff of each node as total profits.

	te (R, R) (T, S)		Defect (S, T) (P, P)	Table 1. Payoff matrix
Cooperate Defect				
Т	R	Р	S	Table 2
5 Temptation	3 Reward	1 Punishment	0 Suckers	Meaning and value of T, P, R, S

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4.2.2 Reputation. Reputation Repu(i) record the reputation of node i,

 $Repu(i) = \frac{\# final \ contracts \ last \ turn}{\# intent \ contracts \ last \ turn}$

4.2.3 Strategies. We use tit-for-tat (TFT) as a game strategy in the second stage of model update. It is a remarkably effective strategy for the iterated prisoner's dilemma, which serves as the best strategy for the maximum interests of both agents. The strategy was first introduced by Anatol Rapoport in Robert Axelrod's two tournaments, held around 1980. Besides, tit-for-tat is in accord with the assumption of the supply chain model in this paper owing to the much emphasis laid on the overall resilience of the model rather than personal profits. The strategy has two steps, the agent will cooperate in the first turn no matter what the other agent act. However, when comes to the second turn, the agent will take the same action as its opponent's last turn. If its opponent betrays the last turn then the agent will also betray this turn, while if its opponent cooperates the last turn then the agent will also cooperate this turn. The strategy fully explains its name "tit-for-tat."

The strategy tit-for-tat has four characteristics in general, friendliness, retaliation, forgiveness and selflessness. The agents cooperate at the very beginning. If the agent is betrayed by the opponent, it will retaliate. However, when the opponent stops betraying and chooses to cooperate, then the agent will forgive him and continue to cooperate. Above all, the user who chooses the tit-for-tat strategy will never get the maximum benefit; however, the strategy is based on the overall maximum benefit.

Besides, the tit-for-tat strategy converges slowly and is easily affected by the initial state and randomness. The final equilibrium may be the opposite, whether that most nodes in the network choose to cooperate or most nodes in the network choose to betray. Therefore, we introduce a reputation mechanism, hoping to increase the cooperation rate of the society to achieve wider society cooperation.

Reputation *Repu* is long-term memory with decay. After games between all agents, the total number of cooperation and betrayals in the current round and the historical data are weighted and sum, and then the cooperation ratio of each agent is calculated with the attenuation factor γ . The specific calculation is shown in the following formula, where *Cooperate*(t + 1) denotes the number of cooperation at timet + 1, *Defect*(t + 1) denotes the number of betrayals at timet + 1.

$$\begin{cases} Cooperate(t+1) = \gamma Cooperate(t) + c(t+1) \\ Defect(t+1) = \gamma Defect(t) + d(t+1) \\ rate(t+1) = \frac{Cooperate(t+1)}{Cooperate(t+1) + Defect(t+1)} \end{cases}$$

In summary, the process of the TFT random strategy game with reputation is as follows: when two agents play a game, for agent 1, it makes decisions based on the reputation, which equals to the cooperation rate of agent 2. In other words, the cooperation rate of agent 1 is equal to the reputation of agent 2. The two agents on each connection play a game, and after all games are completed, the reputation of this round is calculated and the total profit is updated.

4.3 Network dynamics

To simulate the phenomenon that emerging companies enter the supply chain and poorly managed companies go bankrupt and exit the supply chain, we have established a dynamic network mechanism. If the number of nodes on one layer is too small, a new node is Supply chain's randomly generated to enter the supply chain, while if the R and V value of the node is lower than the specific threshold, it will exit the supply chain. It makes the model more practical and the robustness analysis of the supply chain more meaningful.

4.4 Parameter ubdate

After reestablishment of the supply chain and game between agents, important parameters should be updated as follows.

4.4.1 Value of redundancy resources V(i, t). Considering that the resource redundancy of the nodes is related to the reward that nodes can get in the game process, the resource redundancy records the cumulative sum of the long-term benefits. Thus the update function of V(i, t) is:

$$V(i, t+1) = f(V(i, t), reward)$$
⁽²⁾

4.1.2 Resilience R(i, t). An agent's resilience not only depends on its redundancy resources but also its connections with other agents. Also, there will be some noise reflecting randomness. Thus the update function of R(i, t) is:

$$R(i, t+1) = g(V(i, t), V(i, t), V_{ub}(t), V_{down}(t), noise)$$
(3)

where $V_{up}(t)$ means the sum of slack resources V of the nodes in upper layer connecting to node *i*, similarly $V_{down}(t)$ means the sum of slack resources V of the nodes in next layer connecting to node *i*.

5. Experiments

We use simulations to evaluate the resilience of a supply chain network under different setups.

5.1 Simulation setup

We generate a layered network to run simulations. The network has eight layers and each layer has a random number of nodes, ranging from 14 to 18. The original values of the upper limit of redundancy resources A are initialized according to uniform distribution U(3, 10)and the value of redundancy resources V are initialized according to $V = A \times Beta(2,5)$. Then we calculate the resilience of each node. 1000 simulation runs are conducted on the network. In each simulation run, agents game once and the resilience updates. Cooperation rate and payoff in each simulation run are also recorded.

5.2 Results and analysis

5.2.1 Connectivity. We use the special update method proposed in subsection 4.1 to guarantee that the supply chain layered model would not be disconnected between layers, with materials and products flow freely in the network. Here is the detailed proof.

Suppose there are N nodes in the two adjacent layers, and the maximum number of connections of a single node is m. Assuming that the choices of N nodes in the upper layer are evenly distributed, then each node in the lower layer has been chosen *m* times. Therefore, the probability that the first node in the upper layer does not overlap with the lower layer choices is $p = \frac{C_{m}^{m}}{C_{m}^{m}}$, which also means the choices of the first node happen to avoid the m choices.

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$$p = \frac{C_{N-m}^{m}}{C_{N}^{m}}$$

$$= \frac{(N-m)(N-m-1)\cdots(N-2m)}{N(N-1)\cdots(N-m)}$$

$$\leq \left(\frac{N-m}{N}\right)^{m}$$
(4)

If the network is disconnected between layers, then *N* nodes in one layer all satisfy the above condition (4) independently.

$$p \le \left(\frac{N-m}{N}\right)^{mN}$$

As $m \ll N$ and $\frac{N-m}{N} < 1$, then $p \to 0$. Considering that the selection is not evenly distributed in practice, there is a greater possibility of overlap, so p is even smaller. In summary, it is proved that there will be no disconnection in the supply chain layered model under the model update mechanism, contributing to better robustness. It means at least one connection is successfully established between every two adjacent layers so that the supply chain works.

5.2.2 Degree distribution. As the network evolves, the distribution of nodes is more similar to normal distribution in the front stage and will tend to be more and more uneven in the later stage. Figure 2 reflects the distribution of the number of node connections in the front, middle and later stages if the maximum number of connections is 5.

Figure 2 is the distribution of the number of node connections as iterations increases. It can be found that the distribution tends to be polarized. Most of the nodes in the supply chain network have the maximum number of connections 5 or the minimum number of connections 1. It is consistent with the law in reality that the gap between startups is not such considerable. However, as time goes by, monopoly companies gradually appear, which occupy a large amount of market share, while other small companies are being annexed or bankrupt. Consequently, medium-sized companies are disappearing, replaced by a large number of small and large ones.

At the end of the iteration, the network connection is shown in Figure 3. It can be found that several nodes are isolated, which are shown in circles. These nodes may have lower competitiveness and are on the verge of being eliminated by the market. On the contrary, a large number of nodes are fully connected, which are shown in rectangles. These nodes are promising with a certain market share. It is an obvious phenomenon of polarization, which serves as a supplement to Figure 2.

5.2.3 Resilience R over time. Resilience R of the network has experienced a process of first rapidly increasing and then stabilizing which is shown in Figure 4. The final stable value R is related to both network structure and the initial value of redundancy resource V. According to equations (2) and (3), agents game and get rewards at the beginning so that accumulate resilience based on initial connections. The initial stage of rapid growth corresponds to the rapid stage of initial capital accumulation in the supply chain market. After that, the games between agents become complicated because of the dynamic network structure and fluctuant reputation. In the evolution process, agents tend to imitate the behaviors of the ones with higher resilience and more connections for higher robustness. Besides, it is because of the equilibrium of games, the overall resilience finally reaches a stable value. Therefore, after several rounds of games between agents, the supply chain

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Notes: (a) Front stage; (b) middle stage; (c) later stage

becomes more healthy and robust with higher quality connections. It shows the effectiveness and practicability of the update mechanism.

We show the characteristics of R in multiple dimensions including maximum, 90% percentile, average, 10% percentile, minimum of R. Maximum and minimum have large fluctuations while average R is relatively smooth. Besides, the 90% percentile and 10% percentile illustrate that R is concentrated in the overall network while only a small part falls in the extreme value part.

5.2.4 Influence of reputation over cooperate rate. Different reputation settings will have a great impact on the evolution of the entire supply chain. Changing the memory retention rate means changing the agent's emphasis on recent and past actions. The smaller the memory retention rate, the more recent actions, while relatively ignoring past ones. Figure 5–8 lists when the memory retention rate is 100%, 70%, 50% and 0%, how the cooperation and the proportions of various types of cooperation changes with time. As the memory retention drops, the variance of cooperation rate increases.

100% memory retention rate means that memories will be completely retained, and no matter when the action happens, the weight of its influence on the current action is the same. In this case, the cooperation rate will fluctuate sharply in the previous period. After that, the cooperation rate has maintained a relatively stable state. However, the cooperation rate fluctuates around 0.5. As time goes by, the reputation of each node is relatively fixed, and

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Figure 3.

Connections at the end of supply chain evolution (Green edges represent both agents cooperate, red edges represent both agents defect and black edges represent one agent cooperate while one agent defects)





Figure 4. Statistical characteristics of *R*

the new action is difficult to affect the reputation of the past, so the actions including cooperation and betrayal of each node also tend to be stable.

When the retention rate is 70% or 50%, it can be found that the actions of the nodes become more volatile, and the randomness becomes stronger. Because users pay more attention to recent actions, the cooperation rate will fluctuate according to the impact of recent action on reputation.



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When the retention rate is 0%, the update strategy degenerates into the simplest tit-for-tat mechanism. In that case, the current action is only determined by the previous round of action with the agents' behavior fluctuates extremely obviously, which is caused by the randomness of the tit-for-tat strategy.

The profits of ordinary nodes and greedy nodes will be different in Figure 9. There are more fluctuations and greater variance in the profits of greedy nodes, while ordinary nodes are more stable. Because greedy nodes wish to get as much profit as possible so they act more aggressively compared with ordinary ones.

5.2.5 Influence of shocks on the supply chain. There are several distinguished manifestations of nodes after being impacted. One is that the node directly exits the network, similar to permanently corporate bankruptcy in the real market. And the other is



Figure 8. Change of overall cooperation rate and cooperation state ratio at 0% memory retention rate



that the R, V value of the node is reduced to an extremely low value, similar to the inability of corporate capital turnover temporarily. The impact of the shocks on the supply chain network is of great significance. We have studied the dynamic process of the network indicators after the V value of 50% number of the nodes is greatly reduced to an extremely low value when t is 200.

It can be found in Figure 10 that both V and R have gone through a process of drastically decreasing and then slowly increasing, and the stable value after rising is lower than the stable value before the impact, which reflects the slow recovery of the supply chain network after a large-scale shock. Besides, it was unable to recover to the same state before the impact.

Besides, it is surprising that although most of the Rs in the network has dropped significantly after the impact, the maximum R of the supply chain network has risen sharply. However, we can find an explanation in the real market. There is no doubt that financial crisis and other shocks will cause a large number of companies to bankrupt while also give birth to oligopoly companies. Although society as a whole suffers a substantial loss, the oligopoly company annexes other companies through the crisis and seizes its market share, thus increasing its profits and improving its robustness.

The change process of R variance in the network also speaks for the finding that the maximum R rises sharply while most of R values drop as shown in Figure 11. The shock will cause a huge increase in the variance of the network, and then gradually decreases during the recovery process, but it cannot be restored to the level before the impact, resulting from the formation of an oligopoly market.

Moreover, the profits of the supply chain network also have a trend similar to the changes of R and V as shown in Figure 12. It recovers slowly but cannot return to the state before the shocks. Besides, greedy nodes are likely to recover faster than ordinary nodes by gaining more rewards owing to its attention to payoff.

6. Conclusion

We established a theoretical framework of supply chain resilience based on a layered structure model. It has clear definitions and detailed measures of resilience which has been ignored in the previous work. Because of the adaptability of the model, it can be extended to other graph structures such as stars and circles in future work. Additionally, supply chain network dynamics, both emerge and disappearance of nodes and edges, are also added to the model. It contributes to enhanced credibility of the model and increased stability of the



Figure 10. Dynamic process of the network indicators after shocks. (a) Change of average V after shocks; (b) change of distribution of R after shocks.

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supply chain itself which is confirmed by the experiments. Thus, the theoretical framework we proposed contains various factors and well fits the real supply chain market. Compared with Tukamuhabwa's CAS theory, our framework has better scalability and is easier to understand (Tukamuhabwa *et al.*, 2015). Organizations are hungry for effective and practical methods and mechanisms to improve their resilience against risks. Moreover, this paper proposed a method in detail for the agent to improve its strategy according to its neighbors' situation, which concept is borrowed from EGT.

We conduct experiments to help to evaluate the health of the supply chain from various perspectives. And an equilibrium will be achieved after a repeated game in the supply chain, which is a satisfying state overall. Reputation is also an important factor serving as a necessary condition for developing extensive cooperation, which gives birth to a supply chain with higher profits, higher stability and stronger risk resistance capacity.

To conclude, we analyze the robustness of the supply chain based on EGT and reputation mechanism, which lay a solid foundation for future work. It will eventually be able to provide an important theoretical basis for effectively promoting the transformation of a networked intelligence-based economy and society, controlling and guiding the evolution of events in the intelligence network and avoiding collapse and standing sudden changes.

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