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International Journal of Global Economics and Management

ISSN: 3005-9690 (Print), ISSN: 3005-8090 (Online) | Volume 3, Number 1, Year 2024
DOI: https://doi.org/10.62051/IJGEM.v3n1.02
Journal homepage: https://wepub.org/index.php/IJGEM/index

Research on Risk Propagation in Fresh E-commerce Supply Chain Based on Complex Networks

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ABSTRACT

In recent years, the rapid growth of the fresh e-commerce industry has introduced several potential risk factors to the supply chain that necessitate preventative measures. This paper aims to study the risk propagation within the fresh e-commerce supply chain and propose strategies for risk control. Firstly, a dual local world fitness network model is constructed by combining the fitness model with the local world model. This model is then validated, showing consistency with the actual network. Building upon this, an improved SEIRS risk propagation model is developed, and the basic reproduction number is calculated to simulate the risk propagation within the fresh e-commerce supply chain. The results indicate that the degree of risk propagation is positively correlated with the initial infection rate, risk outbreak rate, and loss of immunization rate, while negatively correlated with the risk recovery rate and risk elimination rate.

KEYWORDS

Fresh e-commerce supply chain; Complex network; The improved SEIRS model; Risk propagation

1. INTRODUCTION

The onset of the COVID-19 pandemic in 2020 acted as a catalyst, expediting the integration of fresh food retail into online platforms. In 2020, online retail accounted for 14.6% of China's fresh food market, reflecting a growing acceptance and adoption of online fresh food purchasing among consumers. As a result, the fresh e-commerce sector has seen a swift maturation, with an increasing emphasis on online retailing and advancements in technology. This shift has led to a notable surge in the penetration rate of fresh e-commerce. By 2022, the market size of fresh e-commerce had reached an estimated 560.14 billion RMB, marking a substantial year-on-year growth of 20.25%.

Managing risk within the supply chain of fresh products, from production to distribution, poses a significant bottleneck that impedes the growth of fresh e-commerce. Operational risks can cause delays, losses, and other disruptions, thereby preventing timely, quality, and accurate delivery to downstream partners. Additionally, environmental risks and natural disasters threaten the integrity of fresh products during both sourcing and transportation phases. When a risk event occurs, it often triggers a cascading effect within the supply chain, amplifying the impact and spreading across the network. This poses a profound challenge for the entire supply chain's stability and efficiency. Addressing the propagation mechanisms of risk among node enterprises within the fresh produce e-commerce supply chain is thus a critical issue that demands immediate attention.

This study aims to explore these dynamics by focusing on the fresh e-commerce supply chain as the primary subject. We establish a network model specific to this sector and apply an improved SEIRS model to investigate the mechanisms of risk propagation from a network perspective. The objective is to enhance risk management practices and foster the sustainable development of fresh e-commerce by providing strategic insights into effective risk control measures. This study poses the following research question:

How to build a fresh e-commerce supply chain network?

How to model risk propagation in fresh e-commerce supply chain?

What ideas can the results of risk propagation studies provide for enhancing risk control?

2. LITERATURE REVIEW

With the continuous development of fresh e-commerce, in recent years, scholars at home and abroad for fresh e-commerce supply chain research is also constantly enriched, the relevant research mainly focuses on inventory optimization, pricing strategy, quality control, optimal channel selection and other supply chain decision-making behaviors, supply chain performance, supply chain coordination and other aspects. Song et al. [1] investigated the impact of market preference changes on supply chain decisions of fresh e-commerce based on game models in different supply chain decision-making scenarios. Wang et al. [2] consider online reviews and study optimal pricing strategies using the Stackelberg game and a two-stage repeated game. Zhong et al. [3] utilized Stackelberg game theory to develop a profit model and investigate the impact of different types of subsidies and decisions on the profitability of agricultural e-commerce supply chains.He [4] studied overall profit maximization based on a collaborative supply chain optimization model for fresh e-commerce platforms with improved bacterial foraging algorithms.Research in fresh e-commerce supply chain risk has focused on risk identification and evaluation.Wang [5] analyzed the existing operation mode of e-commerce, analyzed the main bottlenecks of fresh food cold chain operation, and analyzed its risk factors from both internal and external perspectives.

In the context of supply chain networks, numerous studies have demonstrated that frameworks built on the principles of complex network theory effectively encapsulate the dynamics of real-world supply chain networks. Liao et al. [6] conducted an empirical study on the topology of smartphone supply chain networks, and the results showed that smartphone supply chain networks have scale-free characteristics and small-world characteristics. Kito and Ueda [7] investigated the structural characteristics of real-life auto parts supply networks through complex network theory. Zhang et al. [8] constructed a hierarchical supply chain network model by considering node degree and similarity between nodes in the same layer based on the types of companies in real supply chain networks, and the results showed that the new model can better describe real supply chain networks.

In terms of supply chain risk propagation, the research results of infectious disease propagation dynamics models such as SIS and SIRS have been more prominent in recent years, and the results of several researches have also confirmed that the propagation dynamics model on the complex network can better reflect the law of risk propagation from the perspective of the supply chain as a whole [9–13].

By combing through the above related literature, most of the supply chain network modeling is based on BA scale-free network or small-world network modeling, and further research is needed in cross-level connectivity. The SEIRS model is less in fresh e-commerce supply chain risk propagation and control. Therefore, this paper constructs a network model in line with reality from the perspective of complex network, based on the improved SEIRS model of fresh e-commerce supply chain risk propagation can bring some theoretical value.

3. BUILDING THE FRESH E-COMMERCE SUPPLY CHAIN NETWORK

3.1. Network Model Description

In this paper, we will construct a supply chain network with each enterprise in the fresh e-commerce supply chain as a node and the cooperative relationship between enterprises grouping edges. The nodes in the fresh e-commerce supply chain network are categorized into four types: producers, wholesalers, fresh e-commerce platforms and logistics service providers. In order to simplify the model, this paper does not consider the difference in business volume between node enterprises. In addition to the two basic components of nodes and edges, the direction of edges also needs to be considered when constructing the network. And the risk propagates in a radial direction. When an enterprise in the network is infected by risk, the upstream and downstream enterprises adjacent to it have the probability of being affected, so the fresh e-commerce supply chain network constructed in this paper is directionless.

The transaction and cooperation between enterprises in the real supply chain network is not random, but is the result of mutual selection, and the determination of the transaction and cooperation relationship is affected by factors such as enterprise scale, operation status, product attributes, geographic location, etc., and there are different types of enterprises choosing to cooperate with different selection ranges. Therefore, this paper considers the node adaptability and the local world of nodes to construct the supply chain network model. Table 1 shows the local world for different types of nodes.

Table 1. Localized World of Nodes

Node Category	the Localized World A1
Producer	Wholesaler + fresh e-commerce platform + logistics service provider
Wholesaler	Producer + fresh e-commerce platform + logistics service provider
Fresh e-commerce platform	Producer + wholesaler + logistics service provider
Logistics Service Provider	Producer + wholesaler + fresh e-commerce platform

The second localized world of the node consists of a certain number of nodes and connected edges randomly selected in the first localized world.

3.2. Formative Mechanisms

(1) Initial network. At the initial moment, the network is a small network with m_0 nodes. These nodes include producers, wholesalers, fresh e-commerce platforms and logistics service providers. The network is randomly connected into edges based on the upstream and downstream neighboring levels of the supply chain. The fitness of all types of nodes is selected according to the power law distribution, assuming that the proportion of nodes in the network is $\mathrm{N}_1:\mathrm{N}_2:\mathrm{N}_3:\mathrm{N}_4$.

(2) Network growth. Whenever a node is added at moment t, the category of the new node is randomly generated based on the proportion of the number of nodes in each type of hierarchy in the network. The category of the new node is determined, the fitness value is assigned to it based on the fitness distribution η_i, and the number of connected edges m_i is determined.

(3) Meritocratic connection. A new node added into the network determines its local world A_1 according to its type and then randomly selects m_i node from A_1 as its dual local world A_2 and

connects with m_i node in A_2, then the probability that a node v_i in the local world of A_2 connects with the new node v_j is determined by the node's degree and fitness, depending on the proportion of the product of the node's degree k_i and fitness η_i in that local world as shown in equation (1) :

$$\prod_{l\in W_j}(j\to i)=\frac{\eta_i k_i}{\sum_{l\in W_j}\eta_l k_l} \qquad (1)$$

Repeat this step until the target network is generated at the set time. The growth process of the network is shown in Figure 1.

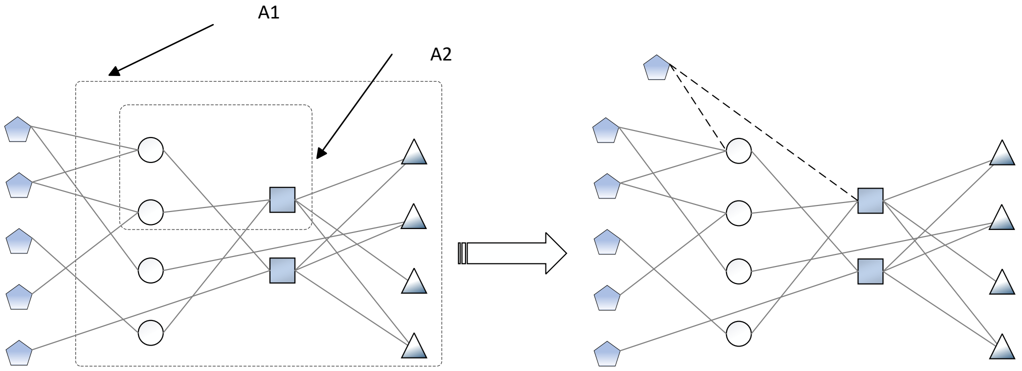

Figure 1. Schematic Diagram of the Growth of the Supply Chain Network of Fresh E-commerce

3.3. Model Simulation

In this paper, we simulate and analyze the supply chain network model in the dual localized world to verify whether the network model conforms to the actual situation and to lay the foundation for the subsequent research on risk propagation models.

(1) Initial network. The number of each node in the initial network is set to 12 producers, 4 wholesalers, 1 fresh e-commerce platform and 2 logistics service providers. The number of nodes $m_0 = 19$ and the number of connected edges $e_0 = 38$ in the initial network can be calculated.

(2) Network growth. As the market develops and time advances, new node enterprises continue to join the supply chain network, set the generation ratio of various types of nodes on the network as 12:4:1:2, the new joining nodes with the number of nodes of all types of tiers as the probability of belonging to tiers, belonging to the four tiers of producers, wholesalers, fresh e-commerce platforms, and logistics service providers with the probability of 63%, 21%, 5%, and 11%, respectively. Referring to the small-scale research data and considering the power index characteristics of large-scale real networks, the fitness distribution parameters of each type of nodes are set as $\eta_1 \propto 2000\eta_1^{-2.2} + 50, \eta_2 \propto 3000\eta_2^{-2.2} + 200, \eta_3 \propto 5000\eta_3^{-2.2} + 300, \eta_4 \propto 2000\eta_4^{-2.2} + 100$.

The simulation is carried out by Python with the total network size N as 500, 1000, 2000, 3000, 5000, 8000, and 10000, respectively, visualized by D3blocks, and repeated 10 times to take the average value as the simulation result. The generated network is shown in Figure 2.

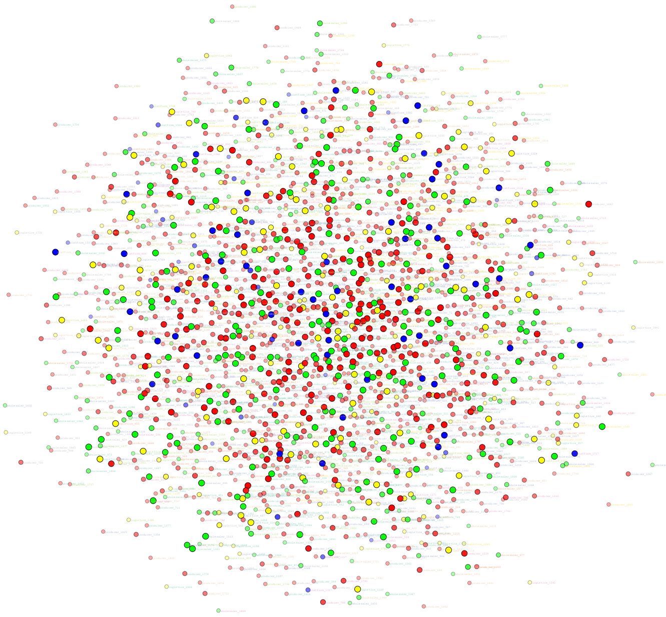

Figure 2. Simulation of Fresh E-commerce Supply Chain Network Model (*N*=2000)

The statistical characteristics of the fresh e-commerce supply chain network are analyzed through python simulation, and the comparison with the empirical research results of existing literature verifies that the fresh e-commerce supply chain network established by the model has the similar characteristics of other real supply chain networks, and the research of supply chain risk propagation can be carried out through this network model [6, 14–16].

4. ESTABLISHMENT OF THE IMPROVED SEIRS SUPPLY CHAIN RISK PROPAGATION MODEL

4.1. Model Description

In the classic SEIRS model, the infected person will be cured after treatment, however, in the real situation of fresh e-commerce supply chain, some of the risk-infected enterprises are likely to be eliminated from the market due to the lack of risk coping ability and disappear from the supply chain network In order to make the risk propagation model more in line with the reality of the evolution of fresh e-commerce supply chain network, and to make it more in line with the research background, this paper introduces the infected enterprise elimination rate δ to improve the SEIRS model and establish the fresh e-commerce supply chain risk propagation model. The risk propagation model is shown in Figure 3.

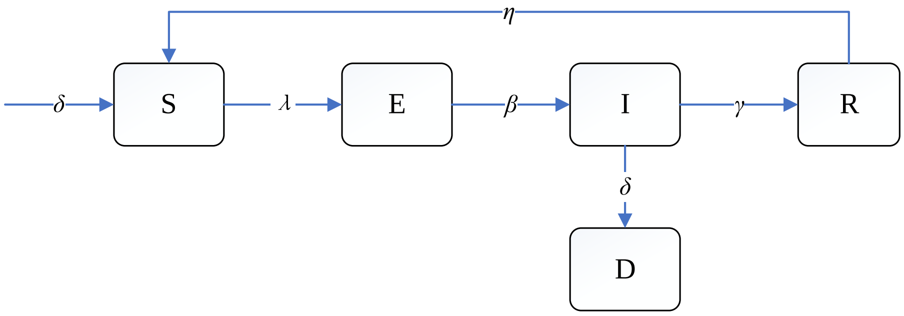

Figure 3. Risk Propagation Mechanism of the Improved SEIRS Model

The rules of infection are as follows.

(1) After contacting the infected enterprise, the susceptible enterprise will be infected with a certain probability, but it will not break out immediately, it will first change from from a healthy state to an exposed state, and it is not infectious during the period of exposure.

(2) The risk is brewed after a little time before it breaks out, and the exposed enterprise turns into the infected enterprise.

(3) After a period of adjustment, the infected individual will be cured with a certain probability and return from the infected state to the healthy state, and there exists a certain probability of death, i.e., changing from the infected state to the eliminated state.

(4) An infected individual will develop autoimmunity and be in an immunized state after returning to health. However, with time, this immunity disappears with some probability and the individual reverts to a state of susceptibility to infection.

The improved SEIRS model is based on several basic assumptions:

(1) In a supply chain network, when a risk spreads, it only affects nodes with direct business relationships. The chance of risk spreading is controlled by the starting risk value of the network and the effective contact rate between nodes. (2) The supply chain network constructed in this paper is an illegal network, and the transmission process does not take into account the volume and direction of transactions between the node firms because the risk spreads radially around the network. (3) During the node state change process, each susceptible node is at risk from only one linked infected node at a time and must transform infected nodes into recovery and elimination nodes. (4) The network structure remains unchanged and the total number of node firms in the system is a constant N. When a node is eliminated, the supply chain finds its own backup to replace the original node position, and the size of the nodes in the network remains unchanged. In other words: S(t)+E(t)+I(t)+R(t)=N(t).

Based on the above description, the improved SEIRS-based fresh e-commerce supply chain risk propagation model can be expressed by the following equation:

$$\begin{cases} \frac{ds(t)}{dt} = -\lambda s(t)i(t) + \eta r(t) + \delta i(t) \\ \frac{de(t)}{dt} = \lambda s(t)i(t) - \beta e(t) \\ \frac{di(t)}{dt} = \beta e(t) - \gamma i(t) - \delta i(t) \\ \frac{dr(t)}{dt} = \gamma i(t) - \eta r(t) \\ \frac{dd(t)}{dt} = \delta i(t) \end{cases} \tag{2}$$

The variables and parameters related to the model are set and described in relation to Table 2.

Table 2. Meaning of Variables and Parameters Related to the Model

Variant	**Define**
$S(t)$	Indicates the number of susceptible firms at time *t*
$E(t)$	Indicates the number of risky latent firms at time *t*
$I(t)$	Indicates the number of risk-infected firms at time *t*
$R(t)$	Indicates the number of firms recovering from risk at time *t*
$D(t)$	Indicates the number of firms eliminated by a risk shock at time *t*
$s(t)$	Indicates the number of enterprises susceptible to the risk of infection as a percentage of the total number of enterprises at time *t*
$e(t)$	Indicates the number of risky latent firms at time *t* as a percentage of the total number of firms
$i(t)$	Indicates the number of enterprises infected with the risk at moment *t* as a percentage of the total number of enterprises
$r(t)$	Indicates the number of enterprises recovering from risk at time *t* as a percentage of the total number of enterprises
$d(t)$	Indicates the number of enterprises phased out at time *t* as a percentage of the total number of enterprises.
λ	Indicates risk transmission rate
β	Indicates risk outbreak rate
γ	Indicates risk-recovery rate
δ	Indicates risk phase-out rate
η	Indicates loss of immunization rate
$< k >$	Network average degree

4.2. Model Threshold Analysis

In order to further study the risk propagation behavior on the fresh e-commerce supply chain network, the nodes on the network are classified according to degree, and it is assumed that a node with a degree of is susceptible, latent, infected, and recovered at the moment t. The relative densities of susceptible, latent, infected, and recovered are $s_k(t)$, $e_k(t)$, $i_k(t)$, $r_k(t)$ respectively. According to the mean field theory, the improved SEIRS risk propagation model after classification according to degree is shown below:

$$\begin{cases} \frac{ds_k(t)}{dt} = -\alpha k s_k(t)\Theta i_k(t) + \eta r_k(t) + \delta i_k(t) \\ \frac{de_k(t)}{dt} = \alpha k s_k(t)\Theta i_k(t) - \beta e_k(t) \\ \frac{di_k(t)}{dt} = \beta e_k(t) - \gamma i_k(t) - \delta i_k(t) \\ \frac{dr_k(t)}{dt} = \gamma i_k(t) - \eta r_k(t) \\ \frac{dd_k(t)}{dt} = \delta i_k(t) \end{cases} \tag{3}$$

Where, $\Theta i_k(t) = \sum_k k\, p(k) i_k / \langle k \rangle$, denotes the probability that a node of degree k at time t connects to an infected node.

This leads to two sets of solutions $M = (1,0,0,0)$ and $M^* = (s^*, e^*, i^*, r^*)$.

In this paper, we introduce the concept of basic regeneration number in supply chain risk communication to determine the threshold of risk diffusion transmission. Driessche and Watmough [17] proposed a new method for calculating the fundamental regeneration number, the regeneration matrix method, to analyze the asymptotic stability of the equilibrium point by calculating the spectral radius of the regeneration matrix, which is the fundamental regeneration number. In this paper, based on Eq. (3), combined with the regeneration matrix method to obtain:

$$F = \begin{pmatrix} 0 & \alpha k s_k \Theta \\ 0 & 0 \end{pmatrix};\ V = \begin{pmatrix} \beta & 0 \\ -\beta & \gamma + \delta \end{pmatrix} \tag{4}$$

Then $\Re_0 = \rho(FV^{-1}) = \alpha k s_k \Theta \ / \ (\gamma + \delta)$.Substituting $M = (1,0,0,0)$ into $\Re_0$ yields:

$$\Re_0 = \frac{\alpha < k^2 >}{(\gamma+\delta) < k >} \tag{5}$$

The basic regeneration number is the threshold of whether the supply chain risk propagates and spreads. When $\Re_0 < 1$, the disease-free equilibrium point is globally asymptotically stable, and eventually the risk will disappear; when $\Re_0 > 1$, the system exists a unique endemic equilibrium point M^* and is globally asymptotically stable, at which point the risk will continue to propagate in the supply chain [18, 19]. For scale-free characteristic networks, the larger the network size its infinity, so it can be assumed that when the network size is large enough, as long as the risk infection rate is greater than 0, the risk will continue to propagate in the network and maintain a stable state.

5. SIMULATION RESULTS AND DISCUSSION

Based on the established fresh e-commerce supply chain network model and the improved SEIRS model, this paper will use Python to simulate the process of fresh e-commerce supply chain risk propagation on the network.

It is assumed that the proportion of enterprises in each risk state in the supply chain at the initial time is: the proportion of susceptible enterprises is 0.9, and the proportion of infected enterprises is 0.1. the size of enterprise nodes in the supply chain is 2000, $< k >= 4.5929$. By referring to the relevant literature to set the model parameters as$\lambda = 0.2374$, $\beta = 0.2377$, $\gamma = 0.2766$, $\delta = 0.2337$, $\eta = 0.4637$, then at this time$\Re_0 = 5.0152 > 1$, according to the results of the threshold analysis can be known that the risk will continue to propagate in the supply chain network. The model simulation is run for 100 time steps and the simulation results are obtained as shown in Figure 4.

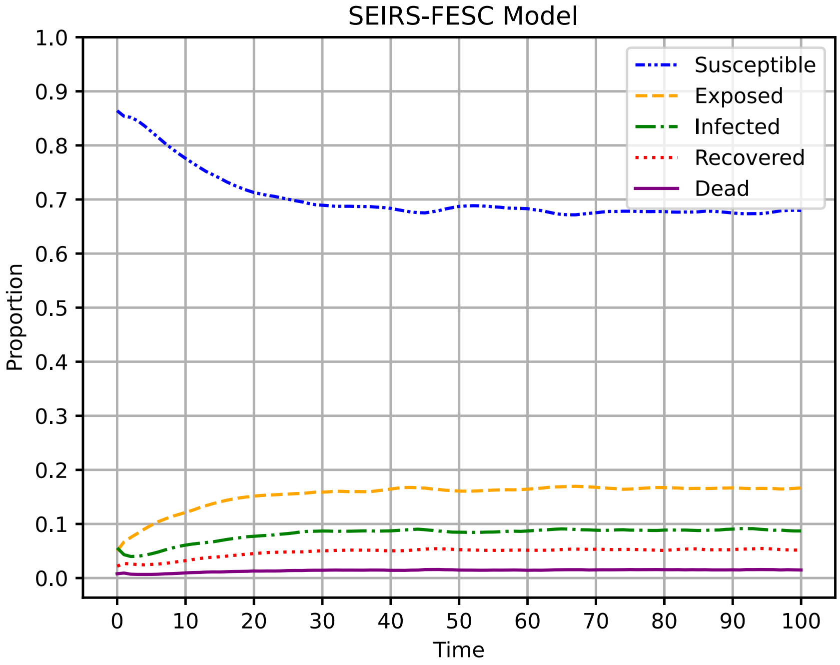

Figure 4. Risk Propagation Process in Fresh E-commerce Supply Chain

The simulation results show that once an enterprise in the network generates a risk and becomes an initial infected node, the risk will spread rapidly in the whole supply chain network. The proportion of risky latent enterprises and infected enterprises rises and reaches the maximum at =40 time step, from the initial proportion of about 0.05 to about 0.16 and 0.08 respectively; the number of easily infected enterprises decreases rapidly, and tends to be stabilized at =50 time step, and the proportion of susceptible enterprise size reaches 0.68 or so, and the risk propagation of the whole network reaches a stable state by this time. Simulation experimental results are consistent with theoretical results.

To further explore the propagation of risk in the fresh e-commerce supply chain, we investigate how various parameter changes influence risk propagation by adjusting the values in the risk propagation model.

The simulation results show that the degree of risk propagation is positively correlated with risk infection rate, risk outbreak rate, and loss of immunity rate, and negatively correlated with the risk recovery rate and risk elimination rate.

Consequently, for susceptible enterprises, it is crucial to identify risks and take preventive measures before a risk outbreak, to develop resistance and reduce risk infection rate. For latent enterprises, measures should be taken to enhance risk immunity or decrease risk intensity, reducing the risk outbreak rate. For infected enterprises, a series of strategies should be employed to improve risk management and recovery capabilities. For enterprises with weak risk resistance and competitive capacity in products or services, other supply chain enterprises should consider avoiding cooperation or eliminating them from the supply chain. For recovering enterprises, they should reflect on the flaws and vulnerabilities exposed by risk events, learn from them, and improve risk learning to reduce the loss of immunity rate, thereby ensuring more sustainable risk immunity for the supply chain enterprises.

6. SUMMARY

In this paper, a cross-layerable fresh e-commerce supply chain network model is constructed by considering the dual localized worlds of node adaptability and node firms, and the propagation of fresh e-commerce supply chain risks on the network is investigated based on the improved SEIRS model by considering node elimination, and it is found that the risks continue to propagate and reach an equilibrium state in the network when the scale is large enough. By adjusting the parameter analysis, it is found that the degree of impact of risk propagation is positively correlated with the rate of risk infection, risk outbreak, and loss of immunity, and negatively correlated with the rate of risk recovery and risk elimination.

Through this paper's summary of the research on the risk propagation of fresh e-commerce supply chain, although some progress has been made, there are still the following aspects that need further in-depth research:

(1) When this paper constructs the dual local world network model of fresh e-commerce supply chain, the adaptation degree is fixed since the nodes are generated from the network, and it will not change with time. Future research can consider the network with time-varying adaptability.

(2) Due to the difficulty of obtaining business data among enterprises in the fresh e-commerce supply chain, the weighting situation of the network model edges is not considered in order to simplify the model. Therefore, in order to better fit the actual situation of dynamic changes in the supply chain network, future research can consider establishing a weighted supply chain network model with transaction weights.

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