Research on System Dynamics Simulation of Building Materials Supply Chain

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Abstract. The bullwhip effect of supply chain under non-information sharing and information sharing environment is analyzed theoretically. The model of building materials supply chain in two environments is constructed, and the system dynamics flow chart is established by Vensim PLE simulation software. The correctness of the theoretical analysis is verified by an example simulation. The sensitivity analysis of transportation delay time and manufacturer's production cycle shows that extending transportation time can reduce manufacturer's inventory, but raw material inventory in transit will increase; Shortening the production cycle of producers under the information sharing environment is more conducive to reducing the bullwhip effect of the supply chain.

Keywords: Building materials supply chain; System dynamics; Bullwhip effect; Vendor managed inventory.

1. Introduction

As a pillar industry in China, the construction industry is an important material production department in China [1]. The management of building materials has its importance and complexity, which is mainly reflected in the fact that the cost of building materials accounts for 50-60% of the working capital of the project, that the project can not be completed on time due to the delay of building materials, and that the definite quantity of building materials needed at the initial stage of project construction increases the uncertainty of purchasing and supplying building materials [2]. In order to reduce the stock capital occupation of building materials, the demand for building materials of construction enterprises began to tend to the order mode of small batch and multi-batch, which made the demand for building materials face greater uncertainty and volatility. Therefore, how to effectively manage the supply chain of building materials is a major challenge facing the construction industry. The supply chain of building materials consists of raw material suppliers, manufacturers, wholesalers and retailers of building materials, and even the final project construction unit [3-4]. The complexity of construction engineering in the construction process and the uncertainty of the demand for building materials make every member in the supply chain of building materials face the important problem of how to order and produce accurately and reasonably.
At present, the research on building materials supply chain mostly focuses on the construction, evaluation, cost management and pricing of supply chain. In view of the high energy consumption characteristics of traditional building materials supply chain, Qu Peng analyzed the feasibility of building green building materials supply chain and put forward the design process of green building materials supply chain. The research results show that building green building materials supply chain is conducive to improving the overall competitiveness of building materials industry [5]. On the basis of analyzing the ceramic industry with high energy consumption and high emission in building materials, Lin Jingliang discussed in detail the necessity of implementing green supply chain management in ceramic industry, constructed the green supply chain model of ceramic industry, and put forward the implementation strategy [6]. How to evaluate the operation process of building materials supply chain is an important problem after the construction of building materials supply chain. Therefore, Mao Yunyun and Zhou Zhixia established the evaluation index system of building materials supply chain based on the concept of green supply chain management, and used the principle of set pair analysis to evaluate [7].

Lin Jingliang studied the evaluation system of China's ceramic supply chain, which has the highest output in the world but is not competitive, and established the evaluation index system by using the principles of systematicness, scientificity, feasibility, combination of quantitative and qualitative. According to the evaluation results, he put forward specific strategies to enhance the competitiveness of ceramic supply chain [8]. In view of the problem of high inventory cost caused by conservative and extensive methods in the process of building materials management, Shao Bilin, Lin Sen and Wang Ying established an inventory cost control model under the supply chain environment, and compared it with the traditional inventory model by using mathematical modeling, which proved that the inventory cost model under the supply chain environment can save inventory cost more than the traditional model, and suggested that building materials enterprises should establish long-term cooperative relations [9]. In the recycling of construction waste materials, Huang Li, Wang Xiaoli and Sai Ming established a closed-loop supply chain model composed of construction material manufacturers, retailers and third-party recyclers of waste construction materials, and analyzed the optimal pricing, optimal recycling price and optimal recycling quantity of all parties in the supply chain by using the three-party game model of supply chain. The results show that the cooperation model has lower sales price, more sales volume and greater overall profit than the competition model [10]. Du Juan established a two-level reverse supply chain model composed of manufacturers and retailers, and compared the two situations under cooperative and non-cooperative games. The results show that there is a positive correlation between the regeneration rate and the efficiency of reverse supply chain system [11]. In the bullwhip effect of building materials supply chain, Min and Bornsson found that in construction projects, the order quantity of materials and equipment procurement put forward by building materials demanders to suppliers is often larger than the actual demand, which proves that the bullwhip effect also exists in building materials supply chain system [12]. On this basis, Feng Yahong and Zhang Muyuan analyzed the causes of bullwhip effect in building materials supply chain, and thought that individual decision-making bias and social preference were the main causes of bullwhip effect in building materials supply chain, while realizing information sharing, promoting collaborative decision-making and establishing trust mechanism were beneficial to alleviate bullwhip effect [13].

In the research of building materials supply chain, there are few researches on building materials supply chain management based on VMI mode. In this paper, the traditional building materials supply chain model and VMI-based building materials supply chain model are comprehensively compared, the operation process of building materials supply chain is simulated by using system dynamics theory and computer simulation method, and the influence of two system elements, transportation delay time and manufacturer's production cycle, on each member of the supply chain is studied, and the optimization countermeasures are put forward.
2. Theoretical analysis of bullwhip effect

2.1. Bullwhip effect of supply chain under non-information sharing

In the building materials supply chain, members at all levels of the supply chain do not share information, but only have order information from downstream, and members at all levels order or produce according to the order information of downstream members. It is assumed that in a multi-level building materials supply chain system, the ordering method is fixed-point ordering method, and each level member of the supply chain sets its own ordering point. When the inventory drops to the order point, an order is sent to the upstream to replenish the inventory. Each member in the supply chain sets the order point according to the order lead time and expected demand, and the order point of the $k$-th member in the $t$ cycle is

$$R^k_t = L_k \cdot \bar{d}^k, \quad \bar{d}^k = \frac{\sum_{i=1}^{h} q_i^{k-1}}{h}. \quad \text{In which: } \bar{d}^k \text{ is the expected demand, } L_k \text{ is the lead time for the } k \text{th member to order from the } (k-1) \text{ member, } h \text{ is the smooth cycle, and } q_i^{k-1} \text{ is the order quantity issued by the } (k-1) \text{ member to the } k \text{th member in the } t \text{ cycle.}
$$

To describe the relative difference of demand forecast variance between two adjacent members in the supply chain, it is expressed by the ratio of variance. Therefore, the ratio of the predicted variance of the $k$-th supply chain members to the predicted variance of the most downstream members is:

$$\frac{\text{Var}(q_i^k)}{\text{Var}(d_i)} \geq \prod_{i=1}^{k} \left(1 + \frac{2L_i}{h} + \frac{2L^2_i}{h^2}\right) \quad (1)$$

2.2. Bullwhip effect of supply chain under information sharing

In a multi-level building materials supply chain system, the terminal demand information is shared among all members of the supply chain, and members at all levels can make predictions according to the terminal demand information, so each member has the same expected demand. That is,

$$\bar{d}^k = \frac{\sum_{i=1}^{h} d_i}{h}, \quad \text{the order point of the } k \text{th member in } t \text{ cycle is } R^k_t = L_k \cdot \bar{d}^k + z\sqrt{k}\sigma_d^k. \quad \text{Therefore, the ratio of the predicted variance of the } k \text{-th supply chain members to the predicted variance of the most downstream members is:}
$$

$$\frac{\text{Var}(q_i^k)}{\text{Var}(d_i)} \geq 1 + \frac{2\sum_{i=1}^{k} L_i}{h} + \frac{2(\sum_{i=1}^{k} L_i)^2}{h^2} \quad (2)$$

Obviously, it can be seen from formulas (1) and (2) that due to the existence of lead time, the bullwhip effect of building materials supply chain can not be eliminated, and the upstream members of the supply chain have greater bullwhip effect than the downstream members, while the increase of smooth period can weaken the bullwhip effect. The bullwhip effect in the non-information sharing environment is greater than that in the information sharing environment, which indicates that the degree of information sharing is negatively correlated with the bullwhip effect, and enhancing information sharing is conducive to weakening the bullwhip effect in the supply chain.
3. Establishment of system dynamics model of building materials supply chain

3.1. Modeling of building materials supply chain in non-information sharing environment

Disney considered two state variables, inventory and in-transit inventory, and established the dynamic model of supply chain system [14]. Using this model for reference, this paper constructs a building materials supply chain model under non-information sharing environment and a building materials supply chain model based on VMI under information sharing environment. The research object is a building materials manufacturing enterprise in Guangdong Province, whose supply chain consists of raw material suppliers, manufacturers and distributors. Its supply chain network operation model is shown in Figure -1:

Figure 1. Supply chain model of building materials under non-information sharing environment

Taking the multi-level supply chain system composed of building materials manufacturer, raw material supplier, distributor and customer group as the research object, the multi-level supply chain system considers two main state variables of building materials manufacturer inventory and distributor inventory, and the building materials manufacturer inventory is controlled by two rate variables of raw material arrival rate and production consumption rate. It is assumed that the supply capacity of raw material suppliers is infinite, and there are delays in order processing and transportation, and there is in-transit inventory of raw materials. Manufacturers have enough production capacity, they produce according to orders, and the finished products are delivered immediately. There are delays in production and transportation, in-transit inventory of finished products, and no inventory of finished products. The expected inventory of raw materials of manufacturers is affected by demand forecast, which in turn affects the ordering rate of manufacturers. Therefore, it constitutes a causal feedback loop of building materials manufacturers in the upstream of supply chain. In the same way, the inventory of downstream distributors consists of two rate variables: arrival rate and sales rate, with expected inventory, inventory adjustment period, inventory coverage period and forecast smoothing time as auxiliary variables. The supply chain system introduces the manufacturer's production cycle and transportation delay as constants to simulate the model. Vensim PLE simulation software is used to model the supply chain. The upstream members of the supply chain only make predictions according to the orders of the downstream members. The dynamic model of the building materials supply chain system in the non-information sharing environment is shown in Figure -2.
3.2. Modeling of building materials supply chain based on VMI model

The development of information technology provides support for the reform of traditional building materials supply chain. By introducing an information sharing central data platform, the demand and inventory information of all members of the building materials supply chain can be shared in real time, and the upstream members of the supply chain can share the terminal demand information and the inventory information of the downstream members in real time, thus solving the problem of information distortion caused by the delay of information dissemination. With building materials manufacturers as the core enterprise, based on the original supply chain structure, a central data
platform for realizing real-time information sharing can be built, and the VMI model can be implemented, as shown in Figure -3.

![Diagram of Building materials supply chain model based on VMI mode in information sharing environment](image)

**Figure 3.** Building materials supply chain model based on VMI mode in information sharing environment

Building materials supply chain based on VMI mode can effectively realize the sharing of terminal demand information and inventory information of all levels of supply chain members. Compared with the traditional supply chain model, the upstream members of the supply chain can directly grasp the terminal demand information and forecast the future demand according to the terminal demand information, thus reducing the errors caused by the intermediate members of the supply chain in demand forecasting. At the same time, the downstream members share the inventory information with the upstream members, and the upstream members make replenishment plans in time according to the inventory deviation of the downstream members, so that the downstream members do not need to place orders with the upstream members, reducing the workload and saving costs. The dynamic model of building materials supply chain system based on VMI mode with information sharing capability is shown in Figure -4:
4. Simulation results and analysis

4.1. Main variable equation and parameter setting

The system dynamics model of building materials supply chain is simulated by Vensim PLE software. A building materials manufacturer and distributor in Guangdong Province were investigated, and the actual operating data needed for simulation experiment was obtained. The simulation period was 300 days. The main variable equations and parameters of building materials supply chain system dynamics model under non-information sharing environment are set as follows:

In-transit inventory of finished products = \text{INTEG} (\text{Distributor replenishment rate} - \text{Distributor arrival rate}, 0)

Distributor inventory = \text{INTEG} (\text{Distributor arrival rate} - \text{Sales rate}, 200)

In-transit inventory of raw materials = \text{INTEG} (\text{Supplier delivery rate} - \text{Raw material arrival rate}, 0)

\textbf{Figure 4. Dynamic model of building materials supply chain system based on VMI model}
Manufacturer inventory = INTEG (Arrival rate of raw materials-Raw material consumption rate, 200)
Backlog of finished goods orders = INTEG (Generation rate of finished goods orders-Completion rate of finished goods orders, 0)
Backlog of raw material orders = INTEG (Raw material order generation rate-Completion rate of raw material orders, 0)
Completion rate of finished goods orders = IF THEN ELSE (Backlog of finished goods orders > Manufacturer's delivery rate, manufacturer's delivery rate, backlog of finished goods orders)
Generation rate of finished goods orders = Distributor ordering rate
Completion rate of raw material orders = DELAY1 (Raw material order generation rate, raw material order processing cycle)
Raw material order generation rate = Ordering rate of manufacturer
Sales rate = Customer demand rate
Distributor ordering rate = Distributor inventory deviation ÷ Distributor inventory adjustment cycle
Replenishment rate of distributors = Manufacturer delivery rate
Distributor arrival rate = DELAY1 (Distributor replenishment rate, replenishment transportation delay)
Ordering rate of manufacturer = Raw material inventory deviation ÷ Manufacturer's inventory adjustment cycle
Supplier delivery rate = Completion rate of raw material orders
Arrival rate of raw materials = DELAY1 (Supplier delivery rate, raw material transportation delay)
Raw material consumption rate = Distributor inventory deviation = Distributor inventory adjustment cycle
Manufacturer delivery rate = DELAY FIXED (Raw material consumption rate, production cycle, 0)
Distributor demand forecast = SMOOTH (Customer demand rate, distributor forecast smoothing cycle)
Expected inventory of distributors = Distributor demand forecast × Distributor inventory coverage cycle
Distributor inventory deviation = IF THEN ELSE (Expected inventory of distributors > (Distributor inventory + Intransit inventory of finished products), Expected inventory of distributors-Distributor inventory-Intransit inventory of finished products, 0)
Raw material demand forecast = SMOOTH (Distributor order rate, manufacturer forecast smooth cycle)
Manufacturer's expected inventory = Raw material demand forecast × Inventory coverage cycle of raw materials
Raw material inventory deviation = IF THEN ELSE (Manufacturer's expected inventory > (Manufacturer inventory-In-transit inventory of raw materials), Manufacturer's expected inventory-Manufacturer inventory-In-transit inventory of raw materials, 0)
Customer demand rate = 20 + STEP (10, 100)
Replenishment transportation delay = 5 days
Transportation delay of raw materials = 5 days
Distributor forecast smoothing period = 5 days
Distributor inventory coverage period = 14 days
Distributor inventory adjustment cycle = 5 days
Manufacturer predicts smoothing period = 5 days
Raw material inventory coverage period = 14 days
Manufacturer's inventory adjustment period = 5 days
Raw material order processing cycle = 3 days
Production cycle = 6 days

The main variable equations and parameters of building materials supply chain system dynamics model based on VMI mode are mostly the same as those of building materials supply chain system dynamics model under non-information sharing environment, and the main changes are as follows...
Raw material demand forecast = Customer demand rate ÷ Manufacturer predicts smoothing cycle

Producer replenishment plan = Distributor inventory deviation ÷ The manufacturer supplements the adjustment period

Completion rate of manufacturer's replenishment order = IF THEN ELSE (Backlog of manufacturer's replenishment orders > Manufacturer's delivery rate, manufacturer's delivery rate, manufacturer's replenishment order backlog)

Producer replenishment order rate = Producer replenishment plan

Backlog of manufacturer's replenishment orders = INTEG (Manufacturer replenishment order rate ÷ manufacturer replenishment order completion rate, 0)

Manufacturer replenishment adjustment period = 5

4.2. Simulation comparison of two building materials supply chain system dynamics models

The simulation results from the above parameters are shown in Figure -5:
Figure 5. Dynamic simulation results of building materials supply chain system
It can be seen from Figure -5 that the two building materials supply chain system dynamics models fluctuate to a certain extent under the initial conditions, such as distributor ordering (producer replenishment plan), finished goods order backlog (producer replenishment order backlog), distributor inventory deviation, finished goods in-transit inventory and distributor inventory, which gradually tend to be flat with the passage of time. When the jump demand occurs, the fluctuation range of the two models increases, but there is no difference between the two models. However, the manufacturer's ordering rate, raw material order backlog, raw material inventory deviation, raw material in-transit inventory and manufacturer's inventory all fluctuate greatly, and the fluctuation degree is greater than that of upstream distributors, which indicates that both models have bullwhip effect, which expands gradually from downstream to upstream and gradually tends to be flat with time. Compared with the dynamic model of building materials supply chain system in non-information sharing environment, the dynamic model of building materials supply chain system based on VMI mode has less fluctuation degree, which indicates that information sharing is beneficial to alleviate bullwhip effect. When the jump demand occurs, both models will increase volatility, and the volatility is less in the information sharing environment, and the period of flattening is shorter, which shows that information sharing is more conducive to responding to market demand fluctuations quickly and reducing waste.

4.3. Parameter sensitivity analysis

Parameter setting of building materials supply chain system dynamics model will affect the simulation results. Sensitivity analysis of parameters will help enterprises to grasp the influence direction of the change of parameter values on the simulation results, which will help enterprises to improve the supply chain and improve the efficiency of supply chain operation.

4.3.1. Sensitivity analysis of transportation delay time. The transportation delay time of distributors and manufacturers is set to 3 days, 5 days and 7 days at the same time, and the simulation results are shown in Figure -6.

It can be seen from Figure -6 that the transportation delay time has no influence on the distributor order rate (manufacturer replenishment plan) and the finished product order backlog (manufacturer replenishment order backlog) of the two building materials supply chain system dynamics models. In the information sharing environment, the backlog of raw material orders and the deviation of raw material inventory have no effect, but in the non-information sharing environment, the transportation delay time has no effect on the backlog of raw material orders and the deviation of raw material inventory in the declining period, while the fluctuation amplitude decreases with the shortening of transportation delay time, and the fluctuation response time increases with the shortening of transportation delay time. The distributor inventory of the two models decreases with the increase of transportation delay, while the in-transit inventory of finished products increases with the increase of transportation delay. The manufacturer's inventory of the two models decreases with the increase of transportation delay time, while the in-transit inventory of raw materials increases with the increase of transportation delay time, and the increase in information sharing environment is less than that in non-information sharing environment.
4.3.2. Sensitivity analysis of manufacturer's production cycle. The manufacturer's production cycle is set to 5 days, 6 days and 7 days for simulation, and the simulation results are shown in Figure 7:
Figure 7. Sensitivity analysis results of manufacturer's production cycle
It can be seen from Figure -7 that the fluctuation range and smooth cycle of distributor inventory, finished goods in-transit inventory, finished goods order backlog (manufacturer's order backlog) and distributor order rate (manufacturer's replenishment plan) of the two building materials supply chain system dynamics models increase with the extension of manufacturer's production cycle, and there is no difference between the two models. Under the two models, the fluctuation range of manufacturer's inventory, in-transit inventory of raw materials, backlog of raw materials orders, and the period of flattening increase with the extension of manufacturer's production cycle, and the increase range in information sharing environment is less than that in non-information sharing environment, and the period of flattening is shorter. It shows that shortening the producer's business cycle is conducive to reducing the bullwhip effect of the supply chain, and the effect is better under the information sharing environment.

5. Conclusions
The construction industry is an important material production department in China, and the management of building materials is of great importance and complexity. This paper combs the research status of building materials supply chain, and theoretically analyzes the bullwhip effect of supply chain under the environment of non-information sharing and information sharing. The building materials supply chain model in non-information sharing environment and the building materials supply chain model based on VMI mode in information sharing environment are constructed. The Vensim PLE simulation software is used to build the system dynamics flow chart, and the main variable equations and parameters are set. Using the real data of building materials manufacturers and distributors, the simulation results are consistent with the theoretical analysis. Sensitivity analysis of transportation delay time and manufacturer's production cycle is carried out, and the following suggestions are put forward based on the analysis results:

(1) Compared with the dynamic model of building materials supply chain system in non-information sharing environment, the dynamic model of building materials supply chain system based on VMI mode in information sharing environment has less fluctuation degree, which indicates that information sharing is beneficial to alleviate bullwhip effect. When the jump demand occurs, both models will increase volatility, and the volatility is less in the information sharing environment, and the period of flattening is shorter, which shows that information sharing is more conducive to responding to market demand fluctuations quickly and reducing waste. Therefore, all members of the supply chain should make joint efforts to build a supply chain based on VMI mode, so as to improve the overall operation efficiency and competitiveness of the supply chain.

(2) The distributor inventory of the two models decreases with the increase of transportation delay, while the in-transit inventory of finished products increases with the increase of transportation delay. The manufacturer's inventory of the two models decreases with the increase of transportation delay time, while the in-transit inventory of raw materials increases with the increase of transportation delay time, and the increase in information sharing environment is less than that in non-information sharing environment. Therefore, as the core enterprise of building materials supply chain, the manufacturer should be able to introduce the third-party logistics enterprise to undertake the transportation enterprise, reasonably set the transportation time, transfer the inventory to the in-transit inventory, and reduce the inventory pressure of supply chain members.

(3) The fluctuation range of manufacturer's inventory, in-transit inventory of raw materials, backlog of raw material orders and order rate of raw materials, as well as the gradual cycle of the two models all increase with the extension of manufacturer's production cycle, and the increase range in information sharing environment is less than that in non-information sharing environment, and the gradual cycle is shorter. It shows that shortening the producer's business cycle is conducive to reducing the bullwhip effect of the supply chain, and the effect is better under the information sharing environment. Therefore, manufacturers should strive to improve production efficiency and shorten production cycle, thus reducing the bullwhip effect of supply chain and enhancing the stability of supply chain.
In this paper, only one manufacturer of building materials is studied, and the interaction between multiple manufacturers and competitive market is not considered. The structure of supply chain composed of many building materials manufacturers is more complex. In the future, it is planned to study the complex building materials supply chain network with many manufacturers at the same time, so as to reduce the difference with the actual situation and improve the practical value of the research results.

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