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INVENTORY MANAGEMENT MODELS IN CLUSTER SUPPLY CHAINS BASED ON SYSTEM DYNAMICS

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Abstract. This study introduces the methods of supply chain inventory management into the cluster supply chains and proposes the implementation of supply chain inventory management strategies under this circumstance. First, we analyze the system behavior patterns of the co-operation planning, forecasting and replenishment (CPFR), vendor-managed inventory (VMI), and jointly managed inventory (JMI) models of cluster supply chains. Therefore, we establish the inventory management models of CPFR, VMI and JMI in cluster supply chains. These models are simulated by VENSIM software. The simulation results show that compared with those in the VMI and JMI models, the inventory fluctuations of manufacturers, wholesalers and retailers in the CPFR model correspond; the total inventory is reduced while its stability is greatly improved. Therefore, the application of CPFR in cluster supply chains can effectively restrain the bullwhip effect, reduce the inventory and improve the efficiency of the entire supply chain.

Mathematics Subject Classification. 90B05.

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1. Introduction

Cluster supply chain is a new form of enterprise network organization that combines the industrial cluster with the supply chain. It integrates small and medium-sized enterprises in the cluster using the theory of supply chain management and improves the overall efficiency of the cluster supply chain and the rapid response ability of the market through the division of labor and synergy between enterprises. It also promotes the competitiveness of the industrial cluster. Competition and cooperation relationships exist in all the supply chains in a cluster. Aside from horizontal cooperation between enterprises in different chains vertical cooperation within enterprises in the same chain exists as well. The industrial cluster provides a natural platform for cross-chain coordination for these enterprises. However, the low development level and the lack of reasonable planning and scientific management of organizations underlie the limited agglomeration advantages of many industrial clusters. Moreover, highlevel inventory and the bullwhip effect have been restricting cluster supply chain development. The bullwhip effect, which is the amplification of demand variability from a downstream site to an upstream site, is considered one of the forces that paralyze supply chains [19]. It has many harmful consequences, such as high-level inventory, extra

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capital investment, or stock out. Therefore, this paper aims to find a useful and efficient inventory management method to suppress the bullwhip effect, coordinate inventory, and improve cluster supply chain efficiency.

2. Literature review

2.1. Cluster supply chain

Currently, research on cluster supply chain mainly focuses on its optimization. Through the use of the augmented Lagrangian coordinate method, Qu *et al.* [27] set up a common optimized model of distributed cluster's supply chain, and depending on different circumstances, they make sensitivity analysis on the optimal supply chain structure and provide relative method in seeking optimal cooperation of cluster supply chain to meet the demand of cluster enterprises' independent decision-making. In the coordinate game condition, Zhou *et al.* [36] apply different game theories (symmetrical coordinate game theory, non-cooperative game theory and evolutionary game theory) separately to make game analysis on the coordination among several parts of cluster supply chain, set different parameters and compared these three game theories in order to get more realistic consequences and provide effective forecasting and Pareto optimization method for cluster supply chain's development. Meanwhile, some scholars focus on the application status of cluster supply chain in a specific industry to promote cooperation among enterprises in industry clusters. After the empirical test of supply chain of petroleum and gas industry, Yusuf *et al.* [34] find that supply chain formed by clusters has stronger response ability, but it may not be able to enhance the industry's competitiveness in using cluster supply chain. By investigating the local characteristics of the food supply chain and distribution system and using a series of methods like establishing cluster production, Bosona and Gebresenbet [6] apply GIS system to analyze the location of large-scale producers and food distribution center, and determine the best product collection centers to improve logistic efficiency, reduce impact to environment, increase potential of local food market and improve the consumer's tracing ability of food origins. After combining logistic performance and industrial agglomeration theory together, Vadali and Chandra [32] formulate a direct measure system that can be used to evaluate a directness metric of immediate buyer and supplier markets (transactional and/or proximate neighbors) and transport-economic logistical linkages between firms that are part of manufacturing value chain cluster, then they apply it to Alabama automobile manufacturing industry's cluster supply chain in USA. Purwaningrum *et al.* [26] explore the various linkages of knowledge flow in the Jababeka Industrial Cluster, Indonesia, in order to develop a strong knowledge based cluster which could enhance company performance. Zeng and Xiao [35] develop a new entropy approach to study the vulnerability of cluster supply chain network and to analyze and predict the dynamic performance of the vulnerability during the process of failure spreading. Ng and Lam [24] find that clusters are formed based on the supply-demand interactions with the processing facilities and their specific functions. This clustering of industrial facilities is expected to bring better group interaction and possibly induce the application of industrial symbiotic practices among facilities in the cluster.

2.2. Solutions to the bullwhip effect

Many studies have focused on the bullwhip effect and inventory management. On the basis of a two-echelon serial supply chain, Agrawal *et al.* [1] analyzed the influences of information sharing and lead time on bullwhip effect and inventory. Results show that bullwhip effect is not completely eliminated, but it can be decreased through information sharing or lead time reduction. Chatfield *et al.* [11] find that lead-time variability exacerbates variance amplification in a supply chain, and that sharing and quality of information are highly significant by simulation. Barlas *et al.* [4] suppose that information sharing can weaken bullwhip effect and eliminate undesirable fluctuations. Based on a two-stage supply chain, Kelepouris *et al.* [18] studied how demand information sharing can help to reduce order oscillations and inventory levels in the upper nodes of a supply chain. Considering a serially linked two-level supply chain, Trapero *et al.* [30] find that information sharing substantially improves forecast accuracy. Ciancimino *et al.* [12] propose a new model and find that a synchronized supply chain responds to violent changes by resolving the bullwhip effect and by creating stability in inventories. Using system dynamics (SD) simulation, Cannella *et al.* [9] examine a multi-tier collaborative supply chain and prove how an IT-based supply chain eliminates the demand amplification phenomenon and inventory oscillation by sharing real-time point-of-sale information, sales forecasts, inventory order policies, and inventory reports.

Additionally, some studies focus on the replenishment rule to curb and harness the bullwhip effect. Cannella *et al.* [8] assess the effect of collaboration and smoothing the replenishment rule on supply chain operational performance and customer service level in three supply chains: traditional, information exchange, and synchronized. Cannella *et al.* [7] present a new replenishment strategy in a multi-echelon supply chain, and they show that smoothing the replenishment rule is effective and depends on the level of information sharing. According to Dominguez *et al.* [13], collaboration or smoothing the replenishment rule can considerably reduce the bullwhip effect in divergent supply chain networks. Cannella *et al.* [10] propose a coordinated, decentralized simulation model of linear supply chain to avoid the bullwhip effect.

2.3. System dynamics

A number of optimal and simulation approaches emulate reality to solve complicated problems and draw conclusions. Discrete event simulation imitates system operation as a discrete sequence of events in time. It considers not only the event itself but also the uncertainties associated with it. However, the supply chain is neither completely continuous nor a fully discrete system. Conversely, the bullwhip effect is mostly modeled using SD and not discrete event simulation [29]. Therefore, discrete event simulation has some flaws. The idea of modeling based on control theory is mainly based on control subject theory, and the relationship between input and output of the supply chain system is described by a series of differences or differential equations. The advantage of this method is that it has a simple and rigorous expression and a good dynamic performance, but it often requires a large number of linear assumptions that are not realistic in the actual supply and demand chain [33]. The complexity of interactions between various enterprises in the supply chain system is due to many non-linear relationships that change over time, and such complexity is aggravated by the uncertainty and dynamics of the market. Therefore, conventional methods cannot produce an acceptable description and conduct productive investigations on the problems. Agent-based simulation and SD are the two main nonlinear modeling techniques. Agent-based simulation considers models of complex systems and that simple and complex phenomena can be the result of interactions between autonomous and independent entities, which operate within communities in accordance with the different modes of interaction [3]. SD is an approach to understanding the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, and time delays [14]. The two simulations have several differences. Agent-based simulation focuses on the simulation of a discrete event based on individual agents in the microscopic view, whereas SD is suitable for the simulation of a feedback loop based on a system under a macroscopic angle [5, 22, 28]. Compared with agent-based simulation, SD can reflect the causal loop supply chain among various elements. Moreover, it can show the flow process of information, logistics, or cash within the system, thus focusing on the continuity of the supply chain system. Therefore, we choose SD for this work. System dynamics is the most ideal one among all of the available research methods for studying the complex and multivariate nonlinear changes in systems over time (Mendoza and Prabhu [21]). As an effective method of investigating complicated systems and problems, system dynamics has been used in many aspects. Haghshenas *et al.* [17] use system dynamics model based on pertinent data of world cities to analyze impacts of various transportation policies. Ahmad *et al.* [2] try to analyze a policy in promoting solar PV (photovoltaic) investments in Malaysia by using a dynamic systems approach. Ha *et al.* [16] concentrate on the process simulation of ships and offshore structures and develop a multibody system dynamics simulator in order to get a better simulation process. Nazareth and Choi [23] focus on the area of managing security for information assets, they build a system dynamics model to provide managers guidance for security decisions. Tsolakis and Anthopoulos [31] attempt to assess the sustainability of the eco-city with the System Dynamics simulation-based technique, and believe that the model can assist decision-makers, local governments and managers to design and adopt effective policies. System dynamics can also be used to solve some problems of the supply chain. To explore dynamics of remanufacturing process and improve strategies of evaluating system, Poles [25] uses system dynamics simulation method to establish a production and inventory system of remanufacturing. Lehr *et al.* [20] use system dynamics to analyze the dynamic behavior of closed-loop supply chains comprehensively and identifies leverage points for the improvement of decisions concerning reverse logistics. Golroudbary and Zahraee [15] use system dynamics simulation of Closed-loop Supply Chain (CLSC) to evaluate the system behavior of an electrical manufacturing company.

We know that CPFR, VMI and JMI can reduce the bullwhip effect and make the supply chain coordination by sharing information. Therefore, in order to improve the development level and efficiency of cluster supply chain, we use system dynamics to design the inventory management models of co-operation planning, forecasting, and replenishment (CPFR), vendor managed inventory (VMI), and jointly managed inventory (JMI) for cluster supply chains. The results are simulated thereafter.

3. Model

3.1. Model hypotheses

For the system dynamics model established in this study, we posit the following:

(1) the system is composed of two single chains namely, SC1 and SC2, each of which has one manufacturer, one wholesaler and one retailer;
(2) the two chains are located in the same specialized town. Their products are of the same type and can be substituted completely;
(3) the retailers of the two supply chains predict jointly;
(4) the manufacturers' production capacity is unlimited and one entire supply chain produces only one kind of product;
(5) the conversion ratio of raw material and finished goods is 1:1 regardless of the capacity limit of logistics warehousing and the constraints of transport capacity of each node enterprise in the supply chain;
(6) production and transport delays exist, and the delay time is a fixed value;
(7) the expected inventory cover time and adjustment time are fixed.

3.2. CPFR model

CPFR is a type of collaborative supply chain management technology that uses a series of processing and technology models to provide a cooperation process of the entire supply chain. It improves the partnership between retailers and suppliers through the joint management of the business process and information sharing. It can improve the accuracy of forecasting, reduce the inventories of the suppliers and increase their supply at the same time. The implementation of CPFR means that the information of inventory, prediction and sales will be shared among the entire supply chain nodes. Moreover, information sharing will have no time delay. Its information flow and logistics are shown in Figure 1. The manufacturers, wholesalers and retailers use unified sales forecast data to develop unified plans and replenishment.

The system flowchart of the CPFR model is shown in Figure 2. It includes six sub-modules, namely, Manufacturer 1 (M1), Wholesaler 1 (W1), Retailer1 (R1) and Manufacturer 2 (M2), Wholesaler 2 (W2), and Retailer 2 (R2). Retailers 1 and 2 predict jointly based on the demands of Customers 1 (C1) and 2 (C2), and the joint prediction is a smooth function of the average of their demand rate. Joint prediction determines the demand forecasting of all level enterprises, and the demand forecasting determines the expected inventory and the expected in-transit inventory of all level enterprises. The enterprises first adjust the demand forecasting according to the difference between the expected inventory and the inventory onhand. Thereafter, they decide the productivity rate or order rate according to the difference between the expected in-transit inventory and the in-transit inventory.

3.3. VMI model

VMI is a type of inventory operation mode under the supply chain environment. It is a new type of management mode in which the upstream enterprises (*e.g.*, manufacturers and wholesalers) control the circulated

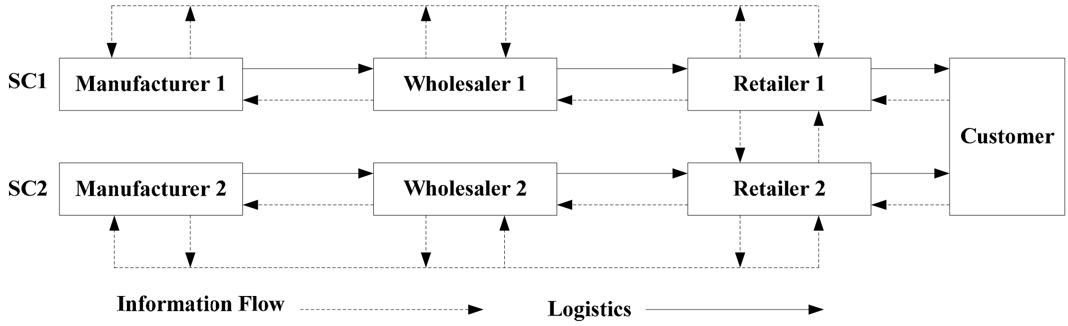

FIGURE 1. Information flow and logistics of the CPFR model.

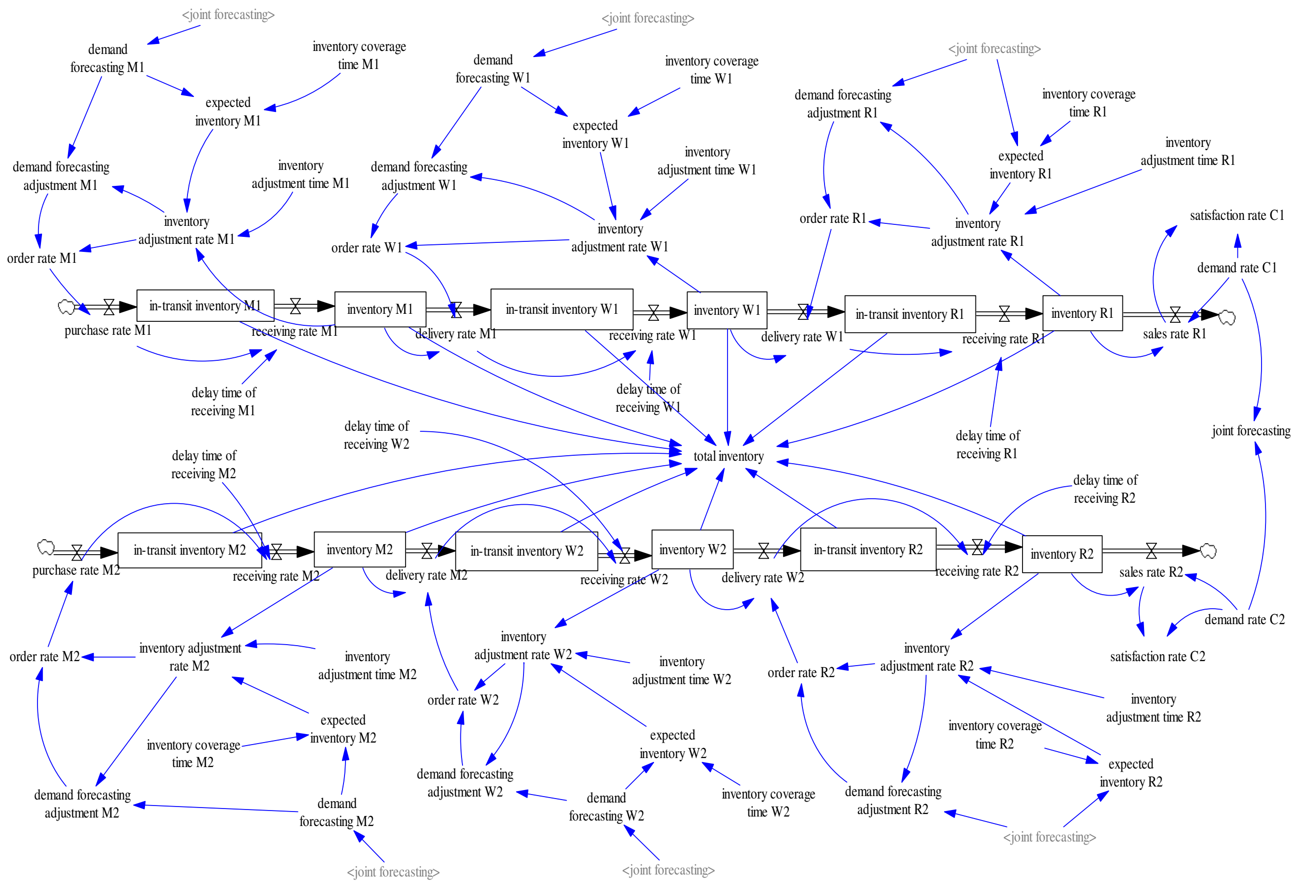

FIGURE 2. System flowchart of the CPFR model in a cluster supply chain.

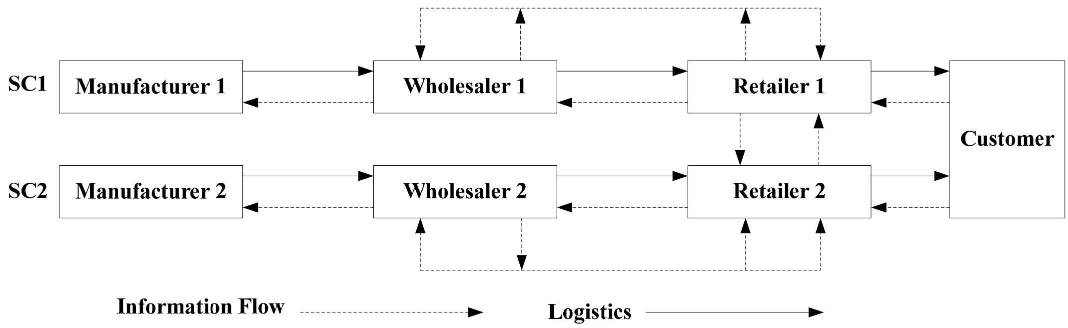

FIGURE 3. Information flow and logistics of the VMI model.

inventory of the downstream enterprises (*e.g.*, distributors and retailers) uniformly. It stresses only the information sharing between the retailers and the retailers' superior suppliers and does not involve the suppliers' upstream. Therefore it is actually a local cooperation mode. Retailers and wholesalers share information mutually (Fig. 3). First, the retailers predict the sales condition and deliver the information of sales forecasting and inventory to the wholesalers. Afterwards the wholesalers arrange a unified production and replenishment strategy.

The system flowchart of the VMI model is shown in Figure 4. It contains six sub-modules, namely, Manufacturer 1, Wholesaler 1, Retailer 1 and Manufacturer 2, Wholesaler 2, Retailer 2. Retailers 1 and 2 predict jointly based on the demand of Customers 1 and 2, and the joint forecasting is a smooth function of the average of their demand rate. The joint forecasting only decides the demand prediction of retailers and wholesalers, and the demand prediction of manufacturers is determined by the order rate of the wholesalers.

3.4. JMI model

JMI is an inventory management model developed based on VMI, in which the upstream and downstream enterprises have balanced rights and responsibilities and share risks. It improves the supply chain synchronization by building joint and coordinate mechanisms to solve the phenomena of demand amplification and inventory increase due to the independent inventory operation of the enterprises in the supply chain. The wholesalers comprise the core enterprise and the upstream manufacturers and downstream retailers establish the joint inventory; all enterprises develop a stock plan together and share risks (Fig. 5).

The system flowchart of the JMI model consists of four sub-modules, namely, the joint module of manufacturers, module of Wholesalers 1 and 2 and the joint module of retailers (Fig. 6). The enterprise demand forecasting is a smooth function of the downstream demand rate. The demand forecasting of retailers, wholesalers and manufacturers is decided by the customer demand, retailer order and wholesaler order rates, respectively. To conduct a comparative analysis on CPFR and VMI, the variables and inventory of Manufacturer 1 and Retailer 1 are added to the JMI model to reflect the average inventory of the manufacturer and the retailer in a single chain.

4. Model simulation and result analysis

4.1. Model parameter settings

Taking the CPFR model of SC1 as an example, we establish the DYNAMO equation of system dynamics. There are three modules as follows, retailer 1 module, manufacturer 1 module and wholesaler 1 module.

4.1.1. The DYNAMO equation of retailer 1 module

For the retailer 1 in SC1, the equation relates to the order rate, inventory and sales rate. When the inventory of the retailer is equal to or greater than the expected inventory, its order rate is 0; when the expected inventory

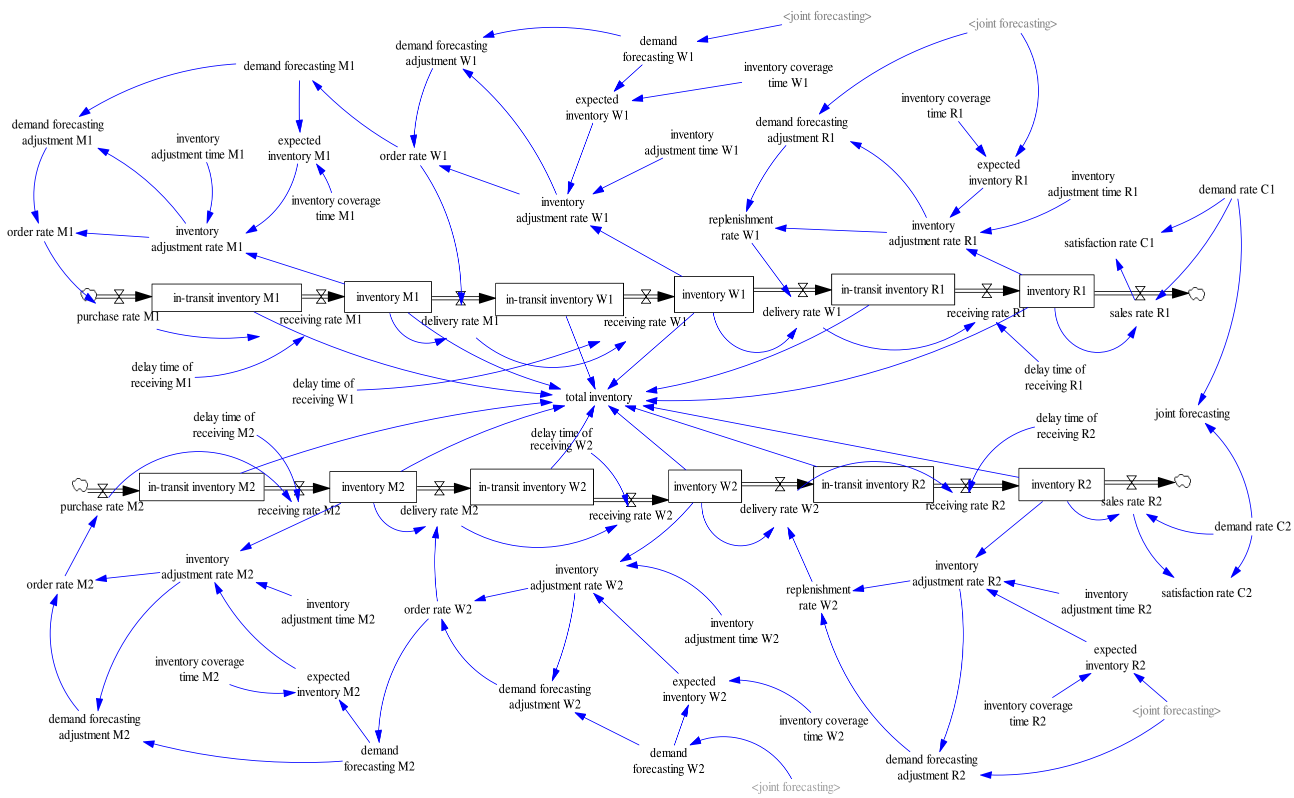

FIGURE 4. System flowchart of VMI model in a cluster supply chain.

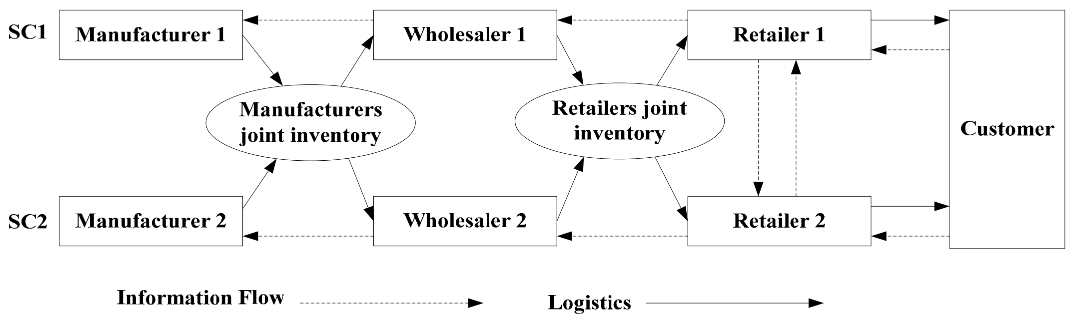

FIGURE 5. Information flow and logistics of JMI.

of the retailer is equal to or greater than the inventory in the corresponding moment, the order rate is its prediction plus inventory adjustment rate. The joint forecasting is obtained from the SMOOTH function of the average demand of Customers 1 and 2. The inventory adjustment rate is the difference between the expected inventory and the inventory divided by the inventory adjustment time. The expected inventory is the product of the retailer's forecasting and the inventory coverage time.

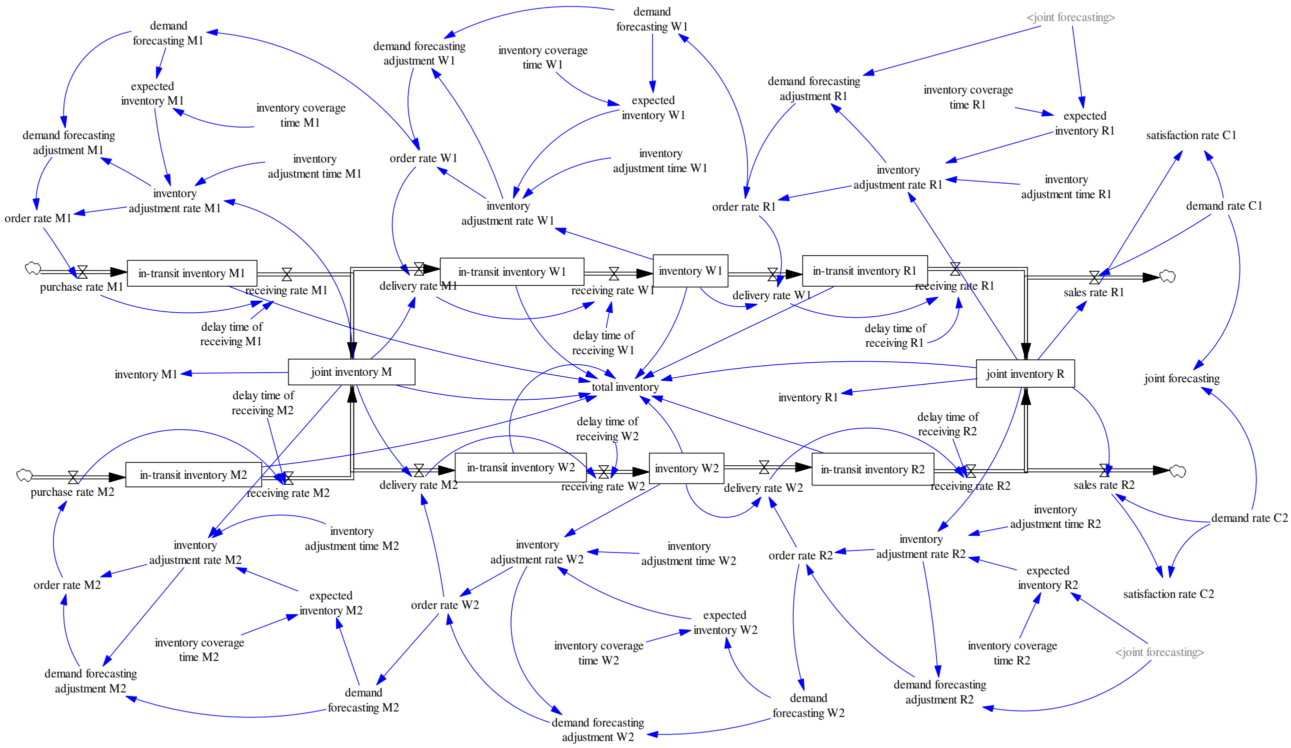

FIGURE 6. System flowchart of the JMI model in a cluster supply chain.

For simplicity of expression, we define the variables as follows:

(1) the order rate of Retailer 1 = OR_{R1};
(2) the inventory adjustment rate of Retailer 1 = IAR_{R1};
(3) the demand forecasting adjustment of Retailer 1 = DFA_{R1};
(4) the expected inventory of Retailer 1 = EI_{R1};
(5) the inventory of Retailer 1 = I_{R1};
(6) the inventory adjustment time of Retailer 1 = IAT_{R1};
(7) the joint forecasting = JF;
(8) the sales rate of Retailer 1 = SR_{R1};
(9) the delivery rate of Retailer 1 = DR_{C1};
(10) the demand rate of Customer 1 = dr_{C1};
(11) the delay time of receiving of Retailer 1 = DTR_{R1};
(12) the receiving rate of Retailer 1 = RR_{R1};
(13) the in-transit inventory of Retailer 1 = ITI_{R1};
(14) the satisfaction rate of Customer 1 = sr_{C1};
(15) the demand rate of Customer 1 = dr_{C1};
(16) the sales volume of Retailer 1 = SV_{R1}.

Therefore, the DYNAMO equation of Retailer 1's order rate can be expressed as follows:

$$OR_{R1} = INTEGER(IF\ THEN\ ELSE\ (IAR_{R1} > 0, DFA_{R1}, 0)),$$

where IAR_{R1}, EI_{R1}, and DFA_{R1} are as follows:

$$IAR_{R1} = IF\ THEN\ ELSE(I_{R1} \geq EI_{R1}, 0, (EI_{R1} - I_{R1})/IAT_{R1});$$
$$EI_{R1} = JF \times IAR_{R1};$$
$$JF = SMOOTH((dr_{C2} + dr_{C1})/2, 2).$$

To guarantee the rationality of sales, the sales rate of Retailer 1 is the minimum of the inventory of Retailer 1 and the demand rate of Customer1 in this model. Therefore, the DYNAMO equation of Retailer 1's sales rate is

$$SR_{R1} = MIN(dr_{C1}, I_{R1}).$$

The receiving rate of Retailer 1 is the delivery rate of its upstream enterprise (*i.e.*, Wholesaler 1). If the inventory of Wholesaler 1 can meet the order rate of Retailer 1, the delivery rate of the former is equal to the order rate of the latter; otherwise, the delivery rate of the former is equal to its inventory. The receiving rate of Retailer 1 is obtained by the delay function (DELAY) of Wholesaler 1, and the delay time is the receiving delay time of Retailer 1. Therefore, the DYNAMO equation of Wholesaler 1's delivery rate is

$$DR_{W1} = MIN(OR_{R1}, I_{W1}).$$

The DYNAMO equation of retailer 1's receiving rate is

$$RR_{R1} = DELAY\ FIXED(DR_{W1}, DTR_{R1}, 100).$$

The DYNAMO equation of retailer 1's inventory is

$$I_{R1} = I_{R1}.J + DT \times (RR_{R1}.JK - SR_{R1}.JK).$$

If the inventory of Retailer 1 can meet the demand of Customer 1, the satisfaction rate of Customer 1 is 1; otherwise, it is equal to the inventory of Retailer 1 divided by the demand of Customer 1. According to this position, the DYNAMO equation of the satisfaction rate of Customer 1 can be expressed as follows:

$$sr_{C1} = IF\ THEN\ ELSE(dr_{C1} > SR_{R1}, I_{R1}/dr_{C1}, 1);$$
$$ITI_{R1} = INTEGER(DR_{W1} - RR_{R1}, 100).$$

4.1.2. The DYNAMO equation of Manufacturer 1 module

We define the variables as follows:

(1) the purchase rate of Manufacturer 1 = PR_{M1};
(2) the order rate of Manufacturer 1 = OR_{M1};
(3) the inventory adjustment rate of Manufacturer 1 = IAR_{M1};
(4) the demand forecasting adjustment of Manufacturer 1 = DFA_{M1};
(5) the delivery rate of Manufacturer 1 = DR_{M1};
(6) the order rate of Wholesaler 1 = OR_{W1};
(7) the inventory of Manufacturer 1 = I_{M1};
(8) the receiving rate of Manufacturer 1 = RR_{M1};
(9) the expected inventory of Manufacturer 1 = EI_{M1};
(10) the inventory adjustment time of Manufacturer 1 = IAT_{M1};
(11) the inventory coverage time of Manufacturer 1 = ICT_{M1};
(12) the demand forecasting of Manufacturer 1 = DF_{M1};
(13) the joint forecasting of Manufacturer 1 = JF;
(14) the delay time of receiving of Manufacturer 1 = DTR_{M1};
(15) the in-transit inventory of Manufacturer 1 = ITI_{M1}.

Therefore, the DYNAMO equation of Manufacturer 1 can simply be expressed as follows:

(1) $PR_{M1} = OR_{M1}$;
(2) OR_{M1} = INTEGER (IF THEN ELSE ($IAR_{M1} > 0$, DFA_{M1}, 0));
(3) DR_{M1} = MIN (OR_{M1}, I_{M1});
(4) I_{M1} = INTEG ($DR_{M1} - DR_{M1}$, 300);
(5) IAR_{M1} = IF THEN ELSE ($I_{M1} >= EI_{M1}$, 0, $(EI_{M1} - I_{M1})\ IAT_{M1}$);
(6) $EI_{M1} = ICT_{M1} \times DF_{M1}$;
(7) $DF_{M1} = JF_{M1}$;
(8) $DFA_{M1} = IAR_{M1} + DF_{M1}$;
(9) DR_{M1} = DELAY FIXED ($PR_{M1}\ DTR_{M1}$, 100);
(10) ITI_{M1} = INTEG ($PR_{M1}\ RR_{M1}$, 300).

4.1.3. The DYNAMO equation of Wholesaler 1 module

We define the variables as follows:

(1) the order rate of Wholesaler 1 = OR_{W1};
(2) the inventory adjustment rate of Wholesaler 1 = IAR_{W1};
(3) the demand forecasting adjustment of Wholesaler 1 = DFA_{W1};
(4) the delivery rate of Wholesaler 1 = DR_{W1};
(5) the order rate of Retailer 1 = OR_{R1};
(6) the inventory of Wholesaler 1 = I_{W1};
(7) the receiving rate of Wholesaler 1 = RR_{W1};
(8) the expected inventory of Wholesaler 1 = EI_{W1};
(9) the inventory adjustment time of Wholesaler 1 = IAT_{W1};
(10) the inventory coverage time of Wholesaler 1 = ICT_{W1};
(11) the demand forecasting of Wholesaler 1 = DF_{W1};
(12) the joint forecasting of Wholesaler 1 = JF;
(13) the delay time of receiving of Wholesaler 1 = DTR_{W1};
(14) the in-transit inventory of Wholesaler 1 = ITI_{W1}.

Therefore, the DYNAMO equation of Wholesaler 1 can simply be expressed as follows:

(1) OR_{W1} = INTEGER (IF THEN ELSE ($IAR_{W1} > 0$, DFA_{W1}, 0));
(2) DR_{W1} = MIN (OR_{W1}, I_{W1});
(3) I_{W1} = INTEG ($DR_{W1} - DR_{W1}$, 200);
(4) IAR_{W1} = IF THEN ELSE ($I_{W1} >= EI_{W1}$, 0, $(EI_{W1} - I_{W1})\ IAT_{W1}$);
(5) $EI_{W1} = ICT_{W1} \times DF_{W1}$;
(6) $DF_{W1} = JF_{W1}$;
(7) $DFA_{W1} = IAR_{W1} + DF_{W1}$;
(8) DR_{W1} = DELAY FIXED ($DR_{M1}\ DTR_{W1}$, 100);
(9) ITI_{W1} = INTEG ($DR_{M1} - RR_{W1}$, 200).

The DYNAMO equations of all the modules of the VMI and JMI models can be expressed accordingly.

Guzhen town in Zhongshan City is the largest lighting production base and wholesale market in China. To ensure the authenticity of the data and model, the simulation data are derived from a survey on the Guzhen lighting cluster supply chain in Zhongshan. By combining an actual situation with a model structure and lighting industry data, the initial values of the model for all state variables and constants are obtained, and they are as follows: the smooth cycle of forecasting is 4 weeks; the inventory adjustment time of manufacturers, wholesalers, and retailers are 2 weeks, 1.5 weeks and 1 week respectively; their inventory cover time and delay time of receiving are 1.5 weeks and 1 week, respectively; the initial value of inventory and in-transit inventory is 200. The time limit setting of the system dynamics model is as follows: initial time = 0; final time = 100;

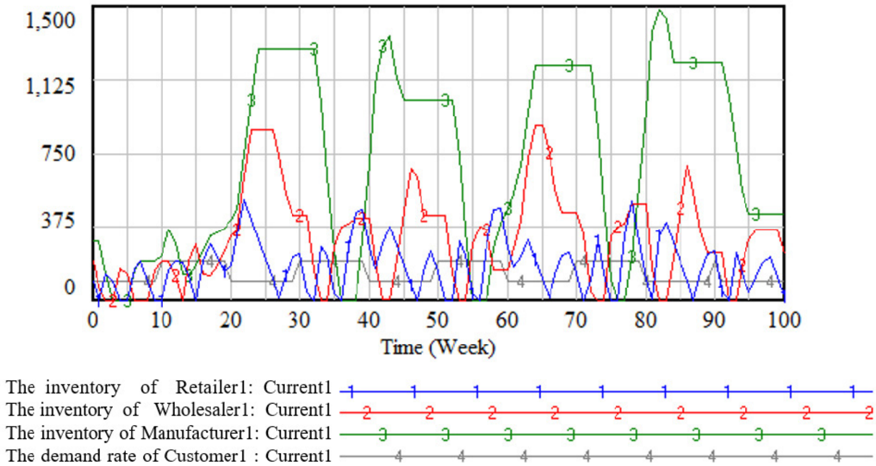

FIGURE 7. Output in CPFR model of cluster supply chain under continuous pulse demand.

time step = 1; unit for time = week. The evaluation indicators are the inventories of Manufacturers 1 and 2, Wholesalers 1 and 2, and Retailers 1 and 2, the satisfaction rate of Customers 1 and 2, and the total inventory.

4.2. Model testing

4.2.1. Behavioral reproduction test

When factors affecting the model behavior and interference are changed, the purpose of behavioral reproduction test is to assess whether or not the model is able to reproduce behavior pattern that is consistent with the actual situation. The test also examines whether or not the changes in relevant variables based on experience and related data in the analysis model are consistent with the actual situation in the test time.

In this paper, the CPFR model is used to conduct a behavior reproduction test. When the customer demand function occurs, the continuous pulse changes. We observe changes in inventories of manufacturers, wholesalers, and retailers. We assumed that the demand rate of Customers 1 and 2 is $100 + 100 \times$ Pulse train (10, 10, 20, and 90). Thus, the initial rate of customer demand is 100, and the continuous pulse changes begin from the 10th week; then, the rate of customer demand value increases from 100 to 200. Pulse duration is 10 weeks; pulse period is 20 weeks; and pulse changes continue for 90 weeks. The customer demand rate reverts back to 100 in the last 10 weeks.

We assume that the initial values of inventories of retailers, wholesalers, and manufacturers are 100, 200, and 300, respectively. Figure 7 shows the output of the CPFR model simulation in the cluster supply chain under continuous pulse demand. The results show that the CPFR model in a cluster supply chain can reproduce system behavior, which conforms to the actual situation.

4.2.2. Sensitivity test

Parameter sensitivity test examines the influence of some system parameters on model behavior. It also determines if the variables are sensitive and if the model is consistent with the actual situation.

Through several sensitivity tests on the CPFR model in cluster supply chains, we find that delay in receiving time of retailers, wholesalers, and manufacturers is a high-sensitivity parameter, whereas prior inventories of retailers, wholesalers, and manufacturers are low-sensitivity parameters.

We consider the delay in receiving time of retailers and assume that customer demand for the model is a normal distribution function. The random normal values are 70, 150, 110, 5, and 15 representing the minimum, the maximum, the mean, the standard deviation, and the noise seed, respectively. For the three currents,

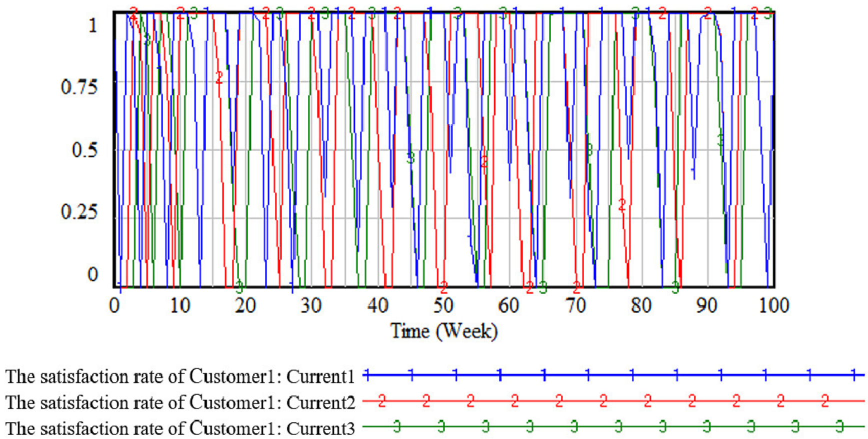

FIGURE 8. Simulation output of the satisfaction rate of customer 1 in different retailers receiving delay times.

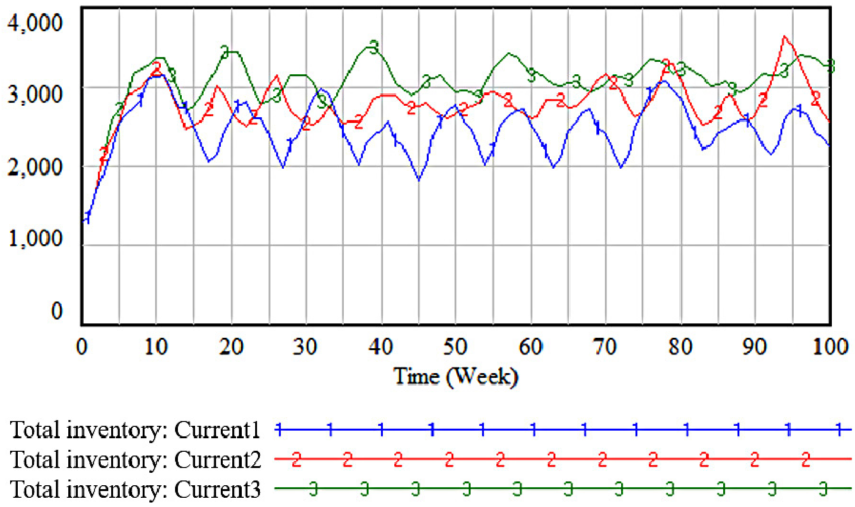

FIGURE 9. Simulation output of the total inventory in different retailers receiving delay times.

the delay times are one, two, and three weeks, respectively. Figures 8 and 9 illustrate the inventory simulation results at different retailer receipt delay times of Retailer 1 and Manufacturer 1, respectively. The results show that delay in receiving retailers is a high-sensitivity parameter and that shorter delay times of receiving retailers have a higher customer satisfaction rate and lower total inventory levels.

4.3. Simulation

In this section, we use the VENSIM software to simulate the models under study. Combined with the survey data, the customer demand rate of the two supply chains follows a uniform distribution [150, 250]. Changes in the evaluation indicators are shown in the following figures.

Figure 10–12 show that the enterprises at all levels in SC1 have irregular fluctuations influenced by the random function, whereas the manufacturer1's inventory for the CPFR model is more stable. The mean and standard deviation of the simulation data of the enterprises in SC1 in Table 1 show that the customer satisfaction

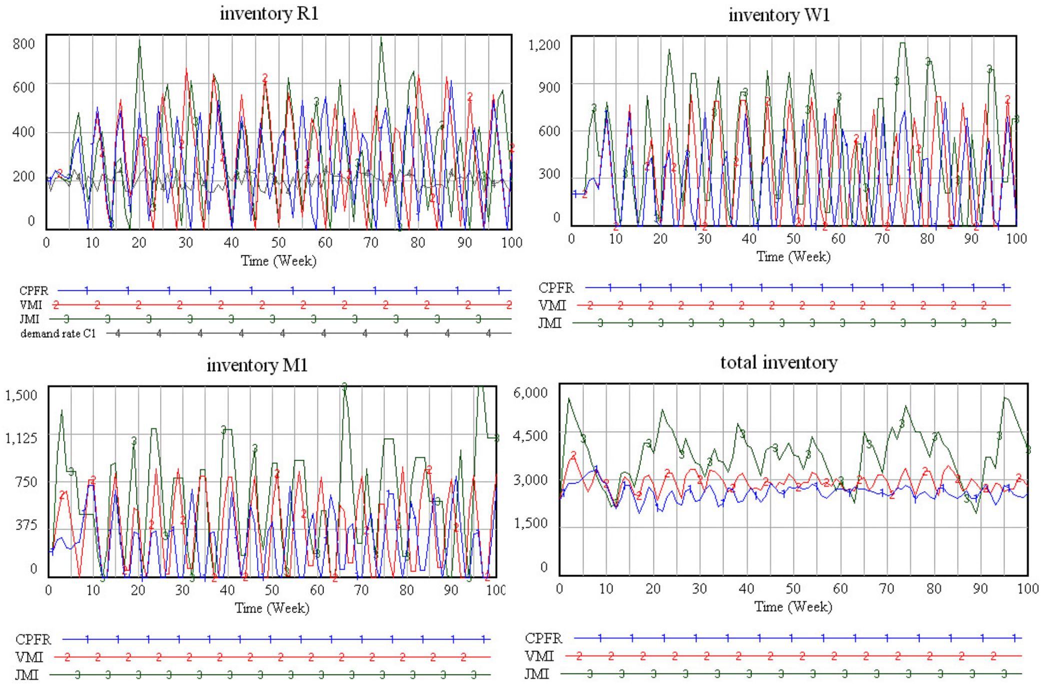

FIGURE 10. Simulation output of the inventory.

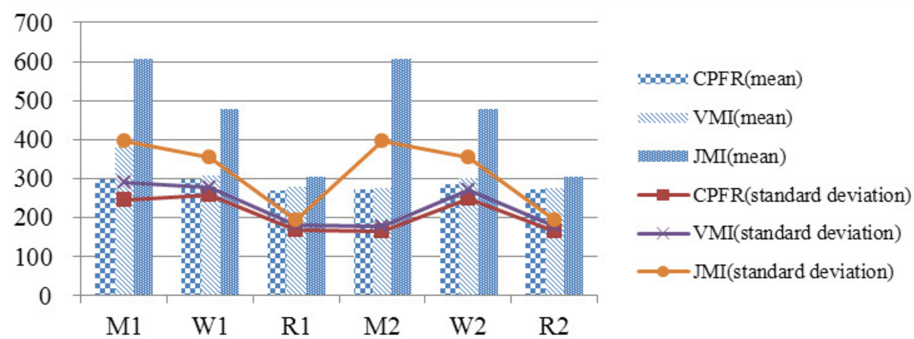

FIGURE 11. Mean and standard deviation of the enterprise inventory at various levels.

rate of the CPFR model does not deviate from those of the VMI and JMI models. This finding is due to the application of joint forecasting in the retail nodes of all three models. Therefore, a minimal difference exists in the order rate and inventory between the retailers. Moreover, the bullwhip effect is larger in the VMI and JMI models than in the CPFR model because the upstream enterprises therein do not share the inventory information. The customer satisfaction rate is higher in these models because the inventory level is sufficiently high to meet the retailers' order rate.

The mean of the total inventory and standard deviation of the CPFR model are 2657.4 and 220.096, respectively (Tab. 1), which amount to reduction rates of 7.6% and 40.4%, respectively, compared with the VMI model, and 29.3% and 65.6%, respectively, compared with the JMI model. The CPFR model has an absolute advantage in the total inventory, which is similar to the inventory of each supply chain member. This result

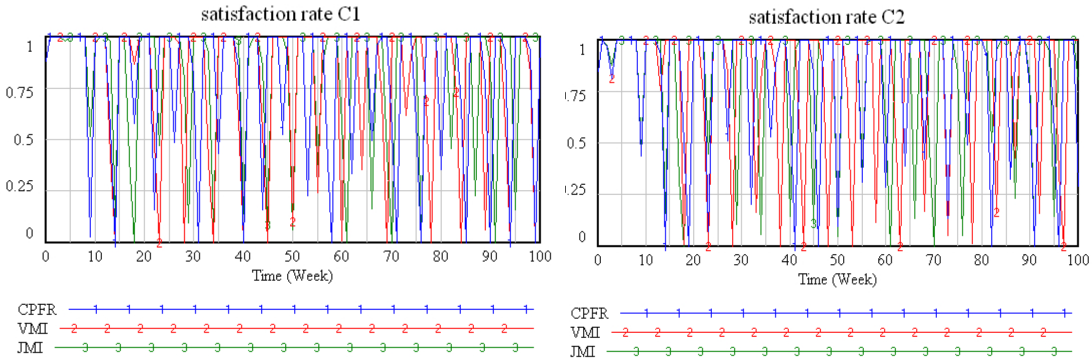

FIGURE 12. Comparison analysis diagram of the customer satisfaction rate.

TABLE 1. Comparison of the Evaluation Indicators of the Three Models.

	CPFR		VMI		JMI	
	mean	standard deviation	mean	standard deviation	mean	standard deviation
M1	298.000	246.170	383.158	289.550	607.020	395.141
W1	296.782	256.662	308.455	276.228	477.624	353.632
R1	269.819	167.890	277.945	179.773	303.165	194.844
M2	272.100	166.160	277.102	178.582	607.020	395.141
W2	283.772	248.294	301.941	271.630	477.624	353.632
R2	272.100	166.160	277.102	178.582	303.165	194.844
total inventory	2657.4	220.096	2874.58	369.005	3760.69	639.604
C1	79.5%	0.355	79.7%	0.370	81.0%	0.344
C2	81%	0.339	80.2%	0.358	81.9%	0.345

is due to all enterprises in the CPFR model sharing information with one another, enabling them to directly respond to the market to effectively restrain the bullwhip effect. By contrast, the information sharing of the VMI and JMI models is only partial, and their prediction includes not only the inventory that can meet customers' demand but also the safe stock of the downstream enterprises. In conclusion, the total inventory level and the inventory of each supply chain member in the CPFR model are the lowest in cluster supply chains.

5. CONCLUSIONS

The goal of supply chain management is to coordinate the supply chain, reduce extra cost, and operate efficiently. Inventory control has been the focus of supply chain management, and the selection of appropriate inventory management model is the key to solving inventory problems. This study uses system dynamics to establish three different inventory management models namely, CPFR, VMI and JMI for cluster supply chains. The supply chain members are the manufacturer, wholesaler and retailer. By simulating the three models using VENSIM software, we find that the CPFR model is the best among the three models.

The CPFR model can collaborate with planning, forecasting, and replenishing the three aspects closely to drive the whole chain. Although VMI and JMI are advanced inventory management methods, they have the disadvantages of inaccurate decision-making data, low supply chain integration degree, and slow response time compared with the CPFR. As a consequence, the application of the CPFR model to cluster supply chains can facilitate the timely sharing of information of inventory, sales and forecasting among all enterprises, effectively restraining the bullwhip effect and significantly reducing the inventory, which provides a new management method for the efficient operation of the supply chain. Therefore, overall operational performance will be improved. In summary, managers should consider the CPFR for decision making for increasing flexibility and ease of management. It should also be used to improve communication and cooperation at all levels of enterprises in the cluster supply chain and to strengthen the competitive advantages of industrial clusters.

The following limitations of this paper should be considered by future researchers. First, this article is based on a two-supply chain model, which can be extended to three or more in the future. Second, rational benefit distribution and risk endurance are more valuable directions in the CPFR. Finally, only the present macro situations are considered in this paper. An accurate forecast demand should be further studied.

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