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Systematic dynamics analysis on bullwhip effects of closed-loop supply chain supported by information system

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Abstract. Advanced information system is the basis of modern supply chain management. This work established the system dynamics model with closed-loop supply chain which is close to reality to reflect main characteristics of modern supply chain. Supported by information system, the model can make rapid reaction. Applying the model, the research investigated the influential degree of recycling logistics on the bullwhip effect of supply chain. The model is established in constraint conditions of limited deliverability and return prohibition, so the system of this model becomes piecewise linear complex system. This work made experiments based on two shortage strategies, respectively. The simulation experiment results show that logistics recycling can weaken bullwhip effects in some conditions..

Key words. Closed-loop supply chain, Information system, Systematic dynamics, Bullwhip effect.

1. Introduction

In recent years, scholars have made a large amount of studies on reverse logistics and closed-loop supply chain. Closed-loop supply chain is a complex non-linear system. Compared with traditional method, system theory and control theory are more suitable for this supply chain. At present, some research achievements have been made [1][2][3]. Akçali et al.[4] studied optimized control over manufacturing system under the effects of uncertain demands and obtained the optimal manufacturing quantity which can make the average expected cost minimum. Tang et al.[5] analyze dynamic characteristics of closed-loop supply chain system in three information transparencies with control theory. Huang et al. established a model of controlling closed-loop supply chain with consideration of recycling uncertainty and gave robust control strategy for closed-loop supply chain[6]. Zhang et al. [7]constructed a transfer function of bullwhip effects on closed-loop supply chain and proposed the optimal recycling strategy with the minimum bullwhip effects. Jing et al. [8] established

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a three-order dynamic model of closed-loop supply chain system and found that reverse logistics can weaken bullwhip effects of forward logistics. Shu et al. [9] proposed re-manufacturing strategies in two models, logistics service supply chain and self-run logistics supply chain and conducted stability analysis on these strategies.

Most of above studies were developed in settled shortage strategy. In this work, considering two different shortage strategies, dynamic behaviour changes of closed-loop supply chain system in different strategies were compared. Advanced information system is the basis of modern supply chain management. Therefore, different from traditional decision-making method, modern managers can receive support from information system when making decisions. In this work, the established model took the support from information system into consideration. In addition, when establishing the model, non-negativity constrains, including order quantity and stock were considered to form a complex non-linear system. System dynamic method is suitable for studying complex non-linear system, so principles and methods of systematic dynamics were used to establish a systematic dynamic model for practical closed-loop supply chain.

Bullwhip effect means that the fluctuation of order quantity will amplify level by level from downstream to upstream of supply chain. This effect is considered as one of key problems affecting the performance of supply chain. In this work, bullwhip effect value is taken as the index investigating the performance of supply chain. This work established a systematic dynamic model with non-negativity restrictions of order quantity and stock according to main characteristics of modern supply chain to investigate the effects of changes of parameters related to closed-loop supply chain on the fluctuation of order quantity and bullwhip effect and the influential degree and give valuable advice to enterprise management practice according to experimental results.

2. Problem description and model hypothesis

Supply chain should be composed of demander, manufacturer and supplier of raw materials, among which manufacturer is the core enterprise in supply chain. Based on this chain, reverse logistics is added to form a closed-loop supply chain.

In order to analyze the system and evaluate the impacts of recycling factors on the performance of supply chain, following hypothesis are proposed in this work:

(1)The manufacturing model of manufacturer is Make to Stock (MTS) which means manufacturing as plan based on the prediction of market demands. Supplier of raw materials will provide raw materials to manufacturer, while manufacturer will produce products for demander. The basic order strategies of manufacturer are automatic pipeline, variable inventory and order based production control system (APVIOBPS).

(2)Manufacturer is responsible for product recycling. Recycled products can be treated as new products after re-manufacturing.

(3)Manufacturer will strive to satisfy with demander's demands, but shortage may occur. Manufacturer has two attitudes toward no replenishment for shortage and delayed delivery.

(4)Life cycle of product and transit time of components have delayed.

(5)Production planning department of manufacturer should make production plan according to demand information and production schedule of demander. This plan will be shared with purchasing department through information system.

(6)Manufacturer will set a certain safety inventory to ensure service quality.

3. Model construction

Founded by Professor Forrester of Massachusetts Institute of Technology in 1956, system dynamics is a discipline integrating, system theory, control theory, information theory and organization theory with the aid of computer technology. This work constructed a three-order model of system dynamics for closed-loop supply chain to study the effects of reverse logistics on the performance of supply chain by quantifying relevant factors of reverse logistics.

Fig. 1 shows the model of system dynamics established in this work. Every stage of route event flow starts from recycling. All the products produced by manufacturer$PSR(t)$in every stage flow into market. All of these products become waste products after$t_c$stages. For various uncertain factors, only$k$percent of products are recycled. The recycling quantity of products in$t$stage can be represented as follows:

$$BO(t) = k \times PSR(t - t_c), k \in [0, 1] \tag{1}$$

After examination, onlyλpercent of recycled products are qualified for re-manufacturing. Therefore, quantity of re-manufactured product is as follows:

$$ABO(t) = \lambda \times BO(t), \lambda \in [0, 1] \tag{2}$$

The flow of manufacturer event in every cycle is: in the beginning of$t$th stage, manufacturer will recycle products to product warehouse with recycling quantity as$BO(t)$. Then, manufacturer will receive products released in$t - delaytime$stage of supplier ($delaytime$is the delay time of transportation) with delivery quantity as$IR(t)$. After that, manufacturer receives products produced with recycled products, which is denoted as$ABO(t)$. Then, manufacturer will deliver goods from physical inventory$PINV(t)$to satisfy demander's demands$DR(t)$and complete incomplete order$PN(t)$with sales volume as$PSR(t)$. Manufacturer will predict the demand to decide the planned output$PL(t)$. Finally, purchase department will decide the order quantity$OR(t)$for every stage according to production plan, inventory and supplier delivery.

Modeling is conducted with difference equation by discrete control theory. For shortage strategy allowing delayed delivery, the inventory of manufacturer at the end of stage can be represented as follows:

$$PINV(t) = PINV(t - 1) + IR(t) + ABO(t) - PSR(t) \tag{3}$$

$$PSR(t) = \max(\min(PINV(t-1) + IR(t), DR(t) + PN(t-1)), 0) \quad (4)$$

Goods received by manufacturer at$t$th stage are released by manufacturer in$t - delaytime$stage, while the delivery quantity released by supplier in$t - delaytime$th stage is the order quantity made by manufacturer in that stage. If the inventory of supplier is smaller than order quantity of manufacturer, supplier will release few goods to manufacturer, causing risk of supply shortage. Considering above restrictions, the relationship between arrival volume of manufacturer$IR(t)$and delivery quantity of supplier$SSR(t)$can be represented as follows:

$$IR(t) = SSR(t - delaytime) \quad (5)$$

$$SSR(t) = \max(0, \min(SINV(t-1) + PR(t), OR(t) + SN(t-1))) \quad (6)$$

where$SINV(t)$is the inventory of supplier,$PR(t)$the output of supplier in that stage, and backlog order of supplier$SN(t)$.

$$IA(t) = (ainv - PINV(t))/atime \quad (7)$$

$$OR(t) = \max(0, IA(t) + PL(t)) \quad (8)$$

Order quantity of manufacture in the stage, $OR(t)$ is composed of inventory adjustment $IA(t)$ and production plan $PL(t)$.

In many contract models of supply chain, delayed delivery is not allowed. The sales volume of every stage is dependent on demand quantity. In this circumstance, shipment amount of supplier and sales volume of manufacturer are different from those in above models. Therefore, Formula (4) and Formula (6) should be changed into:

$$PSR(t) = \max(\min(PINV(t-1) + IR(t), DR(t)), 0) \quad (9)$$

$$SSR(t) = \max(0, \min(SINV(t-1) + PR(t), OR(t))) \quad (10)$$

In above models, Formula (4) and Formula (9) show the restriction by supply service level of supplier. Formula (6) and Formula (10) show the restriction by service level of supplier. Formula (8) shows the restriction of forbidding sales return.

Market demand is represented with stable and reversible time series of $ARMA(1,1)$ following market rule [10]:

$$DR(t) = \mu + \rho DR(t-1) - \theta\varepsilon_{t-1} + \varepsilon_t \quad (11)$$

where$\mu$is the constant,$\rho$the regression coefficient, showing the relevant degree between demands in this stage and that in last stage ($|\rho| < 1$),$\varepsilon_t$the fluctuation deviation of market demand which is the random variable following$(0, \sigma^2)$independent distribution, and$\theta$the error coefficient ($|\theta| < 1$).

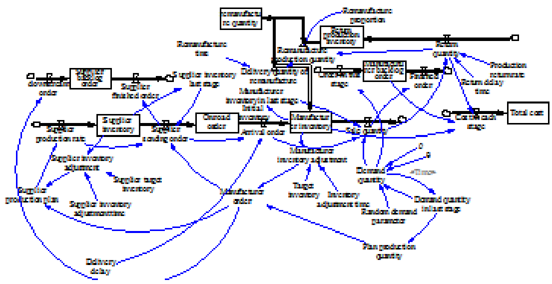

Fig. 1. Model of Systematic Dynamic for Closed-loop Supply Chain

4. Simulation analysis

4.1. No consideration into reclaimed products

Regardless of the remanufacturing of reclaimed products, systematic dynamic model is established for simulation when demands of demander fluctuate to some extent. Table. 1 shows the setting of the simulation parameters, and Fig. 2 shows the fluctuations of demand and order generated in simulation. The value of bullwhip effect can be obtained with the data, $BWV = VAR(OR_t)/VAR(DR_t) = 1.03$

Table 1. Parameters setting for initial model

Delay time	Manufacture target inventory (ainv)	Inventory adjustment time(atime)	Supplier target inventory(sainv)	Stock out cost(cost2)	Inventory cost(cost1)	Demand function parameter		
						ρ	θ	μ
2	24	3	12	1	0.5	0.4	0.5	12

4.2. Strategy not allowing delayed delivery

In management practice, some enterprises regulate that every order should be carried out independently and the insufficient order quantity will not delay delivery, that is, no replenishment for shortage. Simulation experiments were conducted on adjusted parameters of reclaimed ratio to understand the impact on order fluctuation of supply chain when postponement delivery strategy is not allowed. As shown in Fig. 3, two curves represent the fluctuation of the order quantity whose reclaimed ratio parameters were 0 and 0.3 respectively. According to Fig. 3, fluctuation ratio of the order quantity will increase with recycling manufacturing when postponement delivery strategy is not allowed. In order to further analyze the impact of the change of reclaimed ratio parameter, Fig. 4 gives the value of bullwhip effect when the reclaimed ratio parameters change from 0 to to 0.9 by 0.1.

Fig. 4 shows that the value of bullwhip effect is increasing with the increase of the reclaimed ratio parameter. When recovery factor is bigger than 0.5, the change of bullwhip effect value is not obvious, which indicates that the recycling link will reduce the overall performance of the supply chain when the manufacturer takes the strategy of no replenishment for shortage. However, when the recycling re-products increase to a certain number, it has little impact on the bullwhip effect of supply chain. At this time, if only economic benefits is considered in supply chain, recycling is inadvisable, while removing recycling may have a huge negative impact on environmental protection. As a result, enterprises can take measures to increase recycling quantity and minimize the impact of recycling on supply chain.

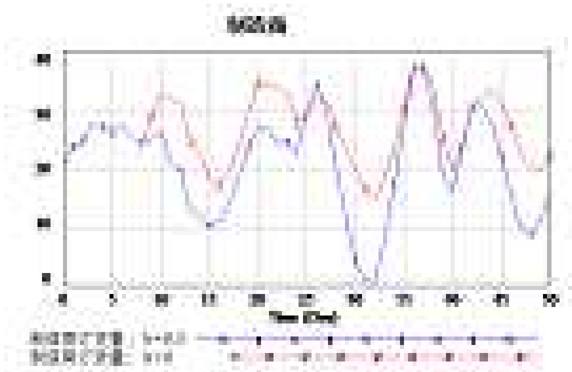

Fig. 2. Order fluctuation with different parameter

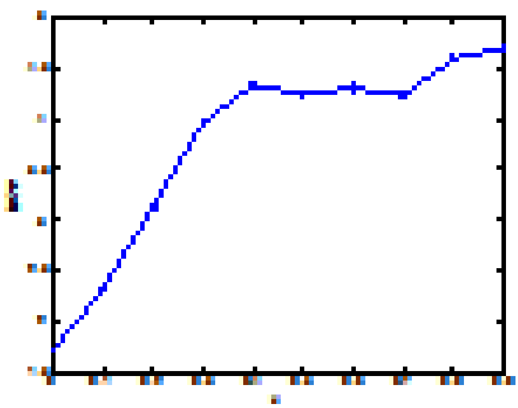

Fig. 3. Bullwhip effect value with different parameter when no delayed delivery

4.3. Delayed delivery strategy

In many cases, manufacturer can complete orders which have not been completed in current stage in next few stages. In other words, delayed delivery is allowed. Fig. 5 shows the impacts of reclaimed ratio on order quantity of manufacturer when taking the strategy allowing delayed delivery. It can be seen in Fig. 5 that the order

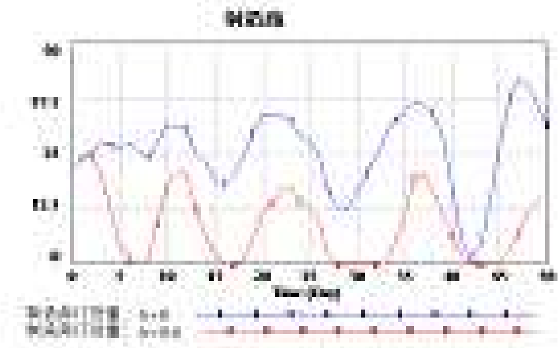

Fig. 4. Order fluctuation with different parameter allowing delayed delivery

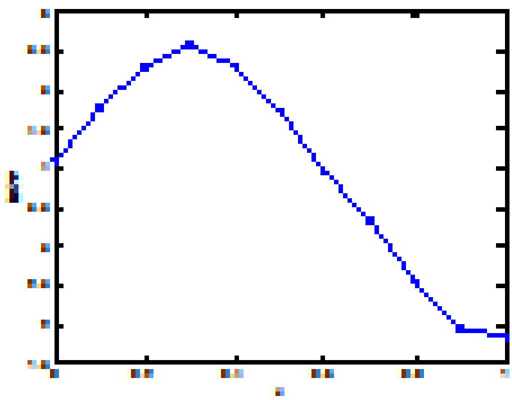

Fig. 5. Bullwhip value with different parameter allowing delayed delivery

quantity fluctuation is significantly reduced when reclaimed ratio coefficient ranges from 0 to 0.6. Fig. 6 shows the changes of bullwhip effect value with reclaimed ratio coefficient when taking the strategy allowing delayed delivery and the value changes with reclaimed ratio coefficient. Different from the strategy with which delayed delivery is not allowed, corresponding bullwhip effect value begins to decrease gradually when reclaimed ratio coefficient is bigger than 0.3. It means that reverse logistics can promote forward logistics to reduce the bullwhip effect under delayed delivery strategy when reclaimed ratio reaches a certain number.

5. Conclusion

This work set non-negativity restrictions to order quantity and supply quantity on closed-loop supply chain system. The supply chain system with restrictions showing piecewise linearity is more complex. Compared with traditional linear model, the model with restrictions is more practical, but more complex. This work studied complex non-linear closed-loop supply chain system by systematic dynamic analysis method. According to different reactions to shortage, two inventory strategy models were established. The results show that the action mechanisms of two shortage models on recycling are different. In the strategy of replenishment for shortage, bullwhip effect enlarges for reverse logistics. In the strategy allowing delayed delivery, reverse logistics can effectively weaken bullwhip effect to improve the performance of supply chain if products can recycle in high proportion.

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