Two-stage supply chain inventory management based on system dynamics model for reducing bullwhip effect of sulfur product

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Abstract
Bullwhip effect is prevalent in supply chains, creating supply and inventory risks that affect marketing, supply and production. However, there are limited researches on the optimization of chemical supply chain inventory management. In order to solve the above problem, this paper took the sulfur product supply chain of a sulfur plant as an example, combined with the idea of system dynamics, and systematically studied the inventory control strategy in the distributor-retailer two-level inventory system constituted by the supply chain. Firstly, the causal loop diagram was drawn according to the system relationship between variables in the two-level supply chain, and then the system dynamics model of sulfur product supply chain was formed. Finally, problems existing in the supply chain were explored through simulation, and optimization suggestions were submitted. It can be concluded from the simulation results that there was bullwhip effect in the sulfur product supply chain, and the delay of transportation time and the change of inventory adjustment time would have an impact on the inventory level of each node enterprise in the supply chain. Therefore, the method of building an information sharing platform, implementing visual information management, and adopting logistics transportation service outsourcing could enhance the information exchange among node enterprises, so as to improve the operational efficiency of the entire product supply chain.

Keywords Supply chain · Inventory control · Inventory management · System dynamics model · Sulfur product · Bullwhip effect

1 Introduction
As a by-product of the petroleum refining process, sulfur is an important chemical raw material. With the development of China’s petrochemical industry in recent years, competition within the sulfur market has become increasingly fierce. Due to excess capacity upstream and weak demand downstream, the economy of the sulfuric acid industry is not doing well...
and the price of sulfur products continues to be low (Chong, 2020, 2021). Nowadays, the focus on competition among enterprises is gradually changing into competition among supply chains. When supply and demand is uncertain, competition and cooperation among nodal enterprises in the supply chain are conducive to improving the overall efficiency of the supply chain (Huo et al., 2014). Nodal enterprises in the supply chain only pay attention to their own interests and ignore the entire supply chain, which is the root cause of oversupply in sulfur acid industry. This makes the real market demand information amplified step by step as the supply chain rises through ranks, and the bullwhip effect emerges (Khosroshahi et al., 2016; Yang et al., 2021). Therefore, as an important part of supply chain management, the role of inventory management in improving the economic efficiency and overall competitiveness of each node in the chain should not be underestimated (Jonas, 2010). Aiming at bullwhip effect in sulfur supply chain, based on system dynamics (SD) model, this research systematically studied the inventory management strategy of reseller-retailer two-level inventory system composed of supply chain, so as to improve the operational efficiency of the whole sulfur supply chain.

The bullwhip effect refers to a phenomenon of amplifying demand variability in the supply chain, also known as demand information amplification or the Forrester (1958, 1997) effect, which is a phenomenon whereby a small variation in end-customer demand leads to a significant fluctuation in orders that the upstream supplier receives in the supply chain system (Lee et al., 1997). Bullwhip effect was widely studied as one of the main obstacles in the supply chain and has been proposed corresponding solutions in the context of production inventory and supply. Dejonckheere et al. (2004) proposed a control engineering-based measure to quantify the variance amplification bullwhip effect or variance reduction. The result showed that information sharing was necessary to reduce order variance at higher levels of the chain. Chatfield (2013) has built a hybrid agent/discrete-event simulation model of a supply chain, which proved that permitting returns significantly increases the bullwhip effect. In order to investigate how the bullwhip effect is reflected in services through quantitative and qualitative case data, the results of this study helped organizations to reduce the negative impact of planned and unplanned fluctuations in their service supply chains (Akkermans & Voss, 2013). A multiple order-up-to policy-based inventory replenishment scheme was proposed to mitigate the bullwhip effect in a multi-stage supply chain scenario, where various transportation modes are available between supply chain participants (Keshari et al., 2018). Tai et al. (2019) proposed the method of quantitative analysis to study the behavior of the bullwhip effect. The results have shown that the influence of lead time and self-focusing coefficient on the bullwhip effect is affected by price, appearance and its interaction with demand. Zhang et al. (2019) proposed analyzing the impact of information sharing on supply chain performance through theoretical analysis and numerical simulation, which provides a new perspective and supplement for understanding and alleviating the bullwhip effect. Garg et al. (2020) proposed a multi-objective optimization framework of genetic programming in the modelling of the bullwhip effect, which was useful for business practitioners to supervise the sudden demand amplification. Dolgui et al. (2020) proposed a simulation-based study which showed that the ripple effect influences the bullwhip effect through backlog accumulation over the disruption time as a consequence of non-coordinated ordering and production planning policies.

Aggregating data may lead to over- or underestimation of the bullwhip effect (Yao et al., 2021), with important theoretical and managerial implications for researchers and managers (Brauch & Größler, 2022). Therefore, how to solve the problem of the bullwhip effect in sulfur supply chain is worthy of study. This paper aims to introduce SD theory to analyze and solve the problems in sulfur supply chain. An optimization method was introduced to study the impact of the Internet of Things on inventory variance and the bullwhip effect. The
results have shown that the Internet of Things can reduce costs associated with inventory fluctuations and eliminate the bullwhip effect in closed-loop supply chains (Papanagnou, 2022). Villa (2022) systematically explored the influence of the bullwhip effect when there was horizontal competition among retailers. The results showed that competition for supply had a strong effect on participants’ ordering decisions, while competition for demand did not impact how retailers inflate their orders.

SD is a kind of computer simulation technology based on the system thinking to analyze production management, inventory management and other enterprise problems (Ekanayake et al., 2021; Luo et al., 2022; Zhang et al., 2020). It had been widely used in the field of supply chain inventory management, and scholars had fruitful research results. Forrester (1958) first proposed impact on the bullwhip effect on firms in the supply chain, analyzed the influence of factors such as decision delays and demand fluctuations of inventory based on SD principles. Ji et al. (2012) built an SD model of the supply chain under the advance payment financing business and simulated with Vensim simulation software. The result proved that prepayments financing has a positive effect on the supply chain performance, and provided a strong theoretical support and reference basis for subsequent research activities.

To promote each node of the supply chain to build a long-term cooperative relationship of benefit sharing, and to realize the efficient allocation of production capacity, warehousing, transportation capacity and cost, scholars have used the SD to study the inventory optimization problem. Yan et al. (2017) established the inventory management model of the co-operation planning, forecasting and replenishment, and used Vensim software to simulate it. The simulation results showed that the application of this model in cluster supply chains could effectively restrain the bullwhip effect and improve the efficiency of the entire supply chain. Demczuk (2017) used Vensim software for simulation on different arrangements of sugarcane yield, gasoline prices and sales tax, and the results showed the effectiveness of the mode. Hofmann (2017) proposed using the SD model to study the positive role of big data leverage in improving the supply chain process. The research results have shown that the data property 'velocity' relatively bears the greatest potential to improve the performance. Abidi et al. (2018) proposed an SD simulation inventory management modeling for a multi-echelon multi-product pharmaceutical supply chain. The models implementation established its ability to illustrate the trade-off between the inventory cost and the service level. Olivares-Aguila (2021) proposed an SD framework to observe the supply chain behavior. The results have shown that expediting after disruptions do not offer benefits to the long-term supply chain performance. Heidary (2022) used the SD method to analyze the global supply chain in COVID-19, and proposed that increasing the flexibility of production capacity is one of the important strategies that global supply chain managers should pursue.

SD was widely used in various fields. Jiang (2021) applied building information modeling, prefabricated buildings and SD to architecture, and studied the cost control of prefabricated buildings. Ghadge et al. (2018) proposed an SD simulation method to evaluate the impact of the implementation of additive manufacturing on the aircraft supply chain network, revealing insights into supply chain performance. Naderi et al. (2021) proposed an SD method to simulate production-inventory-routing system. The results indicated that minimum total transportation cost, the total warehouse capacity of the supply chain, and the maximum production rate are the most influential strategies to achieve an ideal condition. Rathore et al. (2021) proposed the method of SD modeling to analyze the dynamic influence of inventory transportation policy on grain transportation system, which improves the efficiency of food grains supply chain. Khan (2021) proposed effective suggestions for optimizing supply chain performance by simulating SD model of chemical supply chains, which is that product inventories can be reduced by changing ordering methods to cope with uncertain market demand.
Delavar et al. (2022) analyzed the bullwhip effect in the electronic product manufacturing system based on the SD, and proposed that appropriate policies and electronic recycling can effectively reduce the bullwhip effect. Therefore, based on the theory of predecessors, this paper proposed to apply SD to the sulfur industry, optimize the inventory management of sulfur manufacturers, and realize the efficient allocation of production capacity, storage, transportation capacity and cost.

In summary, the research on the use of SD to solve supply chain inventory management problems had been relatively mature, which provided a theoretical basis for this paper. However, there were relatively few studies on the optimization of supply chain inventory management for chemical products. This research took the sulfur product supply chain of a sulfur factory as a case background, applied SD theory to modeling and simulation, and systematically studied the inventory control strategy in the dealer-retailer secondary inventory system composed of the supply chain. The simulation results were analyzed and reasonable suggestions were submitted, which provided a theoretical basis for the future product supply chain of related enterprises.

This research has made the following contributions:

Bullwhip effects are pervasive in supply chains, creating supply and inventory risks that affect marketing, supply and production. However, there are few researches on the optimization of chemical supply chain inventory management. In this paper, the idea of SD was introduced into the sulfur supply chain, and the inventory control strategy in the distributor-retailer two-level inventory system composed of the supply chain was systematically studied. The methods of enhancing the information exchange between nodal enterprises were put forward to improve the operational efficiency of the whole product supply chain.

The structure of the rest of the article was arranged as follows: Sect. 2 introduced the model assumptions and descriptions, Sect. 3 introduced Vensim simulation and sensitivity analysis, Sect. 4 put forward problems and suggestions for optimization and Sect. 5 introduced the conclusion of this paper.

2 Model construction

2.1 Modeling purpose and boundary determination

2.1.1 Modeling purpose

SD was based on the causal relationship from the internal micro-structure of the system to establish a model, at the same time, with the help of computer simulation technology to analyze the internal evolution of the system structure and function and dynamic behavior, and to find solutions to the problem (Ong et al., 2022). In this paper, the SD theory was used to model and analyze the inventory management mode of a sulfur product supply chain in a sulfur factory. Through the analysis of the simulation results, the problems existing in the current supply chain of sulfur products and the impact of the current inventory management mode on the chain and the overall operation of the supply chain of the node enterprises were understood. And this research also explored specific solutions and improvement measures to improve the overall operational efficiency and enterprise competitiveness of the supply chain.
2.1.2 Boundary determination

In this paper, the SD model was established based on the two-level supply chain consisting of distributors’ inventory and retailers’ inventory in conjunction with the operational reality of sulfur plants. As shown in Fig. 1, the entire model starts from the manufacturer’s supply until the end customer receives the goods. In addition to the flow of products in the supply chain, there is also the flow of information, including supply information and demand information. Downstream customers send demand to retailers, who put forward orders to distributors according to the needs of end customers, and upstream manufacturers supply them according to the orders of distributors.

2.2 Model causality analysis

This paper focused on a two-level supply chain consisting of distributors’ inventory and retailers’ inventory. At present, each nodal company in the supply chain of sulfur products of this sulfur plant acts as an independent entity and it is limited to considering its own inventory management and optimization in the operation process. They replenished according to order information received from downstream companies and the companies’ own market demand forecasts and exaggerated the actual demand when ordering from upstream out of consideration for their own safety stock levels, shipping delays, and other factors (Liang et al., 2022). In the current supply chain of sulfur products, there is a lack of timely and effective information communication with enterprises. As a result, the real market demand information cannot be accurately transmitted in the chain, and thus the phenomenon of inventory backlog and higher inventory cost input appears.

Therefore, the causal circuit diagram of sulfur product supply chain model was drawn according to the causal relationship between variables, as shown in Fig. 2. In the whole two-level supply chain, distributors and retailers were connected through orders and inventory to form a systematic supply chain model dominated by two negative feedback loops. Take a retailer as an example, a decrease in the retailer’s inventory will cause the retailer to increase the ordering demand, and then the distributor will increase the delivery rate, which will eventually lead to an increase in the retailer’s inventory. Among them, the retailer’s ordering demand is not only affected by the retailer’s inventory, but also by the retailer’s expected inventory and sales forecast.

2.3 Basic assumptions of the model

Since this model was built in a supply chain environment, to facilitate the model’s simplification and targeted study, the following basic assumptions were made for the model:

(1) Sulfur products were the sole products of the supply chain.
(2) The upstream production capacity and timeliness of the product were not considered.
(3) Customers’ needs were random (Chen et al., 2021).
2.4 Background of the case

There were four main nodes in the supply chain of sulfur products of a sulfur plant - manufacturers, distributors, retailers, and end customers - that constituted the product supply system. The main operational process of the sulfur product supply chain was that when a manufacturer receives an order for a distributor, it begins manufacturing the product and distributing it downstream on time and at each level. It was known that the initial stock in the distributor’s warehouse was 20 million tons, and the initial stock in the retailer’s warehouse was 10 million tons. Shipping delays for manufacturers and distributors were 3 weeks. The expected inventory maintenance time for distributors and retailers was 4 weeks. Inventory adjustment and moving average time were both 3 weeks. The end-customer demand obeyed normal distribution. Therefore, the model had an initial time of 0, a simulation step of 1 week, and an end time of 120 weeks.

2.5 Variable equation description

In this paper, the corresponding names and equations of the main variables in this SD model were explained according to the actual supply chain of sulfur products. See Table 1 for detailed descriptions.

2.6 Inventory-flow diagram

The causal loop diagram qualitatively shows the causal relationship between various variables in the two-level supply chain system. On the basis of the causal loop diagram, the variables could be divided into stock and flow according to different properties. The logical relationship between various variables was established through the equation, and finally the required stock-flow diagram was obtained. According to Fig. 2, the stock variables in the system includes supplier inventory and retailer inventory, the rate variables includes manufacturer supply rate, distributor delivery rate and retailer sales rate, and the other variables are auxiliary variables and constants. On this basis, the inventory flow chart of the sulfur product supply chain inventory model of the sulfur factory was drawn by Vensim software. See Fig. 3 for details.
Table 1 Description of the variable equations

| Variable Name                        | Equations                                                                 | Units   |
|-------------------------------------|---------------------------------------------------------------------------|---------|
| Manufacturer Availability Rate      | $\text{DELAY}_1(\text{Distributor Orders, Transport Delay Time, Distributor Orders})$ | Mt/Week |
| Distributor Shipment Rate           | $\text{DELAY}_1(\text{Retailer Orders, Transport Delay Time})$             | Mt/Week |
| Distributor Orders                  | $\text{MAX}(0, \text{Distributor Market Forecast} + (\text{Distributor Expectation Inventory} - \text{Distributor Inventory})$ | Mt/Week |
| Distributor Market Forecast         | $\text{SMOOTH}(\text{Distributor Shipment Rate, Moving Average Time})$     | Mt/Week |
| Distributors’ Inventory             | $\text{INTEG}(\text{Manufacturer Availability Rate} - \text{Distributor Shipment Rate}, 2000)$ | Mt      |
| Distributor Expectation Inventory   | $\text{Distributor Market Forecast} \times \text{Expected Inventory}$     | Mt      |
| Retailer Sales Rate                 | $\text{MAX}(0, \text{End Customer Needs})$                                | Mt/Week |
| Retailer Orders                     | $\text{MAX}(0, \text{Retailer Sales Forecast} + (\text{Retailer Expectation Inventory} - \text{Retailer Inventory}) / \text{Inventory Adjustment Time})$ | Mt/Week |
| Retailer Sales Forecast             | $\text{SMOOTH}(\text{End Customer Needs, Moving Average Time})$            | Mt/Week |
| Retailers’ Inventory                | $\text{NTEG}(\text{Distributor Shipment Rate} - \text{Retailer Sales Rate}, 1000)$ | Mt      |
| Retailer Expectation Inventory      | $\text{Retailer Sales Forecast} \times \text{Expected Inventory}$         | Mt      |

Fig. 3 Sulfur product supply chain model Inventory-flow diagram

2.7 Establishment of SD model of sulfur product supply chain

Based on the systematic relationship between variables in the two-stage supply chain, this paper drew a causal cycle diagram and establishes an SD model of the sulfur product supply chain to simulate and explore the problems in the supply chain. The flow chart of SD model establishment is shown in Fig. 4.
The implementation steps of SD model establishment were as follows:

Step 1 Drew the causal loop diagram of the sulfur product supply chain model based on the causal relationship among the variables.

Step 2 Made some basic assumptions about the model to simplify the model and study the problem more pertinently.

Step 3 Drew the stock-flow diagram of the sulfur product supply chain model.

Step 4 Set the equation and initial value of each variable, the initial time, simulation step and end time of the simulation, assuming that the end customer demand was 0.

Step 5 Carried out simulation, exported the inventory level change graph of distributors and retailers.

Step 6 Set the random demand function of the end customer, the minimum value was 1500, the maximum value was 2750, and the standard deviation was 445.

Step 7 Carried out simulation and derived the inventory level change graph when customer demand was normally distributed.

Step 8 Exported the order comparison chart of each node company and the speed comparison chart of each node company to analyze the bullwhip effect.

Step 9 Changed the transportation delay time to 1 week and 5 weeks respectively and performed simulation.

Step 10 Exported the inventory level change graph with the transportation delay time of 1 week, 3 weeks, and 5 weeks, and analyzed the results.
Step 11 Changed the inventory adjustment time to 2 weeks and 4 weeks respectively and performed simulation.
Step 12 Exported the inventory level change graph with inventory adjustment time of 1 week, 3 weeks, and 5 weeks, and analyzed the results.

3 Vensim simulation and sensitivity analysis

In this paper, Vensim software was used to simulate the constructed model, and the data came from a survey of a sulfur manufacturer. This part used the SD simulation function to analyze the causes of bullwhip effect in the sulfur product supply chain of the sulfur plant, and its negative impact on the improvement of the overall operational efficiency of the sulfur product supply chain.

3.1 Vensim simulation

3.1.1 Comparison of inventory levels among nodal companies

Firstly, the simulation was performed assuming that the end-customer demand is zero to check the realism and stability of the model. Then, the model was simulated under extreme conditions to derive the inventory of each node firm when there is no order demand for end customers.

As shown in Fig. 5, when the end-customer demand was zero, the nodal companies did not need to order from upstream and did not have to restock downstream. Therefore, 20 million tons of distributor inventory and 10 million tons of retailer inventory were kept at the initial inventory level in the sulfur product supply chain, and the whole curve was horizontal without fluctuation. Since market demand was transmitted upward from downstream, when there was no demand, the retailer did not need to carry out sales activities and therefore did not need to

![Fig. 5 Change in inventory level when customer demand is zero](image-url)
not need to order from upstream. Similarly, the same was true of distributors. Hence, the model was consistent with the actual situation (Sterman, 2002).

However, the needs of end customers did not have a specific pattern of change in practice and it’s usually random (Nuñez Rodriguez et al., 2021). Therefore, simulations could be performed with stochastic functions in Vensim software in connection with reality. In this paper, the random demand functioned RANDOM UNIFORM (1500, 2750, 445), which is applicable to end customers, was selected based on the data provided by the sulfur plant. That was, the minimum value was 1500, the maximum value was 2750, and the standard deviation was 445.

As shown in Fig. 5, when the demand of end customers changes, the inventory level of each node in the supply chain also fluctuates. In terms of overall change, the most significant change was distributor inventory, the second most noteworthy change was retailer inventory, and the least significant change was from end-customer demand. The same was true for the change in the volatility of the three. The bullwhip effect is clearly revealed in Fig. 6 for the current sulfur product supply chain of this sulfur plant. This phenomenon was because each company in the supply chain considered meeting the actual order demand and ordered additional quantities based on the actual demand out of consideration of their own safety stock level situation and order frequency, transportation delays, and other factors. As the upstream of the product supply chain, there was a disconnection between the demand information of distributors and end customers, and the real market demand could only be predicted empirically by the number of the past orders, which has led to a backlog of inventory in the warehouse of each node in the supply chain. In the case of sulfur products, storage in large quantities of warehouses is very likely to cause heat and scorching, and the safety of inventory management is difficult to guarantee.

### 3.1.2 Bullwhip effect analysis

From the above, it was known that the bullwhip effect has occurred in the supply chain of sulfur products from the sulfur plant, so a specific simulation of the problem was performed.
See Fig. 7 for details. As can be seen from the graph, the change in distributor orders is more pronounced than that of retailers and end customers during the comparison of orders between companies. In the comparison of rate fluctuations of companies, the upstream manufacturer’s supply rate was more variable than the distributor’s shipment rate and the retailer’s sales rate. In the context of the sulfur plant’s operations, the plant did not maintain inventory at the manufacturer’s premises to save money on inventory maintenance and relied solely on on-time production and distribution of orders from distributors.

Moreover, manufacturers were located upstream of the entire supply chain, and the attention of business operators was focused on the completion of orders, ignoring the actual demand of downstream end customers and the inventory situation of each node company.
Meanwhile, distributors exaggerated the actual demand when placing orders. Retailers do the same. Therefore, this phenomenon that market demand information fluctuates and amplifies step by step as the supply chain rises directly had a non-negligible impact on each node enterprise in the supply chain, and the inventory service level was also affected. It can also be seen from Fig. 6 that warehouse bursts occur from time to time, and inventory input costs increase accordingly. When sulfur products accumulate in large quantities in warehouses, it will cause safety hazards in the warehouses of nodal enterprises and lead to the enhancement of product acidity, deterioration of quality, and corrosion of transport vehicles and end customers’ mechanical equipment. Sometimes there is also a negative impact on the local climate environment. At the same time, for the upstream sulfur plant, when there is no order demand for inventory accumulation in the middle and downstream warehouses, the products on the production line are not transported in time, which leads to production stoppages. The workers of the factory had to stand by in place, which in turn caused a waste of human and material resources.

3.2 Sensitivity analysis

Sensitivity analysis is used to observe the stability and applicability of the model by changing some parameters or conditions in the model. In this paper, the sensitivity analysis of the supply chain model of sulfur products was performed by the variation of transportation delay time and inventory adjustment time in the time strategy.

3.2.1 Impact of changes in transport delay times

In this paper, we simulated the SD model of sulfur product supply chain when the transportation delay time is 1 week and 5 weeks, respectively, and the results were compared and analyzed with the current supply chain simulation results, which is illustrated in Fig. 8. From the figure, the inventory of each nodal company gradually increased with the increase of transportation delay time, while the frequency of fluctuation of the curve gradually decreased. Also, distributor inventories change curves fluctuate more frequently than retailer inventory.

As can be seen from Table 2, with the increase of transportation delay time, distributor inventory would increase gradually, and the growth rate would increase with the increase of delay time. The analysis of Table 3 shows that, unlike distributors, inventory of retailers tended to decline with the increase of transportation delay time during 0-80 weeks, while after 80 weeks, it tended to rise slightly with the increase of transportation delay time. This means that changes in the length of transport delays have a much stronger impact on downstream companies. When the transportation delay time became longer, although it could reduce the inventory management costs of each node enterprises, at the same time, it was more likely to cause the accumulation of products in the warehouse, increasing the risk of inventory management and management cost investment. Therefore, the delay time of transportation should be minimized to improve inventory accumulation, accelerate its own inventory turnover, and enhance the operational efficiency of the sulfur product supply chain. It could also respond to the needs of downstream and even end customers in a timelier manner. At the same time, it mitigated the safety hazards caused by sulfur buildup and protected the local climate and the operation of the upstream production line (Ahmadini et al., 2021).
3.2.2 The impact of changes in the timing of inventory adjustments

In this paper, we simulated the SD model of the sulfur product supply chain when the inventory adjustment time is 2 weeks and 4 weeks respectively, and compared the results with the simulation results of the current supply chain, as shown in Fig. 9. As can be seen from the graph, inventory levels have decreased as the adjustment time of the inventory of
Table 2  Distributor inventory when shipping delays

| Time | 0   | 20  | 40  | 60  | 80  | 100 | 120 |
|------|-----|-----|-----|-----|-----|-----|-----|
| Distributors’ Inventory: 1 week | 2000 | 8181 | 4897 | 8063 | 8307 | 6693 | 11351 |
| Distributors’ Inventory: 3 weeks | 2000 | 5759 | 5001 | 4626 | 6526 | 15441 | 7195 |
| Distributors’ Inventory: 5 weeks | 2000 | 20026 | 9504 | 12548 | 18846 | 15062 | 7418 |

Table 3  Retailer inventory when shipping delays

| Time | 0   | 20  | 40  | 60  | 80  | 100 | 120 |
|------|-----|-----|-----|-----|-----|-----|-----|
| Retailers’ Inventory: 1 week | 1000 | 7515 | 9054 | 6622 | 9754 | 7411 | 8820 |
| Retailers’ Inventory: 3 weeks | 1000 | 6693 | 7691 | 5677 | 8744 | 7553 | 9323 |
| Retailers’ Inventory: 5 weeks | 1000 | 5972 | 7154 | 4991 | 8999 | 9573 | 9513 |

Table 4  Distributor inventory when shipping delays

| Time | 0   | 20  | 40  | 60  | 80  | 100 | 120 |
|------|-----|-----|-----|-----|-----|-----|-----|
| Distributors’ Inventory: 2 weeks | 2000 | 18390 | 10880 | 1988 | 2048 | 20278 | 5948 |
| Distributors’ Inventory: 3 weeks | 2000 | 5759 | 5001 | 4626 | 6526 | 15441 | 7195 |
| Distributors’ Inventory: 4 weeks | 2000 | 7988 | 6686 | 6598 | 10001 | 14117 | 8627 |

companies at each node extended. Distributors and retailers saw a reduction in the magnitude as well as the frequency of inventory curve fluctuations.

It could be seen from table 4 and table 5 that when the inventory adjustment time is 2 weeks, the inventory of distributors and retailers was significantly higher than that when the inventory adjustment time was 5 weeks. This means that the extension of inventory adjustment time for companies can effectively reduce inventory management and operating costs, and the work pressure on warehouse managers can be reduced. And it makes the supply and demand of inventory in the supply chain more balanced, which plays a certain weakening effect on the bullwhip effect and can also reduce the economic loss caused by excessive inventory backlog.

However, the change of inventory adjustment time should be combined with the actual operation of the product supply chain. Because the sulfur product is a time-sensitive product, if the inventory adjustment time is extended too long, it will be very easy to lead to product quality problems and unable to meet the end customer’s demand.
4 Problems and suggestions for optimization

4.1 Problems

In this paper, we established a sulfur inventory management model based on SD theory in the context of a sulfur plant sulfur product supply chain and simulated it for the actual

![Graph of inventory adjustment time](image)

(a) Impact of inventory adjustment time on distributor inventory

![Graph of inventory adjustment time](image)

(b) The effect of inventory adjustment time on retailer inventory

Fig. 9 Change in inventory adjustment time
situation. Through in-depth analysis of the simulation results, it was concluded that the current bullwhip effect in the supply chain of sulfur products of this sulfur plant is caused by the lack of effective information exchange among the nodal enterprises in the chain, and the fact that real market demand information can not be accurately transmitted in the chain. At the same time, the managers of upstream enterprises only focus on their own corporate interests and management optimization, ignoring the overall benefits of the supply chain, so their management decisions lack scientificity and validity. The emergence of the bullwhip effect had brought higher cost investment and economic loss to each node enterprise while harming their own interests, which had a negative impact on the overall operational efficiency of the sulfur product supply chain.

### 4.2 Optimization suggestions

By analyzing the simulation results, this paper put forward the following suggestions to reduce the bullwhip effect in the supply chain of this sulfur product and improve the operational efficiency of the entire product supply chain.

1. As a frequent problem in the supply chain operation, the research results and solutions of the bullwhip effect have been well established. The current problems such as poor information exchange can be solved by building an information sharing platform. By uploading demand information, their own inventory information and production information to the platform, nodal companies can make orders and distribution based on specific information, mitigating the negative impact of the bullwhip effect.

2. Each node enterprise in the supply chain can be managed by using joint inventory management methods such as vendor-managed inventory and jointly-managed inventory. For the sulfur product supply chain in this case, vendor-managed inventory can be applied for management optimization. That is, upstream suppliers participate in the co-management of supply chain inventory, directly utilizing information such as downstream demand forecasts as a reference.

3. When decision makers make decisions, it is important to recognize that nodal companies, due to their unique characteristics, will inevitably experience demand amplification for securing their own inventories. Therefore, the relationship between demand and order quantity should be taken into account when making decisions, and the ordering strategy should be adjusted in a timely manner. At the same time, we can use relevant software to visualize the information, grasp the market demand more accurately through professional data analysis, and enhance the effectiveness of demand forecasting.
From the simulation results, it can be seen that the delay in transportation time and the change in inventory adjustment time had an impact on the inventory level of each node company in the supply chain. Therefore, the efficiency of product transportation can be improved by setting up transit warehouses to shorten transportation time or outsourcing product transportation services. Appropriate extension of inventory adjustment time can effectively reduce the costs associated with inventory maintenance, abate the impact of the bullwhip effect, and enhance the economic efficiency of the entire supply chain.

5 Conclusion

In this paper, we analyzed the adverse effects of the presence of the bullwhip effect on the product supply chain by establishing an SD model. Taking a sulfur plant sulfur product supply chain as an example, it was found that the bullwhip effect makes the supply of upstream manufacturers much larger than the demand of end customers, and the curve fluctuations in the simulation results confirm the current mismatch between supply and demand of the entire sulfuric acid industry in China. Through the analysis of the simulation results of the model, it was believed that the information sharing platform can be built to realize the visual management of information and scientific decision making of each enterprise based on the information data. The joint inventory management approach is adopted to achieve efficient cooperation among nodal enterprises in the supply chain, which improves the overall operational efficiency of the product supply chain and enhances the market competitiveness of each enterprise. This improved the economic efficiency of the entire product supply chain. Transportation time can also be shortened through the introduction of third-party logistics, and inventory adjustment time can be extended appropriately to save inventory maintenance costs.

This paper mainly studies the inventory control strategy problem in the distributor-retailer two-level inventory system, but the chemical supply chain network structure in real life is more complex, generally involving multiple suppliers, distributors and retailers. Therefore, it is worthy of further research to study the inventory control strategy of chemical product’s supply chain including multi-agent and multi-channel.

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