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Research Article

Simulation and Analysis of the Complex Behavior of Supply Chain Inventory System Based on Third-Party Logistics Management Inventory Model with No Accumulating of Unsatisfied Demand

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Under the third-party logistics management inventory model, the system dynamics method is used to establish a nonlinear supply chain system model with supply capacity limitation and nonpermissible return, which is based on unsatisfied demand nonaccumulation. The theory of singular value and the Jury Test are used to derive the stable interval of the model which is simplified. The Largest Lyapunov Exponent (LLE) of the system is calculated by the Wolf reconstruction method and used to analyze the influence of different parameters of system's stability. Then, the most reasonable and unreasonable combination of decision parameters under different demand environment is found out. Next, this paper compared and analyzed the change of inventory or transportation volume of system members under the combination of rational and irrational decision parameters. All of these provided guidance for decision making, which shows an important practical significance.

1. Introduction

As market competition continues to intensify, competition among enterprises is gradually transformed into competition for interests among supply chains. The competition between supply chains requires that all member companies in the supply chain work together to maximize the overall benefits of the supply chain, thereby increasing the competitiveness of the supply chain. The supply chain is highly competitive, and member companies are highly resistant to risks in the supply chain.

At the same time, maximizing the overall benefits of the supply chain can enable companies to continue to receive significant benefits for longer periods of time. Member companies obtain more benefits, and the company has more funds to carry out research and development innovation and improvement of its own technologies. This, in turn, enhances the competitiveness of the supply chain and enables the supply chain to gain more benefits.

A supply chain network (SCN) is a complex nonlinear system involving multiple entities. The policy of each entity in decision making and the uncertainties of demand and supply (or production) significantly affect the complexity of its behavior [1]. In the traditional SC model, each player is responsible for its inventory control, production, or distribution ordering activities, and each echelon only has their immediate customer information [2]. The lack of visibility of real demand causes a number of problems in traditional SC; many industries were required to improve their SC operations by sharing inventory or demand information for supplier and customer [3]. With the continuous development of information technology, some new supply chain models have gradually emerged. Among them, the application more common is the Vendor-Managed Inventory (VMI) model and the Third-party Logistics Management Inventory (TMI) model. The traditional individualized inventory management model is prone to the phenomenon that the demand follows the supply chain to scale up from the downstream to the upstream, that is, the bullwhip effect [4]. In the new supply chain model, demand information, inventory information, and production information are fully shared. The problem of gradually increasing demand has been well controlled. Whether it is from the traditional supply chain model to the supplier management inventory model or the supplier management inventory model, they all evolve to the third-party logistics management inventory model; these are in line with the concept of supply chain management specialization, refinement, and information.

2. Literature Review

As for the behavior of supply chain system, many scholars have studied it and obtained rich research results [5, 6]. Mosekilde and Larsen [7] and Thomsen et al. [8] adopted a deterministic supply chain and showed the existence of chaotic behavior in it. For linear systems, García et al. [9] considered one-dimensional time-invariant sampled-data linear systems with constant feedback gain, an arbitrary fixed time delay. The following will be divided into two parts to summarize them.

For the traditional supply chain model, the results are rich. Towill [10] proposed an inventory and order-based production control system (IOBPCS) to study the system's ability to calm down shocks and protect the manufacturing process from random changes in consumption. Lee et al. [11] analyzed four causes of the bullwhip effect and discussed possible actions to mitigate the adverse effects of this distortion. Disney and Towill [12] proposed a discrete control theory model for a general model of replenishment rules and analyzed that extending the validity period of historical data and shortening the production lead time can reduce the bullwhip effect. Nagatani and Helbing [13] studied a variety of production strategies to stabilize the supply chain, analyzed whether the response to the inventory level of other members of the supply chain has a stabilizing effect, proved that the prediction of the future inventory level can stabilize the supply chain, and gave the linear system stable conditions and simulations of different control strategies. Wang et al. [14] studied the stability of a constrained production and inventory system with a Forbidden Returns constraint (that is, a nonnegative order rate) via a piecewise linear model, an eigenvalue analysis, and a simulation investigation. Hwarng and Yuan [15] studied the influence of stochastic demand on the complex dynamic behavior of the supply chain. The research results show the complexity of the interaction between the stochastic demand process and the nonlinear dynamics, and the study considers that there are essential differences between the determination of demand and the impact of stochastic demand on the dynamics of the supply chain. Spiegler et al. [16] use a highly referenced Forrester production distribution model as a reference supply chain system to study nonlinear control structures and apply appropriate analytical control theory methods. Then, the performance of the linearized model is compared with the numerical solution of the original nonlinear model and other previous studies in the same model. Considering the nonnegative constraints of order quantities, Li et al. [17] studied the performance of inventory systems, including the effects of system stability, service levels, inventory costs, and transportation delay times, to systematically reflect the impact of order policies on inventory system performance. Under the intervention of the government, Dai et al. [18] constructed a continuous two-channel closed-loop supply chain model with time-delay decision and discussed the existence conditions of the local stability of the equilibrium. In addition, the time-delay feedback control method is used to effectively control unstable or chaotic systems.

For the new supply chain models, Disney and Towill [19] used the APIOBPCS ordering strategy to use mathematical models to study the stability of VMI systems, confirmed the instability caused by poor system design through dynamic simulation analysis, and proved that specific production delay can be avoided by setting reasonable parameters. Supply chain instability occurs. Disney and Towill [20] compared the expected performance of the supplier-managed inventory (VMI) supply chain with the traditional "series" supply chain. The analysis found that VMI performed better in response to changes in volatility demand and through simulated VMI and traditional supply. The chain validates the response to a typical retail sales model. Nachiappan and Jawahar [21] discussed the operation of a two-echelon single vendor–multiple buyers supply chain (TSVMBSC) model under the supplier management inventory (VMI) model and presented a mathematical formulation of an integrated inventory model of a two-echelon single vendor–multiple buyers VMI system. Han et al. [22] discussed a decentralized VMI problem in a three-echelon supply chain network in which multiple distributors (third-party logistics companies) are selected to balance the inventory between a vendor (manufacturer) and multiple buyers (manufacturers), and a tri-level decision model to describe the decentralized VMI problem is first proposed.

Most of the existing literature-based models are traditional supply chain models and supplier management inventory models. Few studies are based on third-party logistics management inventory models. Even the model is still in a stage of gradual improvement, and there are few documents which study the situation that the unmet need does not accumulate to the next cycle. At the same time, there are few relevant studies that have considered the fluctuations of the third-party logistics service providers' transportation workload. This paper analyzes the impact of different demand scenarios and the status of stable and unstable third-party logistics service providers on the number of transportation tasks.

Based on the premise of unsatisfied demand no accumulation, this paper constructs a dynamic model of third-party logistics inventory management supply chain system, simplifies the model and uses the Wolf reconstruction method and singular value theory to determine the conditions for simplifying the system stability, and finally uses

Simulink. The system simulation and data analysis verify the correctness and applicability of the model. At the same time, it gives a reasonable decision area for making the supply chain system in a stable state, which provides a reference for practical decision making and has important practical significance.

3. TMI Supply Chain System Dynamic Model

3.1. System Description. The TMI supply chain consists of one supplier, one retailer, and one third-party logistics enterprise. Both suppliers and retailers entrust the third-party logistics with the right of the inventory operation and decision making through the agreement. The third-party logistics enterprise is responsible for inventory management and logistics transportation tasks of the entire supply chain. In order to ensure timely replenishment of retailers, distribution centers are located near retailers. The work of supply chain members is carried out on a periodic basis. The event flow of each supply chain member is as follows: for retailers, at the beginning of the period, they receive replenishment from distribution centers, shipment according to customer demand, inventory, third-party logistics combined with retailer safety stock, suggest that retailers replenish, and retailers issue replenishment notifications to distribution centers; for the distribution center, at the beginning of the period, the distribution center received replenishment from the warehouse, replenished the goods from the retailer, inventoried the inventory, and issued a replenishment notice to the warehouse; for warehouses, at the beginning of the period, they received replenishment from suppliers, replenished them at the distribution center, counted inventory, and sent replenishment notifications to suppliers; For suppliers, production will be carried out at the beginning of the period t, according to the replenishment notice received at end of period $t-1$.

3.2. Systematic Difference Equations

3.2.1. Demand Forecasting Method. Assume that supply chain members use simple exponential smoothing methods to forecast demand. When suppliers conduct demand forecasting, they do demand forecasting based on the needs of the supply chain's end customer rather than retailer's order. From the perspective of demand forecasting, demand forecasts are more reasonable for the entire supply chain.

$$F(t) = \theta F(t-1) + (1-\theta)D(t). \tag{1}$$

3.2.2. Order Policy. This article adopts APVIOBPCS ordering strategy. The basic idea is that ordering has a fixed ordering period, and the order quantity of each period consists of demand forecasting, inventory adjustment, and transit adjustment. The ordering strategy is considered from the perspective of the Warehouse-Distribution Center System. Suppliers, warehouses, and distribution centers are seen as a system when considering warehouse ordering. The system is called the Warehouse-Distribution Center System. The ordering expression of the system is

$$O(t) = \max\left(0, F(t) + \alpha_S\left(I^0(t) - I(t)\right) + \alpha_{SL}\left(Y^0(t) - Y(t)\right)\right). \tag{2}$$

The supplier's work-in-process inventory at time t is given by

$$Y(t) = Y(t-1) + O(t-1) - R_w(t). \tag{3}$$

The supplier's expected WIP inventory is given by

$$Y^0(t) = G_w F(t). \tag{4}$$

Using the discrete system Z transform theory, we have drawn the block diagram of the inventory system of warehouse as shown in Figure 1.

3.2.3. For Retailers. The retailer's replenishment point is given by

$$I_r^0(t) = G_r F(t). \tag{5}$$

The retailer's inventory level at time is given by

$$I_r(t) = I_r(t-1) + R_r(t) - S_r(t). \tag{6}$$

And the retailer replenishment is given by

$$O_r(t) = \max\left(0, I_r^0(t) - I_r(t)\right). \tag{7}$$

The replenishment of the retailer can be quickly obtained, that is, the replenishment notification is issued at the end of the period, and the replenishment can be received at the beginning of the next period:

$$R_r(t) = O_r(t-1). \tag{8}$$

The retailer's shipments for this period's customer demand is given by

$$S_r(t) = D(t). \tag{9}$$

Using the discrete system Z transform theory, we have drawn the block diagram of the inventory system of the retailer as shown in Figure 2.

3.2.4. For Warehouse-Distribution Center System. The distribution center replenishment point is given by

$$I_d^0(t) = F(t) G_d. \tag{10}$$

The distribution center inventory is given by

$$I_d(t) = I_d(t-1) + R_d(t) - S_d(t). \tag{11}$$

The distribution center replenishment is given by

$$O_d(t) = \max\left(0, I_d^0(t) - I_d(t)\right). \tag{12}$$

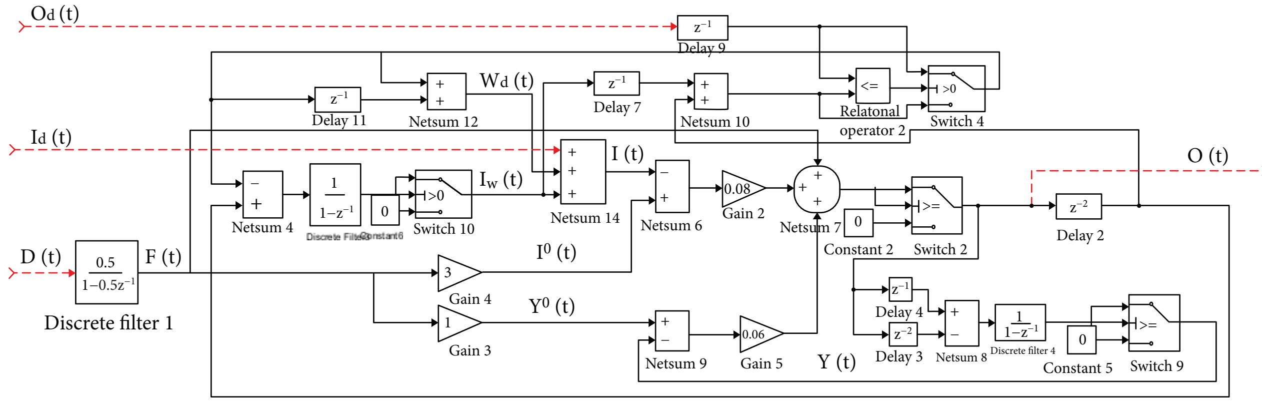


FIGURE 1: The block diagram of the inventory system of warehouse.

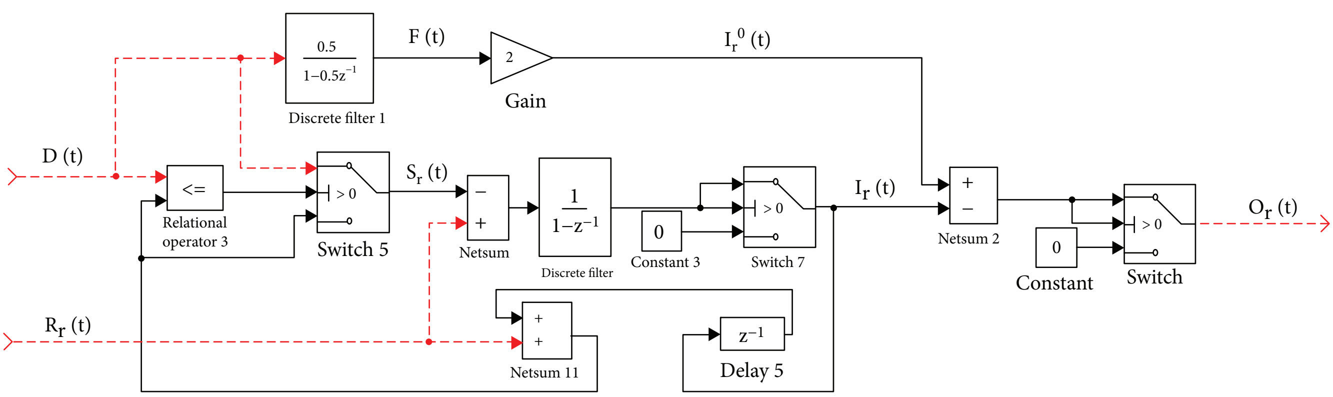


FIGURE 2: The block diagram of the inventory system of the retailer.

The distribution center receiving volume is given by

$$R_d(t) = O_d(t - T_P - 1). \tag{13}$$

The distribution center shipments are given by

$$S_d(t) = \begin{cases} I_d(t-1) + R_d(t) & I_d(t-1) + R_d(t) \le O_r(t-1), \\ O_r(t-1) & I_d(t-1) + R_d(t) > O_r(t-1). \end{cases} \tag{14}$$

And the distribution center inventory in transit is given by

$$W_d(t) = W_d(t-1) + O_d(t-1) - R_d(t). \tag{15}$$

The block diagram of the inventory system of distribution center is drawn using the Z transform theory of the discrete system as shown in Figure 3.

The warehouse inventory is given by

$$I_w(t) = I_w(t-1) + R_w(t) - S_w(t). \tag{16}$$

The warehouse receipt is given by

$$R_w(t) = O(t - T_C - 1). \tag{17}$$

The warehouse shipments are given by

$$S_w(t) = \begin{cases} I_w(t-1) + R_w(t) & I_w(t-1) + R_w(t) \le O_d(t-1), \\ O_d(t-1) & I_w(t-1) + R_w(t) > O_d(t-1). \end{cases} \tag{18}$$

The expected inventory of the system is given by

$$I^0(t) = F(t)(T_C + T_P). \tag{19}$$

And the actual inventory of the system is given by

$$I(t) = I(t-1) + R_w(t) - S_d(t). \tag{20}$$

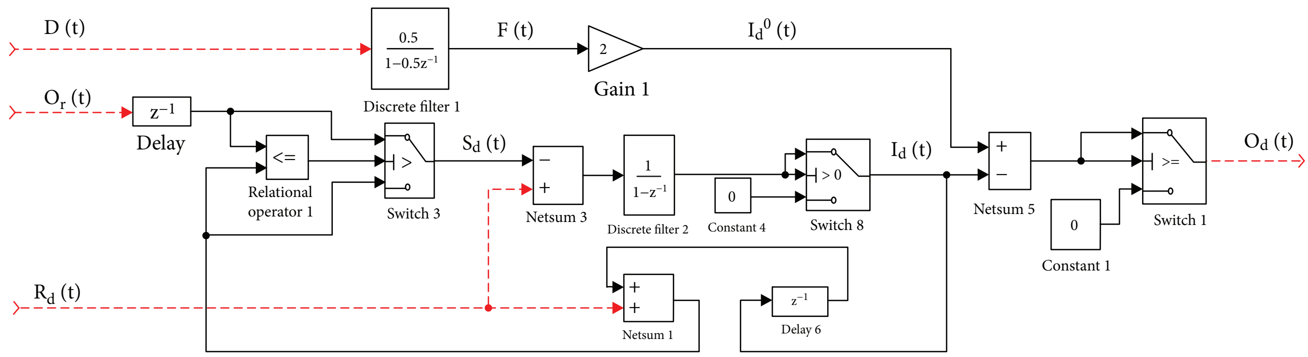


Figure 3: The block diagram of the inventory system of distribution center.

4. System Dynamic Behavior Analysis

The model constructed in this paper has nonnegative constraints and piecewise decision conditions, making the system a nonlinear system with switching. It has complex system dynamic behavior. For complex systems, theoretical derivation has some difficulties. Therefore, this paper uses the Wolf reconstruction method to calculate the Largest Lyapunov Exponent (LLE) value and uses LLE index as a quantitative index of the characteristics to analyze the dynamic behavior of complex supply chain systems.

The Lyapunov exponent quantitatively describes the exponential divergence of adjacent orbits in phase space. An orbit near an attractor of a one-dimensional discrete dynamic system can be expressed as

$$d_k = d_0 e^{\lambda}. \tag{21}$$

Here, d_0 is the initial separation distance of the two orbits, which is the orbital distance after k iterations, and λ is the Lyapunov exponent.

It can be seen that if the Lyapunov exponent is less than zero, the distance between the orbits is gradually reduced, the motion is stable, and the initial value is not felt; if the Lyapunov exponent is equal to zero, it is a critical state, that is, a stable boundary. If the Lyapunov exponent is greater than zero, it means that the adjacent orbits are scattered, and the long-term behavior is very sensitive to the initial value, and the motion is chaotic.

So it can be seen that if the LLE exponent of the system calculated is greater than 0, the system is in a chaotic state.

The model is simplified. It is assumed that there is only a nonnegative constraint on the order quantity of the system in the model. And $S_1 = \{X \mid O \geq 0\}$ and $S_2 = \{X \mid O < 0\}$. If $T_C = 1$, $T_P = 2$, $G_r = 2$, and $G_w = 1$, then the supply chain model in the previous section can be expressed as

$$\begin{cases} O(t) = \max\left(0, F(t) + \alpha_S\left(I^0(t) - I(t)\right) + \alpha_{SL}\left(Y^0(t) - Y(t)\right)\right), \\ I(t) = I_r(t-1) + I(t-1) - 2F(t-1) + O(t-2), \\ I_r(t) = 2F(t-1) - D(t), \\ Y(t) = Y(t-1) + O(t-1) - O(t-2), \\ F(t) = \theta F(t-1) + (1-\theta)D(t). \end{cases} \tag{22}$$

Equation (22) is expressed in the form of a vector equation, which gives the state space description of the system. The following shows

$$\begin{gathered} \mathrm{X}(t) = A_{1f}X(t-1) + A_{2f}X(t-2) + B_f r(t), \begin{cases} X(t-1) \in S_f \\ X(t-2) \in S_f \end{cases} \quad f = 1, 2, \\ \mathrm{X}(t) = [O(t)\, I(t)\, I_r(t)\, Y(t)\, F(t)]^T, \quad r(t) = D(t). \end{gathered} \tag{23}$$

4.1. Subsystem Stability Analysis. Subsystem 1: requirement for replenishment of the warehousing system.

$$\begin{cases} O(t) = -\alpha_{SL}O(t-1) - \alpha_S I(t-1) - \alpha_S I_r(t-1) - \alpha_{SL}Y(t-1) + [\theta(3\alpha_S + \alpha_{SL} + 1) + 2\alpha_S]F(t-1) + (1-\theta)(3\alpha_S + \alpha_{SL} + 1)D(t) + (\alpha_{SL} - \alpha_S)O(t-2), \\ I(t) = I_r(t-1) + I(t-1) - 2F(t-1) + O(t-2), \\ I_r(t) = 2F(t-1) - D(t), \\ Y(t) = Y(t-1) + O(t-1) - O(t-2), \\ F(t) = \theta F(t-1) + (1-\theta)D(t). \end{cases} \tag{24}$$

Equation (24) is expressed in the form of a vector equation, which gives the state space description of the system. The following shows

$$X(t) = A_{11}X(t-1) + A_{21}X(t-2) + B_1 r(t), \tag{25}$$

where

$$A_{11} = \begin{bmatrix} -\alpha_{SL} & -\alpha_S & -\alpha_S & -\alpha_{SL} & \theta(3\alpha_S + 1 + \alpha_{SL}) + 2\alpha_S \\ 0 & 1 & 1 & 0 & -2 \\ 0 & 0 & 0 & 0 & 2 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \theta \end{bmatrix},$$
$$A_{21} = \begin{bmatrix} (\alpha_{SL} - \alpha_S) & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{26}$$

$$B_1 = \begin{bmatrix} (1-\theta)(3\alpha_S + 1 + \alpha_{SL}) \\ 0 \\ -1 \\ 0 \\ (1-\theta) \end{bmatrix}. \tag{27}$$

Subsystem 2: the warehousing system does not need replenishment.

$$\begin{cases} O(t) = 0, \\ I(t) = I_r(t-1) + I(t-1) - 2F(t-1) + O(t-2), \\ I_r(t) = 2F(t-1) - D(t), \\ Y(t) = Y(t-1) + O(t-1) - O(t-2), \\ F(t) = \theta F(t-1) + (1-\theta)D(t). \end{cases} \tag{28}$$

Equation (28) is expressed as the form of a vector equation, which gives the state space description of the system. The following shows

$$X(t) = A_{12}X(t-1) + A_{22}X(t-2) + B_2 r(t), \tag{29}$$

where

$$A_{12} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & -2 \\ 0 & 0 & 0 & 0 & 2 \\ 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & \theta \end{bmatrix},$$
$$A_{22} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{30}$$

$$B_2 = \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \\ (1-\theta) \end{bmatrix}. \tag{31}$$

According to the singular value theory, let $X^* = [O^*\ I^*\ I_r^*\ Y^*\ F^*]^T$ to represent an equilibrium point of (23), then here, the system trajectory near the point can be expressed as

$$X(t) = X^* + \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \end{bmatrix} \lambda^t, \tag{32}$$

where λ is a complex number, $C1$, $C2$, $C3$, $C4$, and $C5$ are five constants. Substituting (32) into (23), for subsystem 1, we can obtain the nontrivial solution of system 1 with respect to parameters ($C1$, $C2$, $C3$, $C4$, and $C5$) if and only if (33) is satisfied [23].

$$\left| I - A_{11}\lambda^{-1} - A_{21}\lambda^{-2} \right| = \begin{vmatrix} 1 + \alpha_{SL}\lambda^{-1} - (\alpha_{SL} - \alpha_S)\lambda^{-2} & \alpha_S\lambda^{-1} & \alpha_S\lambda^{-1} & \alpha_{SL}\lambda^{-1} & -[\theta(3\alpha_S + 1 + \alpha_{SL}) + 2\alpha_S]\lambda^{-1} \\ -\lambda^{-2} & 1 - \lambda^{-1} & -\lambda^{-1} & 0 & 2\lambda^{-1} \\ 0 & 0 & 1 & 0 & -2\lambda^{-1} \\ -\lambda^{-1} + \lambda^{-2} & 0 & 0 & 1 - \lambda^{-1} & 0 \\ 0 & 0 & 0 & 0 & 1 - \theta\lambda^{-1} \end{vmatrix} = 0. \tag{33}$$

The characteristic equation of (25) determines the stability of the equilibrium solution by (33).

$$\left(1-\lambda^{-1}\right)\left[1+(\alpha_{\mathrm{SL}}-1)\lambda^{-1}+(\alpha_S-\alpha_{\mathrm{SL}})\lambda^{-2}\right]\left(1-\theta\lambda^{-1}\right)=0. \tag{34}$$

That is,

$$(\lambda-1)(\lambda-\theta)\left[\lambda^2+(\alpha_{\mathrm{SL}}-1)\lambda+\alpha_S-\alpha_{\mathrm{SL}}\right]=0, \tag{35}$$

where $\lambda \neq 0$. If the root of (35) is within the unit circle, system 1 is stable. From (35), the solution of the equation $\lambda_1 = 1$ and $\lambda_2 = \theta$. According to [24], if the characteristic root of a linear discrete system on the unit circle is the single root of the smallest polynomial of the characteristic polynomial, the system is stable. Because $0 < \theta < 1$, λ_1 and λ_2 are stable. Then, the stability of system 1 is determined by the root of (36).

$$\lambda^2-(1-\alpha_{\mathrm{SL}})\lambda+\alpha_S-\alpha_{\mathrm{SL}}=0, \tag{36}$$

when $\alpha_S = \alpha_{\mathrm{SL}}$.

The roots of (36) are $\lambda_3 = 1-\alpha_{\mathrm{SL}}$ and $\lambda_4 = 0$. According to the judging criterion Jury Test [25], $0 < \alpha_{\mathrm{SL}} < 2$ can guarantee the stability of the system.

Note that α_S represents the magnitude of the deviation of the actual inventory from the expected stock, and α_{SL} represents the magnitude of the deviation of the in-stock inventory from the expected in-process inventory. Then, $\alpha_S = \alpha_{\mathrm{SL}}$ means that the same adjustment range is maintained for inventory deviation and work-in-process inventory deviation. Therefore, when $\alpha_S = \alpha_{\mathrm{SL}}$ and $0 < \alpha_{\mathrm{SL}} < 2$ are set, the system is stable.

When $\alpha_S \neq \alpha_{\mathrm{SL}}$,

(1) $\Delta = (1-\alpha_{\mathrm{SL}})^2 - 4(\alpha_S-\alpha_{\mathrm{SL}}) < 0$, that is, $\alpha_S > ((1+\alpha_{SL})^2/4)$

The root of (36) is $\lambda_3 = ((1-\alpha_{\mathrm{SL}}) + i\sqrt{-\Delta})/2$ and $\lambda_4 = ((1-\alpha_{\mathrm{SL}}) - i\sqrt{-\Delta})/2$. According to the law of stability $|\lambda| < 1$, (37) can be obtained.

$$\left(\frac{1-\alpha_{\mathrm{SL}}}{2}\right)^2+\left(\frac{\sqrt{-\Delta}}{2}\right)^2<1. \tag{37}$$

The solution

$$\begin{cases}\alpha_S-1<\alpha_{\mathrm{SL}}<\alpha_S,\\ \alpha_S>\dfrac{(1+\alpha_{\mathrm{SL}})^2}{4},\end{cases} \tag{38}$$

that is,

$$\begin{cases}\alpha_S-1<\alpha_{\mathrm{SL}}<2\sqrt{\alpha_S}-1,\\ 0<\alpha_S<4.\end{cases} \tag{39}$$

(2) $\Delta = (1-\alpha_{\mathrm{SL}})^2 - 4(\alpha_S-\alpha_{\mathrm{SL}}) = 0$, that is, $\alpha_S = (1+\alpha_{SL})^2/4$

The root of (36) is $\lambda_3 = \lambda_4 = (1-\alpha_{SL})/2$, according to the law of stability $|\lambda| < 1$. λ_3 and λ_4 should satisfy the following conditions.

$$\begin{cases}-1<\lambda_3<1,\\ -1<\lambda_4<1.\end{cases} \tag{40}$$

That is,

$$\begin{cases}\alpha_{\mathrm{SL}}=2\sqrt{\alpha_S}-1,\\ 0<\alpha_S<4.\end{cases} \tag{41}$$

(3) $\Delta = (1-\alpha_{\mathrm{SL}})^2 - 4(\alpha_S-\alpha_{\mathrm{SL}}) > 0$, that is, $\alpha_S < (1+\alpha_{SL})^2/4$

The root of (36) is $\lambda_3 = ((1-\alpha_{\mathrm{SL}}) + \sqrt{\Delta})/2$ and $\lambda_4 = ((1-\alpha_{\mathrm{SL}}) - \sqrt{\Delta})/2$. According to the law of stability $|\lambda| < 1$, λ_3 and λ_4 should satisfy the following conditions.

$$\begin{cases}-1<\lambda_3<1,\\ -1<\lambda_4<1.\end{cases} \tag{42}$$

That is,

$$\begin{cases}-1<\dfrac{(1-\alpha_{\mathrm{SL}})+\sqrt{(1-\alpha_{\mathrm{SL}})^2-4(\alpha_S-\alpha_{\mathrm{SL}})}}{2}<1,\\ -1<\dfrac{(1-\alpha_{\mathrm{SL}})-\sqrt{(1-\alpha_{\mathrm{SL}})^2-4(\alpha_S-\alpha_{\mathrm{SL}})}}{2}<1.\end{cases} \tag{43}$$

Combined with (41), the solution is

$$\begin{cases}2\sqrt{\alpha_S}-1<\alpha_{\mathrm{SL}}<\dfrac{1}{2}\alpha_S+1,\\ 0<\alpha_S<4.\end{cases} \tag{44}$$

To sum up, the parameter range for making subsystem 1 stable is [23]

$$\begin{cases} \alpha_S - 1 < \alpha_{SL} < \dfrac{1}{2}\alpha_S + 1, \\ 0 < \alpha_S < 4. \end{cases} \tag{45}$$

For subsystem 2, we can obtain the nontrivial solution of system 2 with respect to parameters ($C1$, $C2$, $C3$, $C4$, and $C5$) if and only if (46) is satisfied [23].

$$\left|I - A_{12}\lambda^{-1} - A_{22}\lambda^{-2}\right| = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 \\ -\lambda^{-2} & 1-\lambda^{-1} & -\lambda^{-1} & 0 & 2\lambda^{-1} \\ 0 & 0 & 1 & 0 & -2\lambda^{-1} \\ -\lambda^{-1}+\lambda^{-2} & 0 & 0 & 1-\lambda^{-1} & 0 \\ 0 & 0 & 0 & 0 & 1-\theta\lambda^{-1} \end{vmatrix} = 0. \tag{46}$$

The characteristic equation of (25) determines the stability of the equilibrium solution by (46). And (47) can be obtained by (46).

$$\left(1-\lambda^{-1}\right)^2\left(1-\theta\lambda^{-1}\right) = 0. \tag{47}$$

That is,

$$(\lambda - 1)^2(\lambda - \theta) = 0, \tag{48}$$

where $\lambda \neq 0$. If the root of (48) is within the unit circle, system 2 is stable. From (48), the solution of the equation is $\lambda_1 = 1$, $\lambda_2 = 1$, and $\lambda_3 = \theta$. Since the system has 2 characteristic roots on the unit circle, the system is Schur unstable. However, this instability refers to a critical stability. Since the system has no feedback control on the input, its input response is a kind of ramp function, which plays a role in maintaining the initial value. That is, when the inventory system is in this state, inventory keeps declining as demand continues to arrive without replenishment.

4.2. System Switching Model. According to the above analysis, due to the uncertainty of the replenishment volume of the warehouse allocation system, the supply chain system studied in this chapter is not a linear system. It can be regarded as the order control by the warehouse allocation system and the switching between the two subsystems. To switch the system, the two subsystems are determined by (25) and (29), respectively. Since all subsystems are linear systems, the system can be represented as a linear switching system as shown in

$$X(t) = A_{1\sigma(t)}X(t-1) + A_{2\sigma(t)}X(t-2) + B_{\sigma(t)}r(t). \tag{49}$$

The system is an autonomous switching system. The switching rule is a function of the system state. It is the judgment of the $O(t)$ symbol of the order quantity per cycle:

$$\begin{aligned}\sigma(t) &= \min\left(2, -\mathrm{sign}\left(F(t) + \alpha_S\left(I^0(t) - I(t)\right) + \alpha_{SL}\left(Y^0(t) - Y(t)\right)\right) + 2\right) = \min\left(2, -\mathrm{sign}\left(F(t) + \alpha_S\left(F(t)(T_C + T_P) - I(t)\right) + \alpha_{SL}\left(G_w F(t) - Y(t)\right)\right) + 2\right).\end{aligned} \tag{50}$$

The switching function $\sigma(t)$ is the evaluation of the order quantity of the warehouse allocation system. If $\sigma(t) = 1$, it means that the warehouse allocation system needs replenishment. If $\sigma(t) = 2$, it means that the warehouse allocation system does not need to be in replenishment. The actual stock in the warehouse and the WIP inventories can meet expectations of inventory in the warehouse, expected WIP inventory, and demand forecast.

4.3. Analysis of System Dynamic Characteristics. In the subsystem, the subsystem 1 is stable within a certain parameter range; and the subsystem 2 is not stable due to the existence of a characteristic root located on the unit circle. According to the gist of the average dwell time method, the switching system is stable when the activation time of the stable system is large enough and the ratio of the dwell time of the unstable system to the dwell time of the stable system satisfies a certain condition. From the results of the switching rules (50) and the rules, we can see that when the warehouse allocation system sets a higher expected inventory level $I^0(t)$, that is, when the higher parameters T_C, T_P, and G_w are set, system switching can be avoided to unstable subsystem 2. When α_S and α_{SL} are fixed, setting smaller $I^0(t)$ and $Y^0(t)$ will result in larger $-\mathrm{sign}(F(t) + \alpha_S(I^0(t) - I(t)) + \alpha_{SL}(Y^0(t) - Y(t))) + 2$ values, so the unstable subsystem 2 has a long activation time and the system tends to be unstable.

5. System Simulation and Data Analysis

5.1. Order Decision Adjustment Parameters. In order to further study the influence of different ordering strategies and inventory management strategies on the nonlinear supply chain system with constraints, this paper designs the simulation experiment to calculate the Largest Lyapunov Exponent of the system and analyzes the effects of the relevant parameters on the stability of the system under different demand types. When LLE is less than or equal to 0, it indicates that the system is in a stable, periodic, or quasiperiodic state. It is an ideal state for ordering decisions. When LLE is greater than 0, the system is in a chaotic or quasi-chaotic state.

From the analysis in the previous section, it can be seen that the inventory adjustment parameter α_S and the adjustment coefficient of work-in-process inventory α_{SL} have important influence on the dynamic characteristics of the system. This paper designs a simulation experiment and calculates LLE values under various order parameter combinations in the decision space $[\alpha_S, \alpha_{SL}]$ under the condition of certain other factors and uses the size of the LLE to examine the dynamic characteristics of the supply chain system. Considering that in the management practice the decisionmakers pay more attention to the inventory adjustment and the adjustment parameters are all less than 1, this paper assumes that the two parameters range from $0 \leq \alpha_{SL} \leq \alpha_S$ to $0.02 \leq \alpha_S \leq 1$. Both α_S and α_{SL} are changed by 0.02 steps. The simulation experiment needs to calculate the LLE value under various parameter combinations.

5.2. Simulation Analysis. Using Matlab to realize simulation experiments, LLE values for different combinations of parameters are calculated and expressed in the form of a contour graph. The simulation runs 1000 times. If the cycle is calculated in days, it will be the data volume in nearly 3 years. Considering that the actual inventory turnover cycle of the company is short, the data volume in 3 years should be sufficient.

In order to take any situation into account in practice, this paper analyzes three kinds of demand scenarios: random demand obeying normal distribution, random demand obeying uniform distribution, and fixed demand. Simulation and mapping LLE diagram of the retailer and warehouse matching system under different demand scenarios are shown.

First, the LLE value under the fixed constant demand scenario is calculated to obtain the LLE contour graph of the retailer and warehouse matching system, as shown in Figure 4.

As can be seen from Figure 4, under the fixed constant requirement, the inventory system is basically in a stable state in the entire decision area. The fixed constant requirement is an ideal scenario, and there are few in practice. Based on the calculation of the LLE for the entire decision area, this paper finds the value of the decision parameter that makes the inventory system in this scenario unstable. When $\alpha_S = 0.92$, $\alpha_{SL} = 0.04$ and $\alpha_S = 0.98$, $\alpha_{SL} = 0.1$, the retailer's LLE is greater than zero. When $\alpha_S = 0.98$ and $\alpha_{SL} = 0.06$, the LLE value of the warehouse allocation system is greater than zero. There is no decision to make when both are more than zero at the same time. Explain that in an ideal demand scenario, unreasonable parameter settings may also lead to system instability. When $\alpha_S = 0.94$ and $\alpha_{SL} = 0.12$, the average LLE values of the retailer and the warehouse match system are the smallest. Few parameters cause the system to be unstable, which also explains the practicability and effectiveness of the system.

Second, we calculate the LLE value under the random demand with normal distribution and obtain the LLE contour graph of the retailer and warehouse allocation system as shown in Figure 5.

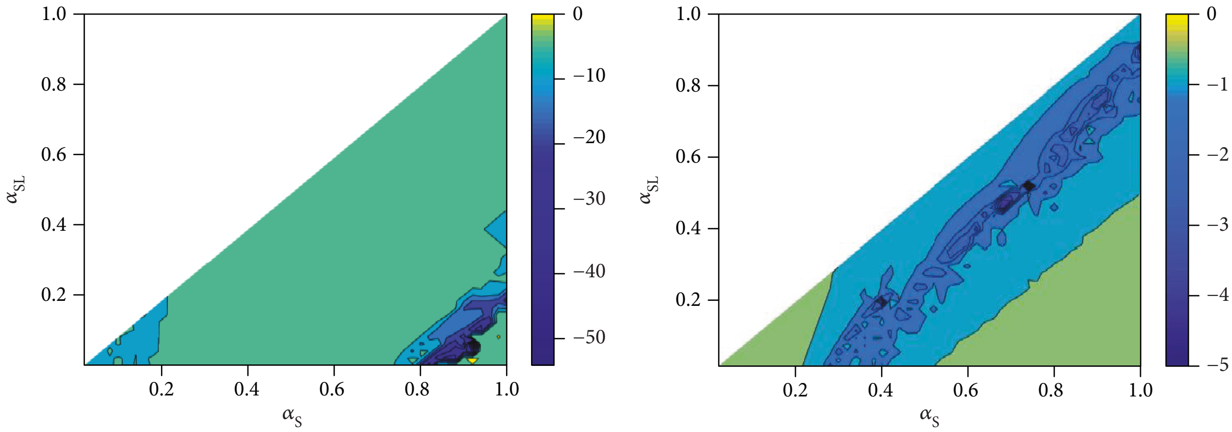
Under the random demand subject to normal distribution, in the entire decision area, the average LLE value of the retailer and the warehouse matching system is the smallest when $\alpha_S = 0.1$ and $\alpha_{SL} = 0.1$. The average value of the LLE value is the largest when $\alpha_{SL} = 1$ and $\alpha_S = 0.16$. From Figure 5(a), we can see that for the retailer, although the LLE value in most regions is greater than zero, there are still some regions whose values are less than zero under random demand. It indicates that there are some decision parameters that can make the inventory of the retailer stable under random demand. The periodic or quasiperiodic state provides a more valuable reference for real-world decision making. From Figure 5(b), we can see that under the stochastic demand, the decision zone with LLE value less than zero in the warehouse allocation system is banded and located above the entire decision zone. As the adjustment coefficient of stock inventory increases, the inventory adjustment coefficient increases. There are some decision-making areas that do not meet this trend and should avoid this part of the decision to prevent the system from entering a chaotic state. That is, when the inventory adjustment coefficient is higher than a certain level, the inventory adjustment coefficient is too high, which may make the system in a chaotic state. Combining the analysis of Figures 5(a) and 5(b), there is a common decision area in which both the retailer's LLE value and the warehouse allocation system's LLE value are less than zero. That is, under random demand, there is a reasonable decision to make each of the TMI supply chain. Member inventory is in a stable, cyclical, or quasiperiodic state, which has important practical significance.

Finally, we calculate the LLE value under the uniform distribution of random demand and obtain the LLE contour graph of the retailer and warehouse allocation system, as shown in Figure 6.

Under the random demand with uniform distribution, in the entire decision region, the average LLE value of the retailer and the warehouse matching system is the smallest when $\alpha_S = 0.08$, $\alpha_{SL} = 0.08$. When $\alpha_S = 0.9$, $\alpha_{SL} = 0.22$, the average LLE value of the retailer and the warehouse matching system is the largest. Figure 6 shows that under the uniform distribution random demand the decision-making area where the inventory of the retailer and the warehouse allocation system is stable is very small because the uniform distribution of demand obeying the 60–100 interval is a very harsh condition for the inventory system. Under actual circumstances, the demand will be subject to periodical laws in a relatively long period of time, and the demand forecast can be more accurate. So it is more likely that the inventory system will be in a stable state. This article draws on existing research and sets safety stock as a multiple of forecasted demand. Safety stocks are inherently more volatile. In order to reduce the volatility of safety stocks, the forecasted demand can be smoothed or smoothed several times, and the volatility of safety stocks can be reduced by reducing the forecasting demand and volatility. In addition, setting the safety stock to a fixed value may also improve the stability of the inventory system. In the existing studies, relevant scholars set the safety stock as a constant and achieved relatively good results. In this regard, this paper does not conduct simulation analysis, leaving it for follow-up studies.

In order to analyze the changes in inventory under different demand scenarios more intuitively, we draw the figure of inventory changes under different demand scenarios. When analyzing the change of inventory in steady state, we select the decision corresponding to the minimum average and the maximum average number of LLEs of retailers and warehouse matching centers under different demand scenarios to simulate them and then map them to steady state and unstable state, respectively. The inventory change chart in steady state and unstable state is shown in Figures 7–12.

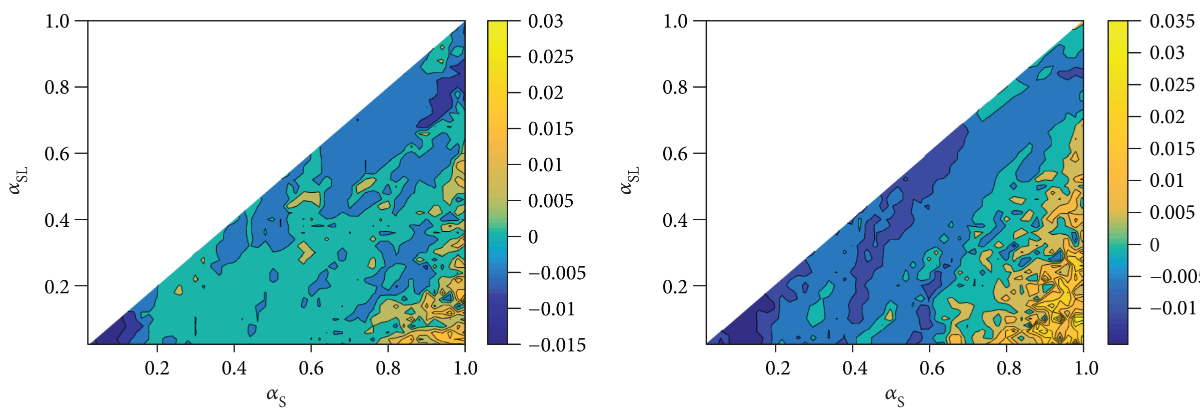
In Figures 7 and 8, the retailer can increase the volatility of inventory changes in a steady state or an unstable



(a) Retailer's LLE chart

(b) LLE chart of warehouse allocation system

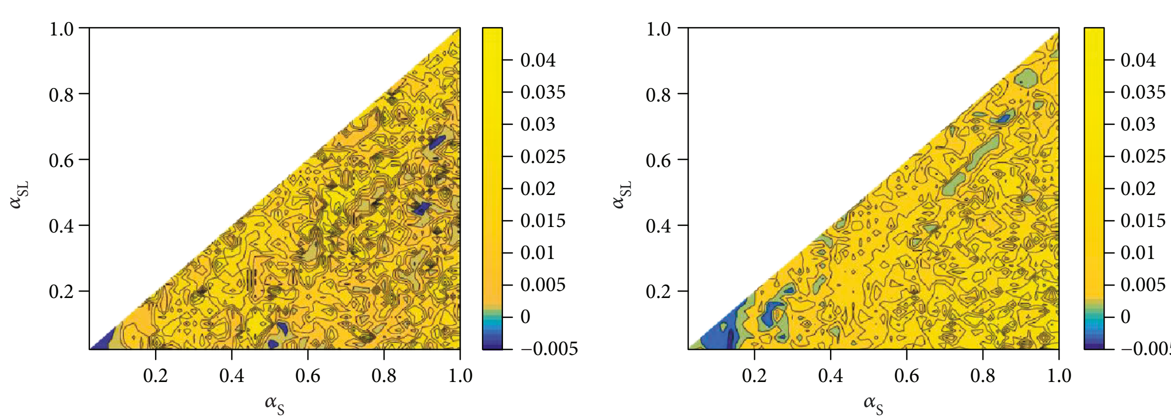
Figure 4: LLE diagram of members following fixed constant requirements.



(a) Retailer's LLE chart

(b) LLE chart of warehouse allocation system

Figure 5: LLE diagram of members under the scenario of random demand obeying normal distribution.



(a) Retailer's LLE chart

(b) LLE chart of warehouse allocation system

Figure 6: LLE diagram of members under the scenario of random demand obeying uniform distribution.

state under a fixed constant demand, a random demand subject to normal distribution, and a random demand subject to uniform distribution. It shows that the demand scenario has a great influence on the stability of the supply chain inventory. The greater the randomness of the demand, the more serious the supply chain instability may be. When the demand is a fixed constant demand, whether the supply chain system is in a stable or unstable

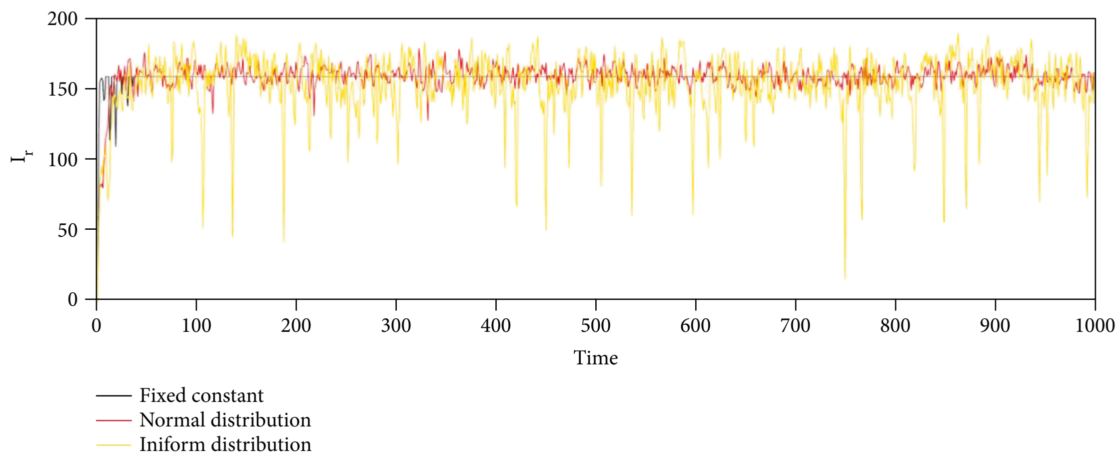


Figure 7: Retailers' initial inventory changes in a stable state under three demand scenarios.

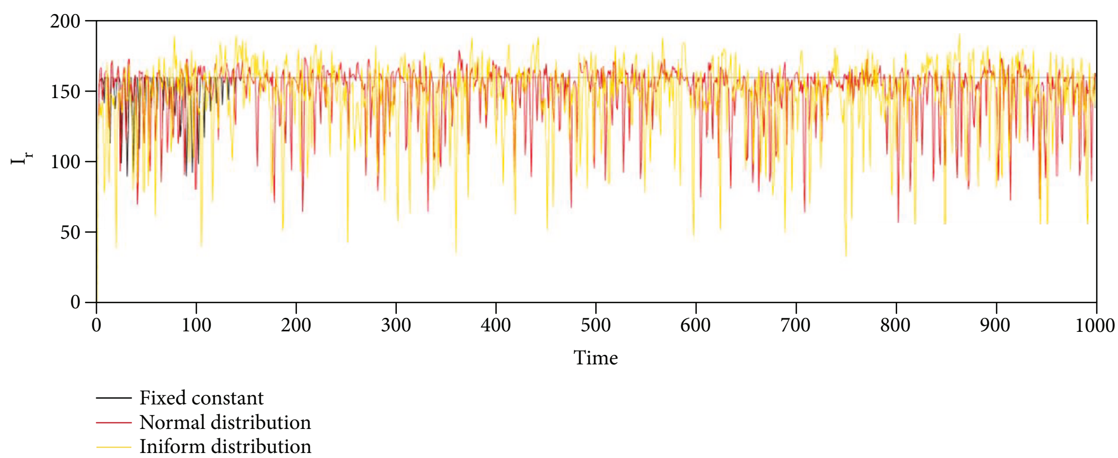


Figure 8: Retailers' initial inventory changes in an unstable state under three demand scenarios.

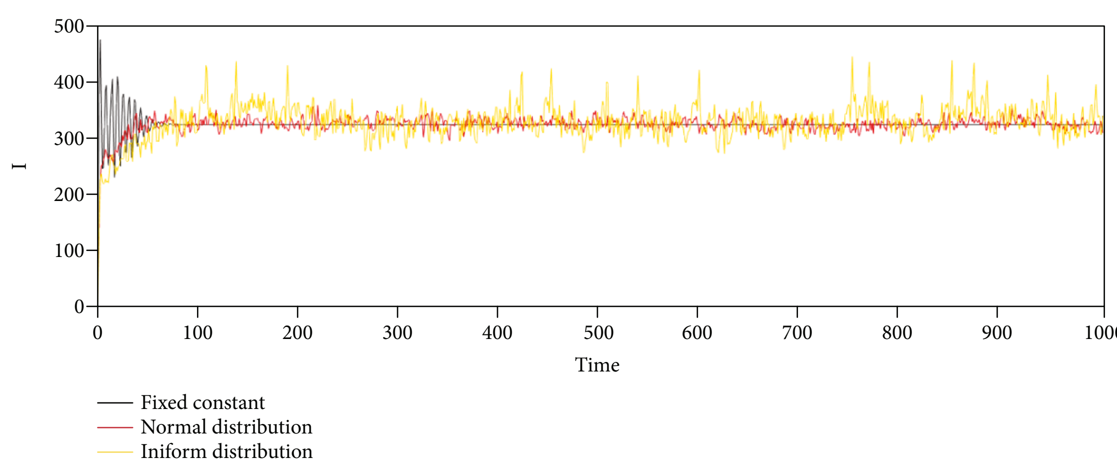


Figure 9: Change of initial inventory of warehouse allocation system in a stable state under three demand scenarios.

state, the retailer's inventory will stabilize to a value after a period of time, but the former will use less time than the latter. When the demand is subject to a uniform distribution of random demand, even if the supply chain is in the most stable state, the volatility of retailer inventory changes is also very large.

From Figure 9, we can see that in the steady state, the initial inventory of the warehouse allocation system under the

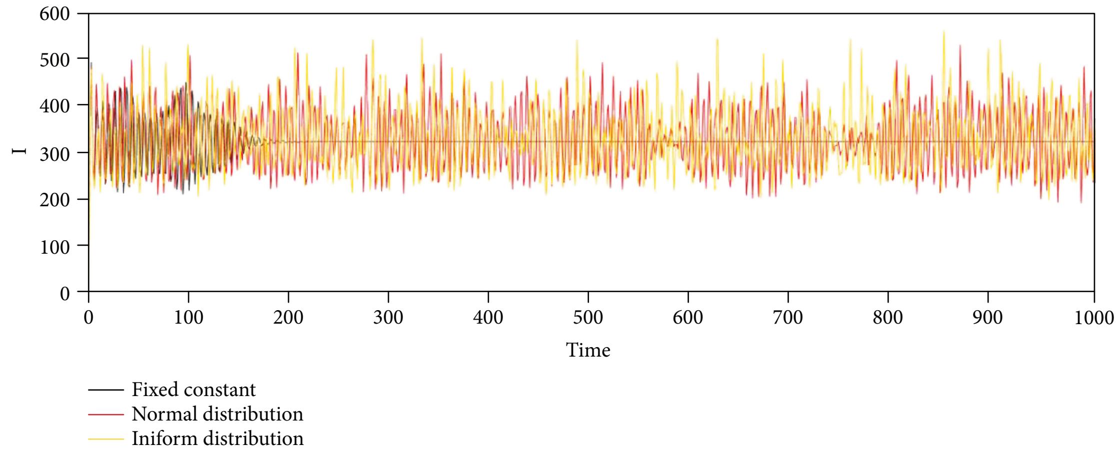


Figure 10: Change of initial inventory of warehouse allocation system in an unstable state under three demand scenarios.

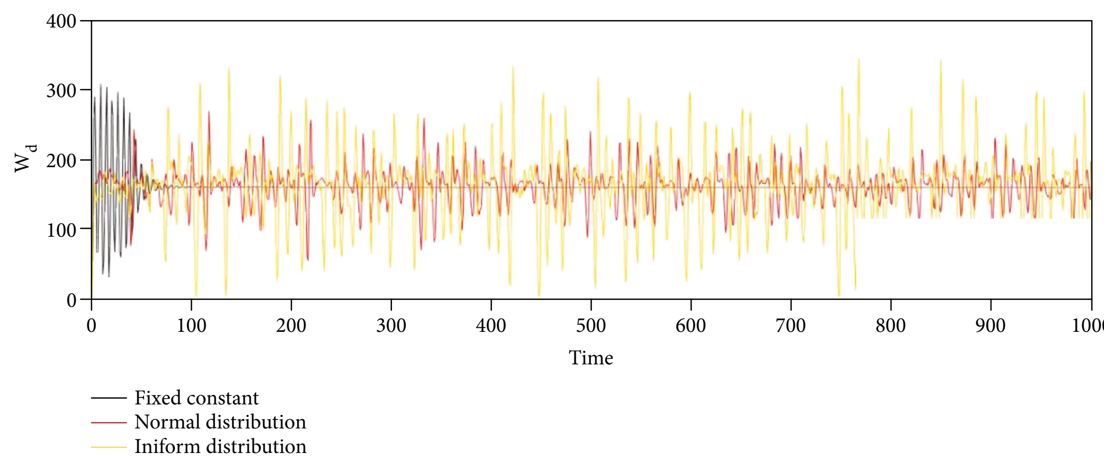


Figure 11: Change in traffic volume of third-party logistics service providers in a stable state under three demand scenarios.

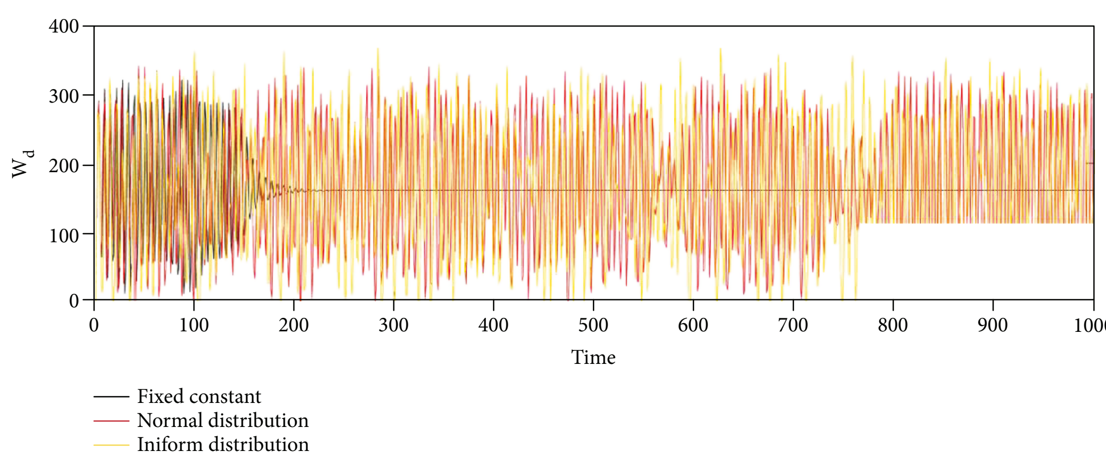


Figure 12: Change in traffic volume of third-party logistics service providers in an unstable state under the three demand scenarios.

fixed constant demand shows greater volatility in the initial stage of the three demand scenarios, which the manager should pay attention to. Under the stochastic demand scenario subject to normal distribution, the inventory of the warehouse allocation system fluctuates in a very small range, which is ideal and expected. For the strict random demand scenario with uniform distribution, the supply chain inventory shows satisfactory fluctuations under reasonable decision parameters. In the unstable state, from Figure 10, we can see that in addition to the fixed constant demand scenario, the inventory change of the warehouse allocation system shows a state of chaos that should be avoided under the three demand scenarios. Under the fixed constant demand scenario, the warehouse inventory system also shows great volatility at the initial stage and then stabilizes.

In the steady state, from Figure 11, we can see that the third-party logistics service provider's traffic under the fixed constant demand scenario has great volatility in the initial stage. For this, logistics service providers are required to make phased planning. Observing that in the steady state, the three-logistics service provider's traffic volume change graph is approximately an axisymmetric pattern under the three demand scenarios. The volatility increases from the fixed constant demand, the stochastic demand with normal distribution to the stochastic demand with uniform distribution. In the unstable state, from Figure 12, we can see that the changes in the traffic volume of the third-party logistics service providers under the three demand scenarios appear chaotic state, and the three curves almost cover the coordinate axis area. However, in the case of fixed constant demand conditions, it eventually stabilized to a certain value after a long period of fluctuation.

In order to analyze the changes of member stocks in stable and unstable conditions under different demand scenarios more clearly, this paper plots the changes in inventory when retailers and warehouse allocation systems are in stable and unstable conditions under different demand scenarios. A comparison chart of changes in traffic volume of third-party logistics service providers in the comparison chart and in different states is shown. Figures 13–15 show the fixed constant demand scenario.

Under the fixed constant demand scenario, it can be seen from Figure 13 that the retailer inventory shows a stable trend after the first fluctuation and a stable state, and the time for the former to reach stability is less than the latter. In Figures 14 and 15, it can be seen that the inventory fluctuations of the warehouse allocation system and the third-party logistics service providers have the same rules as the retailer inventory. In the unstable state, during the simulation period of 0–200 hours, the inventory or transport volume of the three members of the supply chain presented great volatility, which increased the inventory management costs and logistics transportation costs of the entire chain. This is not conducive to the evolution and development of the supply chain.

Under the scenario of evenly distributed stochastic demand, we simulate and draw a comparison chart of changes in inventory when the retailer and warehouse allocation system is in a stable and unstable state. And a comparison chart of changes in the traffic volume of third-party logistics service providers in different states is drawn as shown in Figures 16–18.

Obeying the uniform distribution of stochastic demand is a great challenge for the stability of the supply chain inventory system. In Figures 16 and 17, we can see that the initial inventory of the retailer has a great fluctuation when it is in the stable state and the unstable state under the condition of the stochastic demand that obeys the uniform distribution. However, the inventory at the beginning of the warehousing system can be stable to a very small interval in the steady state, which verifies the advanced nature and practicality of the supply chain model. As shown in Figure 18, the volatility of the transport volume of the third-party logistics service providers in the unstable state and the stable state is very large, and the volatility is relatively small in the stable state of the two states. Under this demand scenario, the third-party logistics will face arduous transportation tasks and face enormous challenges in the rational allocation of resources. On the other hand, the professionalism of third-party logistics service providers can be reflected to reduce inventory management and logistics transportation costs.

Under the normal distribution stochastic demand scenario, a comparison chart of the changes in inventory when the retailer and the warehouse allocation system is in a stable state and an unstable state and a comparison chart of the changes in the third-party logistics service providers' transportation volumes in different states are shown in Figures 19–21.

From Figure 19, we can see that under the scenario of normal distribution random demand, there is a clear difference between the stable state and the unstable state of the retailer inventory, and the inventory fluctuation in the steady state is much smaller than that in the unstable state. The peaks of retailer inventory fluctuations under both conditions have little difference between the two states, but the trough values in the unstable state are smaller than those in the stable state. So in the unstable state, the utilization rate of the retailer stocks will decrease. From Figure 20, it can be seen that, in the steady state, the inventory matching system can reach a stable interval within a short time and then stay in this interval. In an unstable state, the inventory of the warehouse system fluctuates up and down, showing a non-periodical change. Inventory fluctuations have an impact on management and costs. Maintaining a stable inventory is desirable; it is easy to manage and can reduce costs. Comparing Figure 19 with Figure 20, it can be seen that in the steady state, inventory fluctuations of the stock allocation system do not amplify retailer inventory fluctuations, which verifies the feasibility of the supply chain inventory system model. In Figure 21, it can be clearly seen that the volatility of the third-party logistics service providers' traffic in the steady state is far greater than the volatility in the unstable state. At the same time, the total transportation volume of the two is equal, and the cost of smooth transportation tasks may be lower. In the unstable state, the third-party logistics may generate higher service costs. Therefore, higher service prices are not conducive to long-term cooperation among the members of the TMI supply chain.

6. Conclusion

Although there are few existing researches on the new supply chain model, it can be found from the study of this paper that the complex behaviors of both the new supply chain and the traditional supply chain have a common part, which is a

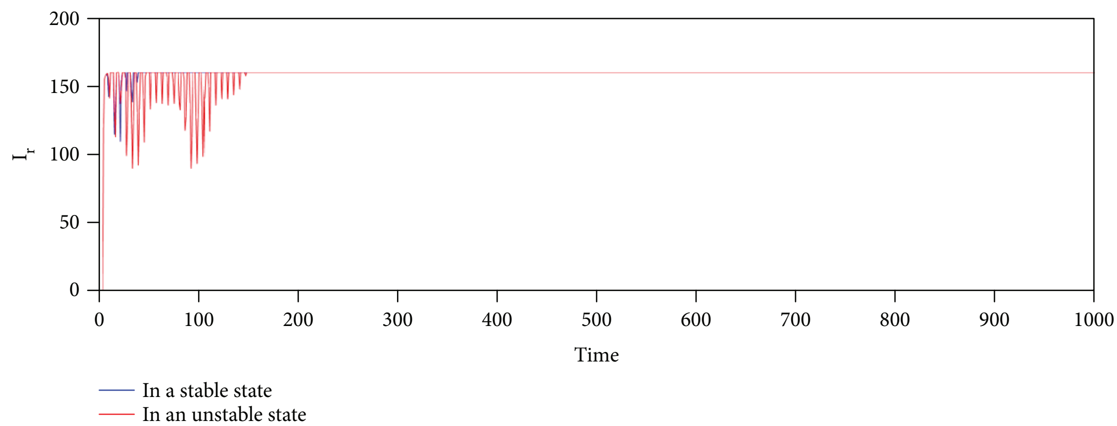


Figure 13: Comparison of retailers' opening stock changes in a stable state and unstable state under fixed constant demand.

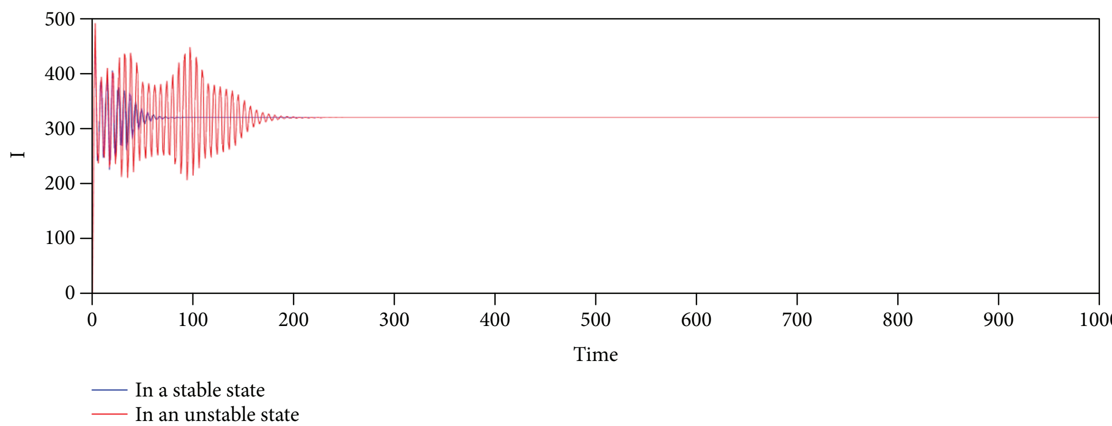


Figure 14: Comparison of initial inventory changes of the warehousing system in a stable state and unstable state under fixed constant demand.

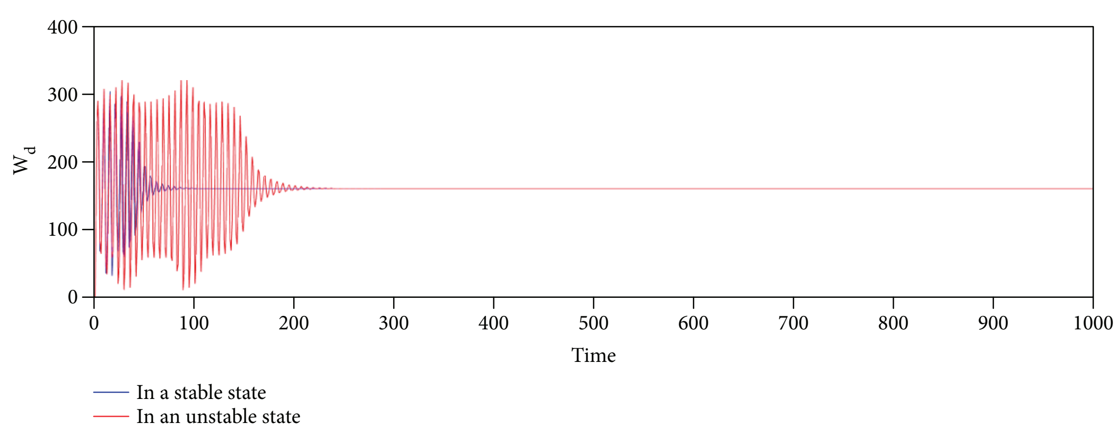


Figure 15: Comparison of traffic volume changes by third-party logistics service providers in a stable state and unstable state under fixed constant demand.

reasonable decision parameter that can make the system maintain a stable, periodic, or quasiperiodic state under random demand.

This article supplements and develops existing researches that is based on the premise that the unmet demand does not accumulate to the next cycle. This paper constructs a three-echelon supply chain inventory system model by using the method of system dynamics. The LLE value of the retailer and the warehouse distribution system of 1275 decision parameters under three different demand scenarios is

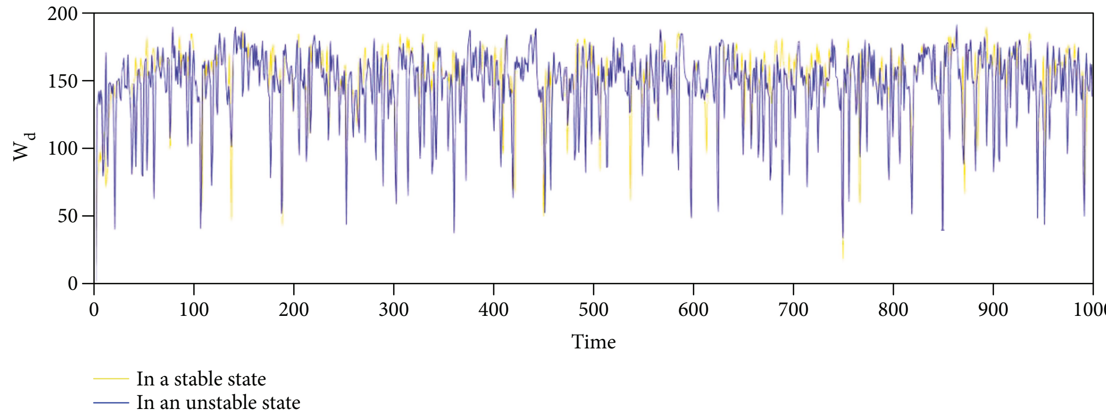


Figure 16: Comparison of retailers' initial stock changes in a stable state and unstable state under the scenario of random demand obeying uniform distribution.

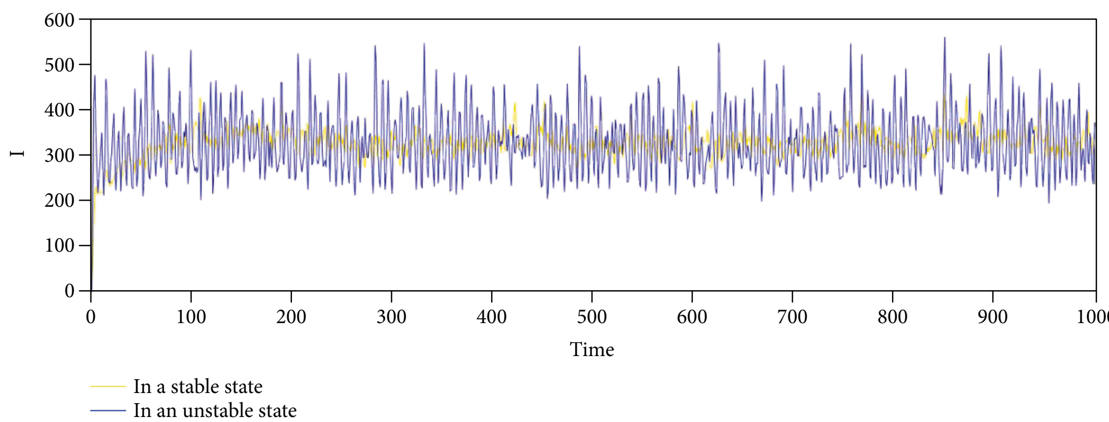


Figure 17: Comparison of initial inventory changes of the warehousing system in a stable state and unstable state under the scenario of random demand obeying uniform distribution.

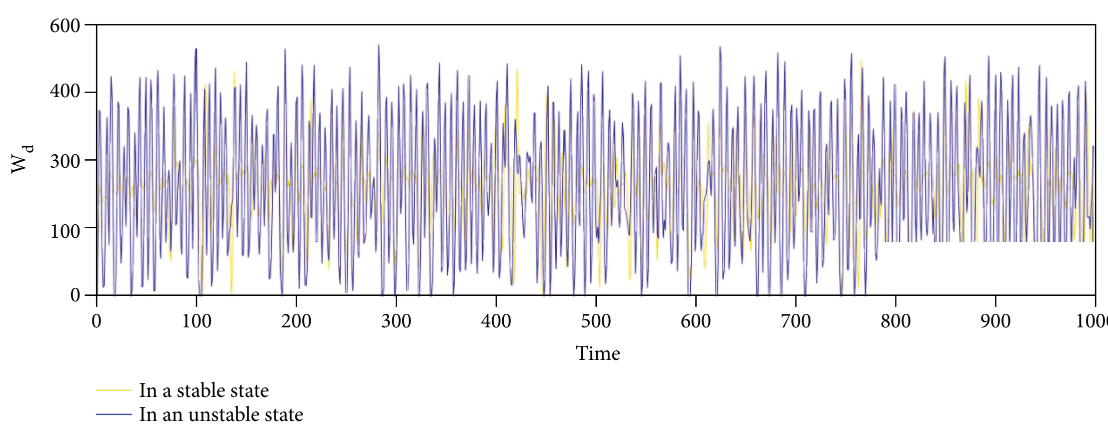


Figure 18: Comparison of traffic volume changes of third-party logistics service providers in a stable state and unstable state under the scenario of random demand obeying uniform distribution.

calculated. The whole decision area is covered. Therefore, the reasonable parameters for the stability of the whole supply chain system can be found, which provide a reference for practical decision making and have important practical significance, and the LLE contour diagram of the retailer and the warehouse distribution system under different demand scenarios is drawn, respectively. At the same time, the paper simulated and plotted the inventory changes of the retailer, the warehouse distribution system, and the transport volume change of the third-party logistics service providers in a

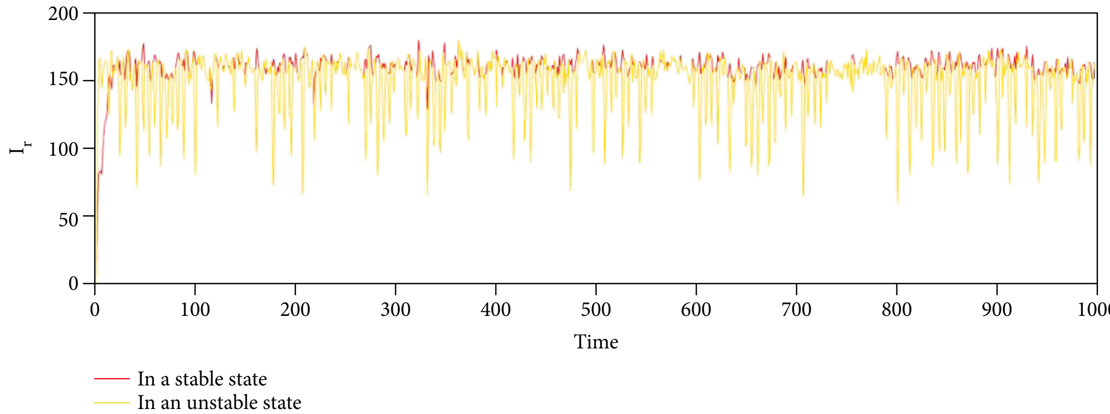


FIGURE 19: Comparison of retailers' initial stock changes in a stable state and unstable state under the scenario of random demand obeying normal distribution.

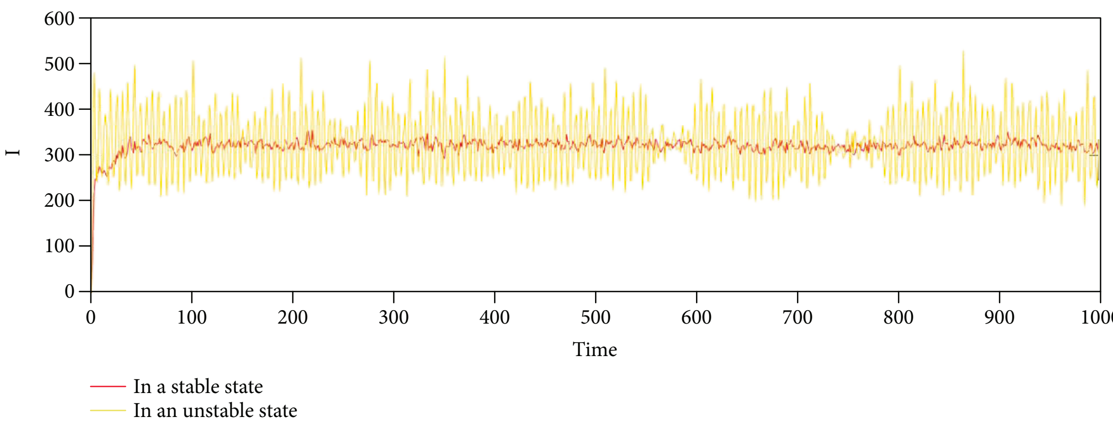


FIGURE 20: Comparison of initial inventory changes of the warehousing system in a stable state and unstable state under the scenario of random demand obeying normal distribution.

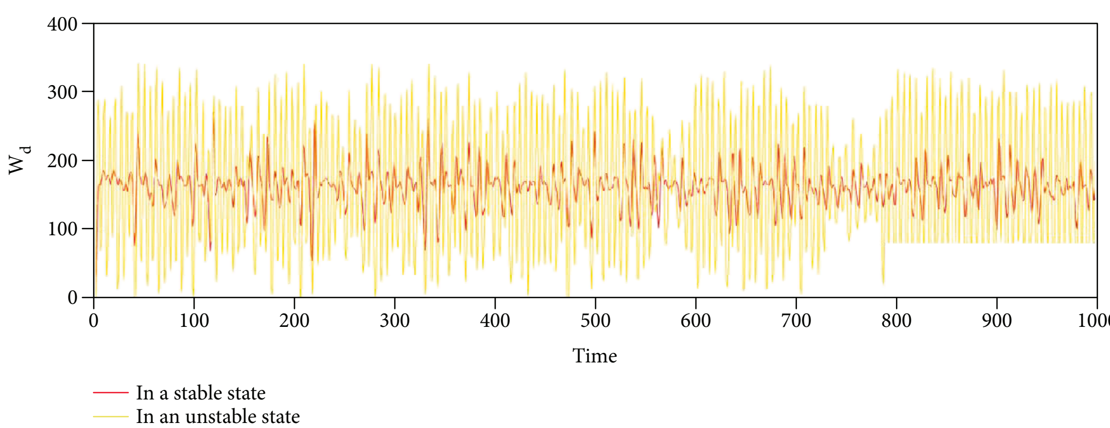


FIGURE 21: Comparison of traffic volume changes of third-party logistics service providers in a stable state and unstable state under the scenario of random demand obeying normal distribution.

stable and unstable state under different demand scenarios. In the steady state, the analysis finds that the initial inventory of the warehouse distribution system and the transport volume of the third-party logistics service providers have more volatility in the initial stage under the scenario of fixed constant demand. However, the volatility of the retailer inventory under the scenario of fixed constant demand is lower than those under the other two scenarios.

Under different demand scenarios, the paper analyzes and compares the changes of the inventory or traffic volume of the members in different states of supply chain, respectively, and concludes the following findings. Under the scenario of fixed constant demand, the inventory or transport volume of the three members of the supply chain has shown great volatility in the steady state during the 0–200 period of simulation, which increases the inventory cost of management and the logistics transportation of the whole chain. It is not conducive to the evolution and development of the supply chain. Under the scenario of random demand, the retailer's initial inventory has a great volatility. But a reasonable decision can make the inventory of the warehouse distribution system stable to a small interval. Under the scenario of random demand obeying normal distribution, there is a distinct difference of the inventory or the transportation task of the members between the stable state and the unstable one. Reasonable decision making can reduce the fluctuation of the stock and transportation volume of the members significantly, thus making the system in a stable state.

Model Parameters and Variables

$D(t)$: The actual demand at time t
$F_r(t)$: The expected demand at time t
$I_r(t)$: Retailer's inventory level at time t
$R_r(t)$: Retailer's receipt amount at time t
$S_r(t)$: Retailer's delivery amount at time t
$O_r(t)$: Retailer's order amount at time t
$S_d(t)$: Distribution center's delivery amount to retailers at time t
$I_d(t)$: Distribution center's inventory level at time t
$R_d(t)$: Distribution center's receipt amount at time t
$W_d(t)$: Distribution center's in-transit inventory at time t
$O_d(t)$: Distribution center's order amount at time t
$I_r^0(t)$: Retailer's expected inventory levels at time t
$I_d^0(t)$: Distribution center's expected inventory levels at time t
$I^0(t)$: Warehouse-distribution center system's expected inventory levels at time t
$S_w(t)$: Warehouse's delivery amount to distribution center at time t
$I_w(t)$: Warehouse's inventory level at time t
$R_w(t)$: Warehouse's receipt amount at time t
$I(t)$: Warehouse-distribution center system's inventory level at time t
$O(t)$: Warehouse-distribution center system's order amount at time t
$Y(t)$: Supplier's work-in-process inventory at time t
$Y^0(t)$: Supplier's expected in-process inventory at time t
α_S: The adjustment coefficient of inventory
α_{SL}: The adjustment coefficient of work-in-process inventory or stock on the way
T_P: Transport lead time
T_C: Production lead time
G_r: Safety inventory coefficient of retailer
G_d: Safety inventory coefficient of distribution center
G_w: Safety inventory coefficient of warehouse.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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