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Dynamics Modeling of Bullwhip Effect in Remanufacturing Closed-loop Supply Chain Based on Third-party Recycler

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Abstract: The main work of this study is done within the bullwhip effect in remanufacturing closed-loop supply chain based on third-party recycler, uses the system dynamics and Vensim software to build a closed-loop supply chain model and analyzes the methods of reducing bullwhip effect. The closed-loop supply chain consists of supplier, manufacturer, retailer and third-party recycler, recycler is responsible for recycling products from consumer market and the products can be used for remanufacturing products and remanufacturing components. Remanufacturing products and remanufacturing components, respectively remanufactured by manufacturer and supplier. Retailer demand is satisfied by the remanufacturing products and new products and similarly, manufacturer demand is satisfied by the remanufacturing components and new components. The market demand is set to random demand and the simulation results show that the bullwhip effect in supplier is the largest, followed by the bullwhip effect in manufacturer, reverse logistics can weaken the bullwhip effect in forward logistics and the recovery rate higher, the reverse logistics weakening effect in the bullwhip effect is more obvious. Information sharing is an effective strategy to reduce the bullwhip effect. Simulation results show that the bullwhip effect under information sharing can be significantly reduced.

Key words: Closed-loop supply chain, remanufacturing, bullwhip effect, system dynamics, information sharing

INTRODUCTION

Reverse logistics management is an effective approach to conserve resources with the economic and social development, the original forward logistics and reverse logistics constitute a complete closed-loop supply chain. Remanufacturing is an important method of product recycling in closed-loop supply chain. As the need for specialized dismantling work, there are a number of third-party recyclers to participate product recovery activities in the closed-loop supply chain. This study is based on remanufacturing supply chain, uses the system dynamics and Vensim software to build a closed-loop supply chain model and analyzes the methods of reducing bullwhip effect; the market demand is set to random demand. Bullwhip effect in supply chain management is a prominent phenomenon. Bullwhip effect refers to a phenomenon that the supplier at the all levels of the supply chain makes supply decisions based on the needs of information from its lower-level neighboring vendors, demand information will generate progressively larger needs. Forrester (1961) described this phenomenon bullwhip effect for the first time; found that there was a significant bullwhip effect through the analysis of a series of case studies. Forrester believes that the main causes of the bullwhip effect resulting delay also include the time delay, demand information fluctuations and system dynamics. Sterman (1989) proposed the bullwhip effect generated mainly in the enterprise supply chain system of irrational decisions. Lee *et al*. (2000) considered the causes of the bullwhip effect are demand forecasting, supply inventory, lead time, order quantity and price volatility. Towill (1996) used the simulation analysis of the bullwhip effect; he found that the demand information along the supply chain to the upstream transmission process, demand information through the supply chain, one for each node, doubling its volatility, resulting from distributor delivered to the manufacturer's changes in demand is almost eight times the initial fluctuations. Disney and Towill (2001) compared the expected performance of a Vendor Managed Inventory (VMI) supply chain with a traditional "serially linked" supply chain. The emphasis of this investigation is the impact these two alternative structures have on the "Bullwhip Effect" generated in the supply chain. Zhang (2004) considered the impact of forecasting methods on the bullwhip effect for a simple replenishment system in which a first-order autoregressive process describes the customer demand and an order-up-to inventory policy characterizes the replenishment decision. Chatfield *et al*. (2004) used a simulation model called "SISCO" to examine the effects in supply chains of

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stochastic lead times and of information sharing and quality of that information in a periodic order-up-to level inventory system. They found that lead-time variability exacerbates variance amplification in a supply chain and that information sharing and information quality are highly significant. Agrawal *et al.* (2009) analyzed a two echelon (ware-house retailer) serial supply chain to study the impact of Information Sharing (IS) and lead time on bullwhip effect and on-hand inventory. Jaksic and Rusjan (2008) examined the influence of different replenishment policies on the occurrence of the bullwhip effect. They demonstrated that certain replenishment policies can in themselves be inducers of the bullwhip effect while others inherently lower demand variability. The main causes of increase in variability are projections of future demand expectations which result in over-exaggerated responses to changes in demand.

MODEL ASSUMPTIONS AND PARAMETER DESCRIPTION

On the basis of model of Disney and Towill (2001), this study uses the system dynamics and Vensim software to build a remanufacturing closed-loop supply chain model and analyzes the methods of reducing bullwhip effect. Remanufacturing closed-loop supply chain uses remanufacturing recycled products, such as remanufacturing components and products. Supplier produces components according to the manufacturer's purchase order arrangements; the components are parts from the production of new materials and parts from remanufacturing components. Manufacturer produces productions according to the retailer purchase order, the retailer orders are met by new products and remanufacturing products; retailer orders products according to customer needs; product recovery is done by the third party recycler. The closed-loop supply chain model is shown in Fig. 1.

The assumptions of model are as follows: (1) There is only one kind of products in the supply chain, (2) There is no difference between remanufacturing products (components) and new products (components) quality, (3) The inventory strategies of this supply chain is classic inventory strategy, (4) Returned products are not allowed, (5) Transport capacity is unlimited and (6) Product life cycle, supplier production capacity, manufacturer production capacity, production capacity of remanufacturing products and production capacity of remanufacturing components all are limited.

System dynamics model involves 3 basic variables they are state variables, rate variables and auxiliary variables. This model has 4 state variables, namely retailer inventory, recycler inventory, supplier inventory and manufacturer inventory; 7 rate variable, namely the retailer's sales rate, the manufacturer's delivery rate, the supplier's delivery rate, component productivity, retailer market sales rate, recovery products rate, recovery remanufacturing products rate and recovery remanufacturing components rate; auxiliary variable is interpreted as affecting any of the variables of the system, some of the modeling process given function can also be regarded as auxiliary variables. Model variables and parameters are shown in Table 1-4.

Table 1: State variables of supply chain model

SI	Supplier inventory
MI	Manufacturer inventory
RI	Retailer inventory
RIS	Recycler in stock

Table 2: Rate variables of supply chain model

CP	Components productivity
SDR	Supplier delivery rate
MDR	Manufacturer delivery rate
RMSR	Retailer market sales rate
RPR	Recovery products rate
RRPR	Recovery remanufacturing products rate
RRCR	Recovery remanufacturing components rate

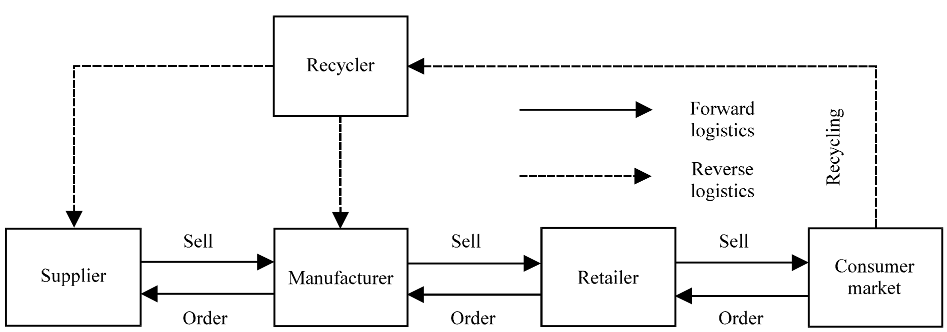

Fig. 1: Remanufacturing closed-loop supply chain based on third-party recycler

MODEL FOR REMANUFACTURING CLOSED-LOOP SUPPLY CHAIN BASED ON THIRD-PARTY RECYCLER

In the remanufacturing closed-loop supply chain based on third-party recycler, the forward part of the supply chain is a three-echelon supply chain: The retailer inventory is determined by the market rate and the manufacturer delivery rate, manufacturer inventory depends on the output rate (supplier delivery rate and products remanufacturing rate) and delivery rate, supplier inventory productivity depends on the output rate (new components productivity and components remanufacturing rate) and supplier delivery rate. Retailer order, manufacturer and supplier of product needs all based on its individual sales forecasting, inventory adjustment and inventory adjustment time.

The dynamics model construction of the closed-loop supply chain based on third-party recycler system is shown in Fig. 2.

Table 3: Auxiliary variables of supply chain model

SPO	Supplier products order
SPDR	Supplier products demand rate
SEI	Supplier expected inventory
SSF	Supplier sales forecast
MPO	Manufacturer products order
MPDR	Manufacturer products demand rate
MEI	Manufacturer expected inventory
MSF	Manufacturer sales forecast
RPO	Retailer purchase order
RSF	Retailer sales forecast
REI	Retailer expected inventory

Retailer purchase order is composed of retailer inventory adjustment volume and retailer sales forecast; the retailer inventory adjustment is based on the expectation of inventory, real-time inventory and inventory adjustment time. Retailer expected inventory and sales forecast both are related to the sustainable time of expected inventory. Retailer inventory is a state variable, the input is the manufacturer delivery rate and the output is the marketing demand rate. Retailer sales forecast is an information delay function of the retailer market rate. Equations of the retailer are as follows Eq. 1-4:

Table 4: Constants of supply chain model

PRR	Product recovery rate
SDD	Supplier delivery delay
SPD	Supplier production delay
RPIAT	Recovery products inventory adjustment time
RPRP	Recovery products remanufacturing proportion
RPRD	Recovery products remanufacturing delay
RCRP	Recovery components remanufacturing proportion
RCRD	Recovery components remanufacturing delay
ROD	Recovery of delay
IAT	Inventory adjustment time
STEI	Sustainable time of expected inventory
MAP	Moving average period
MDD	Manufacturer delivery delay
MPD	Manufacturer production delay
TD	Transportation delay
RP	Recovery products
PLC	Product life cycle
SPC	Supplier production capacity
MPC	Manufacturer production capacity
PCRP	Production capacity of remanufacturing products
PCRC	Production capacity of remanufacturing components

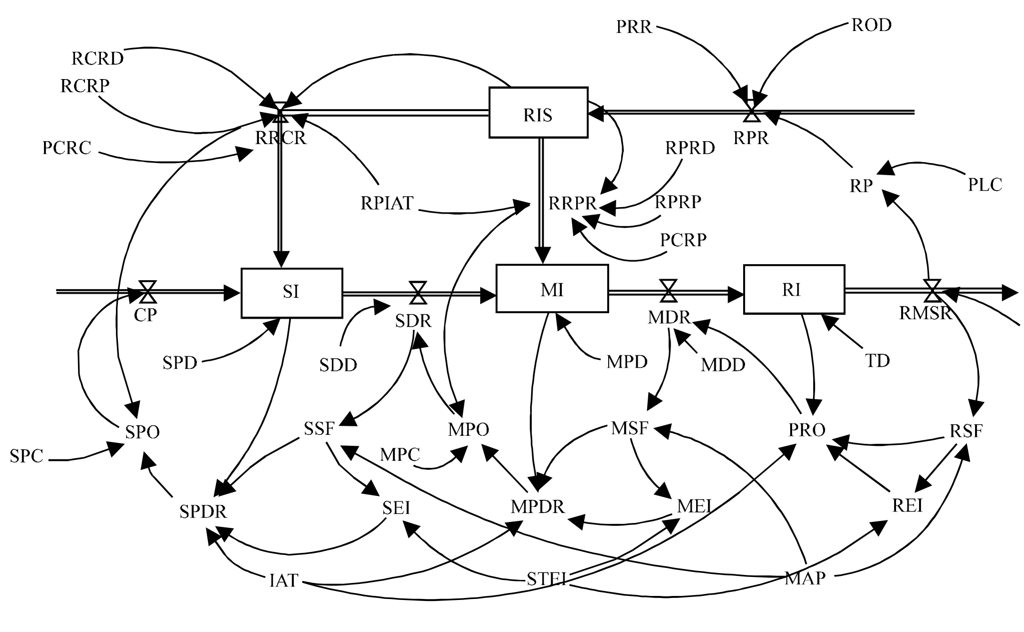

Fig. 2: Closed-loop supply chain system dynamics model

$$PRO = Max(0, RSF+(REI-RI)/IAT) \quad (1)$$

$$RI = Integ(Delay1(MDR, TD)-RMSR, 3000) \quad (2)$$

$$REI = RSF \times STEI \quad (3)$$

$$RSF = Smooth(RMSR, Map) \quad (4)$$

Manufacturer delivery rate depends on the retailer purchase order, manufacturer products inventory is a state variable, whose input is supplier delivery rate and recovery remanufacturing products rate, the output is manufacturer delivery rate. Manufacturer expected inventory and sales forecast both are related to the sustainable time of expected inventory. Manufacturer demand rate is related to the manufacturer forecasts sales and inventory adjustment time. Manufacturer sales forecast is an information delay function of the manufacturer delivery rate. Equations of the manufacturer are as follows Eq. 5-10:

$$MDR = Delay\ 1(PRO, MDD) \quad (5)$$

$$MI = Integ(Delay\ 1(SDR, MPD)+RRPR-MDR, 3000) \quad (6)$$

$$MEI = STEI \times MSF \quad (7)$$

$$MPO = Min(MPC, Max(0, MPDR-RRPR)) \quad (8)$$

$$MDR = Max(0, MSF+(MEI-MI)/IAT) \quad (9)$$

$$MSF = Smooth(MDR, Map) \quad (10)$$

Supplier delivery rate depends on manufacturer products order. Supplier inventory is a state variable, the input is new components productivity and recovery remanufacturing components rate, the output is supplier delivery rate. Supplier expected inventory and sales forecasts both are related to the sustainable time of expected inventory. Supplier demand rate is related to the supplier forecasts sales, inventory adjustment and inventory adjustment time. Supplier sales forecast is an information delay function of the supplier delivery rate. Equations of the supplier are as follows Eq. 11-17:

$$SDR = Delay\ 1(MPO, SDD) \quad (11)$$

$$SI = Integ(Delay\ 1(PP, SPD)+RRCR-SDR, 3000) \quad (12)$$

$$SEI = SSF \times STEI \quad (13)$$

$$SPO = Min(SPC, Max(0, SPDR-RRCR)) \quad (14)$$

$$SPDR = Max(0, SSF+SEI-SI)/IAT)) \quad (15)$$

$$SSF = Smooth(SDR, MAP) \quad (16)$$

$$CP = SOP \quad (17)$$

Recycler inventory is a state variable, the input is products recovery rate and the output is recovery remanufacturing products rate components rate. Recovery remanufacturing products rate and recovery remanufacturing components rate both are related to the recycler inventory and inventory adjustment time. Equations of the recycler are as follows Eq. 18-22:

$$RP = Delay\ 1(RMSR, PLC) \quad (18)$$

$$RIS = Integ(RPR-RRPR-RRCR, RPR \times PTAT) \quad (19)$$

$$RPR = Delay\ 1(RP \times RRR, ROD) \quad (20)$$

$$RRPR = Delay\ 1(Min(PCRP, RIS \times RPRP/RPIAT), RPRD) \quad (21)$$

$$RRCR = Delay\ 1(Min(PCRC, RIS \times RCRP/RPIAT), RCRD) \quad (22)$$

BULLWHIP EFFECT ANALYSIS

To get better real situation simulation, this study sets consumer demand for random fluctuations, using the equation as follows Eq. 23:

$$RMSR = 1000+\text{if then else } (Time>=5, \text{Random normal } (-200, 200, 0, 50, 4), 0)) \quad (23)$$

Equation 23 represents the demand is 1000 week^{-1} at the beginning of 5 weeks, demand has begun random fluctuations from the first 5 weeks, the amount of fluctuations is 200, mean is 0, volatility is 50 times, four random factors. All the constants values are as follows.

PLC = 100, PCRC = 2000, PCRP = 2000, SPC = 2000,
MPC = 2000, TD = 2, MDD2, MPD = 2, SDD = 2,
SPD = 2, IAT = 4, STEI = 3, MAP = 6, ROD = 2,
RPRP = 0.3, RPMD = 1, RPRD = 2, RCRP = 0.6, RPIAT = 2

Fluctuations of orders when PRR = 0, 30, 60 and 90% are shown in Fig. 3-6.

In different PRR cases, the products order of supplier, manufacturer and retailer present different degrees of fluctuations which the supplier products order fluctuations is the largest one, followed by manufacturer

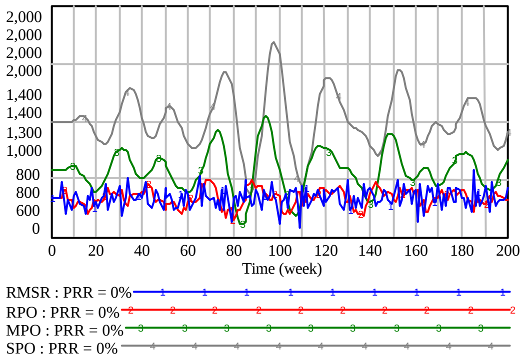

Fig. 3: Fluctuations of orders when PRR = 0%

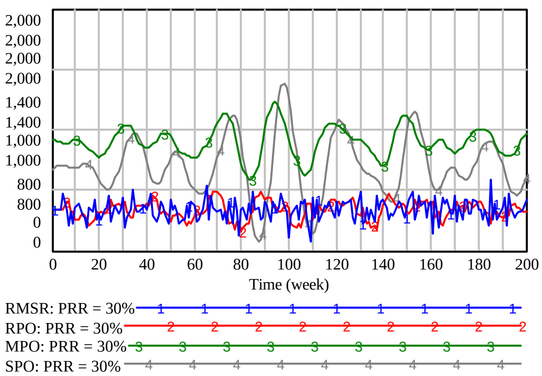

Fig. 4: Fluctuations of orders when PRR = 30%

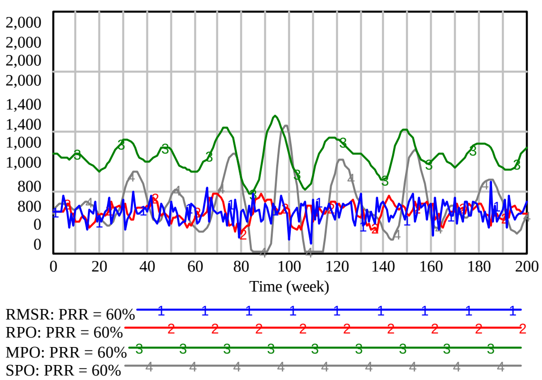

Fig. 5: Fluctuations of orders when PRR = 60%

products order fluctuations, retailers products order rate fluctuations is the smallest, this is because bullwhip effect become more obvious with the increase of the supply chain echelon.

With the increase of PRR, the fluctuations in the products order of supplier and manufacturer are gradually becoming mitigation, retailer products order has not changed, it is because recycler and retailer are not directly linked. Figure 3-6 illustrate that reverse logistics can relieve fluctuations in the products orders of forward logistics.

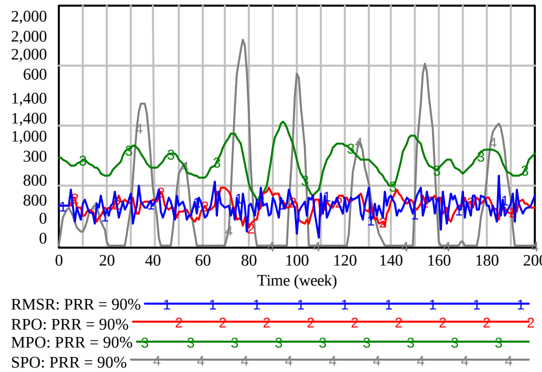

Fig. 6: Fluctuations of orders when PRR = 90%

Table 5: Comparison results of orders variance

PRR (%)	RMSR	RPO	MPO	SPO
0	2278.68	1878.32	15964.28	62247.84
30	2278.68	1878.32	15899.59	61946.94
60	2278.68	1878.32	15846.79	53563.34
90	2278.68	1878.32	15805.77	18038.99

Table 6: Comparison results of bullwhip effect

PRR (%)	RPO	MPO	SPO
0	0.824302	7.005932	27.31749
30	0.824302	6.977540	27.18544
60	0.824302	6.954368	23.50629
90	0.824302	6.936368	7.916418

For the analysis of bullwhip effect of various orders under different PRR, this study uses Chen *et al.* (2000) definition about quantify the bullwhip effect as follows Eq. 24:

$$BWE = \frac{\sigma_O^2}{\sigma_D^2} \tag{24}$$

where, σ^2_O represents the user to the supplier order variance and σ^2_D represents the market demand variance.

By calculating the simulation data of orders and their variance under different PRR, the comparison results of various orders variance are shown in Table 5 and the comparison results of various bullwhip effect are shown in Table 6.

The results show that the bullwhip effect of supplier and manufacturer have weakened, the bullwhip effect of retailer are not changed, this is because recycler and retailer are not directly linked. With the increase of PRR, reverse logistics can relieve bullwhip effect in forward logistics.

APPROACH FOR BULLWHIP EFFECT MITIGATION ANALYSIS

One of the main causes of the bullwhip effect is due to information distortion. To weaken bullwhip effect, this study uses information sharing strategy and uses Vensim simulation, to achieve the purpose of the bullwhip effect mitigation.

If there are not information sharing among the enterprise in supply chain, upstream enterprise and downstream enterprise can not timely access to information and the organization of production can only be predicted based on historical data or orders. There are huge losses because of lack of information, it also leads to a surplus of products. In process of information sharing, the production of supplier and manufacturer are no longer based on their forecast but according to retailer sales forecast and inventory of retailer and manufacturer. In this study, manufacturer products demand order rate is directly affected by retailer sales forecast and inventory and supplier products demand order rate is directly affected by the retailer sales forecast and inventory of manufacturer and retailer.

The new model based on the original closed-loop supply chain is shown in Fig. 7.

The description of changed equations are as follows Eq. 25, 26:

$$\text{SPDR} = \text{Max}\ (0, \text{RSF}+(\text{SEI}\times 3\text{-SI-MI-RI})/\text{IAT}))\quad (25)$$

$$\text{MSDR} = \text{Max}(0, \text{RSF}+(\text{MEI}\times 2\text{-MI-RI})/\text{IAT}))\quad (26)$$

Set consumer demand for random fluctuations as the original model and the constants are the same as original model. Fluctuations of orders when PRR = 0, 30, 60 and 90% are shown in Fig. 8-11.

In the case of different PRR, the products order of supplier, manufacturer and retailer present different degrees of fluctuations which the supplier products order fluctuations is the largest one, followed by manufacturer products order, retailers products order fluctuations is the smallest, this is because bullwhip effect become more obvious with the increase of the supply chain echelon.

With the increase of PRR, the fluctuations in the products order of supplier and manufacturer are gradually becoming mitigation, retailer products order has not changed, it is because recycler and retailer are not directly linked. By contrast with the Fig. 8-11, information sharing and reverse logistics can relieve fluctuations in the products orders of forward logistics.

For the analysis of bullwhip effect of various orders under different PRR in information sharing model, this study computes the simulation data of retailer, manufacturer and supplier and the variance of orders under different proportions, the comparison results of various orders variance are shown in Table 7 and the comparison results of various bullwhip effect are shown in Table 8.

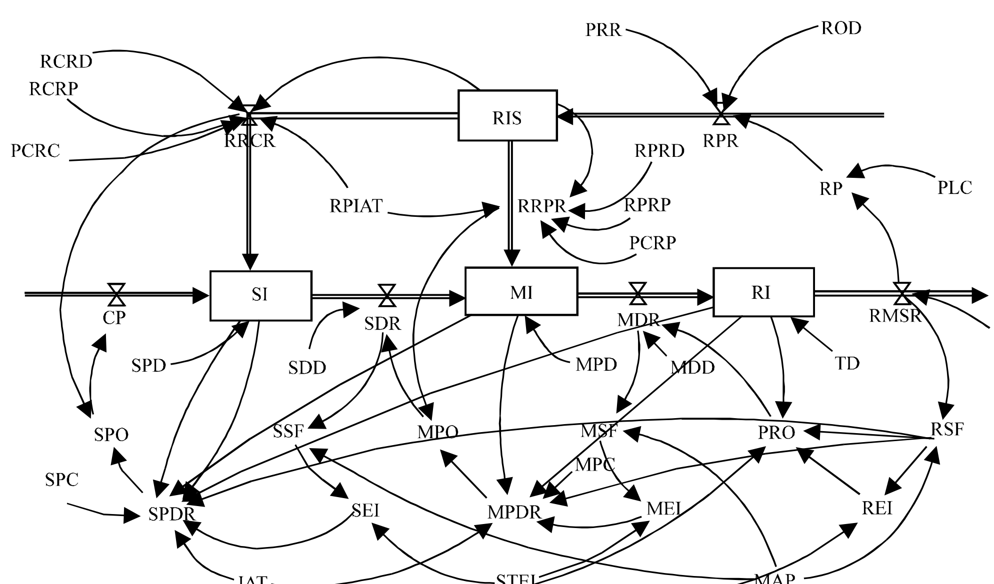

Fig. 7: Closed-loop supply chain system dynamics model under information sharing

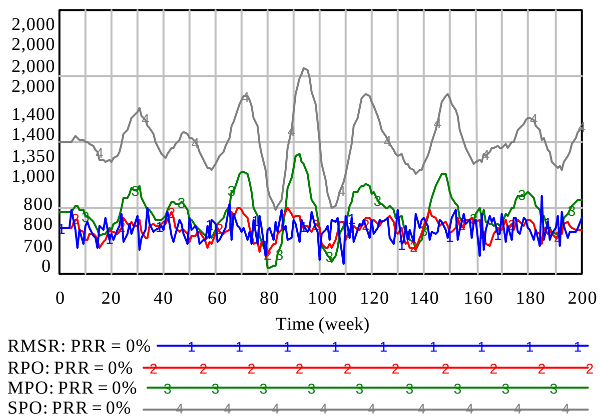

Fig. 8: Fluctuations of orders in information sharing model when PRR = 0%

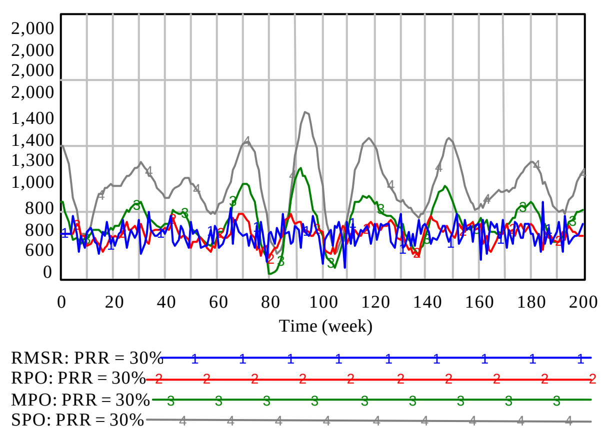

Fig. 9: Fluctuations of orders in information sharing model when PRR = 30%

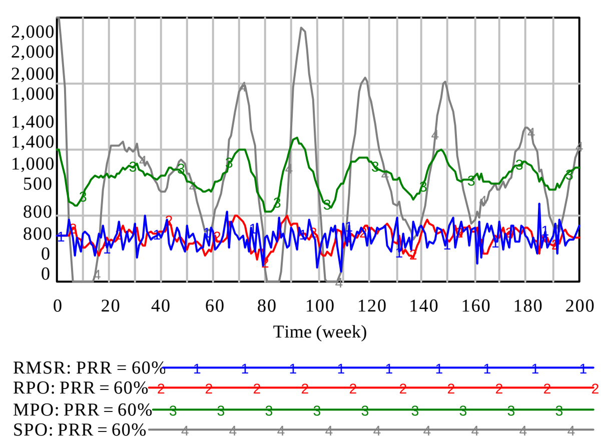

Fig. 10: Fluctuations of orders in information sharing model when PRR = 60%

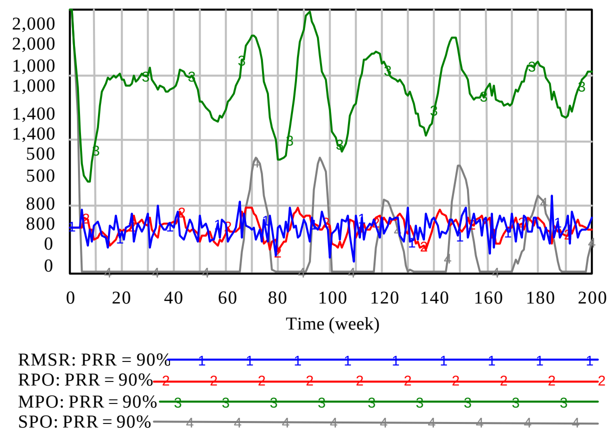

Fig. 11: Fluctuations of orders in information sharing model when PRR = 90%

Table 7: Comparison results of orders variance in information sharing model

PRR (%)	RMSR	RPO	MPO	SPO
0	2278.68	1878.32	11648.73	43434.91
30	2278.68	1878.32	11603.91	43326.01
60	2278.68	1878.32	11571.02	41110.51
90	2278.68	1878.32	11549.87	16104.40

Table 8: Comparison results of various bullwhip effect in information sharing model

PRR (%)	RPO	MPO	SPO
0	0.824302	5.112049	19.06143
30	0.824302	5.092380	19.01363
60	0.824302	5.077947	18.04136
90	0.824302	5.068664	7.067421

The results show that the bullwhip effect of supplier and manufacturer have obviously weakened in information sharing strategy, the bullwhip effect of retailers are not changed, this is because information sharing strategy does not change the retailer sales forecast. With the increase of PRR, reverse logistics can relieve bullwhip effect in forward logistics.

CONCLUSION

This study analyzes the bullwhip effect in closed-loop supply chain based on third-party recycler with using system dynamics and Vensim software, the closed-loop supply chain consists of supplier, manufacturer, retailer and third-party recycler and products can be used for remanufacturing products and components which, respectively remanufactured by manufacturer and supplier. Retailer demand is satisfied by the remanufacturing products and new products and similarly, manufacturer demand is satisfied by the remanufacturing components and new components. This study builds the model of closed-loop supply chain and simulates bullwhip effect under different product recovery rate and information sharing. According to the comparison of the value of the bullwhip effect in different PPR, the presence of reverse supply chain can reduce the bullwhip effect and recovery products rate is higher, the effect of reducing the bullwhip effect is more obvious. In the random demand conditions, with the recovery products rate increases, suppliers bullwhip effect decreased significantly. One of the main causes of the bullwhip effect is due to information distortion which was mentioned in Lee *et al*. (2000) and Disney and Towill (2001). Simulation results show that the bullwhip effect under information sharing can be significantly reduced. Information sharing is an effective strategy to reduce the bullwhip effect.

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