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SUPPLY CHAIN INFORMATION COLLABORATIVE SIMULATION MODEL INTEGRATING MULTI-AGENT AND SYSTEM DYNAMICS

ABSTRACT

Supply chain collaboration management is a systematic, integrated and agile advanced management mode, which helps to improve the competitiveness of enterprises and the entire supply chain. In order to realise the synergy of supply chain, the most important is to realise the dynamic synergy of information. Here we proposed a strategy to integrate system dynamics and multi-agent system modelling methods. Based on the strategy of supply chain information sharing and coordination, a two-level aggregation hybrid model was designed and established. Through the computer simulation analysis of the two modes before and after information collaboration, it is found that under the information collaboration mode, the change trend of order or inventory of suppliers and manufacturers always closely matches that of retailers. After the implementation of supply chain information coordination, ordering and inventory can be reasonably planned and matched, and problems such as over-stocking or short-term failure to meet order demands caused by poor information communication will no longer occur, which can greatly reduce the "bullwhip effect".

KEYWORDS

supply chain management; information collaboration; multi-agent; system dynamics; computer simulation.

1. INTRODUCTION

With the intensification of global market competition and the rapid development of information technology, enterprises should not only enhance the competitiveness of their own products, but also cooperate with other enterprises in the supply chain to form complementary advantages and maximise the benefits of the entire supply chain [1]. The collaborative decision of the supply chain can not only concentrate the resources of supply chain enterprises to achieve overall planning, but also deepen the scope and depth of cooperation between enterprises [2]. It is found that the key problem of supply chain collaboration at this stage is the bullwhip effect caused by the inability to share information, which leads to the failure of supply chain enterprises to achieve global optimisation. This problem is not specific to a particular type of supply chain, it is very general [3, 4]. Therefore, in order to realise the collaborative optimisation of the supply chain, information collaboration is the most important to achieve.

The higher the degree of supply chain information collaboration, the greater the output function and effect will be. That is, the negative effects of the entire system will be significantly reduced, and the results will be more valuable. David Anderson, a well-known supply chain management expert, pointed out that the new generation of supply chain strategy is a collaborative supply chain [5]. The development of information technology has also provided necessary conditions for real-time information collection and sharing in the supply chain, which means that enterprises in the supply chain can share the information resources throughout the entire chain [6].

Information collaboration of a supply chain involves many enterprises, links and factors. It is a complex system problem with the characteristics of nonlinear and multi-feedback loops [7]. Static mathematical modelling and index analysis are the main research methods at present, but it remains difficult to describe the complex characteristics of a supply chain system. The focus on feedback loops and time delays makes system dynamics a valuable tool for studying supply chain information collaboration [8, 9]. In recent years, many studies on supply chain collaboration management have been carried out by system dynamics modelling and simulation. An important advantage of system dynamics is that it is possible to infer the occurrence of specific behaviour patterns, but this requires clear composition and connection of each member in the supply chain before simulation, so it is impossible to effectively model a flexible structure [10, 11]. Based on this, the combination of system dynamics and multi-agent system is a promising method to reduce the complexity of models. The model is simulated by the coupling of two software environments, Vensim and Repast. Vensim is developed by Ventana Systems, Inc. from the United States. It is a graphical interface software that can conceptualise, document, simulate, analyse and optimise dynamic system models. Vensim provides an easy and flexible way to build related models including causal loops, stock and flowcharts. To build a system dynamics model with Vensim, we only need to connect various variables with graphical arrows and write the relationship between the variables into the model as an equation function, and the causal relationship between the variables will be recorded accordingly. Through the process of building a model, we can understand the relationship between the input and output of each variable. REPAST is a well-known software for modelling complex systems, originated from the Institute for Social Science Computing at the University of Chicago. Because of its powerful functions and flexible expressiveness, it has become the preferred application tool for researchers in many fields. At present, REPAST has developed into a general multi-agent simulation platform, which can be used for the realisation and simulation of economic models such as supply chain simulation. It has excellent functions in network structure generation and agent spatial relationship management. The visualisation of the results is more suitable for the simulation of complex social network, economy and other network structure systems. The characteristics of a multi-agent system, such as autonomy, negotiability and expansibility are consistent with the characteristics of enterprises in the process of supply chain information collaboration, and the multi-agent system can simulate the process of independent decision-making and collaborative decision-making between enterprises in a better manner. Therefore, it can break through the flexible technical barriers in supply chain collaboration management [12, 13].

The information generated and interacted by the entire supply chain has become increasingly large and complex, and traditional technical solutions have gradually shown their limitations [14]. This article tries to make use of the advantages of system dynamics in realising complex systems to simulate the independent decision-making that occurs in the fixed behaviour patterns of each enterprise in a supply chain. At the same time, the method based on the multi-agent system can appropriately realise the sharing and integration of heterogeneous information among supply chain enterprises, and then simulate the mutual cooperation process between enterprises, so as to adapt to the complex and changeable supply chain. Based on the above analysis, we propose to apply system dynamics and multi-agent to the supply chain information collaboration process, establish a two-level coupling model to simulate the operation process of a supply chain, and finally verify the effect of information collaboration on the overall process management of a supply chain through simulation analysis. This not only adapts to the development trend of enterprises in a supply chain, but also has a reference value for the future research of supply chain information collaboration process.

2. METHODOLOGY

2.1 System dynamics prediction function

Manufacturers and suppliers need to carry out forecasting in the process of implementing production and purchasing plans. Forecasting methods include time series, recursion, exponential smoothing and so on [15]. Exponential smoothing method is a time series analysis and prediction method, which predicts the future of the phenomenon by calculating exponential smoothing value and combining it with a specific prediction model. Its advantage is that observations at different times are given different weights, and by increasing the weight of recent observations, the forecast can quickly reflect actual changes in the market. At the same time, different types of time series can be processed according to different smoothing times. So, this article adopts the exponential smoothing forecasting method commonly used in supply chain management, and its basic principle is shown in *Equation 1*:

$$F_t = F_{t-1} + \alpha(A_{t-1} - F_{t-1}) \quad (1)$$

where F_t is the prediction function of market demand, F_{t-1} is the predicted value of previous period, A_{t-1} is the actual value of previous period and α is the prediction constant, which is related to time.

The size of the prediction constant (smoothing constant) reflects the role of data in different periods in the prediction. If the prediction constant becomes larger, the dependence on recent data will be greater, the sensitivity of the model will become higher, but the volatility of the prediction results will also become larger. Conversely, when the prediction constant becomes smaller, the model becomes less dependent on the recent data, which eliminates random volatility and reflects the general long-term development trend. In the process of system dynamics modelling, we take exponential smoothing function as a common function of the system. In Vensim7.0, the expression of exponential smoothing function is SMTH(·), which can fit the N-order smoothing process.

According to whether the supply chain information is collaboratively shared, the following two modes of model simulation and analysis are carried out.

Information collaborative sharing mode

Supplier, manufacturer and retailer agents share demand and inventory information in real time through the information collaboration centre, which is the most ideal situation. Then each agent at the second level can make prediction and production plan independently according to the actual situation [16]. Considering the major production links, suppliers and manufacturers will adjust their production according to the product inventory information of downstream manufacturers and retailers, respectively. The main relationship is shown in *Equation 2*:

$$P_{S,M} = P'_{S,M} - Max((Delay(M_{M,R}, \Delta t) - O), 0) \quad (2)$$

where $P_{S,M}$ is the actual productivity of suppliers and manufacturers, $P'_{S,M}$ is the expected productivity of suppliers and manufacturers, $M_{M,R}$ is the inventory of manufacturers and retailers and O is the feedback market demand. $Max(\cdot)$ is the maximum function, $Delay(\cdot)$ is the time delay function.

Suppliers and manufacturers can respectively slow down the production rate according to the actual inventory situation of downstream manufacturers and retailers. When the product inventory of downstream enterprises is larger than the actual market demand, their inventory will be redundant, which leads to their own production slowdown and the demand for upstream materials decline. Therefore, enterprises in the information collaboration supply chain can adjust their own production according to the downstream inventory surplus. This correction is made in advance based on the principle of information coordination, which avoids the time delay of feedback transmission in the system.

Non-information collaborative sharing mode

For a variety of reasons, suppliers, manufacturers and retailers are unable to share information, or can only share it with a delay. Under this circumstance, the market expectations and production adjustments of suppliers and manufacturers will change as shown in *Equation 3*.

$$P_{S,M} = P'_{S,M} - Max((Delay(M'_{M,R}, \Delta t) - O'), 0) \quad (3)$$

$M'_{M,R}$ is still the inventory of manufacturer and retailer, but it is no longer the actual inventory when information is coordinated. Similarly, O' is not an actual feedback requirement. In other words, suppliers, manufacturers and retailers will not share their own inventory information and market demand. Under the premise of forecasting only, general market expectations will be reduced, while the inventory reserves will increase. This would undoubtedly result in a waste of resources and blind operation.

2.2 Initial condition setting of system dynamics model

The initial conditions of system dynamics model are set according to actual problems. Days are selected as the unit time in the model and the simulation step is 1. That is, each time unit is calculated once, and the overall simulation time is 180 days. The final market demand is set to a stable market demand form, and its mathematical expression is defined as normal (1,000, 200), which is a normal

Table 1 – Initial variable value of system dynamics model

Variable	Initial	Variable	Initial
Supplier_Material_Target_Inventory	2000 pcs	Retailor_Inventory_Target	2000 pcs
Material_Target_Inventory	2000 pcs	Economic_Bath_To_Material	2000 pcs
Material_Transit_Time	2 d	Material_Reorder_Point	3000 pcs
Supplier_Material_WIP_Adj_Time	2 d	Material_Target_Inventory	2000 pcs
Target_Delay_Time	2 d	Supplier_Material_Target_Inventory	2000 pcs
Economic_Batch_To_Retailor	2000 pcs	Material_Adjustime	2 d
Manufacure_Target_Inventory	2000 pcs	Material_Cycle_Time	2 d
Retailor_Reorder_Point	3000 pcs	Supplier_WIP_Adj_Time	2 d
Manufacture_CycleTime	2 d	Supplier_Material_Adjustime	2 d
Manufacture_Inventory_Adjust_time	2 d	Retailor_inventory_adjust_time	2 d

distribution with a mean of 1,000 and a standard deviation of 200. This is the main input variable of the entire supply chain model. Other initial variables of the model are shown in *Table 1*.

2.3 Multi-agent system prediction function

For the convenience of simulation analysis, this paper only considers a simple three-level supply chain, and each level contains only one enterprise. Autoregressive models (ARMA), especially the AR(1) model, are often used for demand forecasting in the supply chain process [17]. It is a time series model that uses observations from previous time steps as input to a regression equation to predict the value at the next time step. The advantage of the AR method is that it requires fewer external data and can use its own variable series to make predictions. The orders and inventories of the three-level supply chain described in this paper are economic phenomena that are greatly affected by their own historical factors, so they are very suitable for applying the AR model to forecast. In this paper, price parameter indicator is added on the basis of simulating demand process, and the price-sensitive function is used to predict the change of demand, which can simulate the operation process of the supply chain. Assuming that the price-sensitive demand function conforms to AR(1) process and that market demand is linearly related to the price, the demand function is established as *Equation 4*:

$$f_t = F(R_t, \varepsilon_t) = a - pR_t + \varepsilon_t \tag{4}$$

where a is the market demand of products in period t and p is the price sensitivity coefficient, which is always greater than zero. ε_t is a demand disturbance term, which obeys the normal distribution $N(0,\sigma^2)$.

Assuming that the market price conforms to the AR(1) process, *Equation 5* follows:

$$R_t = \mu + \rho R_{t-1} + \eta_t \tag{5}$$

where μ is a non-negative constant, representing market expectations and ρ is the price autoregressive coefficient, which is always greater than zero. η_t is the price disturbance item, which obeys the normal distribution $N(0,\delta^2)$.

In the constructed three-level supply chain model, it is assumed that the demand in period t is predicted according to the demand situation in period t-1, and both retailers and manufacturers adopt "order-up-to" inventory strategy to calculate the target inventory $k_t^{R,M}$ in period t (R and M represent retailers and manufacturers, respectively). Then, based on the satisfaction of the target inventory, retailers and manufacturers will formulate an ordering plan to upstream companies. Suppose there is an order period $L_{R,M}$, and assuming that the enterprise issue the order request at the beginning of period t, the goods will be received at $t+L_{R,M}$. Therefore, the target inventory function is:

$$k_t^{R,M} = \hat{F}_t^{L_{R,M}} + \omega\hat{\sigma}_t^{L_{R,M}} \tag{6}$$

where $\hat{F}_t^{L_{R,M}}$ is the forecast demand under the lead time L, ω indicates the safety factor and $\hat{\sigma}_t^{L_{R,M}}$ indicates the lead time demand error, which is a constant related to $L_{R,M}$.

Table 2 – Initial variable value of multi-agent model

Variable	Initial	Variable	Initial
Order_Delay_Time	3 d	Supplier_Delivery_Time	2 d
Forecast_Start_Time	4 d	Manufacturer_Delivery_Time	2 d
Information_Collaboration_Strategy	0, 1	Market_Expectation_Constant	100
Number_of_Retailers	1 unit	Price_Autoregressive_Coefficient	0.7
Number_of_Manufacturers	1 unit	Variance_of_Demand_Disturbance	1
Number_of_Suppliers	1 unit	Variance_of_Price_Disturbance	1
Production_Lead_Time	4 d	Safety_Factor	0.8
Product_Inventory_Target_Level	2000 pcs	Product_Market_Demand_Scale	1000 pcs
Initial_Inventory_of_Each_Agent	9	Product_Price_Sensitivity_Coefficient	1

2.4 Initial condition setting of multi-agent system model

In this paper, Repast software is used to analyse the inventory and order changes under the condition of supply chain information coordination. We studied the interaction process between agents and the supply chain environment. By analysing the process model of supply chain, it is found that the inventory and order quantity of enterprises at all levels will reflect the change of supply chain when information sharing is carried out or not. The initialisation of main parameters involved in the multi-agent simulation model is shown in *Table 2*.

3. RESULTS AND DISCUSSION

3.1 Levels of supply chain information collaboration management

From the perspective of decision-making scope and execution content, this paper divides the information collaboration supply chain into two main levels, namely strategic collaboration and execution planning collaboration, as shown in *Figure 1* (only the part of the strategic content is shown).

In our example of the three-level supply chain, core manufacturing enterprises form forecasting and replenishment strategies according to downstream

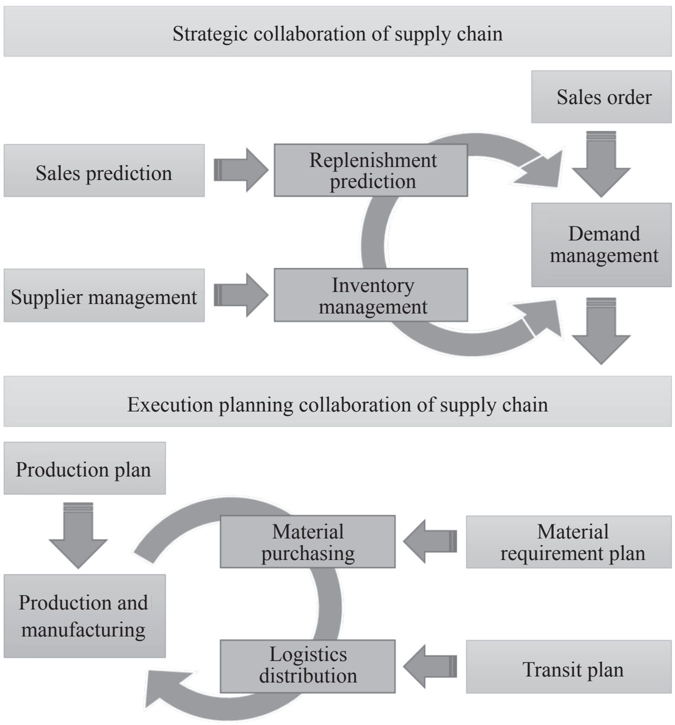

Figure 1 – Levels and contents of supply chain information collaboration

sales forecasts, and form inventory management strategies in coordination with upstream suppliers. Finally, they improve the demand management strategies by summarising supply chain information [18]. In supply chain coordination, execution planning collaboration is at the bottom, which is the basis and premise of other collaboration strategies. Core manufacturing enterprises form production plans, procurement plans, logistics transportation plans, etc. through supply chain synchronisation of operations and information collaboration, so as to guide the completion of the entire manufacturing process cycle of material procurement, production and manufacturing and logistics distribution.

The two levels of collaboration strategies together form a business model for collaborative management of supply chain information, creating a supply chain ecological resource circle with both short-term collaboration and mid-to-long-term collaboration. This facilitates enterprises to make full use of external resources, thereby strengthening the level of information sharing and resource coordination operation.

3.2 Supply chain information sharing and collaboration mode

Three-level supply chain information collaboration mode

By designing the information sharing mechanism of the supply chain, we established the way of information sharing among the members of the entire supply chain and conducted the modelling analysis of the supply chain system for the collaboration strategy. In order to explain the process of supply chain information collaboration, a simple and interactive information sharing model is designed based on the traditional straight-chain information exchange model. As shown in *Figure 2a* (taking a simple three-level supply chain model composed of one supplier, one manufacturer and one retailer as an example), information in the supply chain is summarised, processed and shared through the information collaboration centre.

For the existing supply chain, it mainly adopts the straight-chain information transmission mode, and the information is transferred up or down step by step. For nodes in the supply chain, they can basically only know the downstream demand or the upstream production result. The overall information acquisition channel is not smooth, and there is a lag in time, as shown by the black arrow line in the figure. However, the advanced supply chain information collaboration mode requires each node in the supply chain to be flexible and reactive, not only to be able to understand the production situation of the front and back nodes in time, but also to know the start and end conditions of non-adjacent nodes. The information collaboration centre established in this paper allows nodes to easily establish information exchange channels, avoiding point-to-point information exchange, and can be flexibly operated according to permissions and needs, so as to conveniently complete information exchanges with multiple types of partners. The red dashed arrow line in the figure above illustrates such process. Retailers provide feedback in the form of information such as market demand and marketing plans to the information collaboration centre. When manufacturers provide their own inventory and production status, they can also master the production status of suppliers through information sharing, so as to adjust the purchase plan and production plan at any time. Retailers can adjust their sales plans according to the production and inventory status of manufacturers released by the information collaboration centre, combined with the supply capacity information provided by suppliers. Suppliers also receive relevant information from the information collaboration centre and make decisions on their own production and inventory control based on this information.

Integrated system dynamics and multi-agent for supply chain modelling

The multi-agent system can intelligently assign tasks to each agent subsystem and integrate the services of each agent [19], so as to comprehensively simulate the operation process of a supply chain, obtain more practical and accurate fitting results and provide decision-making basis for supply chain management. Therefore, this paper proposes a more suitable model to study supply chain information collaboration by combining system dynamics and multi-agent system.

Following a comprehensive method of hybrid modelling, supply chain information collaboration can be modelled by two-level aggregation, as shown in *Figure 2b*. At the macro level, it shows the participants in a supply chain and the relationship between them for information sharing and collaborative services through the information collaboration centre. At any specific node during the actual supply chain operation, the structure of the supply chain is

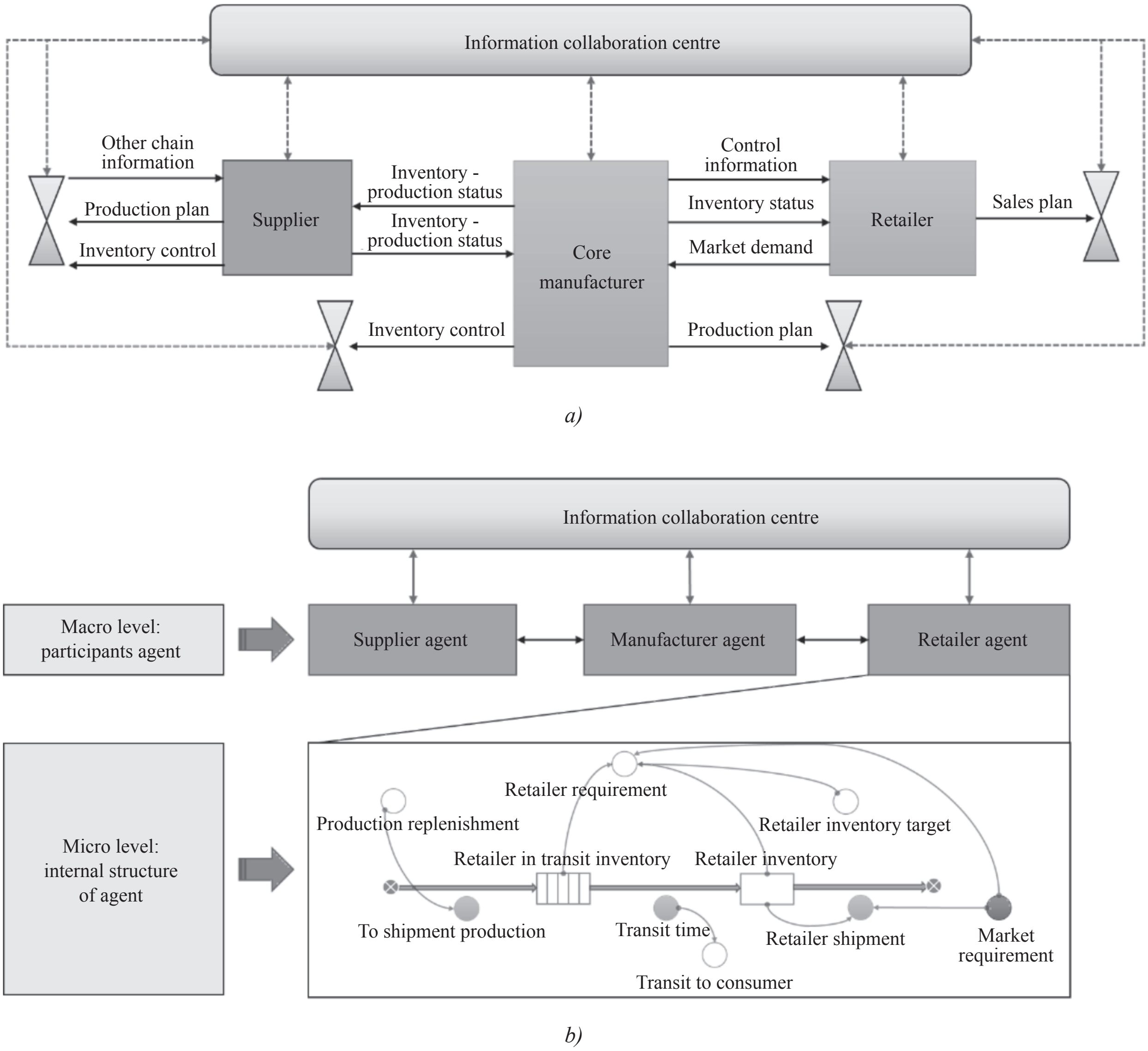

Figure 2 – Mode of supply chain information sharing

determined by the participating agents and the interaction between them. In order to achieve such a flexible structure, we use a typical multi-agent simulation modelling method at the macro level. Of course, the structure of the actual supply chain is definitely much more complicated than that designed in the paper. In order to explain the two-level aggregation problem and facilitate the simulation implementation, we only abstract the supply chain with three main agents.

The internal structure and operation mode of agents are realised at the micro level. Each agent may have different characteristics, but its internal characteristics are generally predetermined and will not change easily. The modelling approach we use at this level is system dynamics, which is a well-tried method of modelling strategy formulation to guide the continuous feedback process of individual decisions. The supply chain operation process generally starts from external demand, and each participant agent will make decisions based on external demand and its own situation, thus forming a closed-loop system with two levels of aggregation.

3.3 Multi-agent based supply chain information collaboration

Multi-agent model construction

The collaborative process of enterprises in modern supply chains has the characteristics of autonomy, dynamic and complexity etc. In order to simulate the information collaboration process of a supply chain, we used a multi-agent system for simulation modelling.

After multi-agent modelling and organisational structure analysis, we used intermediary structure to build a multi-agent system [20]. The system integrates the information of each individual agent, such as decision-making objectives, optimisation schemes etc. The composition structure of a single agent is fixed and the operation mode is relatively stable, so the system dynamics method has been adopted to conduct simulation modelling, which will be described in detail in the next section, to make better decisions and increase the benefits of the entire system. In this multi-agent system, the information collaboration centre centrally controls the information of each enterprise in the supply chain and transfers the coordinated information to the designated enterprise or service. In the process of supply chain coordination, when the individual agent's goals conflict with the overall goals, each agent subsystem communicates through the information collaboration centre. The information collaboration centre proposes the best decision and gives back the results to the individual agent. Finally, feedback will be sent back to the information collaboration centre after individual evaluation. After analysing the information flow of individual agents, the overall system is designed and the supply chain information collaboration simulation structure is established (*Figure 3*).

System dynamics model of agent in each stage

Through the causality analysis of information flow process and feedback situation, we have obtained the supply chain system dynamics model of three-stage agents of supplier, manufacturer and retailer. This refers to the internal stack flow diagram of the following three agents (*Figures 4–6*).

Supplier relationship flow diagram description

The raw material management mode of the supplier is supplier management, and the supplier adopts the integrated replenishment method in the process of organising replenishment. The production link of supplier is still based on the demand of manufacturer. At the same time, when formulating the production plan, it will also refer to the target inventory and the target work-in-process inventory on the basis of demand and production of the manufacturer. Production is pull type and supply is push type. This is also a problem in the actual production process.

Manufacturer relationship flow diagram description

Manufacturer is the core role of the current type of a supply chain. In the supply link, an integrated replenishment strategy is adopted. Manufacturers make judgments based on the retailer's inventory

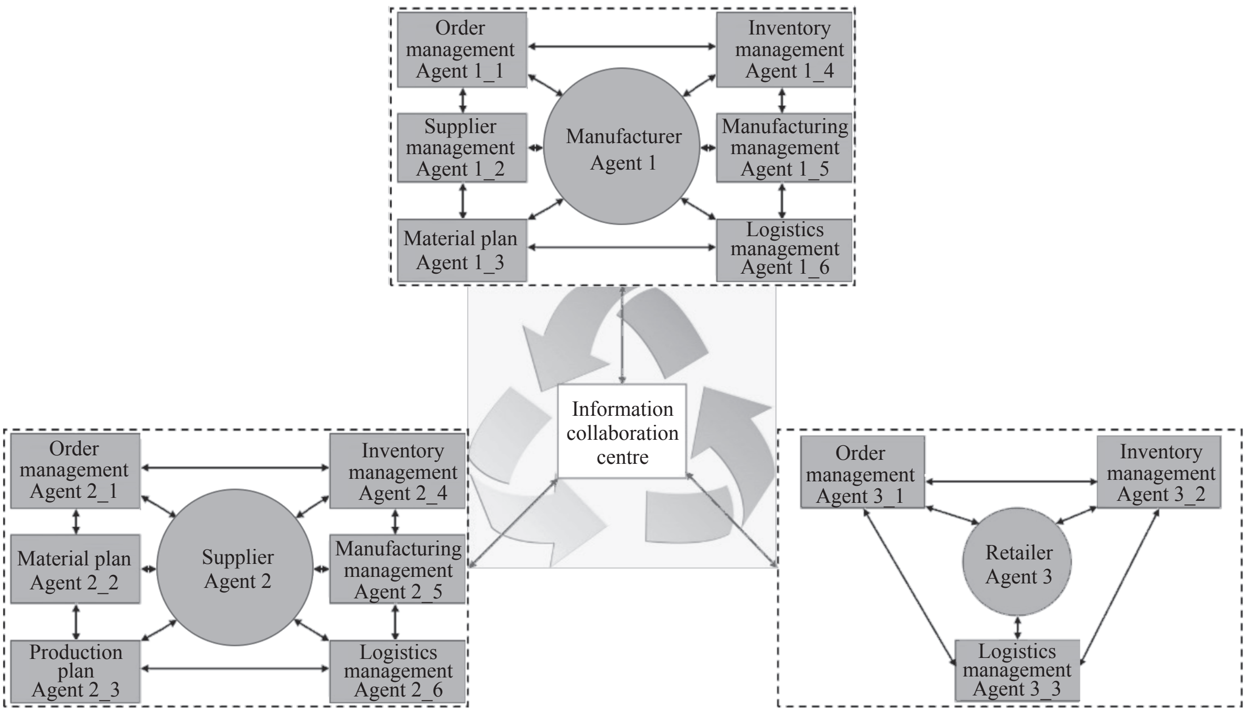

Figure 3 – Simulation structure of supply chain information collaboration

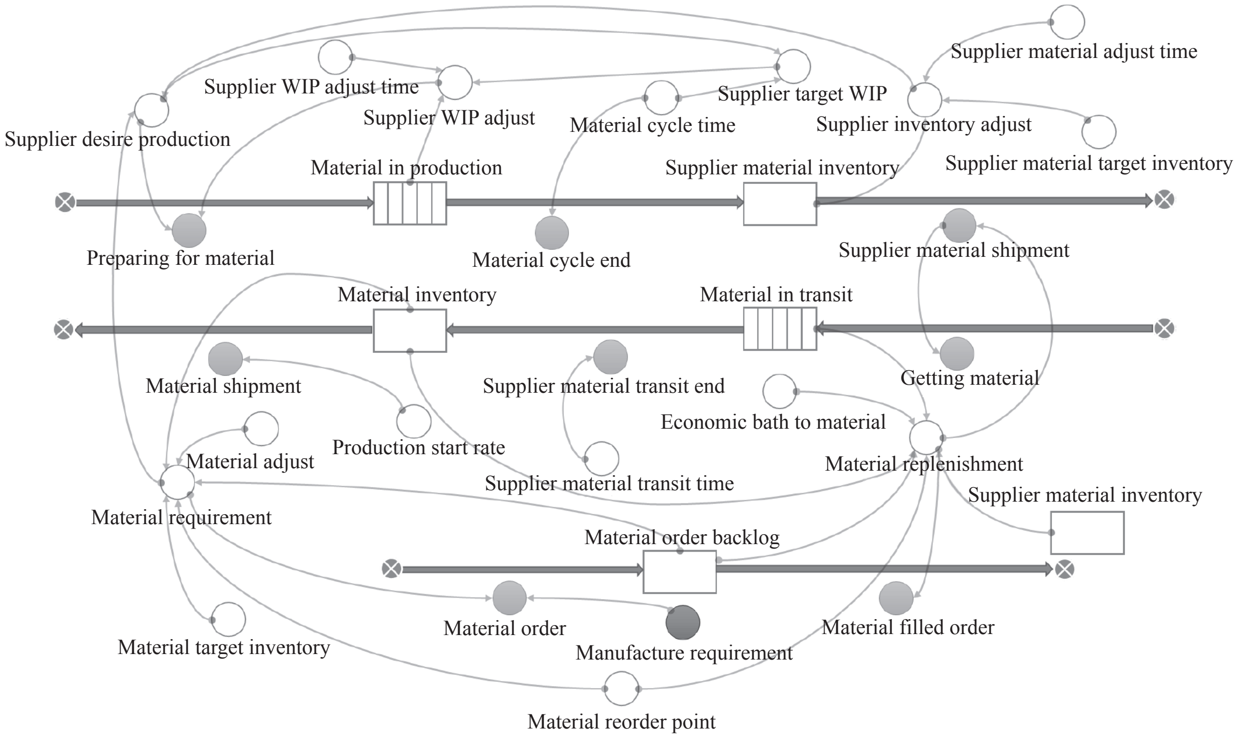

Figure 4 – Supplier stack flow diagram

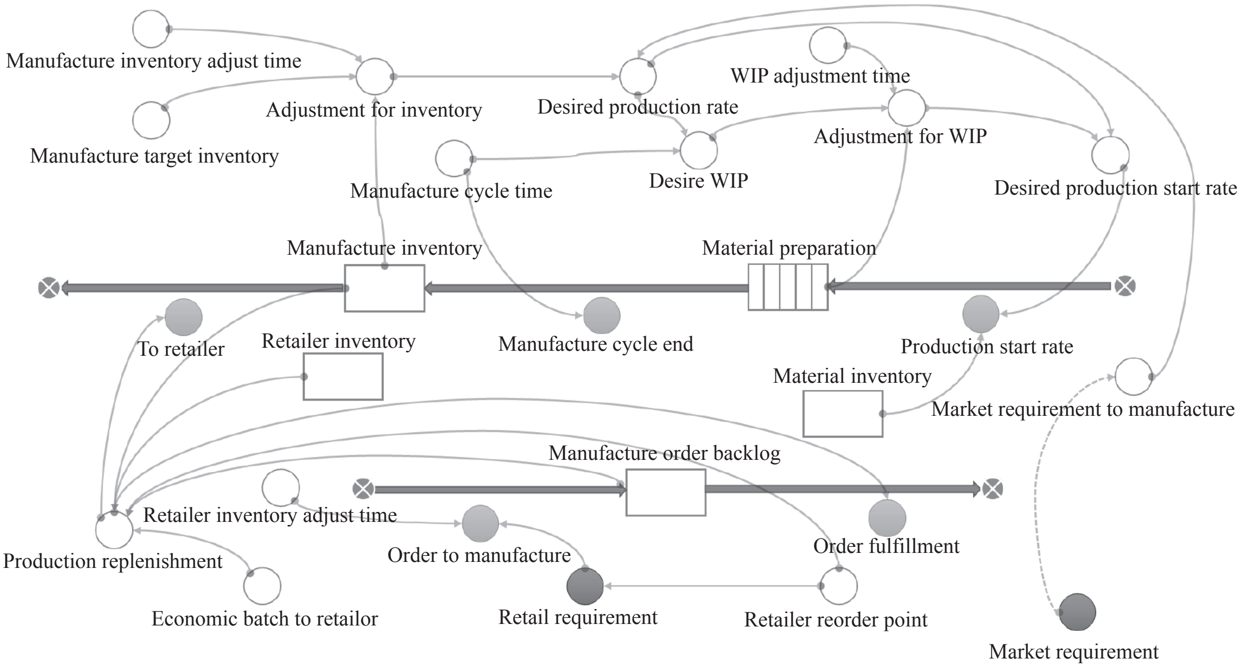

Figure 5 – Manufacturer stack flow diagram

feedback. When the retailer's inventory reaches the reorder point, replenishment is carried out according to a certain economic replenishment batch. However, in the manufacturer production organisation link, production is still carried out according to the expected demand of the market. At the same time, when formulating the production plan, on the basis of market demand, the consideration of the target inventory and the target work-in-process inventory is also substituted.

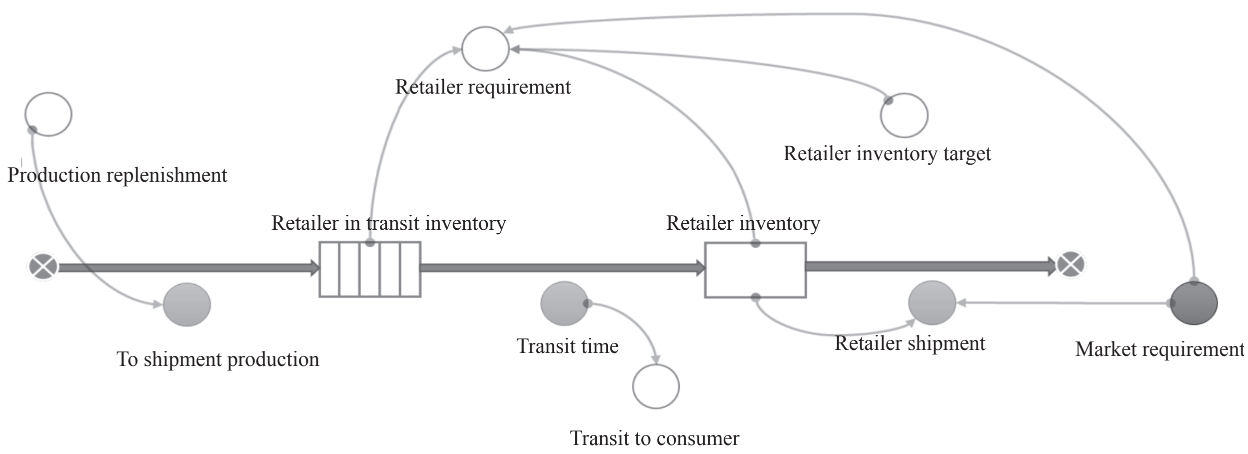

Figure 6 – Retailer stack flow diagram

As manufacturers build up their inventories, the gap between them and their desired inventories becomes smaller and smaller. Therefore, the expected productivity will become smaller, and then the actual productivity will become smaller, but at this time the inventory will gradually decrease with consumption, resulting in a larger gap with the expected inventory. This feedback will balance the production process effect.

Retailer relationship flow diagram description

The retailer's process is relatively simple. The increase in retailers' inventory brings about a decrease in retailers' demand, which in turn reduces manufacturers' orders and reduces supplies. At this point, the retailers' inventory drops, and then enters the opposite cycle. This cycle has a regulating and balancing effect on the system.

Suppliers, manufacturers and retailers are linked through orders and inventory. Orders and inventory are also carriers of information flow. Through their changes and comparisons, many key performance indicators can be obtained to evaluate the supply chain.

3.4 Information collaborative simulation analysis

By analysing the two-level aggregation process model of the supply chain, the inventory and order quantity will reflect the changes of the supply chain when information sharing of three-level supply chain enterprises is carried out or not [21, 22]. This section presents the simulation and analysis results of these two key performance indicators for evaluating the supply chain.

Simulation results without information collaboration

We simulate the changes of the three-level enterprises in the supply chain with the market. In the following graphs, the abscissa represents time (unit time is per day), and the ordinate represents order quantity or inventory. It can be seen from *Figure 7* that the fluctuation of order is amplified step by step. Retailers have the smallest fluctuations in orders, followed by manufacturers, and suppliers have the largest fluctuations. In addition, small fluctuations in lower-level enterprises will lead to violent fluctuations in their upper-level enterprises of the supply chain. The change of enterprise inventory (*Figure 8*) has the same rule as that in order quantity.

The average value and standard deviation of orders for three-level supply chain enterprises are shown in the following *Table 3*. It can be seen from the table that the order fluctuates greatly, and it is gradually enlarged step by step from downstream to upstream, which indirectly increases the backlog of purchase orders.

The average value and standard deviation of inventory for three-level supply chain enterprises are shown in *Table 4*. Similar to the rule of order changes, the inventory fluctuation without information

Table 3 – Average value and standard deviation of order backlog in supply chain enterprises under non-information sharing

Variable	Average value (μ)	Standard deviation (σ)
Supplier	1682.15	631.39
Manufacturer	1146.52	306.72
Retailer	878.87	204.74

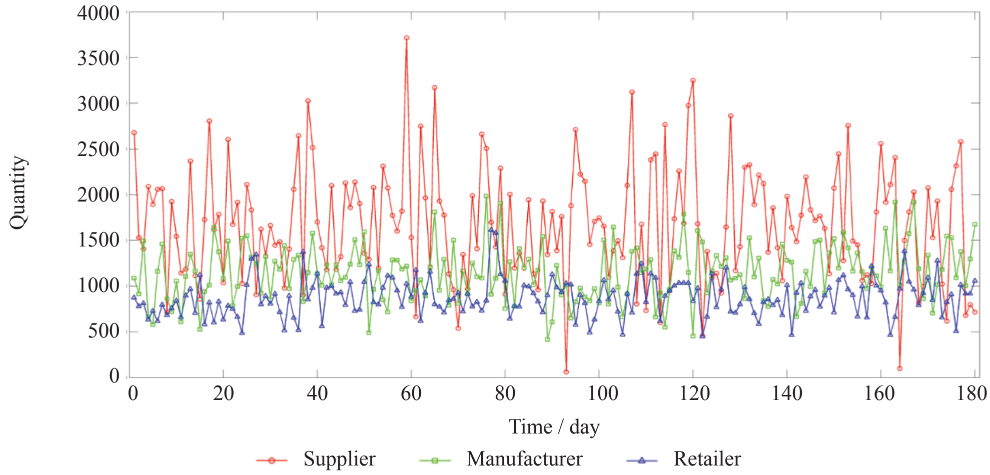

Figure 7 – Order change of supply chain enterprises under non-information sharing

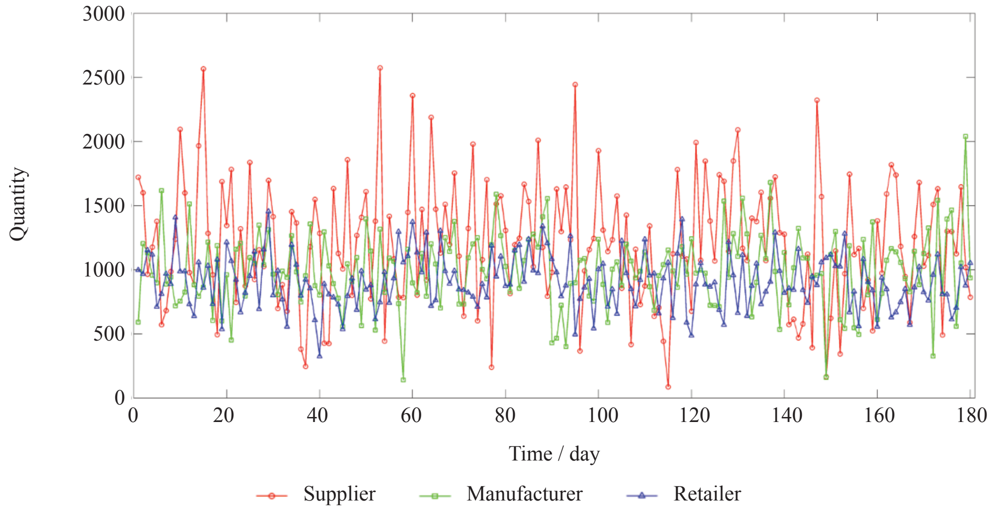

Figure 8 – Inventory change of supply chain enterprises under non-information sharing

Table 4 – Average value and standard deviation of inventory in supply chain enterprises under non-information sharing

Variable	Average value (μ)	Standard deviation (σ)
Supplier	1208.31	490.13
Manufacturer	994.23	289.7
Retailer	909.05	207.56

collaboration is also relatively large, and it amplifies step by step from downstream to upstream, resulting in inventory waste to a large extent.

Simulation results under information collaboration

By comparing the situation of enterprises at all levels of the supply chain under non-information collaboration, we studied the influence of implementing information collaboration on the order and inventory of supply chain member enterprises. After modifying the model parameters, the system adopts information collaboration strategy in order and inventory simulation.

The average value and standard deviation of the three-level supply chain enterprises' orders under information collaboration are shown in *Table 5*. It can be seen that the order backlog is reduced, the fluctuation is small, and the matching degree of the supply chain enterprises is better.

Table 5 – Average value and standard deviation of order backlog in supply chain enterprises under information collaboration

Variable	Average value (μ)	Standard deviation (σ)
Supplier	996.02	118.37
Manufacturer	997.38	144.11
Retailer	983.67	142.43

The average value and standard deviation of inventory in supply chain enterprises under information collaboration are shown in *Table 6*. The inventory and its fluctuation are reduced, and the matching degree of each enterprise in the supply chain is better.

Through the analysis of the above results, it is found that after the supply chain companies choose to implement the information collaboration strategy, the retailers' orders and inventory status are less affected (because the demands of external users have not changed because of our implementation of supply chain information collaboration). However, the orders and inventory of suppliers and manufacturers have undergone tremendous changes. In the information collaboration mode, no matter how the orders or inventory fluctuates, the changing trend of suppliers and manufacturers always closely matches the retailers (*Figures 9 and 10*). In addition, after the implementation of supply chain information collaboration, orders and inventory can be reasonably planned and matched, and problems such as over-stocking or short-term failure to meet order demands caused by poor information communication will no longer occur, which can greatly reduce the "bullwhip effect".

Table 6 – Average value and standard deviation of inventory in supply chain enterprises under information collaboration

Variable	Average value (μ)	Standard deviation (σ)
Supplier	996.97	131.33
Manufacturer	994.11	144.82
Retailer	989.61	144.36

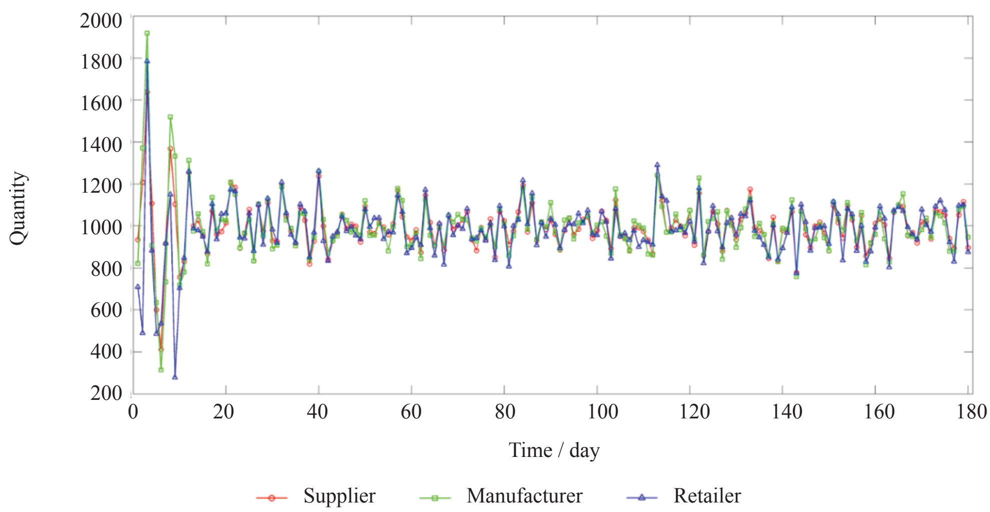

Figure 9 – Order change of supply chain enterprises under information collaboration

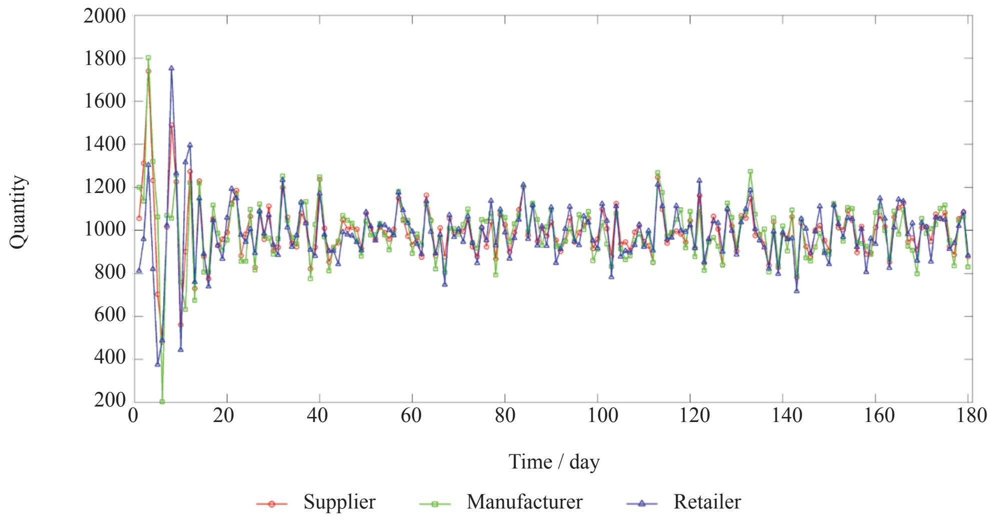

Figure 10 – Inventory change of supply chain enterprises under information collaboration

4. CONCLUSION

The supply chain system itself has many characteristics of a complex system. In the process of studying supply chain collaboration management, we need a set of effective research methods. Both system dynamics and multi-agent system are simulation-based methods that can solve a series of specific supply chain problems through joint application.

The supply chain mentioned in this paper is a good example of the dynamic system with flexible structure. The characteristics of a multi-agent system, such as autonomy, negotiability and expansibility, can meet the demand of dynamic change in the supply chain composition and connection. In this paper, a hybrid modelling method which combines system dynamics and multi-agent system is proposed to build a more flexible two-level aggregation model.

Finally, the algorithms in the model need to be constantly supplemented and improved, and more specific constraints should be put forward to conform to the supply chain system and achieve better simulation results. At present, the model parameters are basically set in advance. In the later stage, we can consider combining this method with some optimisation algorithms (such as Genetic Algorithm, etc.) to optimise the variables and parameters of the system.

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集成多智能体与系统动力学的供应链信息协同仿真模型

摘要

供应链协同管理是一种系统化、集成化、敏捷化的先进管理模式，有助于提高企业自身和整个供应链的竞争力。要实现供应链的协同，最重要的是实现信息的动态协同。本文提出了一种将系统动力学与多智能体系统建模方法相结合的策略。基于供应链信息共享与协同策略，设计并建立了两级聚合模型。通过对信息协同前后两种模式的计算机仿真分析发现，在信息协同模式下，供应商和制造商的订单或库存变化趋势始终与零售商的订单或库存变化趋势紧密匹配。实施供应链信息协同后，可以对订单和库存进行合理的规划和配置，不再出现由于信息沟通不畅而导致的库存过剩或订单需求短期无法满足的问题，从而大大减弱“牛鞭效应”。

关键词

供应链管理；信息协同；多智能体；系统动力学；计算机仿真

REFERENCES

[1] Li ML, Yang H, Guo X. Research on supply chain collaborative manufacturing mode. *Journal of Physics Conference Series*. 2020;1670(1): 012027. doi: 10.1088/1742-6596/1670/1/012027.

[2] Shan HM, Li Y, Shi J. Influence of supply chain collaborative innovation on sustainable development of supply chain: A Study on Chinese Enterprises. *Sustainability*. 2020;12(7): 2978. doi: 10.3390/su12072978.

[3] Cannella S, Dominguez R, Framinan JM, Bruccoleri, M. Insights on partial information sharing in supply chain dynamics. *2015 International Conference on Industrial Engineering and Systems Management, 21-23 Oct. 2015, Seville, Spain*. 2015. p. 344-350. doi: 10.1109/IESM.2015.7380181.

[4] Wiengarten F, et al. Collaborative supply chain practices and performance: Exploring the key role of information quality. *Supply Chain Management*. 2010;15(6): 463-73. doi: 10.1108/13598541011080446.

[5] Wu IL, Chuang CH, Hsu CH. Information sharing and collaborative behaviors in enabling supply chain performance: A social exchange perspective. *International Journal of Production Economics*. 2014;148: 122-132. doi: 10.1016/j.ijpe.2013.09.016.

[6] Yuan HQ, et al. Analysis of coordination mechanism of supply chain management information system from the perspective of block chain. *Information Systems and E-Business Management*. 2020;18(4): 681-703. doi: 10.1007/s10257-018-0391-1.

[7] Zhang F, Xiao F. Simulation research on information sharing value evaluation of supply chain with multi-agent. In: Wang Q. et al. (eds) *4th Conference on Systems Science, Management Science and System Dynamics, CSS 2010, 10-12 Dec. 2010, Shanghai, China*. Beijing: Publishing House Electronics Industry; 2021. p. 99-104.

[8] Abdullah MA, Hishamuddin H. System dynamics approach in supply chain management: A review. In: Haron CHC, et al. (eds) *Proceedings of the International Conference on Advanced Processes and Systems in Manufacturing, APSIM 2016, 28-30 Aug. 2016, Kuala Lumpur, Malaysia*. 2016. p. 61-62. doi: 10.1109/APSIM.2016.1408893.

[9] Angerhofer BJ, Angelides MC. System dynamics modelling in supply chain management: Research review. In: Joines JA, Barton RR, Kang K, Fishwick PA. (eds)

IEEE WSC 2000: Proceedings of the 2000 Winter Simulation Conference, IEEE WSC 2000, 10-13 Dec. 2000, Orlando, FL, USA. New York: IEEE; 2000. p. 342-351. doi:10.1109/WSC.2000.899737.

[10] Dominguez R, Cannella S. Insights on multi-agent systems applications for supply chain management. *Sustainability*. 2020; 12(5): 1935. doi: 10.3390/su12051935.

[11] Hernandez JE, Poler R, Mula J. Modelling collaborative forecasting in decentralized supply chain networks with a multiagent system. In: Cordeiro J, Filipe J. (eds) *11th International Conference on Enterprise Information Systems - Artificial Intelligence and Decision Support Systems, ICEIS 2009, 6-10 May 2009, Milan, Italy.* Setubal: Insticc-Inst Syst Technologies Information Control & Communication; 2009. p. 372-375. doi: 10.5220/0002008503720375.

[12] Hernandez JE, Mula J, Poler R, Lyons AC. Collaborative planning in multi-tier supply chains supported by a negotiation-based mechanism and multi-agent system. *Group Decision and Negotiation*. 2014;23(2): 235-269. doi: 10.1007/s10726-013-9358-2.

[13] Tian J, Tianfield H. Literature review upon multi-agent supply chain management. *2006 International Conference on Machine Learning and Cybernetics, 8-16 Aug 2006, Dalian, China.* New York: IEEE; p. 89-94. doi: 10.1109/icmlc.2006.258877.

[14] Nawarecki E, Kozlak J. Building multi-agent models applied to supply chain management. *Control and Cybernetics.* 2010;39(1): 149-176. doi: 10.1109/WSC.2000.899737.

[15] Bo SY, Jian DX. Research on management of supply chain based on system dynamic. *IEEE ICLSIM 2010 International Conference on Logistics Systems and Intelligent Management, IEEE ICLSIM 2010, 9-10 Jan. 2010, Harbin, China.* New York: IEEE; 2010. p. 1329-1332. doi: 10.1109/iclsim.2010.5461180.

[16] Aslam T, Ng AHC. Strategy evaluation using system dynamics and multi-objective optimization for an internal supply chain. In: Yilmaz L, et al. (eds) *IEEE WSC 2015: Proceedings of the 2015 Winter Simulation Conference, IEEE WSC 2015, 6-9 Dec. 2015, Huntington Beach, CA, USA*. New York: IEEE; 2015. p. 2033-2044. doi: 10.1109/WSC.2015.7408318.

[17] Wikarek J, Sitek P. A multi-level and multi-agent approach to modeling and solving supply chain problems. In: Bajo J, et al. (eds) *14th International Conference on Practical Applications of Agents and Multi-Agent Systems. International Workshops of PAAMS 2016, 1-3 June 2016, Sevilla, Spain.* Berlin: Springer-Verlag; 2016. p. 49-60. doi: 10.1007/978-3-319-39387-2_5.

[18] Shu T, et al. Supply chain grounded on information theory: Tracing to the source of collaborative information. *2008 4th IEEE International Conference on Management of Innovation and Technology, IEEE ICMIT 2008, 21-24 Sep. 2008, Bangkok*. New York: IEEE; p. 1072-1076. doi: 10.1109/icmit.2008.4654517.

[19] Hernandez JE, Poler R, Mula J, de la Fuente D. Collaborative tactical planning in multi-level supply chains supported by multiagent systems. In: Ortiz A, Franco RD, Gasquet PG. (eds) *BASYS: International Conference on Information Technology for Balanced Automation Systems: Proceedings of the Balanced Automation Systems for Future Manufacturing Networks, BASYS 2010, 21-23 July 2010, Valencia, Spain.* Berlin: Springer-Verlag; 2010. p. 260-267. doi: 10.1007/s10726-013-9358-2.

[20] Hernandez JE, Mula J, Poler R, Pavon J. A multiagent negotiation based model to support the collaborative supply chain planning process. *Studies in Informatics and Control*. 2011;20(1): 43-54. doi: 10.24846/v20i1y201104.

[21] Yao YL, Evers PT, Dresner ME. Supply chain integration in vendor-managed inventory. *Decision Support Systems.* 2007;43(2): 663-674. doi: 10.1016/j.dss.2005.05.021.

[22] Wang JR, Li J, Zhang YH, Hu ZW. Simulation study on influences of information sharing to supply chain inventory system based on multi-agent system. *2008 IEEE International Conference on Automation and Logistics, IEEE ICAL 2008, 1-3 Sep. 2008, Qingdao China.* New York: IEEE; 2008. p. 1001-1004. doi: 10.1109/ical.2008.4636297.