The bullwhip effect in the closed loop supply chain

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Abstract: A simple system dynamics model of a traditional/closed loop supply chain system is investigated. Particularly, the effect of remanufacture, remanufacturing lead-time and the return rate on the inventory variance and bullwhip effect were studied. Our results clearly showed that the bullwhip in the closed loop supply chain is bigger than one in traditional supply chain and foreign to the collection rate and the inventory variance in every stage decrease when the remanufacture is introduced into the traditional supply chain. Furthermore, we found that the bullwhip effect in the closed loop supply chain will increase when the short term lead time of remanufacture cycle time increase and is independent of the long term lead time of remanufacture, and inventory variance will increase in first two stages but will decrease for the producer stage.

Keyword: Remanufacturing Inventory variance Bullwhip effect System dynamics

1. Introduction

Today, sustainability has become a focus of many economic development strategies. The importance of the environmental performance of products and processes for sustainable manufacture and service operations is being recognized increasingly. Several European countries have mandated stringent laws for “product take back” after products end their useful life, to force companies to respond with product redesign, changes in packaging, and creative solutions to the problem of product recovery. Efforts in all these areas can be seen in the automotive, computer, copier, and other industries (VROM, 2002; EU, 2002)

While recycling legislation was introduced in Europe, North America, and Japan encourage this awareness. This leads some companies begin to use sustainability as a means of gaining competitive advantage as the growing customers' environmental awareness is changing the marketplace, (Mahadevan et al. 2003). Increasingly, manufacturers are establishing economically viable production and distribution systems that enable remanufacturing of used products in parallel with the manufacturing of new units. Remanufactured products are upgraded to the quality standards of new products, so that they can be sold in new product markets.

Viewed from the production, sustainability covers many aspects of environment friendly production: green manufacturing, intelligent use of natural resources, recycling, material re-use and remanufacturing. However, managing a reverse supply chain involves dealing with many new uncertainties, especially those concerned with the quantity, quality and timing of the returned products, (Seitz et al. 2003). In the recently papers, many issues have been raised, such as how to design a product so that it is easy to be disassembled and reused (Kondo et al. 2003), or how to make decisions on product recovery (van der Laan and Saloman 1999; Teunter and Vlachos 2002), for example reselling, recovery, or disposal. The recovery option may also include repair, refurbishing, remanufacturing, cannibalization and recycling, (Thierry et al. 1995, Fig.1).

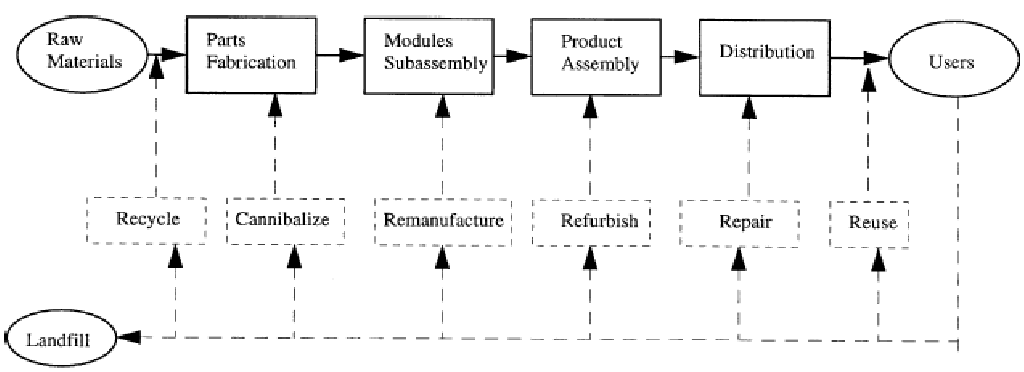


Fig. 1 Product recovery operations (adapted from Thierry et al. (1995)).

Here, we focus on investigating how a remanufacturing process affects traditional supply chain in terms of the variance of the inventory and the bullwhip phenomena to produce new products. The motivation behind this research is twofold: first, we want to examine the effect of remanufacturing on traditional supply chain and the impact of environmental concerns on the bullwhip phenomena in the supply chains; second, we would like to develop a dynamic simulation model for the above system, which facilitates the long-term environmental and remanufacturing capacity expansion.

2. Literature review

In this section, we identify the problems with current descriptions of remanufacturing and bullwhip effect in the traditional supply chain. As re-use is considered environmental friendly, product and material flows have changed throughout the past decades. The ecological and economical benefits of the two-way material flows made researchers to design and investigate such logistics networks in early 1990s, resulting in many related publications (see Fleischmann et al. (1997) and Guide et al. (2000) for complete literature reviews).

Furthermore, many issues such as the planning of closed-loop supply chain operations, such as network design (Krikke 1998), shop-floor control (Guide et al. 1997), and inventory control (van der Laan 1997) were done by a central decision maker to optimize total system performance. Especially, much of the literature on reverse logistics has addressed inventory management, such as Inderfurth and van der Laan (2003), and Kiesmüller (2003).

On the other hand, bullwhip effect (called by Lee et al. (1997)), which is firstly published by Jay.W Forrest(1958) who is looked as a pioneer of modern supply chain management，remains to be a critical issue in supply chain. As illustrated in the literature (Lee et al., 1997; Metters, 1997), a small variance in the demands of the downstream end-customers may cause dramatic variance in the procurement volumes of upstream suppliers via the bullwhip effect under the condition that the distortions of demand-related information exist among the members of a supply chain. As a consequence, the systematic profitability of a supply chain is seriously affected. Correspondingly, the functional coordination of a supply chain may no longer exist due to such inappropriate interactions of supply-demand information flows between chain members. There are many studies on the bullwhip effect. An effort to quantify the bullwhip effect has been undertaken by a few researchers. Chen et al. (1998) defined the bullwhip effect as the ratio of the demand variances at two adjacent supply-chain stages.

They analyzed a simple two-stage system, first analytically, and then by simulation. Chen et al. (2000) developed their study before and quantified the bullwhip effect in a k-stage supply chain by assuming deterministic lead time and stochastic demand. They determined the lower bound of the bullwhip effect and showed that the Bullwhip Effect cannot be eliminated fully by sharing customer demand information with the agents in the supply chain. Dejonckheere et al. (2003) apply a control theoretical approach to bullwhip effect quantification and come to similar conclusions. The bullwhip effect relates to the order we place to maintain the inventory levels. Both the inventory variance and bullwhip directly affect the economics of scenario, (Disney and Grubbström 2003). The higher the variance of inventory levels, the more stock will be needed to maintain customer service at the target level, (Dejonckheere et al. 2002).

However, almost all quantitative literature is based upon a traditional supply chain and few papers studied the closed loop supply chain performance especially inventory variance and bullwhip in it. To the date, only two papers about it were published by Tang and Naim (2004) and Zhou et al. (2004), in which a hybrid inventory system studied by considering simple Push and Pull policies. Zhou et al. (2006) studied the bullwhip and variance of the inventory by used the APIOBPCS (Automatic Pipeline Inventory and Order Based Production Control System) model which is based on the control theory. In our study, by adapting a system dynamics approach, we relax the centralized planner assumption and model the independent decision-making process of each supply chain member. Specifically, we examine the interaction between order decisions in the forward supply chain and the role of remanufacture. Our aim here is to contribute to this field by highlighting how the inventory variance and the bullwhip phenomenon are affected by the reverse logistics operations.

The purpose of this research is to increase the knowledge and understanding of how the inventory variance and the bullwhip phenomenon are affected by the reverse logistics operations. The analysis tool used here is the system dynamics (SD) methodology.

There are already some publications using SD in supply chain modeling, but most of them refer to forward logistics. Forrester (1961) included a model of supply chain as one of his early examples of SD methodology. Towill (1992) used SD in supply chain redesign to generate added insight into system dynamics behaviour and particularly into underlying casual relationships. The outputs of the proposed model are industrial dynamics models of supply chains. Minegishi and Thiel (2000) use SD to improve the knowledge of the complex logistic behaviour of an integrated food industry. They present a generic model and some practical simulation results applied to the field of poultry production and processing. Sterman (2000) presents two case studies where SD methodology is used to model reverse logistics problems. In the first one, Zamudio-Ramirez (1996) analyses part recovery and material recycling in the US auto industry to assist the industry think about the future of enhanced auto recycling. In the second one, Taylor (1999) concentrates on the market mechanism of paper recycling, which usually leads to instability and inefficiency in flows, prices, etc.

In this paper, we set out to study the behavior of a single product closed-loop supply chain with product recovery under environmental influences and capacity planning policies. Although such an analysis may differ from one product to another, we try to keep it as general as possible to facilitate the implementation of the proposed model to more practical cases.

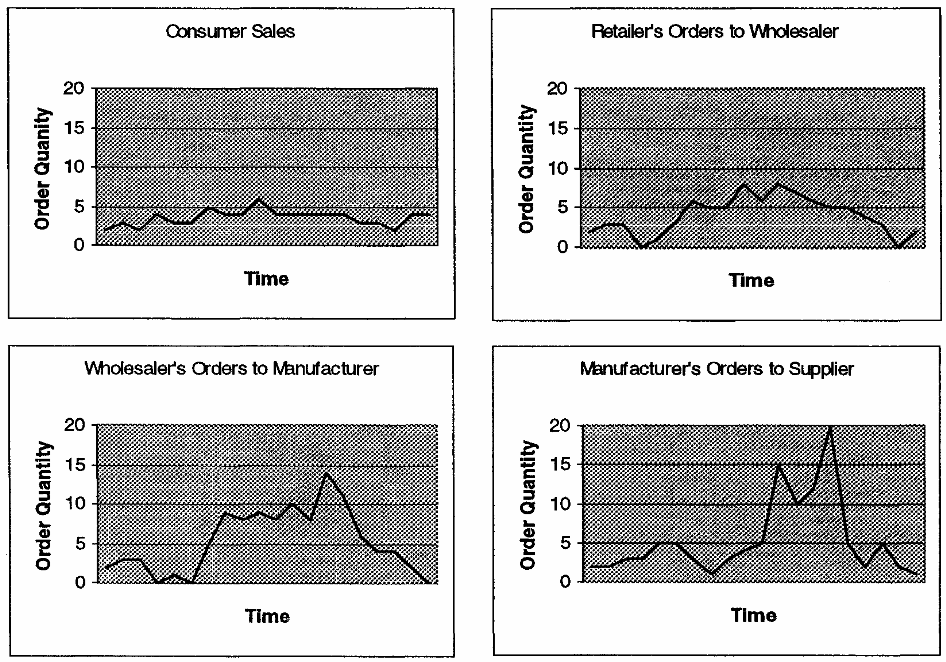
The rest of our paper is organized as follows. The modeling details of the system are presented in Section 3. Behaviour analyse, which examines the effect of remanufacture on the bullwhip effect, compares the bullwhip phenomena and the inventory variance of the remanufacturing supply chain with traditional supply chain and draws out some managerial implications, is presented in Section 4. In the final section we present the main conclusion.

3. Model description

3.1 Problem description

According to the paper published by Lee. H et al. (1997), in the supply chain, the variance of order from the market consumer will amplify in the supply chain stage by stage which is illustrated by the Fig.2.

For the purpose of this paper, we built a simple supply chain to reproduce the bullwhip effect based on the Sterman’s (2000) structure and then introduced the remanufacture factor into the model and to study whether it is true that the remanufacture will decrease the bullwhip effect in the supply chain, and how the lead time of remanufacture influence the bullwhip effect.



Source: Lee *et al.* (1997)

Fig.2 The bullwhip effect

In this study, we considered that the producer is responsible to collect the used products. Here we just considered the used product supplied by the consumer. Producers collect the used products and test and send to the producer to remanufacture. And then the remanufactured products enter the forward supply chain which consists of producer, distributor and retailer.

3.2 Model boundary

A model's scope is reflected by its boundary. Table.1 reveals the primary features that included (endogenous), assumed (exogenous) and excluded (ignored) from the model.

Table.1 the Model boundary

Ignored	Exogenous	Endogenous
Cash flow	Product diversity	Inventory

Personnel resistance Cost of the system Macro economics Technology details Worker force Quality problem	Consumer demand Inventory adjust time Manufacture cycle time Remanufacture cycle time Use life of the product Environment policy pressure Capacity of the manufacture Capacity of collect of disposal used product Time for remanufacture prepare	Pipeline Inventory Order rate Production rate Remanufacture start rate Production start rate Desired inventory

For the purpose of this paper, performance evaluation is based on the variance of order rate and physical inventory. Therefore, variable representing the physical material flows and the information flows are modeled endogenous. The model contains a limited number of exogenous variables as well. Some of them, manufacturing cycle time for example, are physically determined by various technical factors outside the scope of this research. Others can be manipulated as parameters to present various scenarios in the policy design stage. For instance, consumer demand can be used to test the effectiveness of policies under different circumstance.

The variables excluded are those may influence a real world supply chain, but are not relevant to this paper. For example, cash flow plays an important role and has a critical influence on the health of business, but this is not the focus of this paper and is therefore ignored in this model. The exclusion of the cash flow could be regarded as a limitation on the validity of this paper.

3.3 Model assumption and level of aggregation

The primary model assumptions are listed below as the basis for the structure of the model and the level of aggregation chosen.

- In this model, the inventory levels, including finish products, pipeline, remanufacture pipeline and collect used product are represented by the aggregate of all stock-keeping units, since it is not necessary for the purpose of the model to treat each stock-keeping units separately.

- The forward supply chain in this paper consists of one retailer, one distributor and one producer.
- Companies currently can remanufacture their products making them essentially as good as new, thus form part of the serviceable stock. Serviceable stock is the finished goods. In this study the terms inventory used for serviceable stock.
- And we supposed that the producer will give priority to used products in manufacture. We assumed that "used" products are pushed through a remanufacturing process as soon as they are returned from the "customer" (or marketplace). There is a lead-time associated with the time to remanufacture a product and also a lead-time associated with the time that a product is "in use" by the customer. Even both these two lead-times are in the reverse loop and their impacts on the system dynamics performance are the same even though their scale is different (Tang and Naim 2004) , for modeling purpose, we separated out the remanufacturing lead time from the "in-use" lead-time. We assumed constant lead times for both remanufacturing and manufacturing.
- We set equal prices for products, regardless of their source.
- We assumed that the market customer demand does not respond to the remanufacture.
- The recoverable stock is not investigated here because our focus is how the remanufacturing process affects the conventional (forward) supply chain. The manufacture of new products and remanufacture are controlled by a continuous time variant of the order policy.
- And for the purpose of descriptive, we named the supply line inventory and inventory of work in place as the inventory of Pipe line.

3.4 Model subsystems

As description before, in this study, we studied the supply chain consisting of a retailer, a distributor, and a producer. The producer serves as a used product collector and is in charge of the remanufacture. In Figure 3, for the descriptive purpose, the paper just gives the internal structure of the producer and the distributor, because the retailer buys and sells products just as the distributor, the details about the retailer are suppressed ordering and sales.

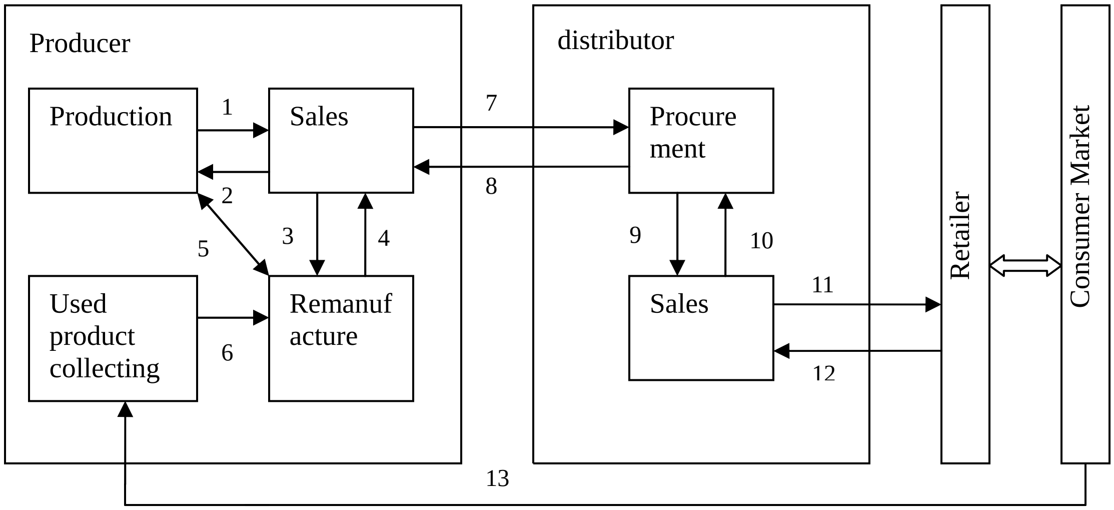


Fig.3 Model subsystem

The producer is divided into four subsystems, sales, production, remanufacture, and used product collecting. These four subsystems cover the major functions and processes of the typical manufacture, remanufacture, and used product collecting.

Production is the core function of a producer. In the sector, raw materials or components are converted into finished products under the guidance of a master production schedule. Finished Products are placed on the finished product inventory. (Arrow1)

Remanufacture sector converts the used product into finished products. In the sector, raw materials or components are converted into finished products under the guidance of a master production schedule. Finished Products are placed on the finished product inventory (Arrow 4). And there is an assignment between the production and remanufacture (Arrow5). Here we considered that producer will firstly use the used product for production.

The sales sector is in charge of the order handing and finished products inventory. It processes the incoming orders from the next down stage-the distributor (Arrow 8) and is responsible for physical shipment of products (Arrow 7). At the same time, based on the order information, the sales sector formulates sales forecasts (Arrow2 and Arrow 3) that will be included in the manufacturing schedule of the production sector and remanufacture sector.

And the used product collecting just collects the used product (Arrow13) from the end consumers and sends the reusable used product to remanufacture (Arrow6). And because capacity of collect of disposal used product is exogenous, the detail of the used product collecting will be explained in the model.

The distributor and the retailer consist of nearly same two sectors, the procurement sector and the sales. The procurement sector maintains the inventory. It orders (Arrow 7), receives (Arrow8) products from producer and serves for the sales (Arrow9). The sales sector serves the same function as it does in the producer subsystem. It processes the incoming orders from the next down stage-the (Arrow 12) and is responsible for physical shipment of products (Arrow 11). And based on the order information, the sales sector formulates sales forecasts (Arrow10).

The whole model structure and equation will be explained in support material.

3.5 Model validation

Model validity and validation have long been recognized as one of the main issues in the field of system dynamics (Forrester 1968). System dynamics modeler has developed a wide variety of specific tests to uncover flaws and improve models. Extreme condition test and sensitivity test of this model showed that the model is robust. There are three extreme condition tests. Firstly, it is supposed the manufacturing cycle time is 10000weeks. Secondly it is assumed that the inventory of retailer was stolen then there is nothing in the warehouse of retailer at the beginning of simulation. Thirdly, we assumed the time series of incoming order from customers is Sin wave.

In sensitivity test, we checked the amplification of the standard deviation of order rate-consumer between standard deviation of order rate-retailer. The time span for this test is 200 weeks. The test result is showed as follows:

Table 2 The sensitivity analysis

	standard deviation of order rate-consumer	standard deviation of order rate-retailer	Amplification	Change%
Step up in consumer order rate				
Original value (50%)	0.3114	0.7129	1.632069396	0
50%Increase (75%)	0.4672	0.8361	1.496282556	-8.31991832
50%Decrease (25%)	0.1557	0.4899	1.541438728	-5.55311362
Fraction of the failure rate				
Original value 0.2	0.3114	0.7129	2.289338471	0
50%Increase (0.3)	0.3114	0.7129	2.289338471	0
50%Increase (0.1)	0.3114	0.7129	2.289338471	0

We can find that the model does not sensitive to these exogenous variables. Extreme condition test and sensitivity showing before provide the model is robust.

4. Behavior analysis

For the purpose of this project, we compared the behavior between the traditional forward supply chain and the closed loop supply chain. In the traditional supply chain, there are producer, distributor and retailer. The closed loop supply chain model was introduced remanufacture function and used products collection sector based on the traditional supply chain model. In these two supply chain, we compared the variance of the inventory and the bullwhip effect.

Firstly, same to the beer game, we assumed that the incoming orders from consumers were 4 unit/week and stepped up to 6 unit/week at the fifth week. As shown in fig 4 and fig 5, the traditional supply chain behaves the oscillation, phase lag and amplification behavior which is called bullwhip effect. Similarly, the closed loop supply chain also suffers from bullwhip, shown in fig.6 and fig7. Here, in the traditional supply chain the production rate can be looked as the order of producer, because he will order some materials from the supplier. And in closed loop supply chain, the sum of the production start rate and the remanufacture start rate can be looked as the order of producer, since he will order some materials from the supplier and reusable products from himself. Comparing the behavior of these two, we can find that there are some different between the order-producer. The order-producer in closed loop supply chain looks more smoothly than traditional supply chain in 12th week because the remanufacture serves as filter here. To get the numerical difference between these two, we calculated the bullwhip by the mathematical definition of bullwhip that has been proposed by Chen et al. (2000) as,

$$Bullwhip^i = \frac{VarOR_i}{VarOR_0}$$

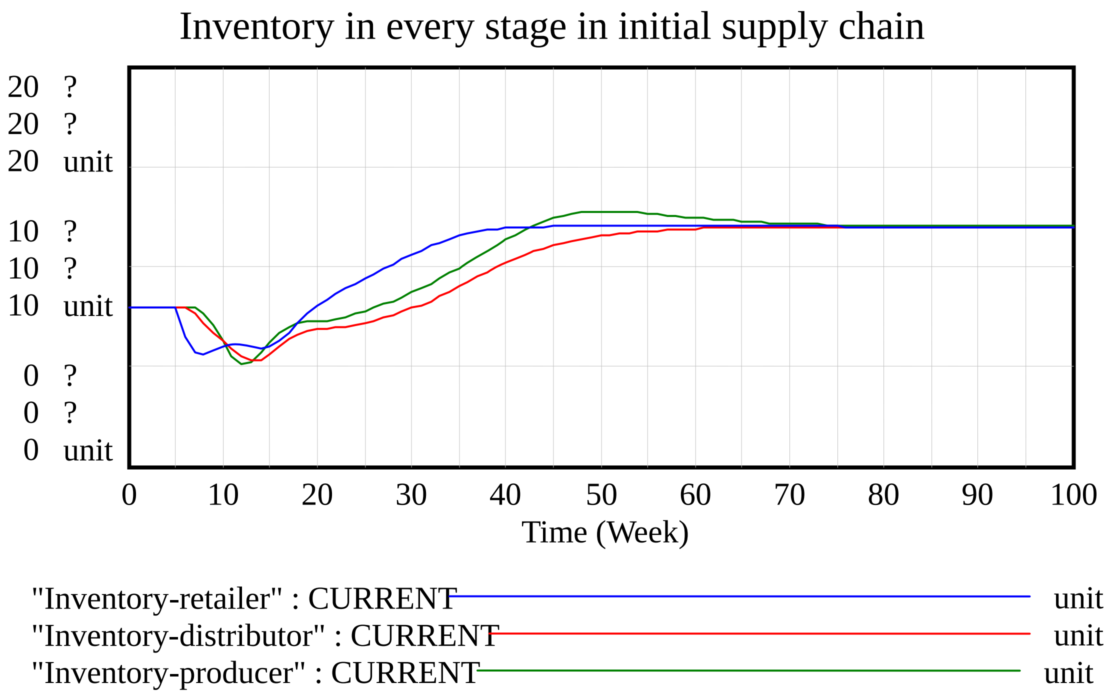


Fig.4 Inventory of every stages initial supply chain

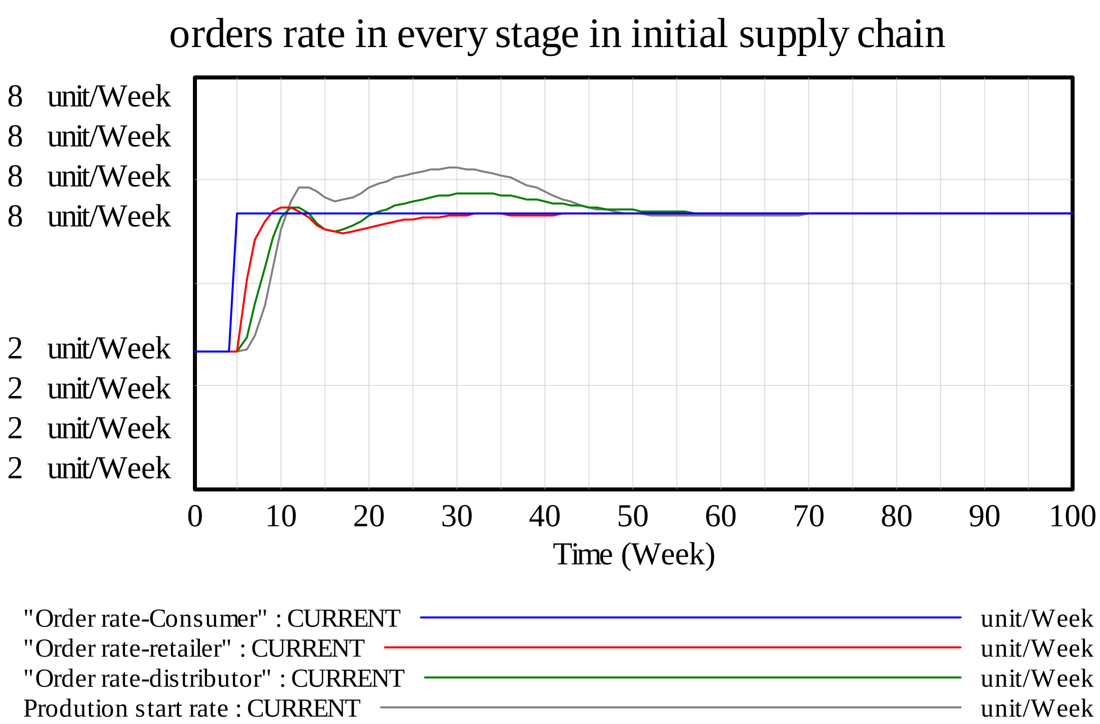


Fig.5 Orders of every stages initial supply chain

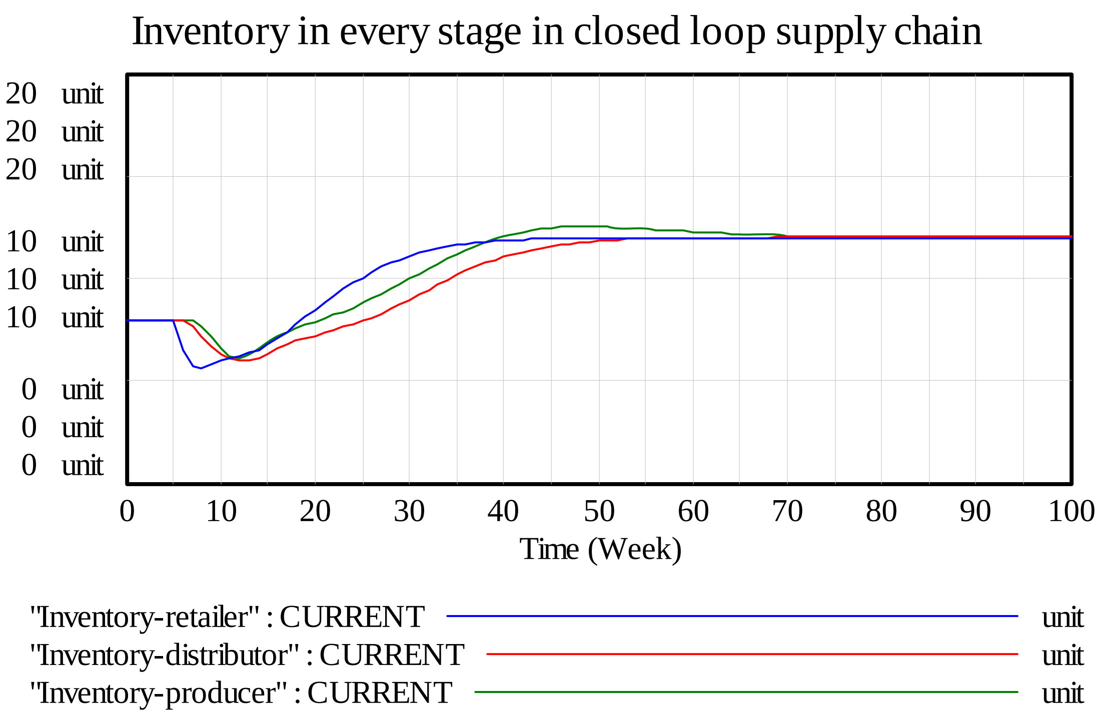


Fig.6 Inventory of every stages closed loop supply chain

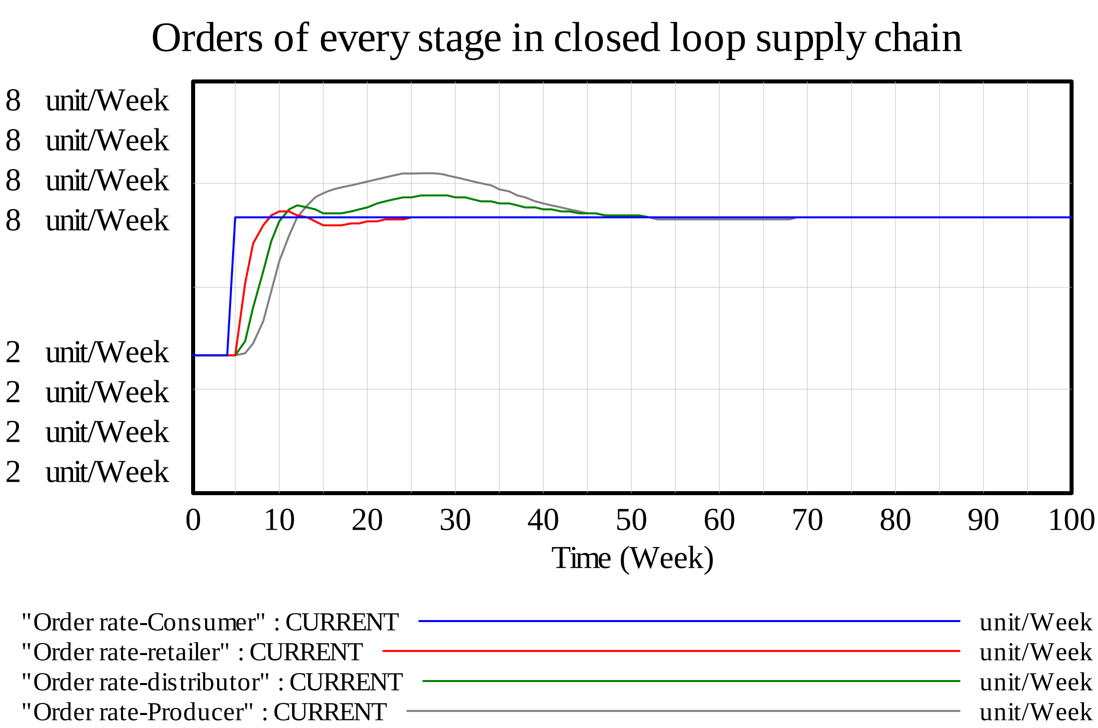


Fig.7 Orders of every stages closed loop supply chain

Table.3 Bullwhip and Inventory variance in traditional supply chain and closed loop supply chain

	Bullwhip in traditional supply chain	Bullwhip in closed loop supply chain
Consumer	1	1
Retailer	1.2138	1.22613
Distributor	1.57083	1.59622
Producer	2.13772	2.20436
	Inventory variance in Traditional supply chain	Inventory variance in Closed loop supply chain
"Inventory-retailer"	4.58627	4.09963
"Inventory-distributor"	5.07997	4.39532
"Inventory-producer"	5.24337	4.09215

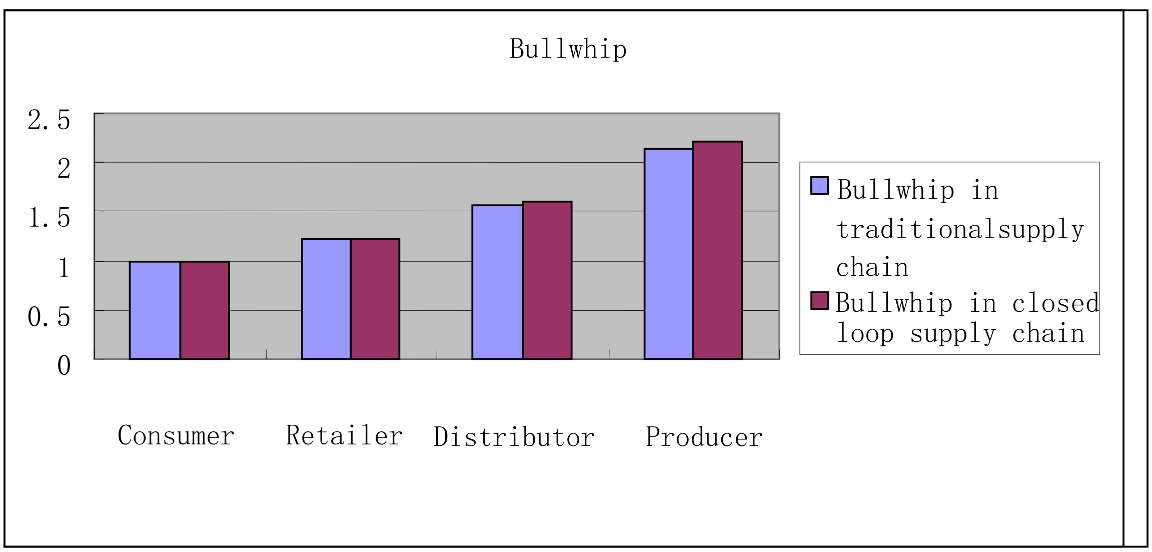


Fig.8 Comparing the bullwhip in these two supply chain

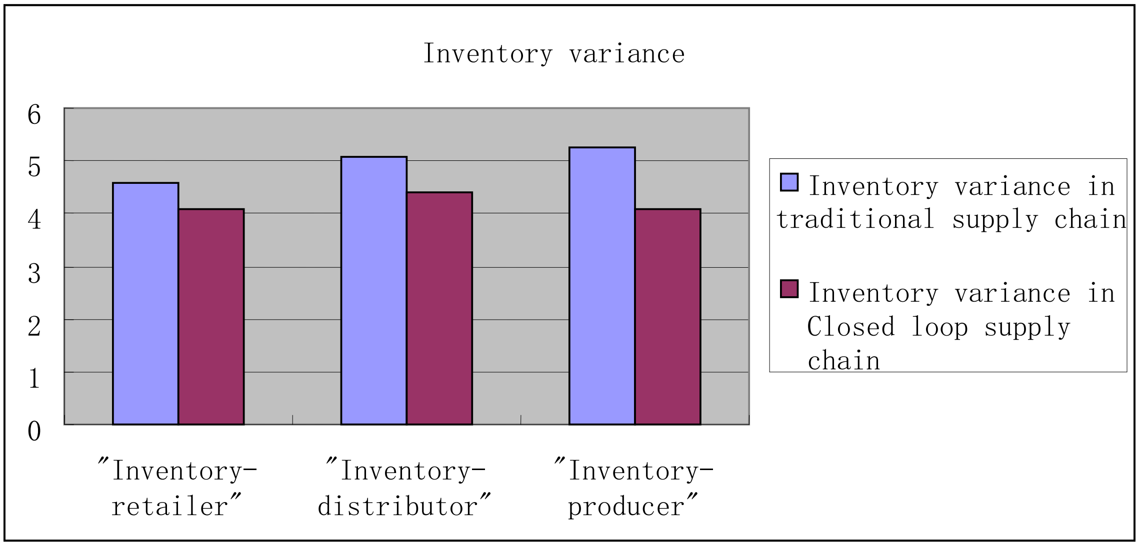


Fig.9 Comparing the inventory variance in these two supply chain

As shown in fig.8, fig.9 and table.3, the bullwhip effect in closed loop supply chain is bigger than it in traditional supply chain. This means that, in our specified case, a supply chain with reverse logistics may be more costly than a traditional one. But the variance of inventory will decrease when producer remanufacture the used products. And we can also find that in the closed supply chain, the variance of inventory in producer is less than one in distributor. Why? The causal loop of the collection sector is reinforcing loop which combine with the balancing loop in forward supply chain can decrease oscillation of stock produced by the balancing loop with delay. But the order serve as the flow, because there is delay of remanufacture, the variance will increase.

Secondly, we changed the environment policy pressure in the closed loop supply chain to survive the effect of collection rate on the bullwhip and the variance of inventory. As shown in fIg.10-13, the collection rate is foreign to the bullwhip in closed supply chain. That also can be said that bullwhip in closed loop supply chain is independent on the environment policy. Because the remanufacture start rate is determined by the remanufacture capacity, indicated production rate and reusable products. So, the collection rate will not effect on the system behavior.

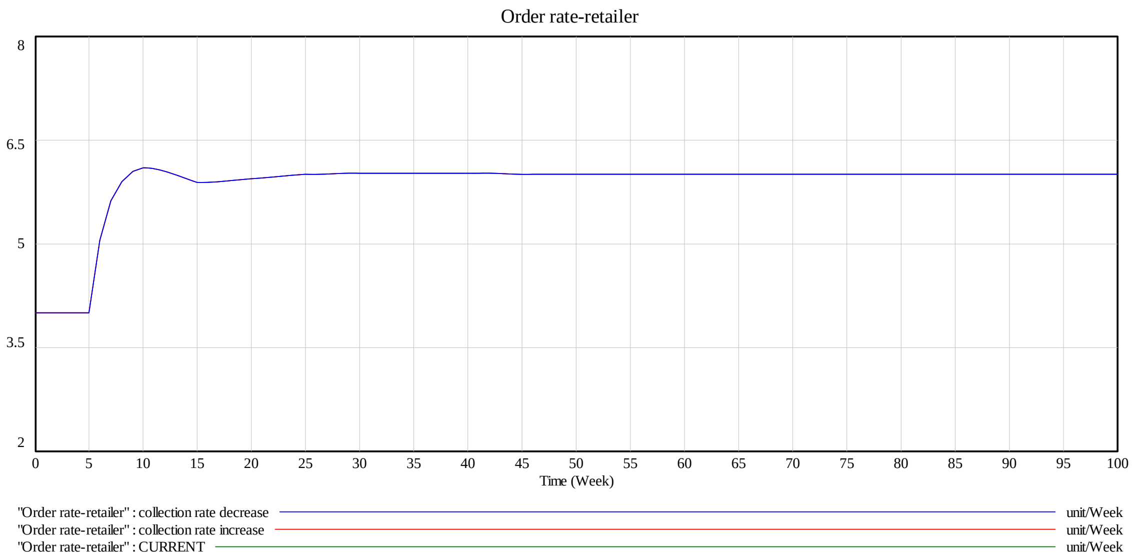


Fig.10 Order rate-retailer when collection rate change in the closed loop supply chain

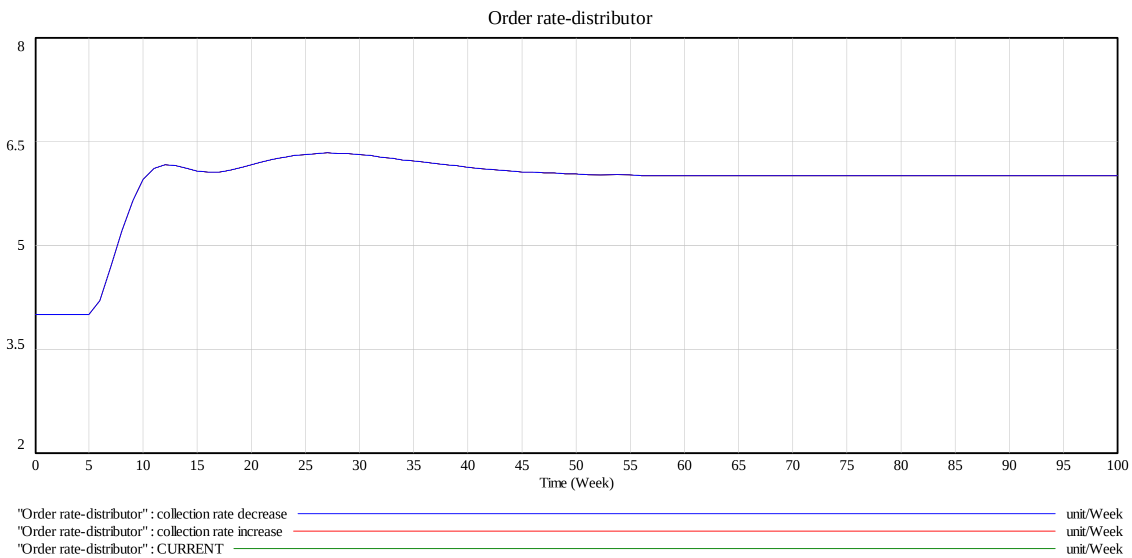


Fig.11 Order rate-distributor when collection rate change in the closed loop supply chain

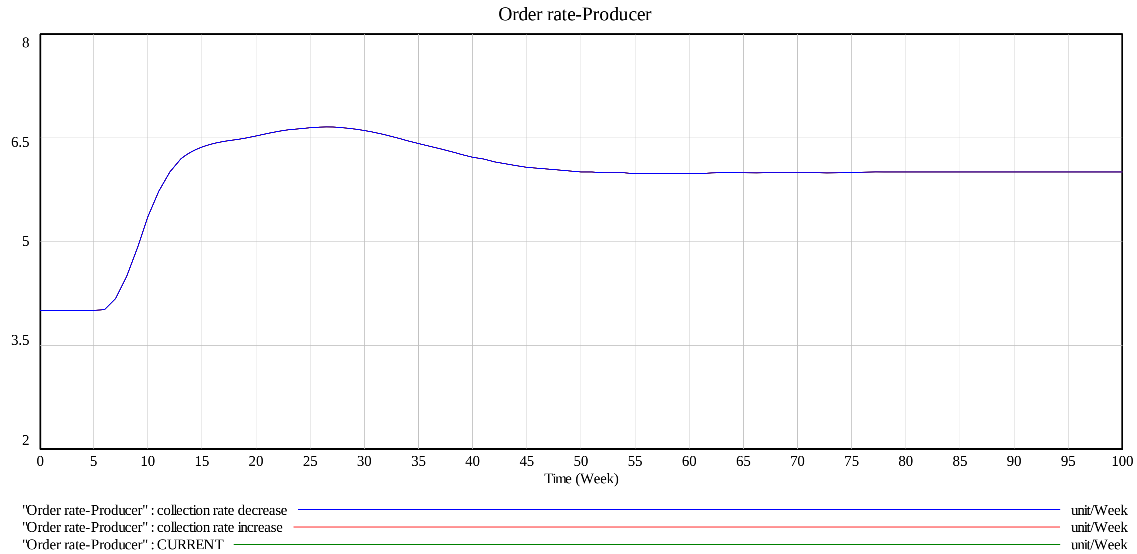


Fig.12 Order rate-producer when collection rate change in the closed loop supply chain

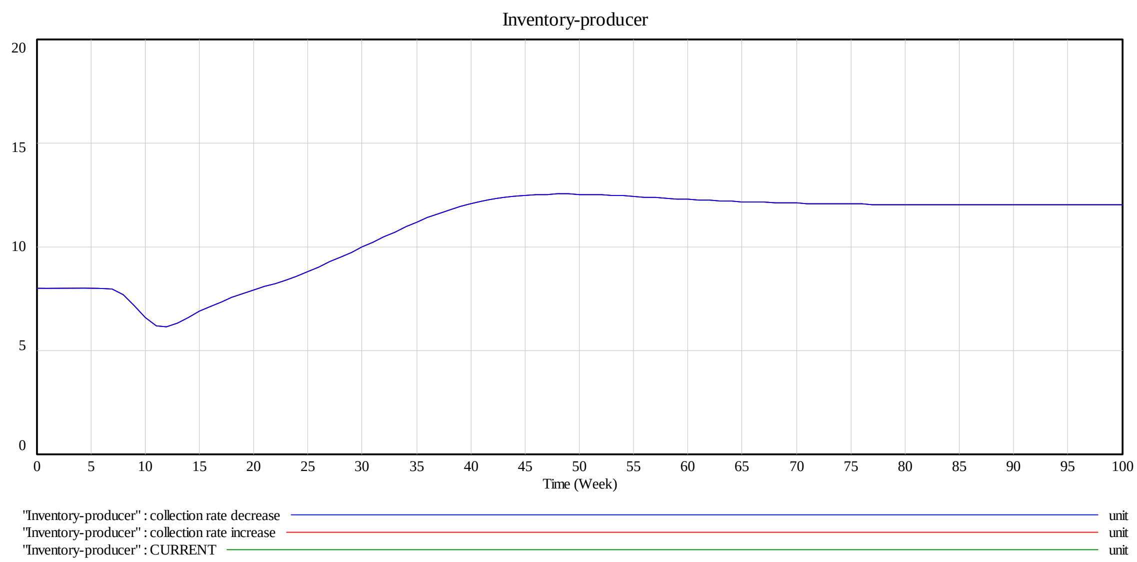


Fig.13 Inventory-producer when collection rate change in the closed loop supply chain

Thirdly, we changed the short-term lead time for remanufacture which is remanufacturing cycle time and the long-term lead time for remanufacture which is useful life. As shown in fig.14-fig.16, we can find that the long-term lead time for remanufacture has not any influence on the bullwhip in closed loop supply chain.

Because the remanufacture start rate is determined by the remanufacture capacity, indicated production rate and reusable products. And the useful life has little effect on the remanufacture start rate which is the neck between the forward supply chain and the reverse logistics. But the remanufacturing cycle time effects on the bullwhip. The longer short-term lead time for remanufacture produces the bigger bullwhip in the closed loop supply chain because of the delay which is the source of the oscillation increases. For the variance of inventory, while the remanufacturing cycle time increases, it increases in first two stages but decreases for the producer stage, because that remanufacturing cycle time increases means the lead time of whole system increase so the oscillation increases, but for producer it means that the adjustment time of pipeline is too short to smooth.

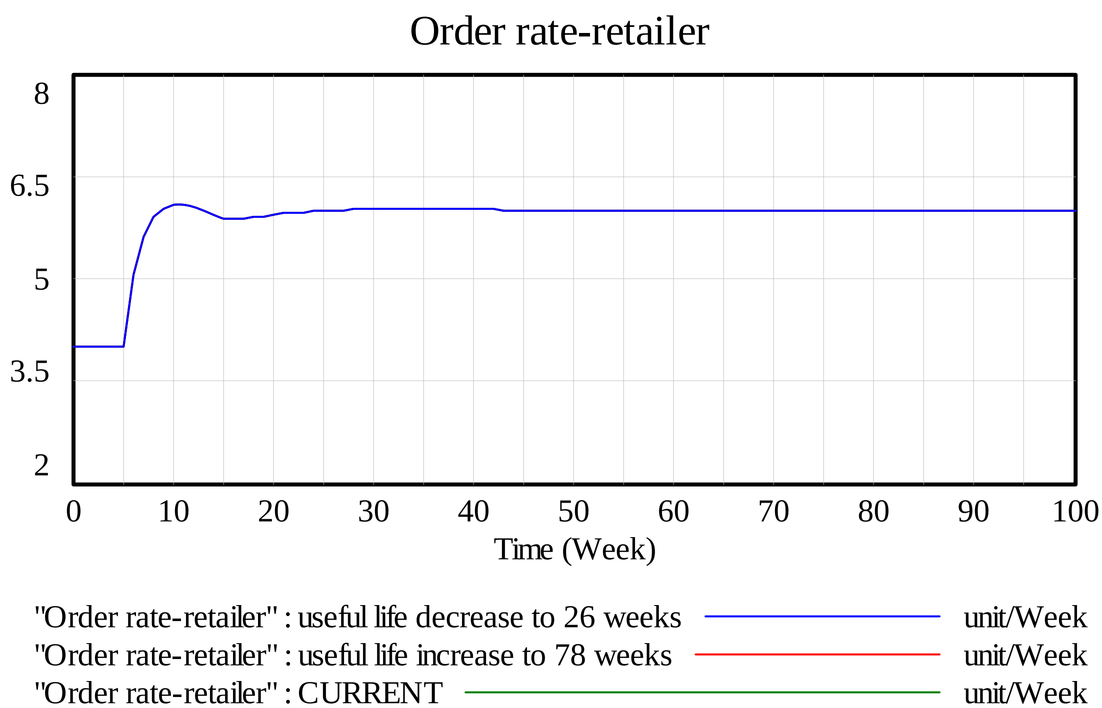


Fig.14 Order rate- retailer when useful life change in the closed loop supply chain

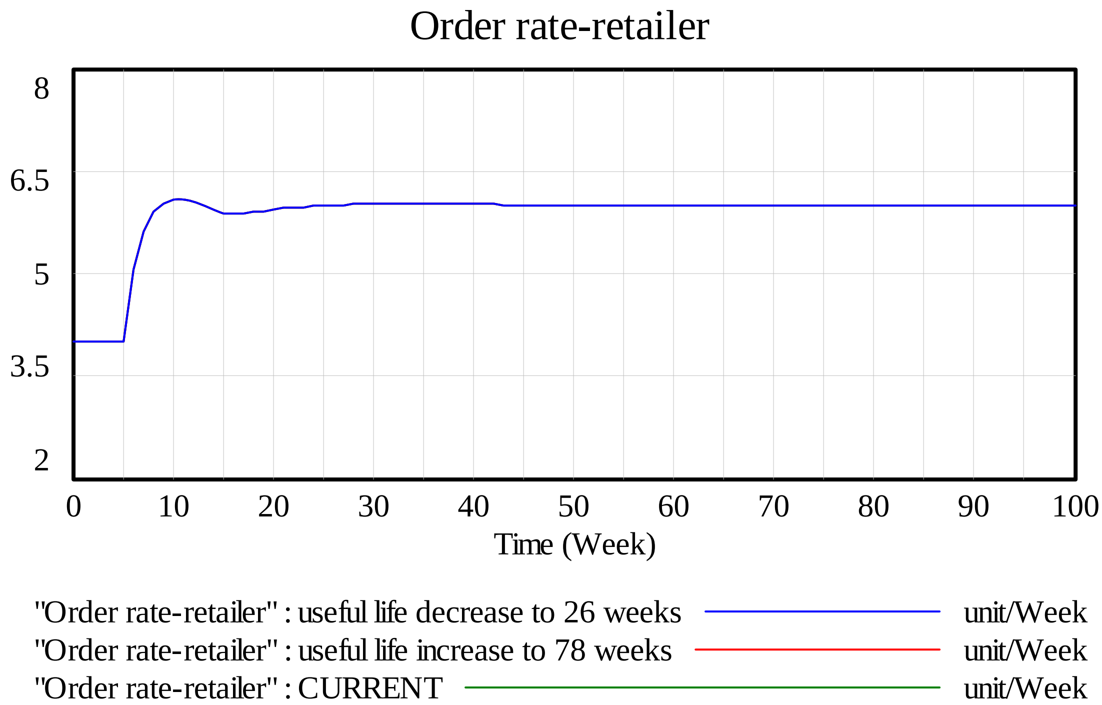


Fig.15 Order rate- distributor when useful life change in the closed loop supply chain

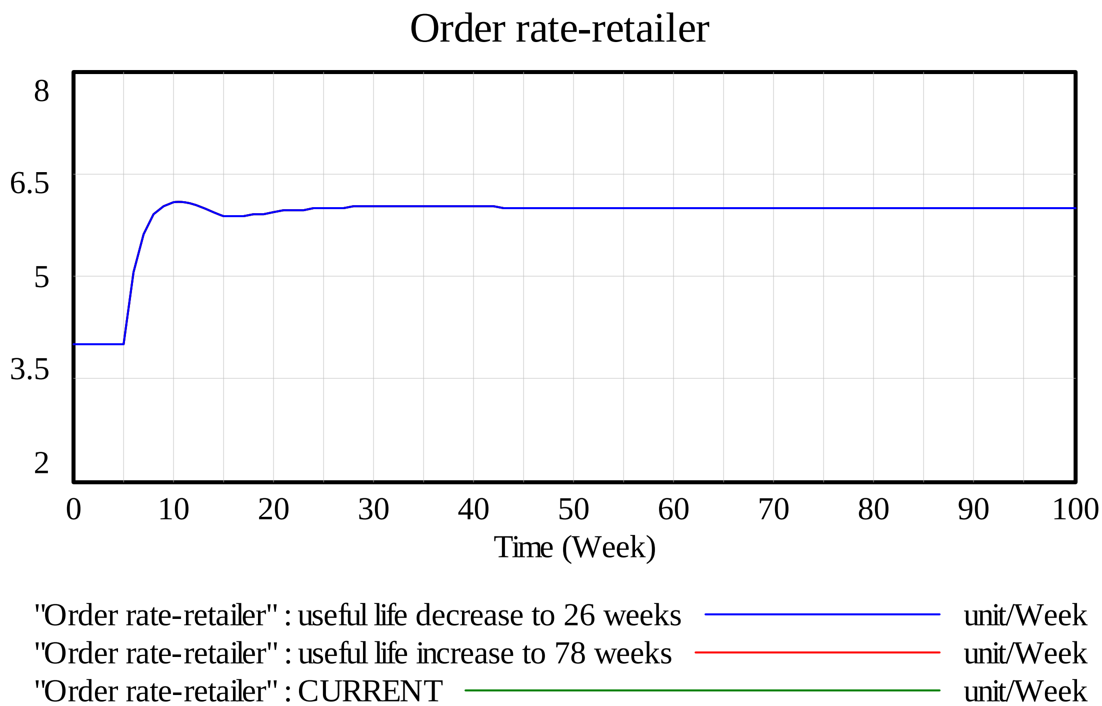
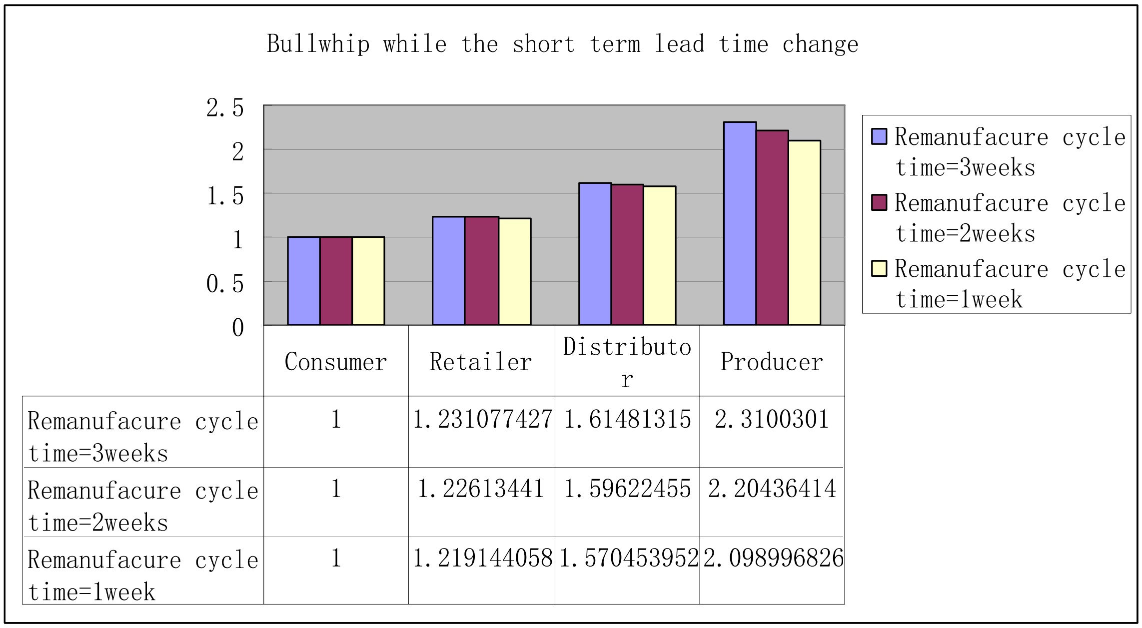


Fig.16 Order rate- producer when useful life change in the closed loop supply chain



	Consumer	Retailer	Distributor	Producer
Remanufacure cycle time=3weeks	1	1.231077427	1.61481315	2.3100301
Remanufacure cycle time=2weeks	1	1.22613441	1.59622455	2.20436414
Remanufacure cycle time=1week	1	1.219144058	1.570453952	2.098996826

Fig.17 Bullwhip while the remanufacture cycle time change in the closed loop supply chain

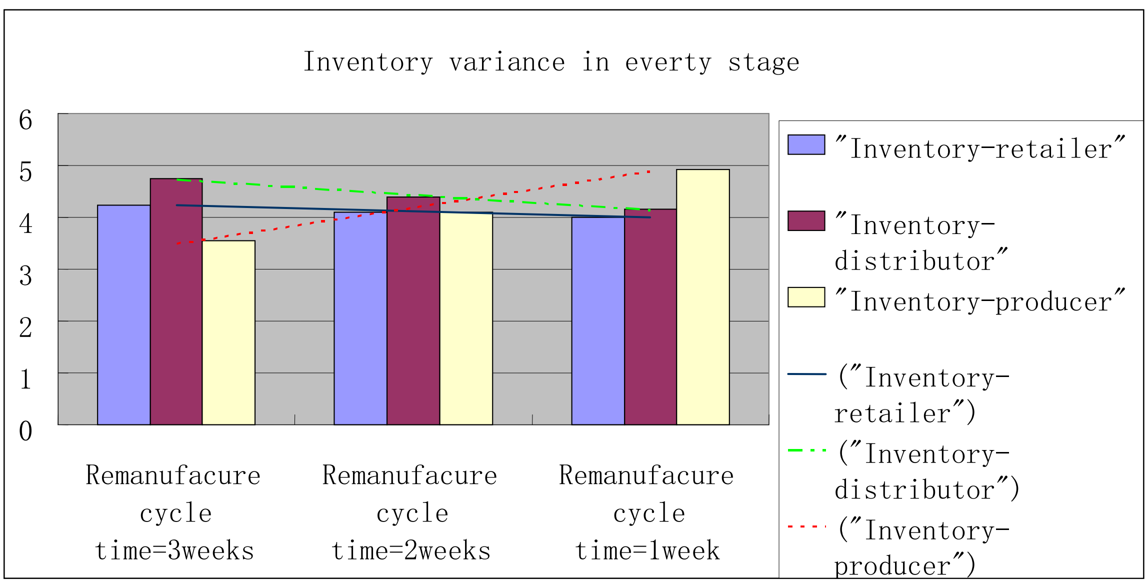


Fig.18 Inventory variance while the remanufacture cycle time change in the closed loop

5. Conclusions

5.1 Major finding of the research

In this paper, we have studied the bullwhip effect in traditional supply chain and closed loop supply chain that reclaims product to as good as new. The findings in my specified case are:

- The bullwhip in closed loop supply chain is bigger than that one in traditional supply chain and independent of the collection rate and the inventory variance in every stage decrease when the remanufacture are introduced into the traditional supply chain. These are in contrast to my intuition and the findings in Zhou et.al. (2006) which shows inventory variance and bullwhip is always less in supply chains with returns than supply chains without returns and a larger return rate leads to less bullwhip and less inventory variance in the plant producing new components.
- The bullwhip effect in the closed loop supply chain increases when the short term lead time of remanufacture becomes longer and is foreign to the long term lead time of remanufacture. This is in contrast to Tang and Naim (2004) showed that both these two lead-times are the same in the reverse loop and their impacts on the system dynamics performance. And while the remanufacturing cycle time increases, inventory variance will increase in first two stages but will decrease for the producer stage.

5.2 Limitations of the research and future work

Even we got some findings in our model, there are some limitations. But some other important things such as the capacity limit of the producer, the worker force, the remanufacture products effect on the demand in the market, the competitor of the supply chain, the quality question in the supply chain, the batching order and so on, were not studied here.

All these limitations are waiting for the future work.

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