# Policy for Weakening the Bullwhip Effect from Mental Perspectives

## -A System Dynamics Based Study



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# Abstract

The bullwhip effect, which is a typical dynamic problem in the supply chain system, was identified over half a century ago. Numerous studies have been undertaken to investigate the cause and the corresponding solutions of it. This thesis aims at investigating the impact of different ways to think about the decision making and the consequences this has for the performance of a supply chain. The first part, i.e. the literature review, summarizes previous studies of supply chain management and the bullwhip effect. It draws upon insight from the myriad of authors in the literature as well as personal reflections. Three beer game experiments are being presented: the traditional beer game; one where participants hold in-transit stock information; and one where participants hold supply line inventory information. When presenting the beer game model, the causal relationships governing the beer game is being discussed as well. The findings of the proposed simulation model are consistent with the results obtained from the experiments. Two groups of policies are discussed in detail, i.e. policies on the information availability, and policies on the utilization way of the information. Guidelines are provided on how the adverse effect of the bullwhip effect can be minimized, if not avoided.

**Keywords:** *information utilization, supply line, perceived delivery delay, degree of sensitivity, degree of aggressiveness, bullwhip effect, beer game, system dynamics*

## Acknowledgements

I here will express my heartfelt gratitude to my respected supervisor Prof. Pål Davidsen. He devoted much attention to guiding my thesis and provided important suggestions, valuable comments, and most important, kindness and encourages. Besides, Pål is a very organized and rigorous professor, I enjoyed his lectures very much during the first year study and surely learned a lot from them, which paved a solid foundation for my research.

Even now I clearly remember the moment when I received admission letter from system dynamics through email. I was busy in writing my thesis with system dynamics in Shanghai at that time. Sincere thanks to Prof. Jac Vennix and Prof. Carmine Bianchi and any other faculty members for offering such a high level program in system dynamics to us.

I also want to express my thanks to all the teaching assistants for their guidance. During the two years study in Europe, I made many new friends from different countries who share many good memories with me.

Finally, I would deliver my truehearted appreciation and love to my family. Without their unconditional love, comprehension and support, I cannot make it happen at all.

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# Chapter 1 Introduction

1.1 Title

This thesis is aimed at studying the impact of decision making processes on the bullwhip effect in a four-sector supply chain system. The research question is "How the performance of supply chain could be improved by way of two different information and three different information utilization policies?" I. e, can we find a robust policy to reduce the bullwhip effect. This thesis includes theoretical study, experimental studies and a model based simulation study.

1.2 Objectives of the Study

Lee et al. (1997a) proposed that the bullwhip effect is the phenomenon of demand distortions that the variance of supplier's order received is larger than the variance of end-customer's needs. In addition, this distortion will be amplified from downstream to the upstream, i.e. the variance amplification phenomenon.

Numerous scholars have attempted to explain the reasons for the bullwhip effect, but these explanations have not been sufficiently comprehensive. In combination with systems thinking in operation management research, Lee (1997b) studied all the aspects of the supply chain as a whole and identified four main reasons for the bullwhip effect: 1) demand forecast updating, 2) batching of order, 3) price fluctuation, and 4) rationing and shortage gaming. In this research we intend to gain more insight into the mechanism underlying the formation of the bullwhip effect based on this, to design mitigating policies, and to offer a sustainable structure of the supply chain

system tested using "What-if" scenario analysis. The performance indicators we use are the cumulative cost and the amplification ratio of ordering, which is the ratio of the maximum change in the order placed rate to the maximum change in the customer demand rate. The inventory and backlog are also being analyzed to investigate the structure of the cumulative cost. The major contents in this study are listed as follows:

(1) Based on the existing literature, this study analyzes the characteristics of supply chains and the causes and corresponding solutions of the bullwhip effect. Hypotheses will be proposed to explain the behavior generated in the beer game experiments. I will analyze the causal relationship in the beer game, expressed in a causal loop diagram, and complete my description of the basic loop structure of the system;

(2) Based on the foregoing analysis, I will build system dynamics models to analyze the mechanism underlying the behavior of in the beer game. I will test the models in the context of various scenarios in which the participants have access to various types of information, and evaluate the impact on the bullwhip effect resulting from different policies, designed to enhance the performance of the supply chain.

1.3 Significance of this Study

The bullwhip effect has been known for over 50 years to exist as a behavior characteristic of supply chains. This effect adversely impacts the fluctuations that typically are exhibited by the effective inventories in such chains. Decreasing the bullwhip effect may thus be advantageous. Many researchers have studied the causes and the solution to bullwhip effects. Even though the technical solution has been implemented, the attitude of people towards the problem and their decision is still different, which in turn would has impact on the effect of policy implementation unconsciously.

## 1.4 Conceptual Model
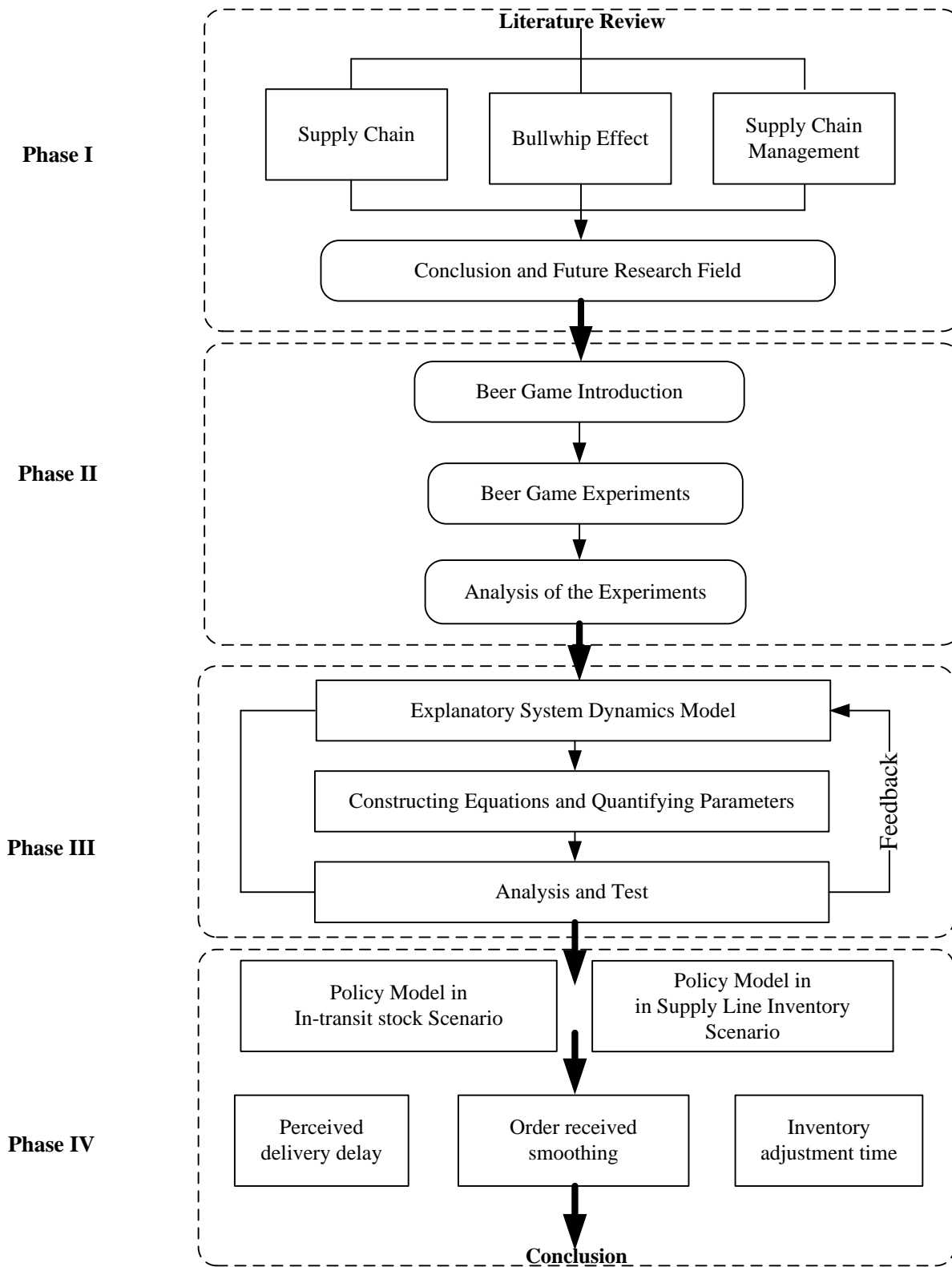


Figure 1- 1 Conceptual model

Phase I is the part of literature review, including three parts: supply chain, supply chain management and the bullwhip effect.

Phase II is about the beer game experiments. I will introduce the beer game first, and then present the three experiments I have done with the corresponding analysis.

Phase III is the explanatory modeling part. Both the qualitative and the quantitative model would be presented here. The model would be validated with three tests: the extreme condition test, the structure-behavior test and the parameter sensitivity test.

Phase IV includes three parts. The first part is about the policy on the information, and I will compare two types of information, i.e. in-transit stock information and supply line information here. The second part is about the policy on the way of information utilization, and I will introduce three policies: policies governing the perception of delivery delays, the estimation of orders received, and the time to adjust inventory. The last part is the conclusion.

# Chapter 2 Review of Literature

2.1 Supply Chain

The concept of supply chain is based on the theory of Michael Porter's (1985) value chain theory. Ganeshan and Harrison (1995) defined it as "A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers." In addition, Lee (1992, 1997b), Stevens (1989), and Reutterer and Kotzab (2000) also introduced many definitions with different focal point and scope.

Compared with the traditional business which the producer sold products to the customer directly, though the supply chain has more sectors between the producer and the end-customer, the supply chain does not decrease the efficiency of the economic activities. On the contrary, it would be much ineffective without the supply chain in modern society. The price of the product increases from the producer to the retailer step by step. However, it is uneconomical for the customer to purchase from the producer directly, since in this way the customer needs to pay additional cost, such as contact fee and delivery fee, and the total cost may even higher than the price offered by the retailer. Additionally, the customer has to wait for production and delivery, while he/she could have bought from the retailer immediately. On the other hand, the producer will not achieve the economic scale if the products are sold to the customer directly.

## 2.2 Supply Chain Management

Christopher (1992) described that supply chain management covers the process from suppliers through the manufacturer and distributor and finally reaches the consumer. Houlihan (1987) noted that supply chain management is by using the industrial dynamics techniques to deal with the physical distribution and transportation operations. Thomas and Griffin (1996) went further, defined supply chain management as material and information flow management within and between organizations. Stern et al. (1996) considered supply chain management as a new pattern of service and information flow management from the material source to the client. Stevens (1989) defined supply chain management from the perspective of information, in other words, it is a mixture of supply, procurement, inventory, capacity, delivery, customer service based on the feedback of material and information flow. Lambert (1998) further noted that it also includes cash flow and ownership flow integration.

## 2.3 Bullwhip Effect

### 2.3.1 Existence of the Bullwhip Effect

Scholars have demonstrated the existence of the bullwhip effect by using mathematical models. The core areas involved in this process include the ordering policy and demand estimation.

Many scholars have used ordering policy (s, S) to demonstrate the existence of the bullwhip effect. Blinder (1981) first used this method and proposed a probable explanation for retailers' behavior patterns observed through an inventory control strategy econometric model. Caplin (1985) assumed that retailers continuously monitor their inventory levels, and he showed that the bullwhip effect exists both in the case of purchase order with a single retailer and aggregate orders with multiple retailers.

There are also various studies from the perspective of demand estimation. Lee et al. (1997a) researched the bullwhip effect in relation to multiple retailers' allocation gaming and three different ordering time (balanced, synchronized and random) as well as price fluctuations under the premise of the supplier's stock-out. Chen et al. (2000a) proved the effect of demand forecast on the bullwhip effect. He not only verified the existence of the bullwhip effect in a theoretical way, but also quantified its amplification at every sector. Lee et al. (2000) proved that the bullwhip exists regardless of whether demand information error is shared.

*2.3.2 The Negative Effect of the Bullwhip Effect*

Previous studies have proven the existence of the bullwhip effect and discussed the factors involved. Bullwhip effect can lead to stock-outs, large and expensive capacity utilization swings, lower quality products, and considerable production/transport on-costs as deliveries are ramped up and down at the whim of the supply chain. Metters (1997) quantified the bullwhip effect, describing its impact on a company's financial performance. He expressed the hope that people could realize its adverse effects on firm performance and take measures to weaken the effect. His work proved that the bullwhip effect has significant impact on a company's earnings.

The supply chain bullwhip effect causes upstream and downstream enterprises to have different perceptions about market demand. It has a significant negative effect on all suppliers, manufacturers, distributors, wholesalers, retailers, and customers. For suppliers and manufacturers, the bullwhip effect is likely to create the illusion of increased demand and lead manufacturers to expand their production capacity, which results in a low utilization rate of capacity. The bullwhip effect is one of the contributors to the blind investment in a hot industry. The production plan has to be changed frequently, and the corresponding cost increases. For distributors, wholesalers, and retailers, the direct impact is the excess inventory and occupied cash

flow. These parties also face issues related to the expiration date of the product. For clients, their demand cannot be satisfied effectively. Furthermore, all those additional cost of the entire supply chain will ultimately cause the increasing of the price undertaken by the customer.

*2.3.3 Cause and corresponding solution of the Bullwhip Effect*

Various studies emphasized the importance of collaboration in the supply chain (Mason-Jones & Towill, 1999; Towill, 1991 & 1992; Taylor, 1999 & 2000). They typically pay great attention to the structure of the supply chain, and suggested that information integration could alleviate the bullwhip effect. New supply chain management techniques have been proposed to integrate the supply chain, such as QR (Quick Response) ( Iyer A. V., 1997), ECR (Efficient Consumer Response) (Buzzell, R. D., & Ortmeyer, G., 1995), VMI (Vendor Managed Inventory) (KaiPia R., Holmstrom J. & Tanskanen K., 2002), CPFR (Collaborative Planning, Forecasting & Replenishment) (Holmström J, Främling K, Kaipia R, & Saranen, J., 2002).

However, they pay more attention to the technology, rather than to the decision-makers who use the technology. Participants' performances are quite different in practice, though they can have the same kind of technology. Bullwhip effect arises also because of the human decision making. In beer game, participants only need to make one decision, i.e. placing the order. Ordering consists of two parts: demand estimation and inventory adjustment.

Many scholars have studied the information utilization in demand estimation (Forrester, 1961; Baganha MP & Cohen MA, 1998; Kahn J., 1987; Lee H., So Kut C. & Tang Christopher S., 2000; Graves S C., 1999; Gunasekaran, A., & Ngai, E. W., 2004). Chen et al. (2000a, 2000b) proved the effect of demand forecasting on the bullwhip effect and quantified the amplification in every stage. They analyzed the effect of different demand forecasting techniques on the bullwhip effect and suggested

that the bullwhip effect could be weakened by adjusting the demand forecasting algorithm while based on same kind of order received information.

In the inventory adjustment field, Mosekilde and Larsen (1988) proved the variability of dynamic behavior depending on the order policy, but did not fully examine the reasons of the bullwhip effect. Their research shows the importance of the supply line. Croson and Donohue (2006) found that decision makers consistently underweight the supply line when making order decisions. Another possible reason is the overestimation of the delivery delay in the supply chain (Forrester, 1958 & 1961; Blackburn J.D., 1991; Cachon G. P., 1999).

Blanchard (1998) noted that the degree of aggressiveness in inventory adjustment may be the main factor leading to unbalanced inventory behavior. He examined data on the U.S. auto industry and found that even if seasonal factors are under control, production variability remains considerably greater than the fluctuation in sales. He found that the underlying cost structure appears to include substantial costs for changing production as well as substantial costs for being away from the target inventory. The former situation leads to production smoothing, and the latter is unstable.

# Chapter 3 Beer Game Experiments

3.1 Beer Game Hypothesis

Sterman (1989a) noted the common behavior that participants tend to determine order placed according to their own inventory in hand minus undelivered demand; they forget to consider the beer in the supply line (orders in the supply line are the orders that have been placed but not received; according to inventory theory, participants should use the sum of the inventory in hand and in the supply line minus the undelivered demand to determine their order placed). This irrational decision making causes the enormous variability in the demand information.

Larsen et al. (1999) found that participants apply simple rules for making ordering decisions when playing the game. Some participants consider the inventory on the supply line, whereas others may ignore or forget it. Mosekildes et al. (1991) demonstrated that more complex forms of chaos occur when an aggressive stock adjustment policy with low desired inventory and a tendency to neglect supply line adjustments is applied. Croson and Donohue (2003) found that determining the pattern of consumer demand did not significantly weaken the bullwhip effect. Croson et al. (2004) found that there was no significantly improvement even if the demand remained constant and known to all. Estimation results showed that subjects significantly underestimated the supply line.

Another interesting point is that people do not improve their performance after playing repeatedly. Supply line underestimating, which is sufficient to cause instability (Sterman, J.D., 1989a, 1989b, 2000), persisted even when subjects were allowed to play a second time. Diehl and Sterman (1995), Wu and Katok (2005), and Paich and Sterman (1993) have shown that learning from repeated play in the beer game and related dynamic decision making tasks is slow and uneven.

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There are four steps in human decision making process (figure 3-1). Decision makers also follow this process when they are making ordering decision in beer game.
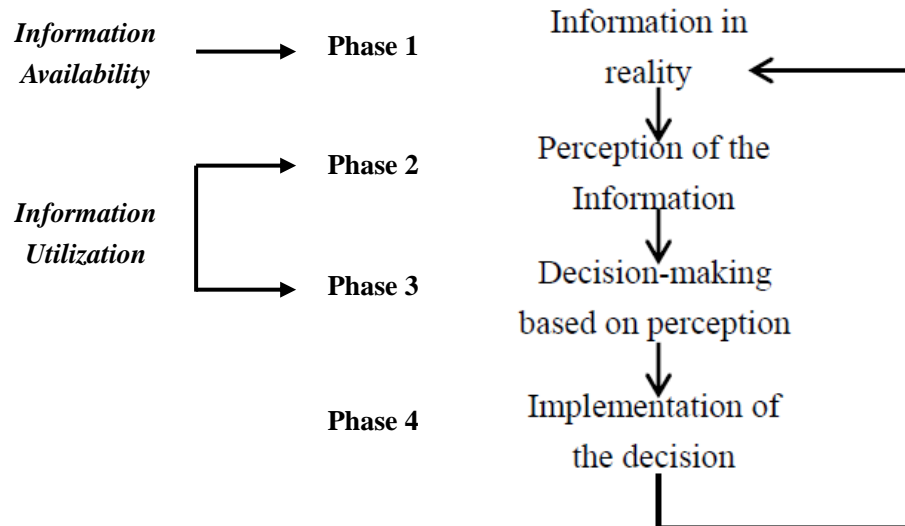


Figure 3- 1 Four steps in human decision making

The hypotheses are as follows:

1. Additional supply line information may weaken the bullwhip effect, and the entire supply line information is more effective than a portion of it (in-transit information).

2. The way information is utilized in the decision making process has a significant impact on the decision itself:

   2a. Information interpretation (Phase 2)

   2b. Transformation of information into a decision (Phase 3)

Using retailers as an example, the supply line information indicates the total unfilled orders, and the in-transit stock information allows the retailers to know how many products are on the way from the wholesaler, which could be considered as the information of a portion of the supply line inventory. The in-transit stock information can be considered as a portion of the supply line information.

3.2 Beer Game Experiments

*3.2.1 The First Experiment*

Three experiments were conducted in Norway, the UK and China, to eliminate the impact of cultural background. The first experiment was conducted in the University of Bergen on March 19, 2013. Eight postgraduates in system dynamics were invited to physically play the beer game.

Compared with the control group with ordinary rules, the experimental group had only one additional piece of information, the in-transit stock information. The time span of the game was planned as 36 weeks, but one participant had a previous commitment in week 35, so we ended the game then.
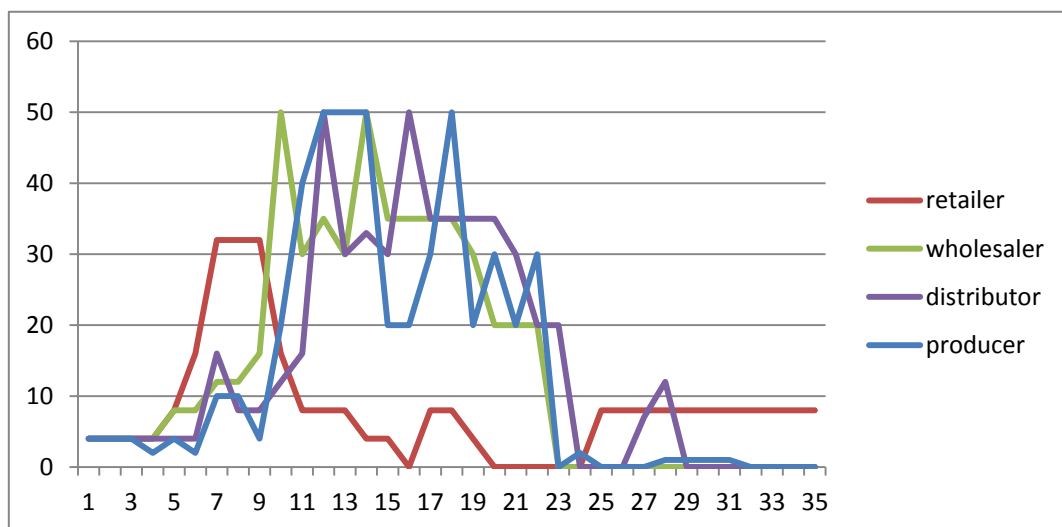


a. Order placed rate for the control group
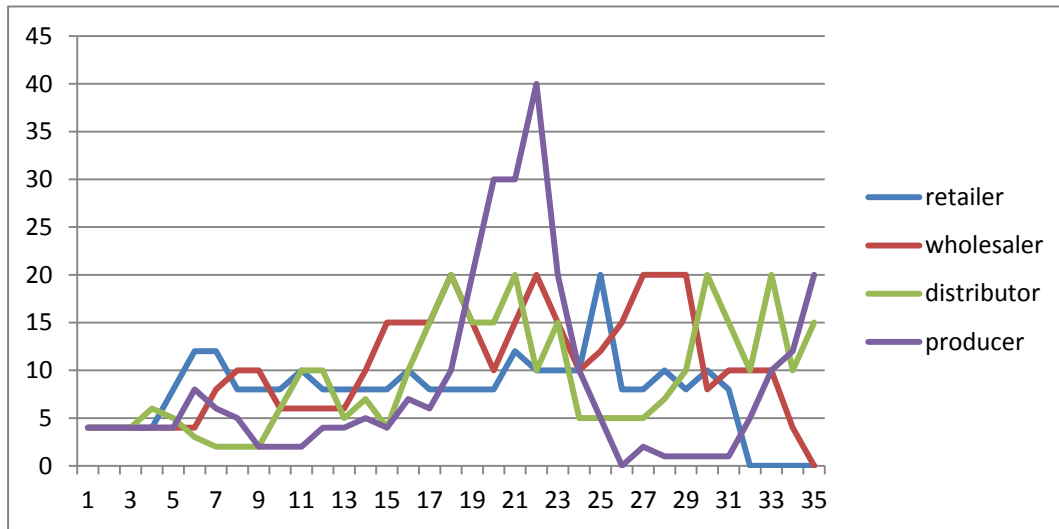
b. Order placed rate for the experimental group

Figure 3- 2 Order placed rate in the first experiment

In figure 3-2 a, we can see that the peak value of the order is 50 for the wholesaler, distributor, and producer, whereas the retailer's peak is approximately 30. However, if the in-transit information is provided, these numbers are significantly reduced. The peak value of the order is 40 for the producer, and the highest order for the others is 20. For the producer, the order is barely over 20 for a short period and then decreases and stabilizes between 0 and 20. The demand of the customer changed from 4 to 8 at week 5, a 100% step increase. The maximum change in the order placed rate of the retailer in the control group is 700% greater than the initial value, an amplification ratio of 7. Comparing the amplification ratio of the two groups, we can see that with in-transit stock information the participants do have a significant better performance.

Table 3- 1 Amplification ratios of the control group and experimental group in the first experiment

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Control Group | 1 | 7 | 11.5 | 11.5 | 11.5 |
| Experimental Group | 1 | 4 | 4 | 4 | 9 |
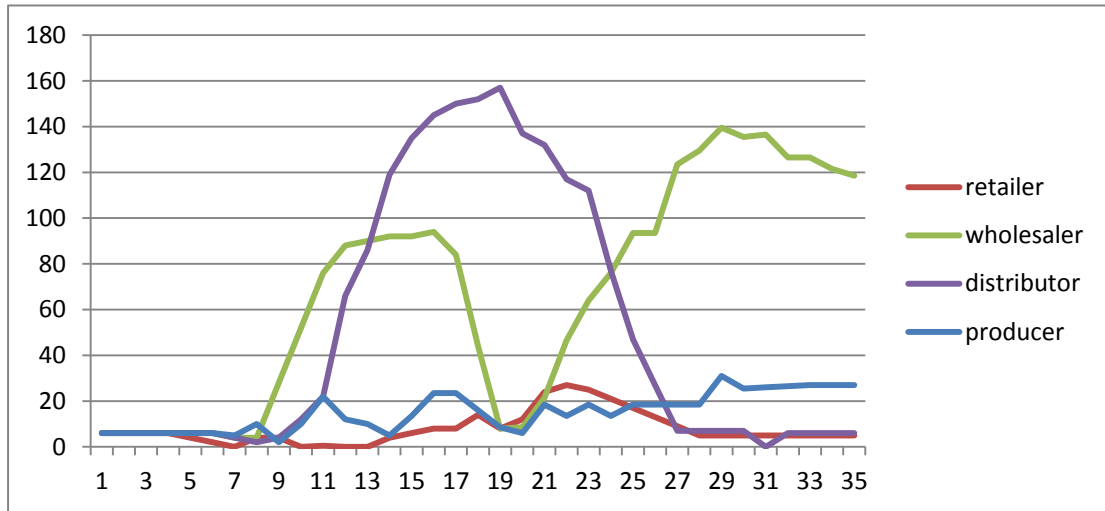
a. Cost of the control group
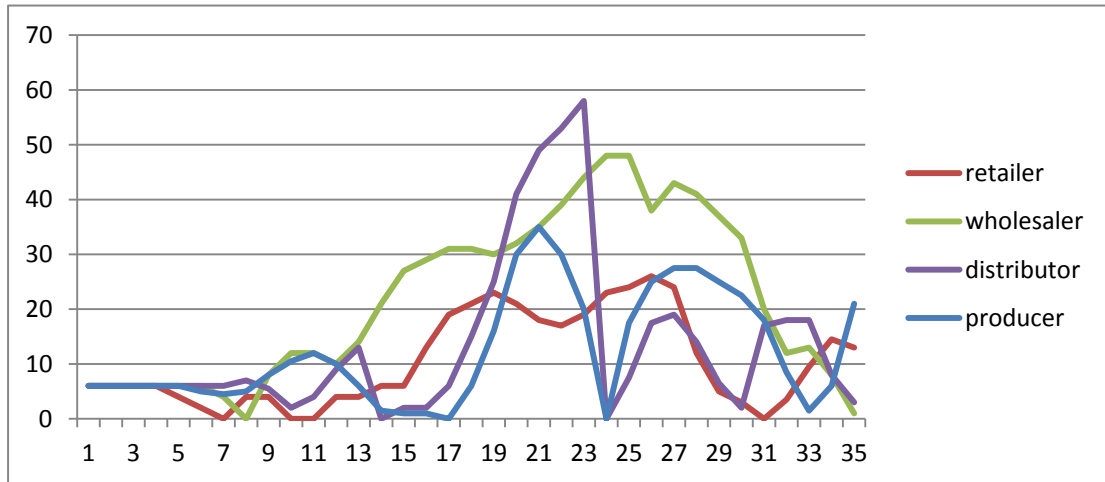


b. Cost of the experimental group

Figure 3- 3 Cost in the first experiment

Considering the costs associated with inventory holding (0.50 per case per week), the inventory level should be kept as small as possible. However, failure to deliver on request may force consumers to seek alternative suppliers. For this reason, there are costs associated with backlogs of unfilled orders (1.00 per case per week). The cost of the control group is amplified from the retailer to the distributor. Regardless of the fact that the backlog of the distributor is growing rapidly, the order placed rate do not increase significantly. Therefore, the producer can plan the production well and can keep the costs very low. For the experimental group, the cost is considerably lower for all sectors.
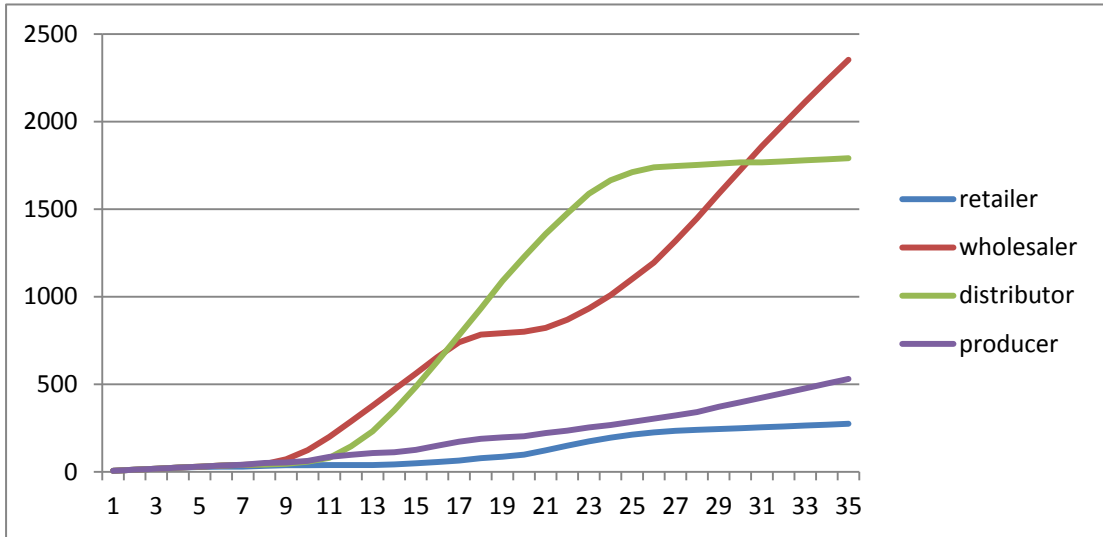
a. Cumulative cost of the control group
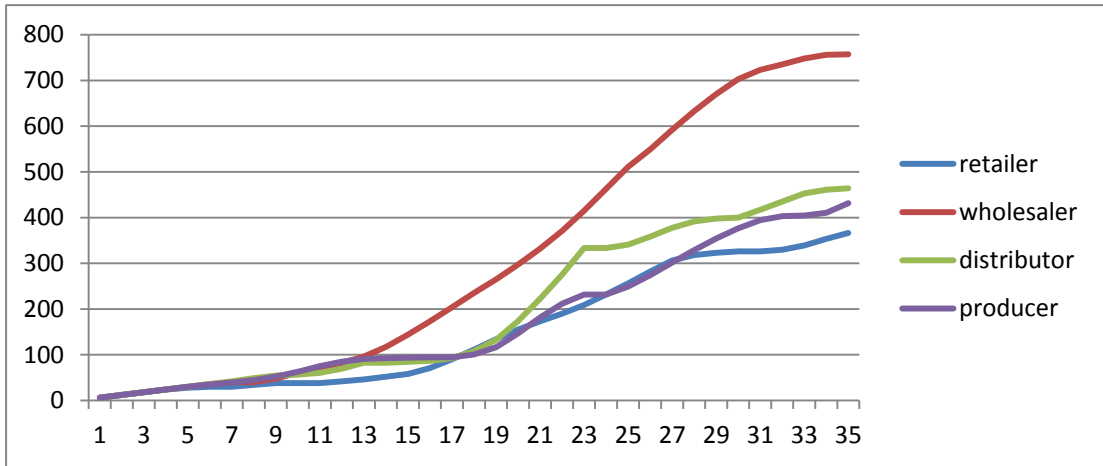


b. Cumulative cost of the experimental group

Figure 3- 4 Cumulative cost in the first experiment
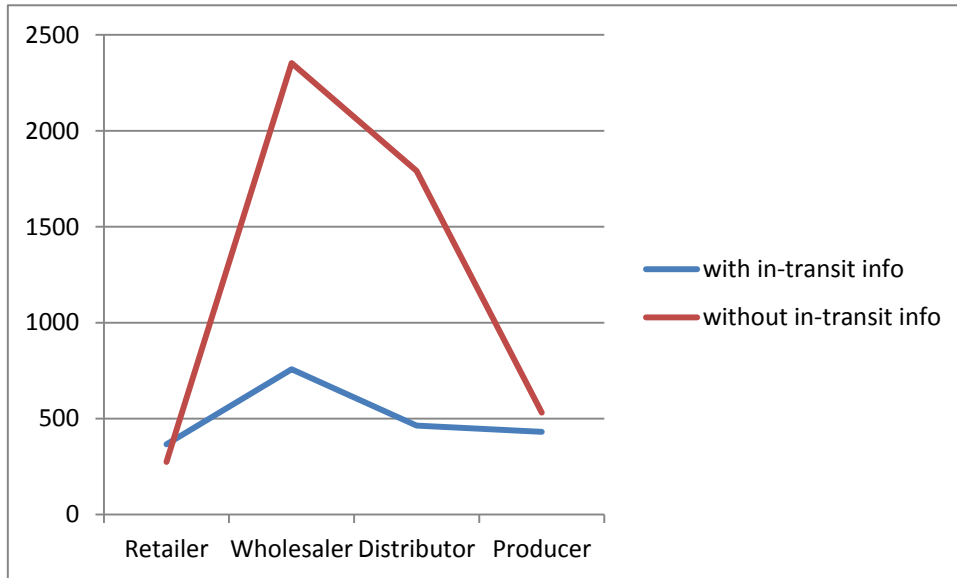
Figure 3- 5 Cumulative cost comparison for the first experiment

From figure 3-4, we can see that the general pattern of the cumulative cost for all eight participants is an S shape. The cumulative cost is stable at first, because it takes time for the upstream participants to receive the increased order from downstream participants. It also takes time for them to realize that the change is not temporary when their order received rate is high for a few more weeks, so they would make the estimation of demand based on the new perception. Later, the cumulative cost increases very fast in the game, this is because their order received rate from downstream players is increasing, while their inventory is insufficient, so the level of the backlog increases rapidly. After inventory adjustment finished, their inventory will increase to an unexpected high level. They will neither place nor receive a large order anymore, so normally neither of them will have backlog, especially when they also have a large quantity of inventory. In this way, the cost will be stable in the end.

The cost of the wholesaler in the experimental group is relatively high compared to the other three sectors in the same group. The wholesaler does not order much though the level of the backlog is high from week 9 to week 34. This decision also disrupts the intent of the producer to effectively satisfy the customer's demand, and causes the backlog of the retailer very high. Thus the cumulative cost of the retailer in the

experimental group is even higher than that in the control group. However, from figure 3-5, we can still conclude that the performance of the group with the in-transit stock information is obviously much better.

*3.2.2 The Second Experiment*

To further support this conclusion, the second experiment was conducted with eight college students from Shanghai University of International Business and Economics on March 26, 2013. This time, the game was played on a website rather than physically. (URL: http://www.masystem.com/o.o.i.s/1365).
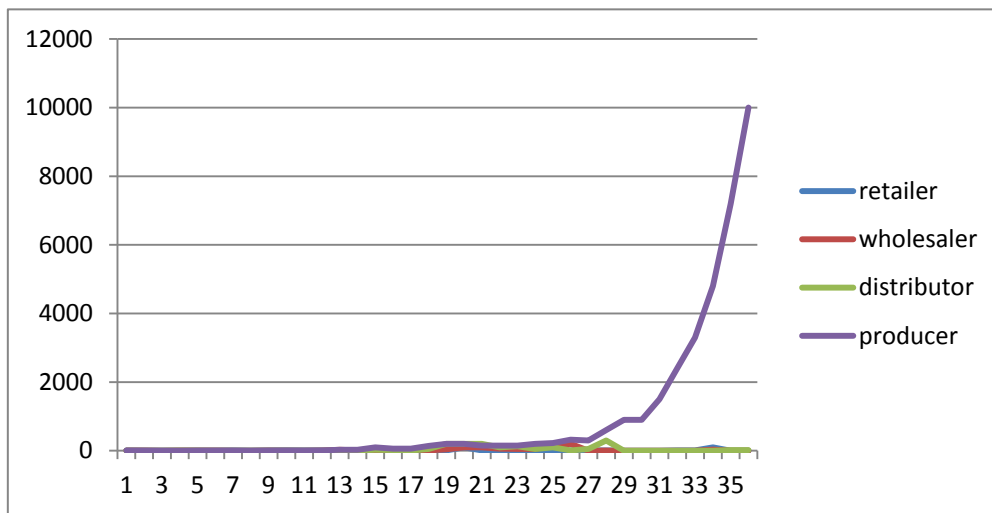


a. Order placed rate for the control group
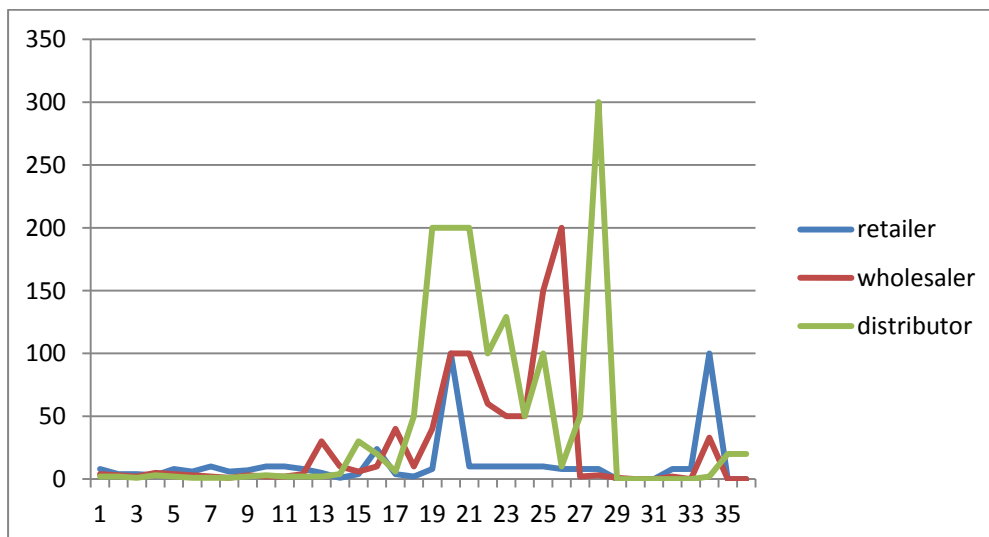
b. Order placed rate for the control group (without the producer)
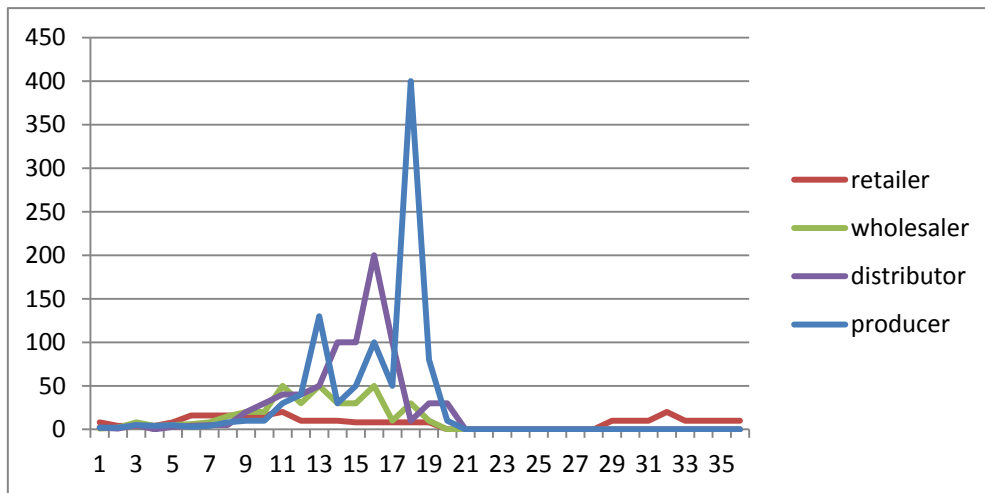


c. Order placed rate for the experimental group

Figure 3- 6 Order placed rate in the second experiment

The order placed by the producer in the control group is exceedingly high as can been seen from figure 3-6 a. The producer's order placed rate increases from 600 to 9999 from week 28 to week 36, whereas the previous peak is 300. However, from figure 3-6 b (without the producer), we can see that the order peaks for the retailer, wholesaler, and distributor are 100, 200, and 300, respectively. Again, if the in-transit information is provided, these order placed rates are significantly reduced. The order placed rate in the experimental group is also amplified along the supply chain. The order peaks are 20, 50, 200, and 400 for the retailer, wholesaler, distributor, and producer, respectively, which are considerably lower than the control group.

Table 3- 2 Amplification ratios of control group and experimental group in the second experiment

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Control Group | 1 | 24 | 49 | 124 | 2498.75 |
| Experimental Group | 1 | 4 | 9 | 49 | 99 |
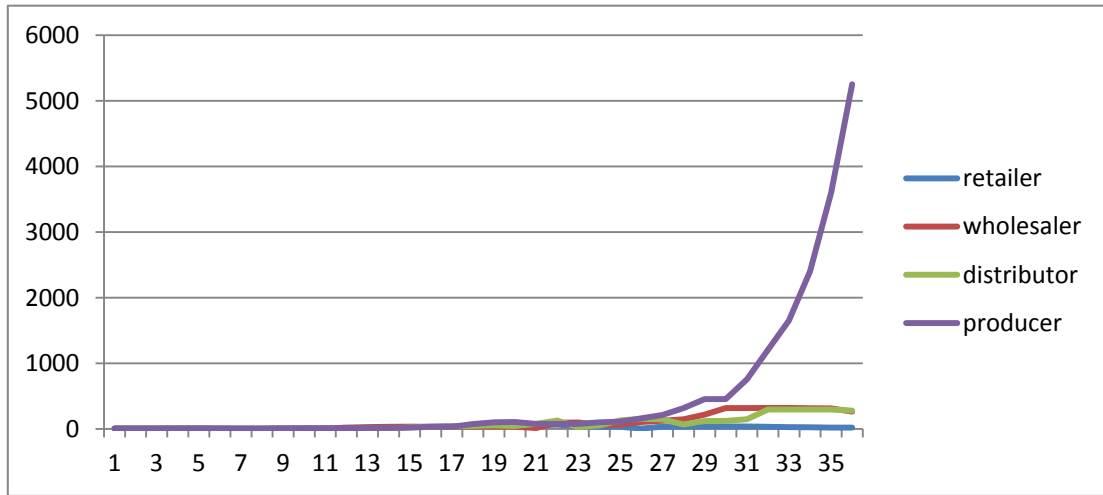
a. Cost for the control group
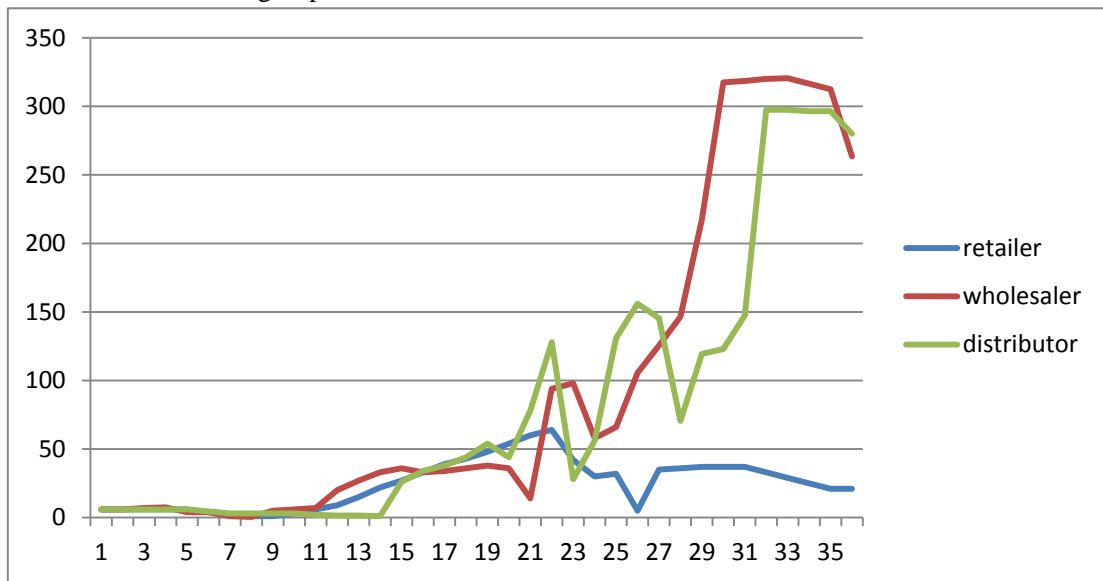


b. Cost for the control group (without the producer)
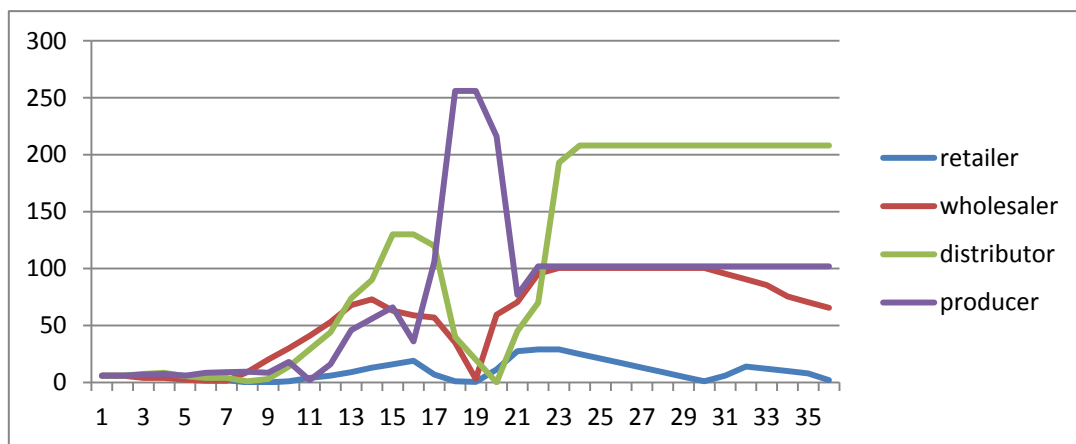


c. Cost for the experimental group

Figure 3- 7 Cost in the second experiment

The cost of the producer in the control group increases steadily from week 28. The

peak costs of the other three players are 64, 320.5, and 297.5, and the peak costs of the experimental group are 29, 100.5, and 208. The peak cost of the producer in the experimental group is only 256.

For the experimental group, the cost of the producer is higher than the distributor around week 18, but it subsequently decreases. The cost of the wholesaler increases at the same time due to the received orders from the producer. The retailer's and wholesaler's costs decrease because they receive the order. The costs of the distributor and producer are stable because the participants do not order more and because they do not receive any orders.
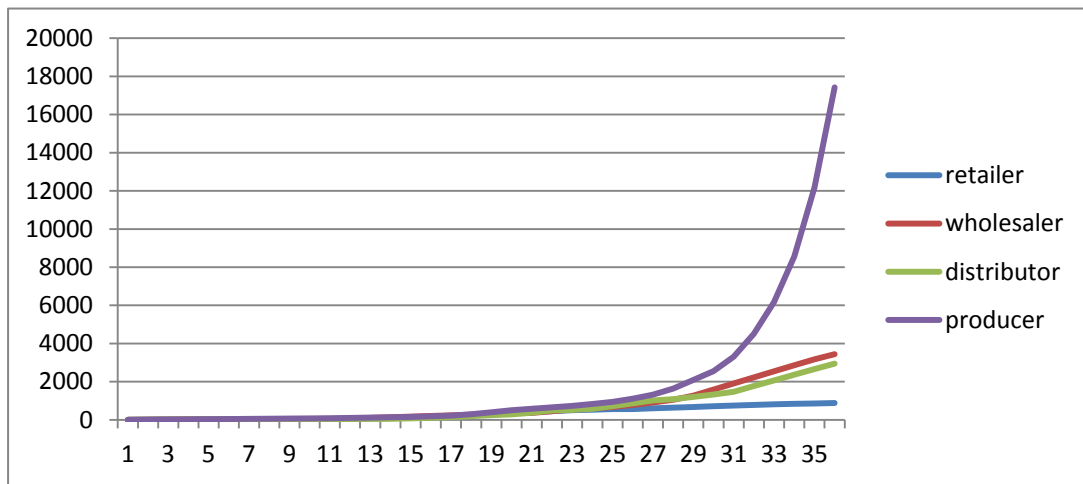


a. Cumulative cost for the control group
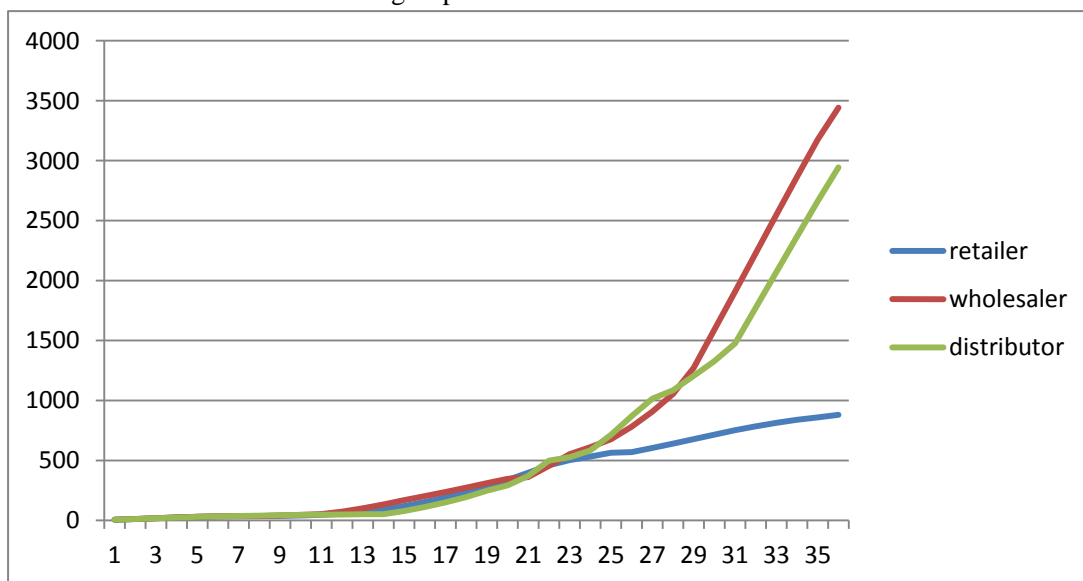


b. Cumulative cost for the control group (without the producer)
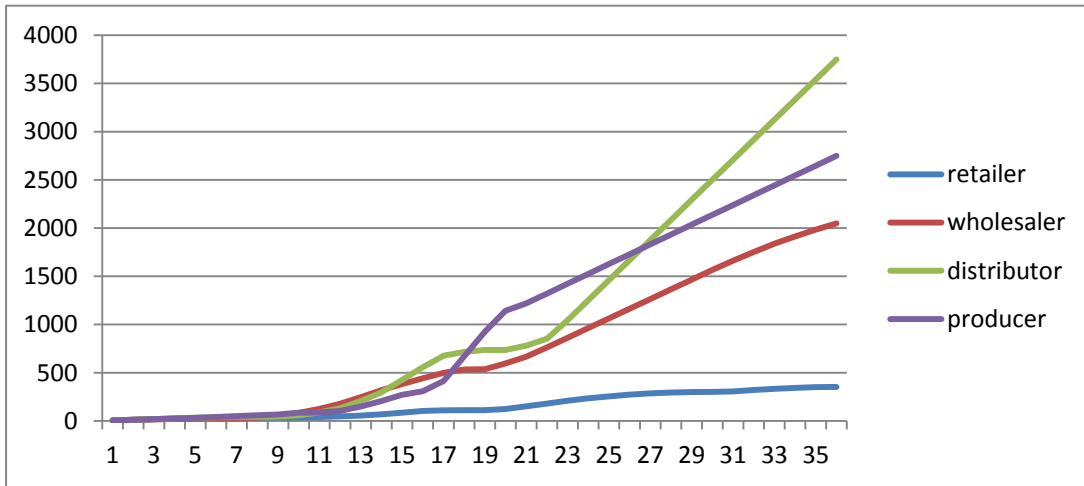
c. Cumulative cost for the experimental group

Figure 3- 8 Cumulative cost in the second experiment
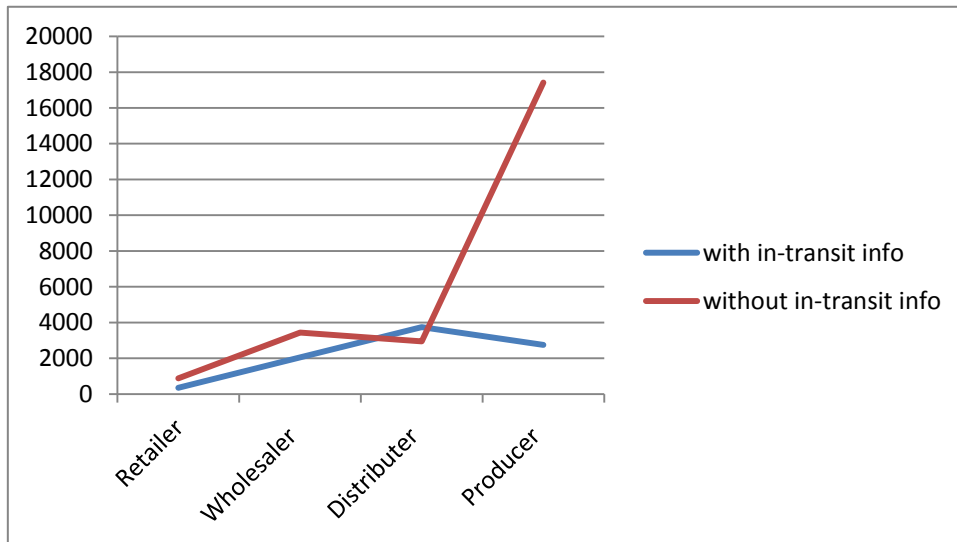


Figure 3- 9 Cumulative cost comparison for the second experiment

The overall pattern of the cumulative cost for all eight participants is also an S shape. The cumulative cost of the experimental group (with in-transit stock information) is lower than that of the control group in all sectors except for the distributor. This may be because the distributor in the experimental group had an excessive backlog from week 13 to week 17, causing the distributor to panic and to place a large order in the next week and thus remedy the situation effectively. As a consequence, the backlog of the producer also increases suddenly in the period, and the cumulative cost increases correspondingly as can be seen from figure 3-8 c.

*3.2.3 The Third Experiment*

Regardless of whether the game is played physically or on the website, in the first and second experiments we see a common result: the performance of the group with in-transit stock information is better than the performance of the control group. We now change the supplementary information for the experimental group to the supply line inventory, to compare whether the in-transit stock information is more useful. The third experiment was conducted with four college students from Beijing Jiaotong University on April 20, 2013, as the control group and four college students from the University of Huddersfield on May 22, 2013, as the experimental group. In this experiment, the game was played on the website as well. A significant difference compared with the two previous experiments was that the students were required to note their perceived delivery delay (URL: http://www.masystem.com/o.o.i.s/1365).
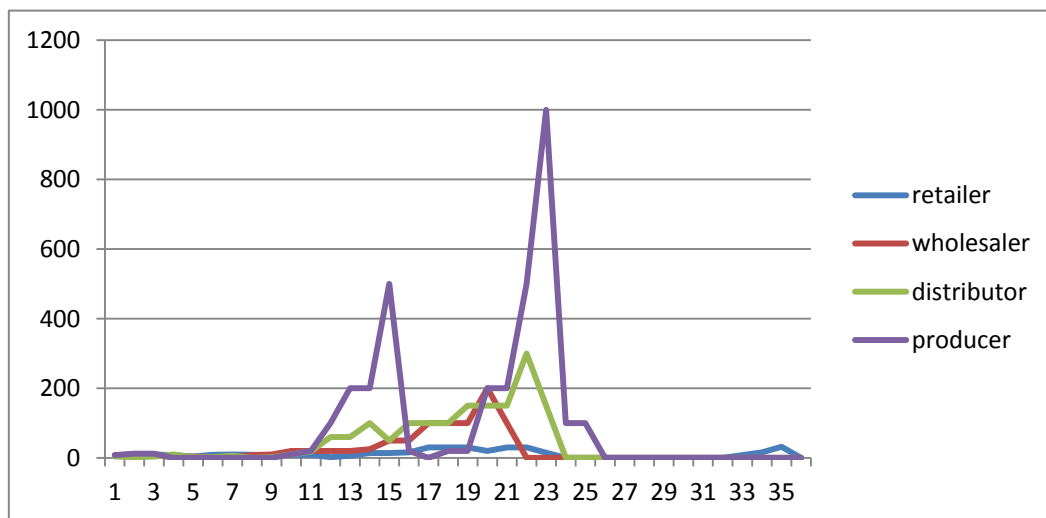


a. Order placed rate of the control group
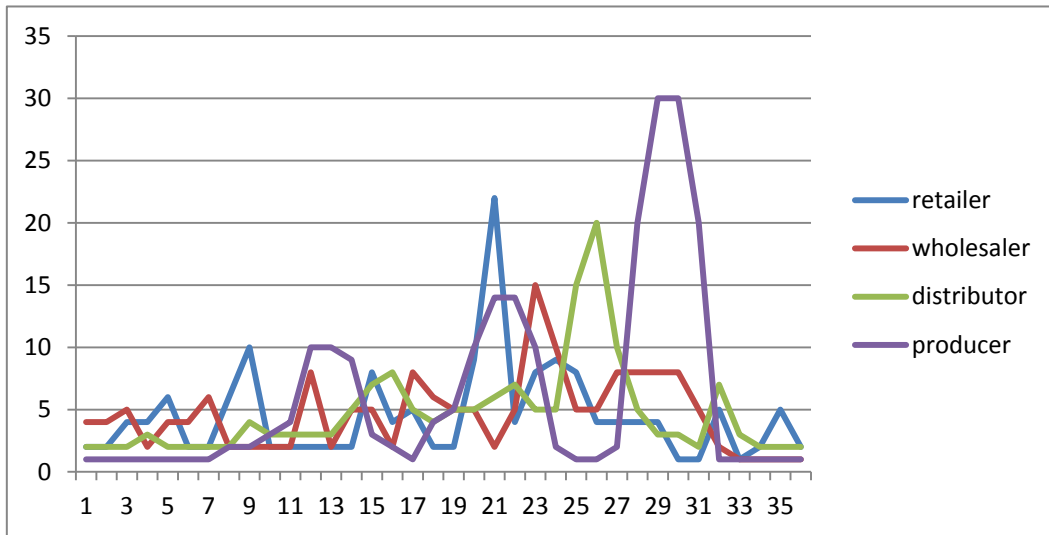
b. Order placed rate of the experimental group

Figure 3- 10 Order placed rate in the third experiment

Although the order placed rate of the retailer is relatively large once for the experimental group, we can still find that the order increases from the wholesaler to the producer. Furthermore, we can clearly see that the experimental group's performance is much better.

Table 3- 3 Amplification ratios of control group and experimental group in the third experiment

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Control Group | 1 | 7 | 49 | 74 | 249 |
| Experimental Group | 1 | 4.5 | 2.75 | 4 | 6.5 |

3.3 Beer Game Analyses

*3.3.1 Validation of hypothesis 1*

As proposed in the hypothesis, "Information availability will affect the bullwhip effect". Here we will first analyze the results based on a comparison between the second and third experiments first.
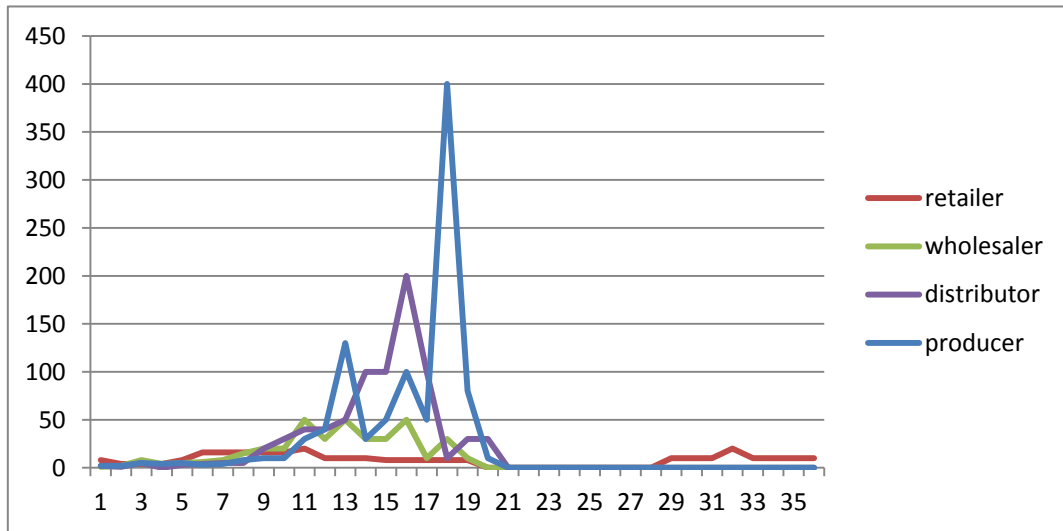
a. Order placed rate of the experimental group in the second experiment
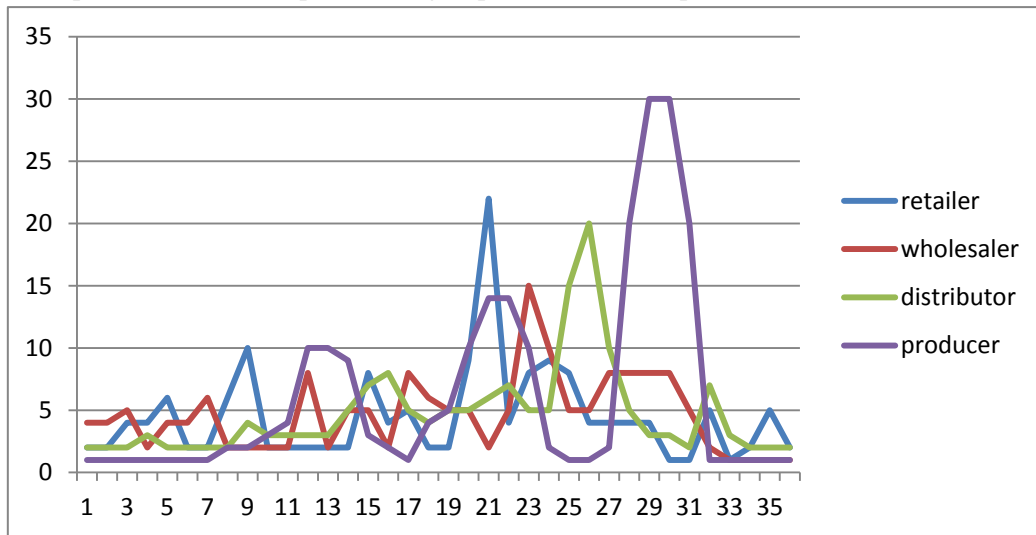


b. Order placed rate of the experimental group in the third experiment

Figure 3- 11 Order placed rate of the experimental group in the second and third experiment

The performance of the group with the supply line information is much better than the group with in-transit stock information. The peak order of the formal group is barely 30, whereas that of the latter group is in the hundreds. This gap is still quite large. The performance of the supply line information is more effective than the in-transit information. We can conclude that the entire supply line information is more effective than a portion of it.

To further support our hypothesis, the following analysis combines the three experiments. It is clear that the amplification ratio in the group with the supply line

inventory information is the smallest.

Table 3- 4 Amplification ratios of three scenarios in the experiments

| | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Control Group | 1 | 7 | 49 | 74 | 249 |
| In-transit Group | 1 | 4 | 9 | 49 | 99 |
| Supply Line Group | 1 | 4.5 | 2.75 | 4 | 6.5 |
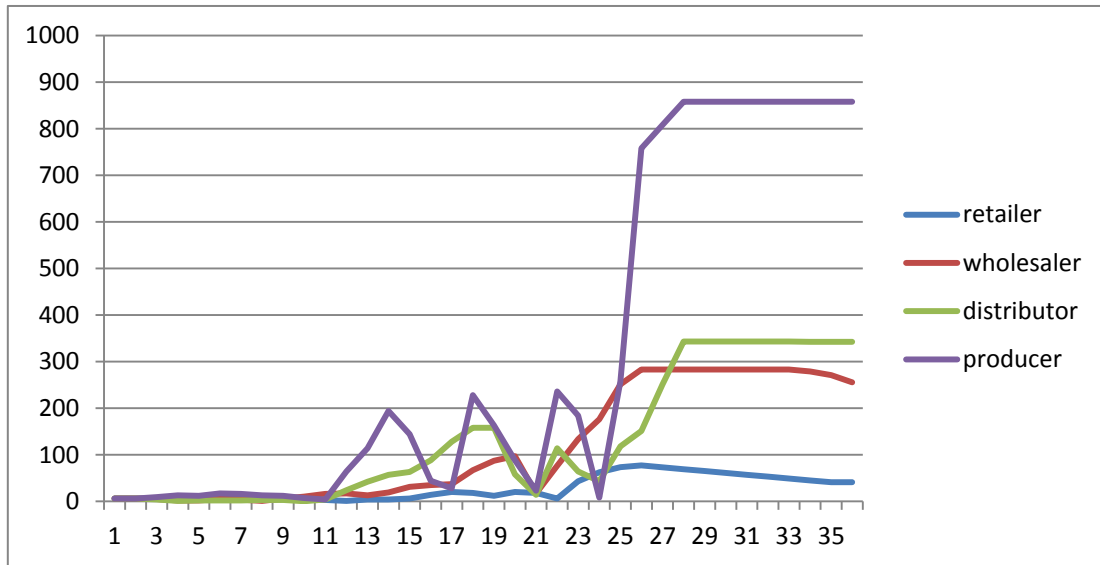


a. Cost for the control group without any additional information in the third experiment
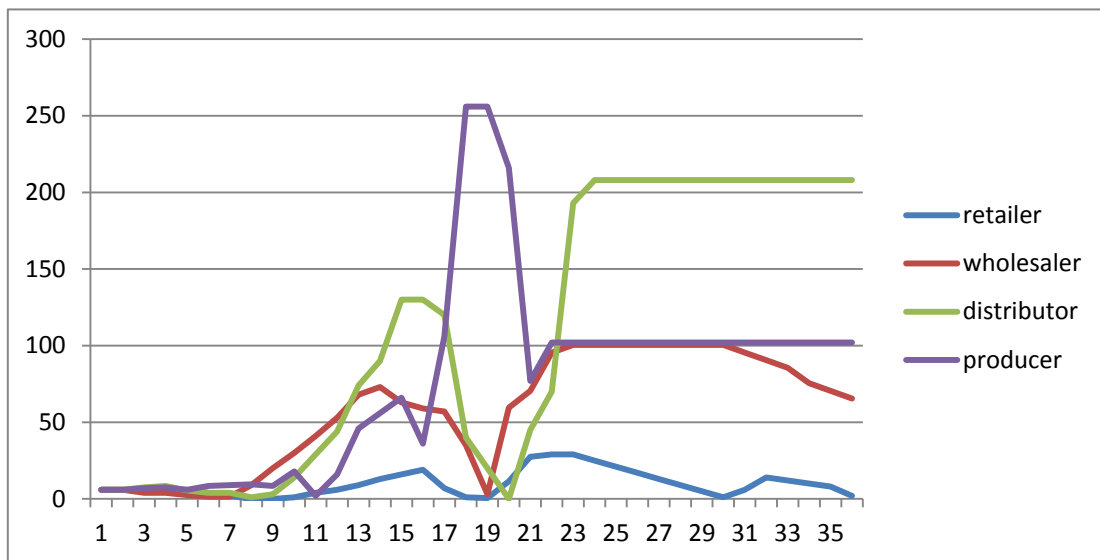


b. Cost for the experimental group with the in-transit stock information in the second experiment
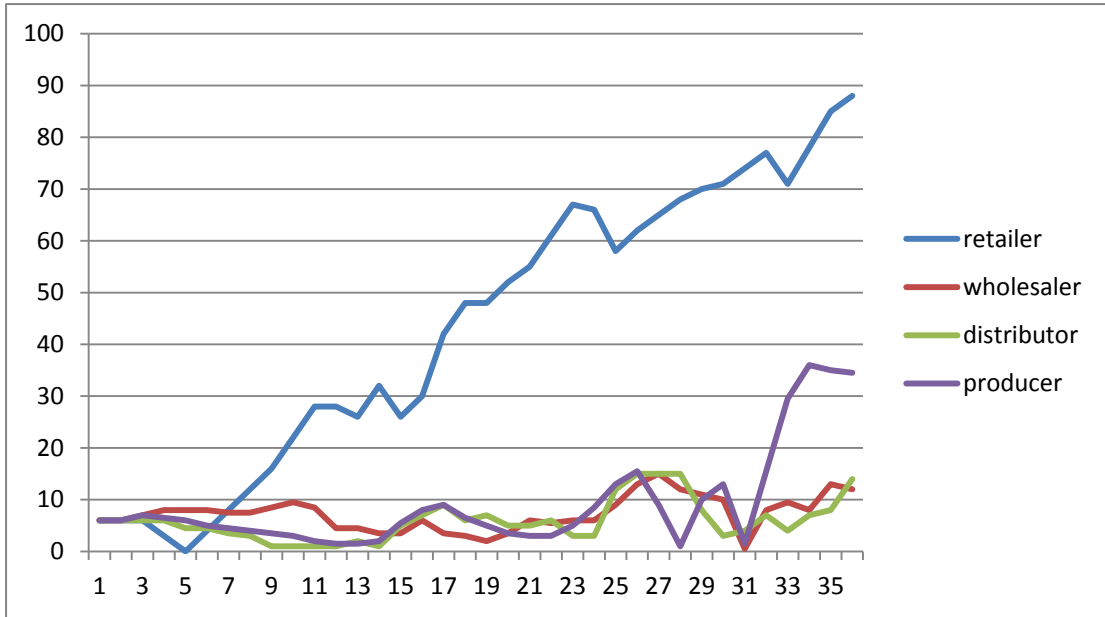
c. Cost for the experimental group with the supply line information in the third experiment

Figure 3- 12 Cost of the three experiments with different information
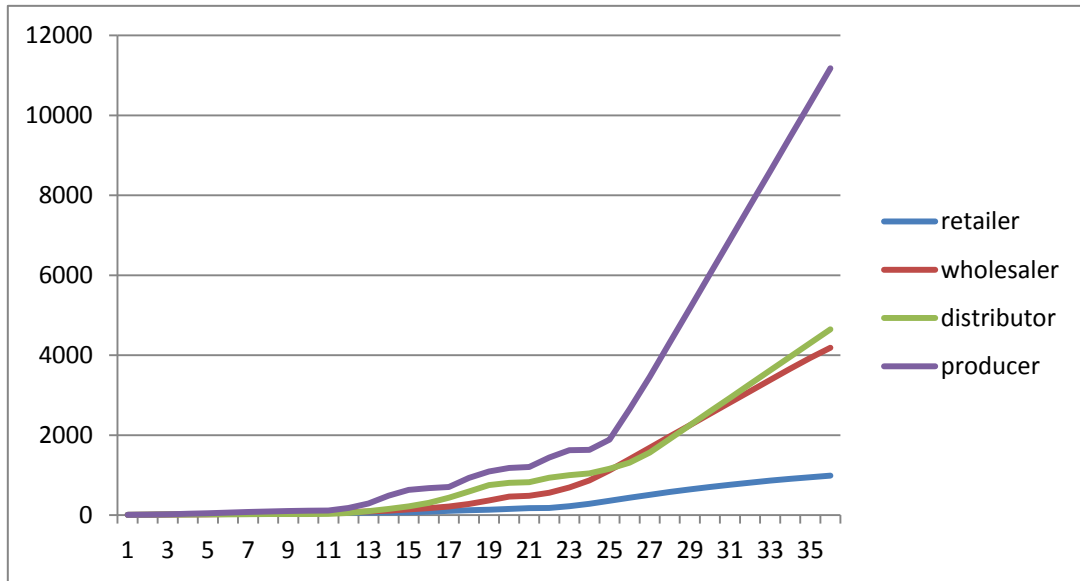


a. Cumulative cost for the control group without any additional information in the third experiment
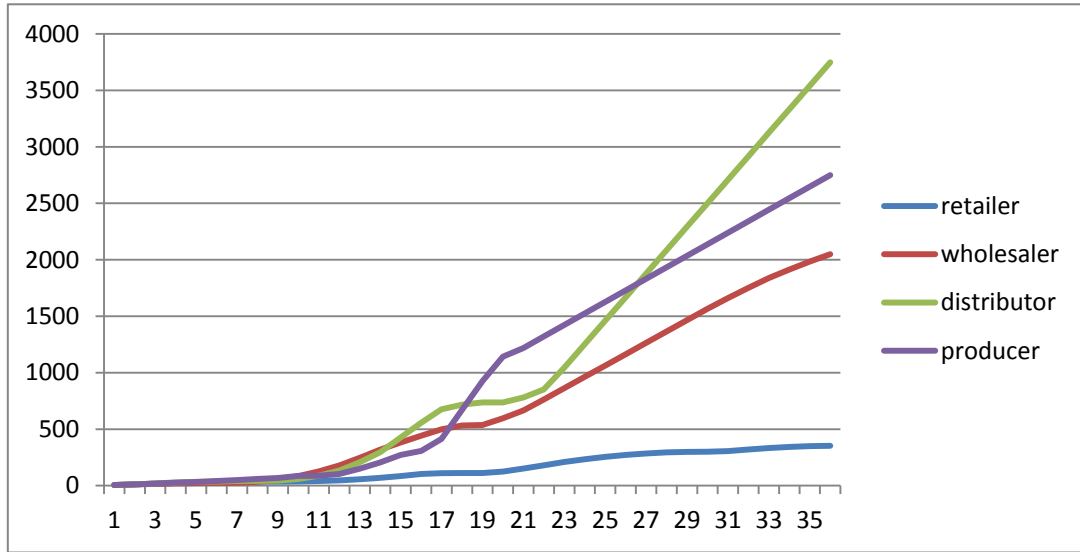
b. Cumulative cost for the experimental group with the in-transit stock information in the second experiment
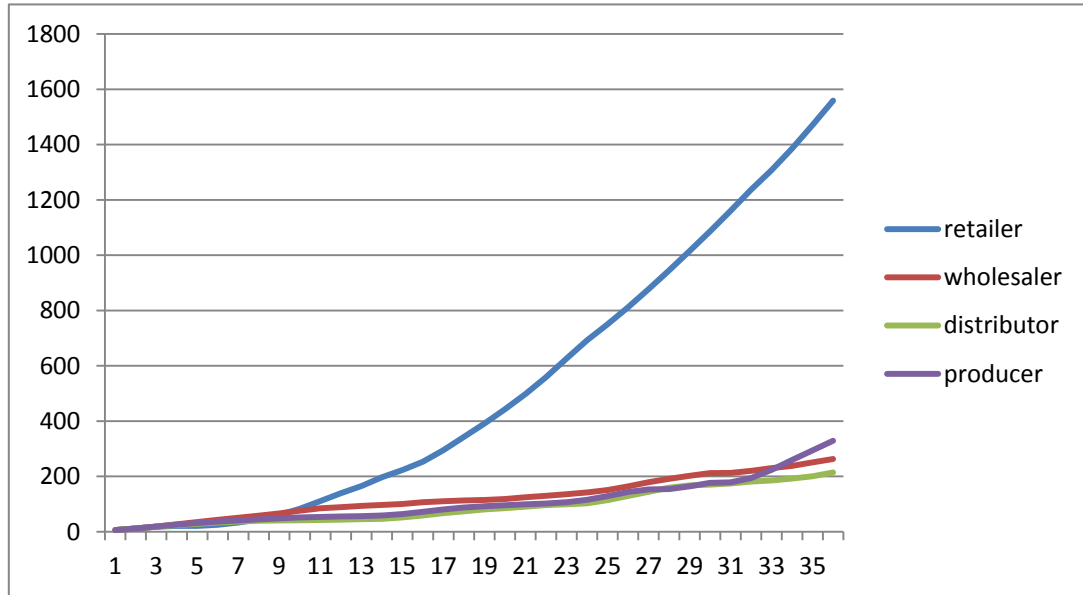


c. Cumulative Cost for the experimental group with the supply line information in the third experiment

Figure 3- 13 Cumulative cost for the three experiments with different information
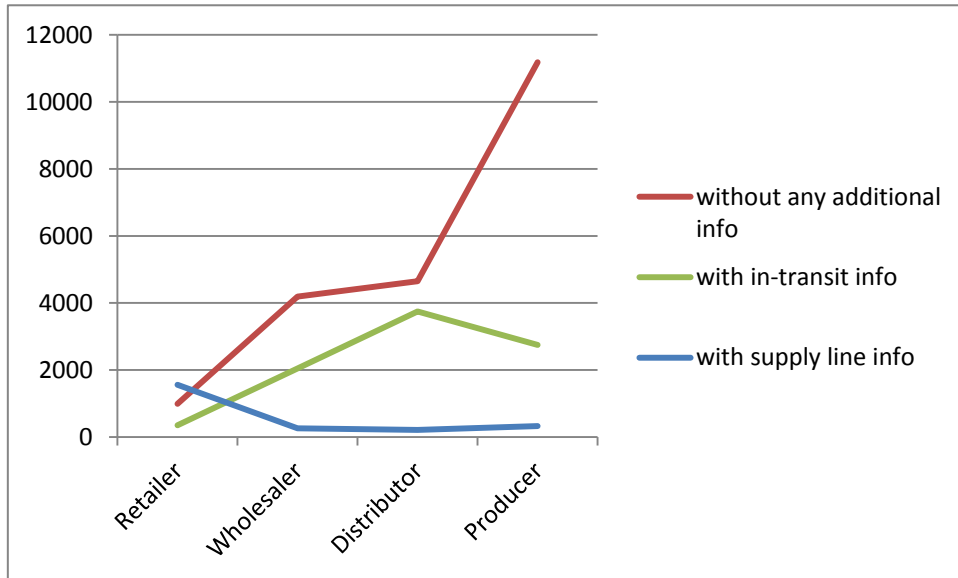
Figure 3- 14 Cumulative cost comparison for the three experiments with different information

From the above figures we can see that, for the weekly cost and the cumulative cost, the control group is the highest for nearly all four sectors of the supply chain, whereas the other two groups with additional information have better performance. In figure 3-13 c we can see that the cumulative cost for the wholesaler, distributor, and producer in the experimental group with the supply line information is less than 500. We can conclude here that additional information does weaken the bullwhip effect. Another interesting thing is that the cumulative cost of the retailer in this group is high. We will return in more details about that.

*3.3.2 Validation of hypothesis 2*

If the input (i.e. the structure and the kind of information provided) is the same, then the output would be almost the same in a model. However, this may not be the case in real life. The results could be widely divergent even the participants is available with the same kind of information. As proposed in the hypothesis, "The way information is utilized in the decision making process has a significant impact on the decision itself". We can demonstrate this based on the comparison of the experimental group between the first and the second experiment.

Table 3- 5 Amplification ratios of the experimental group in the two experiments

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| first Experiment | 1 | 4 | 4 | 4 | 9 |
| second Experiment | 1 | 4 | 9 | 49 | 99 |
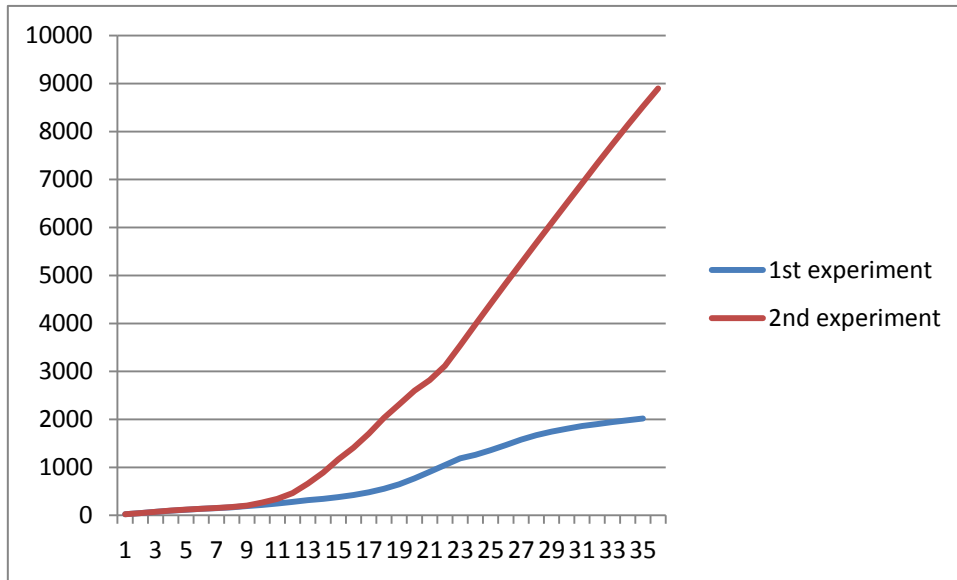


Figure 3- 15 Cumulative cost of the experimental group in the two experiments

We can find from the above that, although under the same kind of information provided (i.e. in-transit stock information), the performances of the two groups are very different.

In order to further support this hypothesis, I will put the results of the control group in the three experiments together in the following analysis. It's clear that neither the amplification ratio nor the cumulative cost is the same.

Table 3- 6 Amplification ratios of basic scenario in the three experiments

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| first Experiment | 1 | 7 | 11.5 | 11.5 | 11.5 |
| second Experiment | 1 | 24 | 49 | 124 | 2498.75 |
| third Experiment | 1 | 7 | 49 | 74 | 249 |
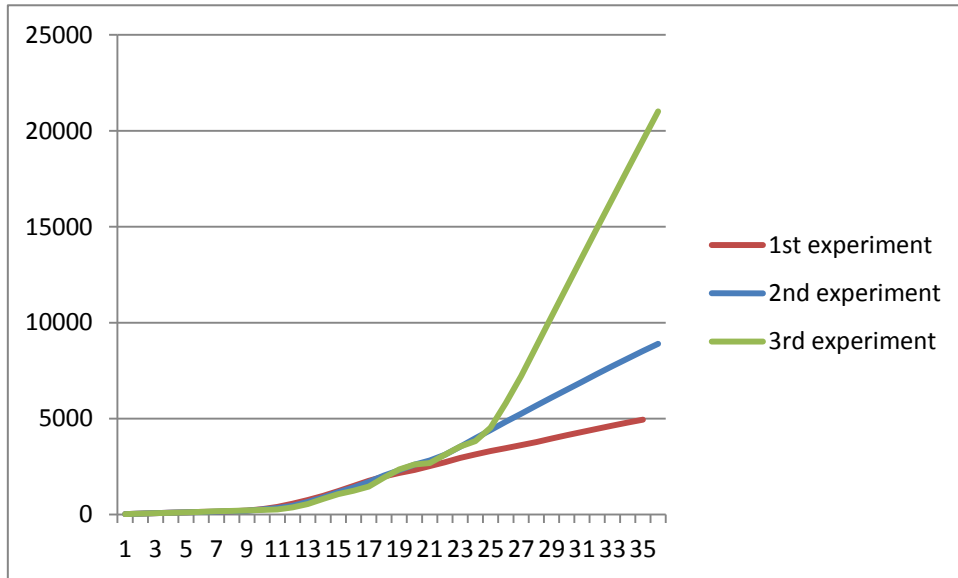
Figure 3- 16 Cumulative cost of the basic scenario in three experiments

In the following part we would investigate the underlying mechanism that may cause participants to perform differently.
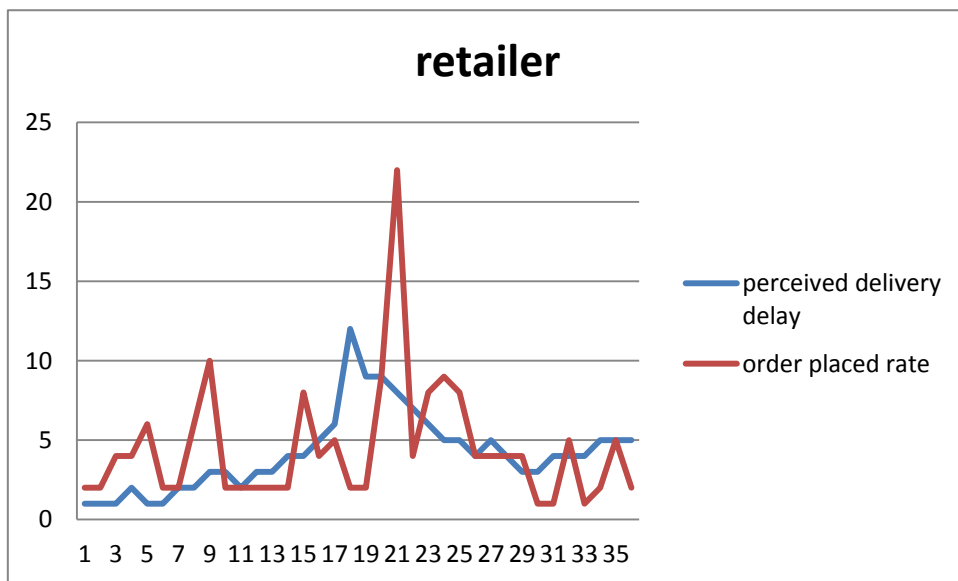


a. Relationship of the order placed rate and the perceived delivery delay for the retailer
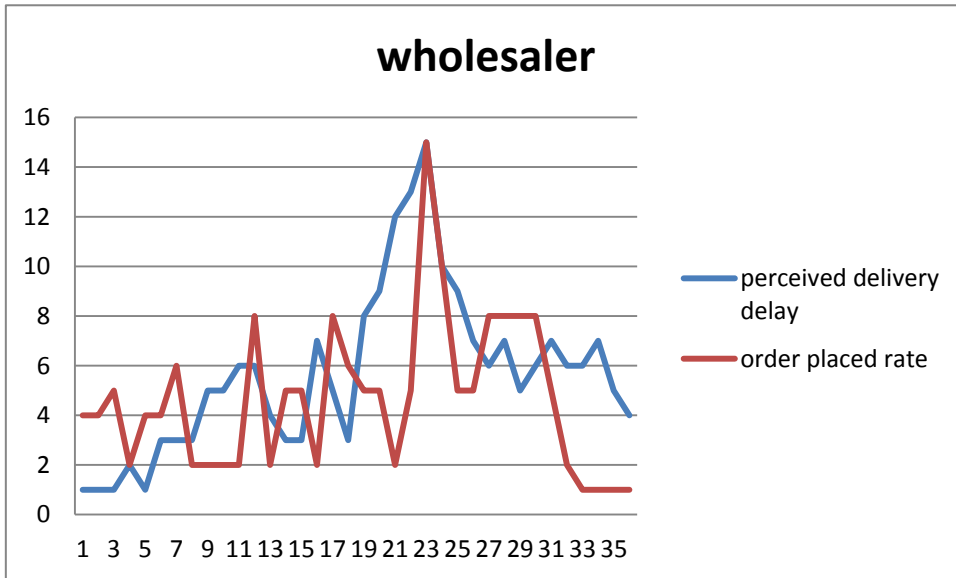
b. Relationship of the order placed rate and the perceived delivery delay for the wholesaler
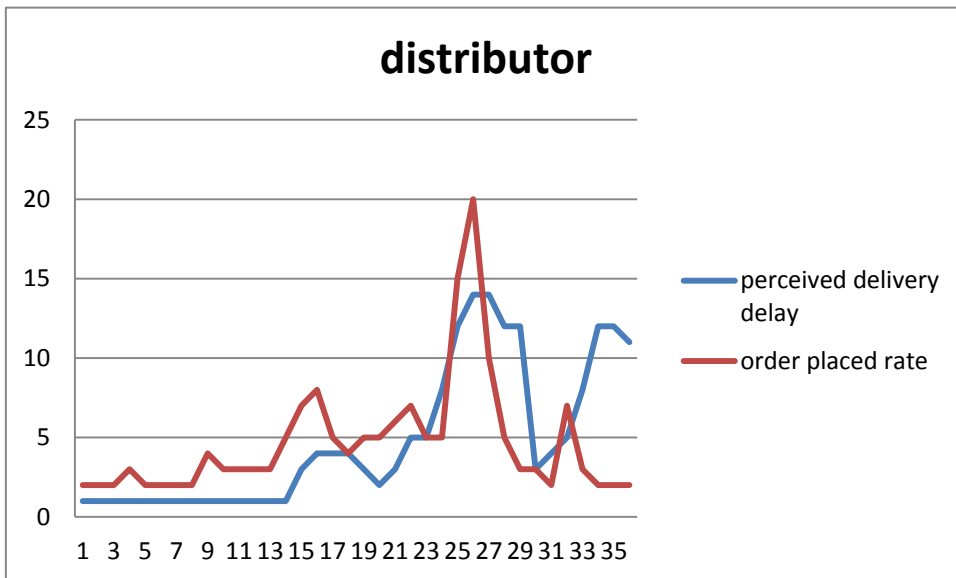


c. Relationship of the order placed rate and the perceived delivery delay for the distributor
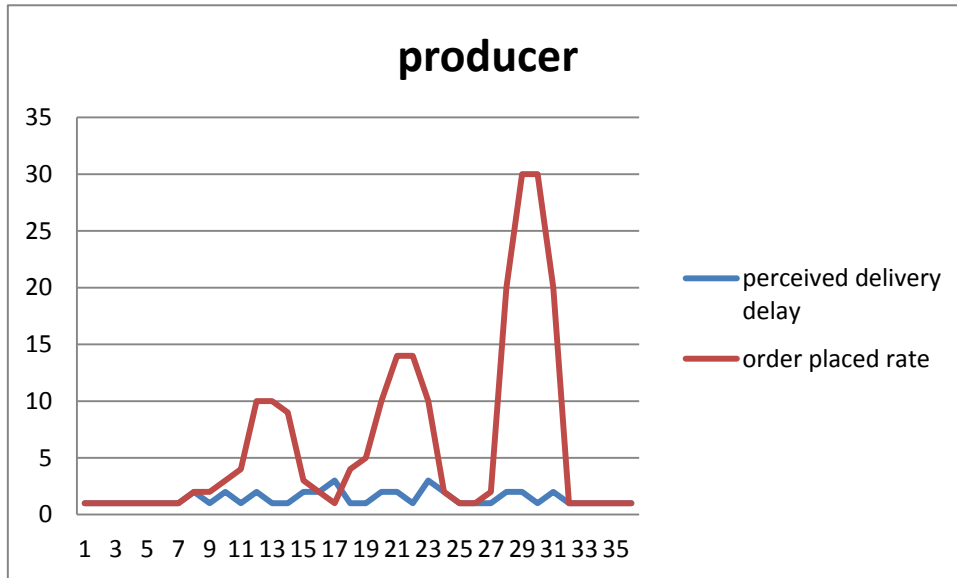
d. Relationship of the order placed rate and the perceived delivery delay for the producer

Figure 3- 17 Relationship of the order placed rate and the perceived delivery delay for four sectors in the experimental group in the third experiment

As we know, there is no limitation of production, and the time needed for the production is constant. However, the producer in this game is not being informed about this. The result of the perceived delivery delay, as portrayed in the figure 3-17 d, is almost stable all the time, indicating that the perception of the participant is reliable.

An interesting phenomenon can be found from figure 3-17 that the order placed rate and the perceived delivery delay seems to be positively correlated (hypothesis 2a).

The perceived delivery delay, the players' perception of the total time it takes to receive the beer after ordering, may increase when the upstream players have a backlog and cannot deliver on time. We would expect that the participants are more sensitive to this situation when they also have a backlog, though there might be exceptions which could be seen in the next page. In this case, the players would be more concerned when their perceived delivery time increases. They are more likely to make ordering decisions based on their temporary perception of such a delay. We can see from the figure 3-17 that the order placed rate increases when the perceived delivery delay increases.

The range of the perceived delivery delay for the retailer, the wholesaler and the distributor is the same that between 0 and 15, but the range of their order placed rate is quite different. This suggests that, for different people, their decision may be different based on the same information interpretation, in other words, people may have different degree of sensitivity to their perception. Furthermore, for the producer, the order placed rate changes significantly, whereas the perceived delivery delay is nearly constant. This further suggests that for the same participant, his/her decision can be different based on the same perceptions, which indicates that, for the same person, probably the degree of sensitivity to the information perception varies (hypothesis 2b).

In the material presented, some interesting issues remain. For example, the cumulative cost of the retailer is the highest (rather than the producer's cumulative cost). In the following section, I analyze the transformation process of the perception into an order placed decision of all four sectors in the experimental group in the third experiment.
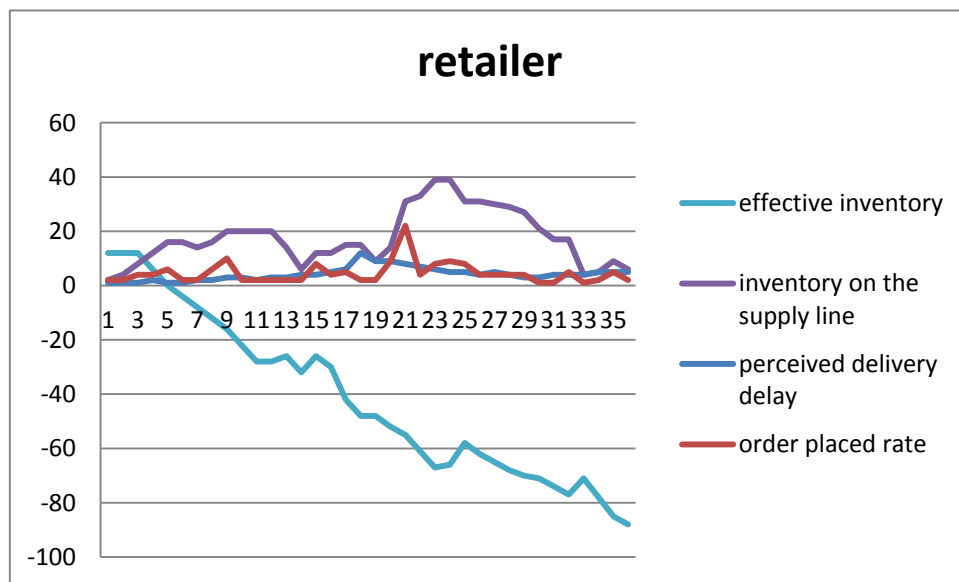


a. Relationship of the order placed rate and the inventory for the retailer

b. Relationship of the order placed rate and the demand estimation for the retailer

Figure 3- 18 Analysis of the retailer's decision process of the order placed rate

The effective inventory means the result of the inventory minus the backlog. It is unusual that a retailer would have a significant negative effective inventory, but not choose to add to the number of orders he/she placed. The participant said that when the effective inventory decreased very quickly, he panicked and increased the order. But shortly thereafter (week 9), he believed that the decreasing was only temporary when the decreased speed of the effective inventory flattened. The effective inventory decreased fast between week 15 and week 19, and his perceived delivery delay increases correspondingly. The order he placed increases a little bit later, since it takes time to transform the perception into the decision making. The order placed rate decreases again when he realizes the large quantity of the inventory on the supply line. His perceived delivery delay decreases a little bit then, and he was certain that his order would arrive to meet the temporary backlog. We can see here that both the inventory on the supply line and the effective inventory influence his perception of the delivery delay. Therefore, the number he ordered after week 22 was quite small. Thus, the negative effective inventory situation remained and ended up with the highest cost. In the last few weeks, we can see that his perceived delivery delay increases gradually when the inventory on the supply line decreases to a low level. However, it needs time to adjust the perception. The order placed rate changes while

most of the time the incoming order rate is stable.



a. Relationship of the order placed rate and the inventory for the wholesaler



b. Relationship of the order placed rate and the demand estimation for the wholesaler

Figure 3- 19 Analysis of the wholesaler's decision process of the order placed rate

The wholesaler's perceived delivery delay increased when he had negative effective inventory (week 23) for the first time, and then he increased his order as a countermeasure. However, the wholesaler did not do for the entire period with negative effective inventory (i.e. between week 23 and week 31). This is because the inventory on the supply line was exceptionally large, and he knew he would receive a large amount of beers in the near future. This decision, based on correctly interpreted

information about the supply line, significantly weakens the bullwhip effect. In addition, the order placed rate is positively correlated with the order received rate as portrayed in figure 3-19 b. The demand estimation is made based on the order received rate. Normally, the order placed rate is an amplification of the order received rate, since there is a safety inventory within. However, it is opposite here. This may be also due to the relatively large supply line inventory, so the wholesaler does not consider about the safety inventory as well.
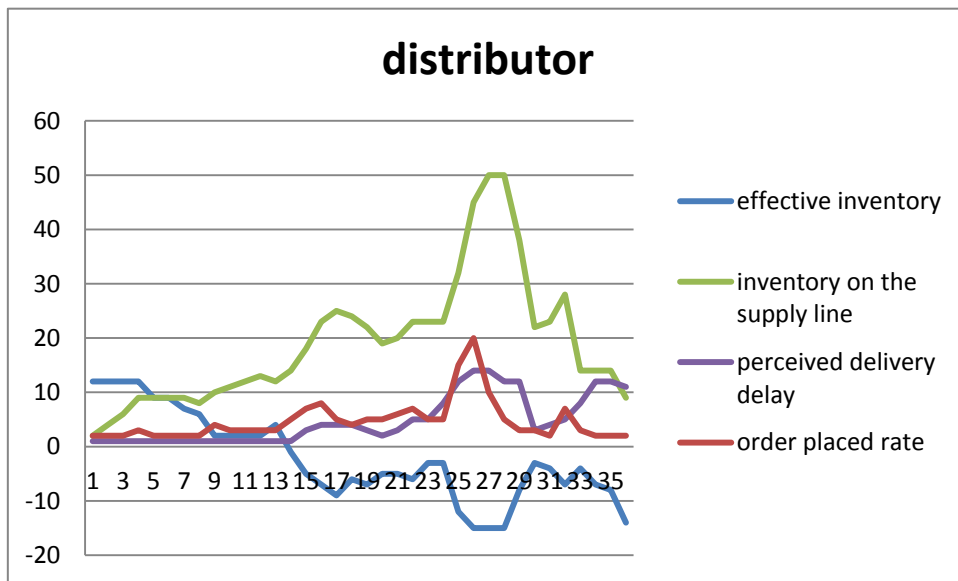


a. Relationship of the order placed rate and the inventory for the distributor
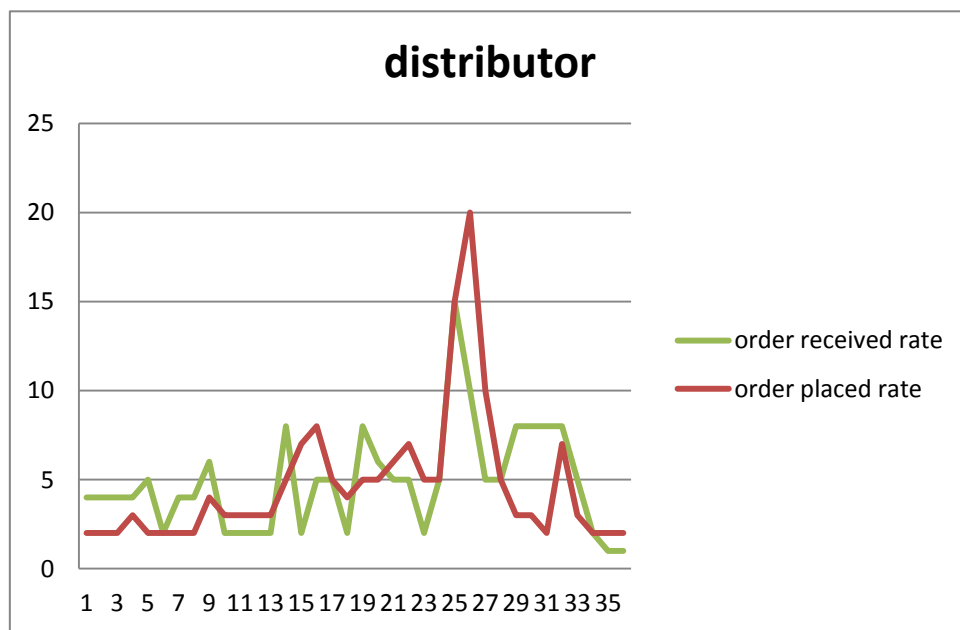


b. Relationship of the order placed rate and the demand estimation for the distributor

45

The perceived delivery delay, the effective inventory, the inventory on the supply line, and the order placed rate of the distributor show a pattern nearly identical to that of the wholesaler. It is reasonable that the perceived delivery delay increased when the effective inventory decreased, and the concern this raised caused a larger order rate. Around week 25, the effective inventory was very small, but the order was very large for only approximately 2 weeks, and then decreased rapidly because of the large inventory on the supply line. The effective inventory increased very quickly even without substantial ordering. However, during the last several weeks, although the effective inventory decreased again, the participant did not change the ordering rate because that individual knew that there were still some beer on the supply line, and they already had experienced the power of the supply line inventory. Obviously, this policy dampened the variation in the order rate. The order placed rate is still positively correlated with the order received rate, but the order placed rate is an amplification of the order received rate here.
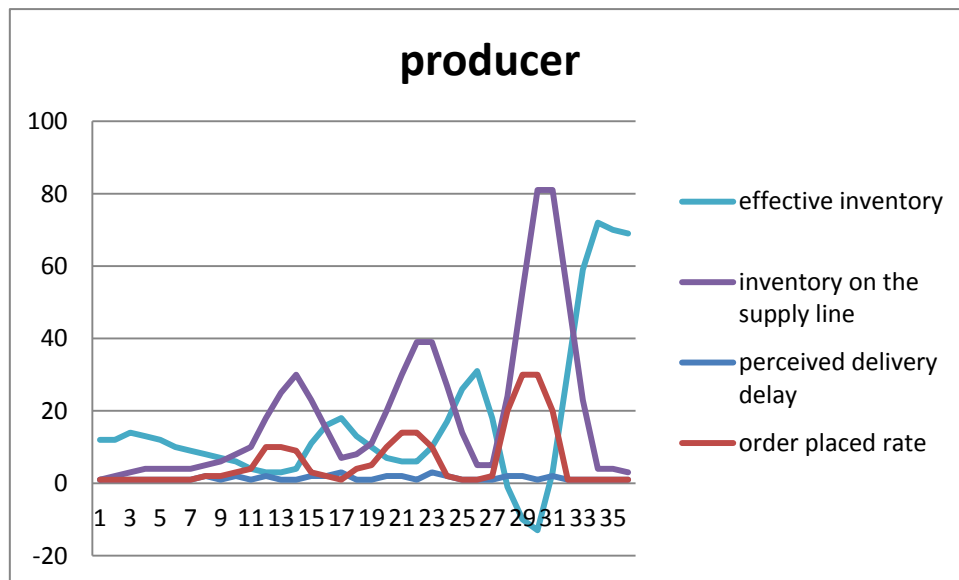


a. Relationship of the order placed rate and the inventory for the producer
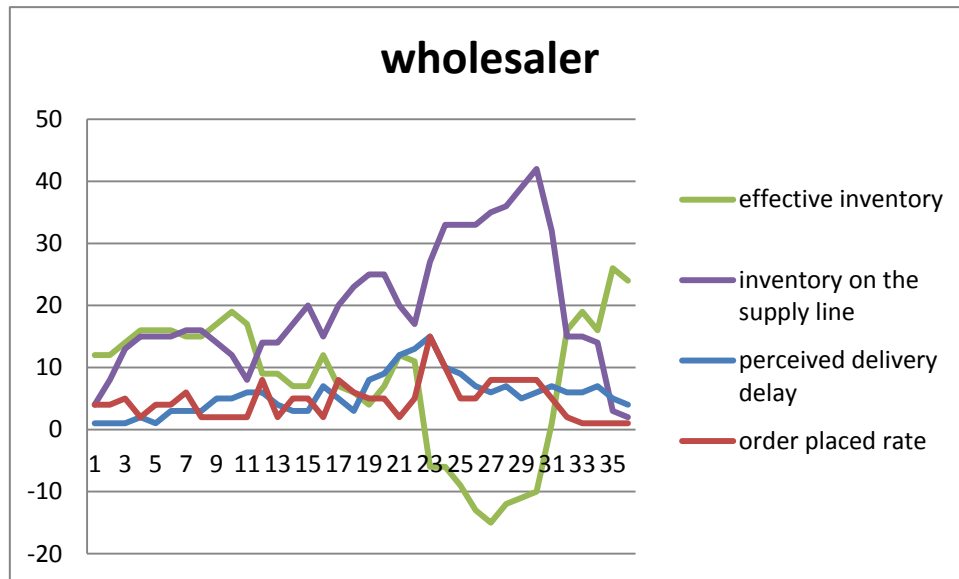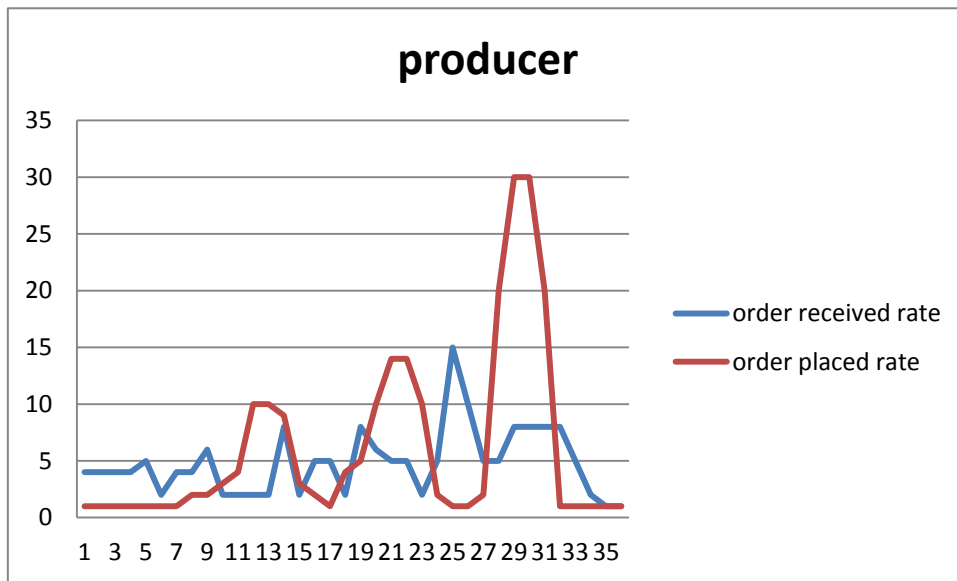
b. Relationship of the order placed rate and the demand estimation for the producer
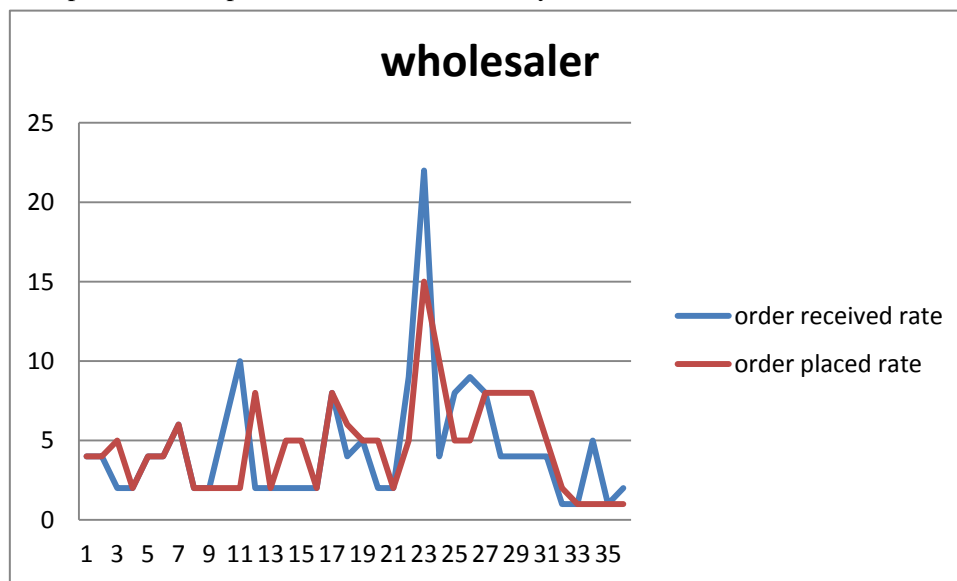
Figure 3- 21 Analysis of the producer's decision process of the order placed rate

As portrayed in figure 3-21 a, the perceived delivery delay changed very slightly. The effective inventory was negative only around week 29, almost at the same time as the peak in order placed rate. We can see that the three peaks correspond with the increasing order rate of the distributor. The producer's ordering placed rate decreased rapidly as the player became increasingly familiar with the information of the supply line inventory. In addition, compared to figure 3-20 b, the producer is much more aggressive in placing the order when the incoming order changes. This indicates that their perception can be influenced by their degree of sensitivity.

In summary, a portion of the supply line information (i.e. the in-transit information), is helpful to weaken the bullwhip effect. The entire supply line information helps a lot. Moreover, the perception of the available information has a significant impact on the performance, while people may have imperfect interpretation based on different degree of sensitivity and degree of aggressiveness. Furthermore, People can gradually learn to interpret the given information effectively, but they may have different ways of transformation that into a decision when they are presented the same kind of information. They may have different degree of aggressiveness with the same

perception which will result in different responses and decisions to the information they perceived. These findings indicate strongly that the hypotheses are correct.

In real life, participants do not need very sophisticated structural information to perform significantly better, but they need information relevant to make the right decision. This is reflected in the experimental group of the beer game experiments, that the supply line information, or a portion of it, is available to the participants. They can make right decision to weaken the bullwhip effect, though they do not know what happens to their supplier. In the next chapter, I would analyze our finding further based on a system dynamics model.

# Chapter 4 Beer Game Model

4.1 System Dynamics

*4.1.1 Characteristics of Supply Chain Systems*

Mosekilde et al. (1991) noted that large-scale oscillations grow in amplitude from retailer to producer in the supply chain. Those large surplus of orders placed during the out-of-stock period will be finally produced. Three motives for ordering: provision for expected demand, adjustment of inventory, and adjustment of supply line. He demonstrates that misperception of supply line inventory can produce enormous oscillation in the system.

Ren (1999) noted that it is difficult to forecast in the supply chain domain; in essence, it is a turbulent storage environment. Chai and Liu (2001) noted two aspects of the complexity of the supply chain structure: the complexity of the network of supply and demand, and the complexity of the participants in the supply chain.

*4.1.2 System Dynamics Model*

System dynamics provides a viable theory to address dynamic and complex issues, ideas, methods and tools. System dynamics is an experimental approach to systems analysis. It defines the boundary of the system and the process of operations and information transfer based on the perspective of systems thinking. The dynamic complexity is captured by a representation of the causal feedback structure of the system.

A quantitative model is used to simulate and analyze various scenarios. Changing the structure may help people understand the structural causes of dynamic behavior and to

analyze and design high leverage solutions to resolve dynamic and complex issues and improve system performance (Forrester, 1958).

Forrester (1958) was the first to study supply chain management using system dynamics. Forrester (1961) expanded on the explanatory model and analyzed it in greater details, establishing a link between this issue and management education.

Many system dynamics models have been developed in the supply chain field (Angerhofer, B. J., & Angelides, M. C., 2000). In the supply chain system, commodities are accumulated in inventories and orders are accumulated in backlogs. The perception of delivery delays are accumulated in the perceived delivery delays. Behavior is a consequence of the delay, feedback and nonlinearity in the structure. Experimental studies clearly show that supply chain instability remains even after the operational causes, such as quantity discounts, are eliminated. Instability is a behavioral phenomenon arising from the failure to account for time delays, feedbacks, and the supply line of unfilled orders. This is a typical area for system dynamics modeling and analysis (Richardson & Pugh, 1981).

4.2 Beer Game Modeling

*4.2.1 Causal Loop Diagram*

Causal loop diagrams are a powerful tool to map the feedback structure of complex systems (Sterman, 2000). Three feedback loops are identified in the model of a two sector supply chain, as shown in figure 4-1. The structure of the four-sector supply chain is shown in figure 4-2. For easier understanding, the variable of ordering is used as the point of departure from which all loops begin and where they end. Because the loops overlap, table 4-1 is provided to clearly trace the loops and show how endogenous variables are influenced by and, conversely, influence orders.
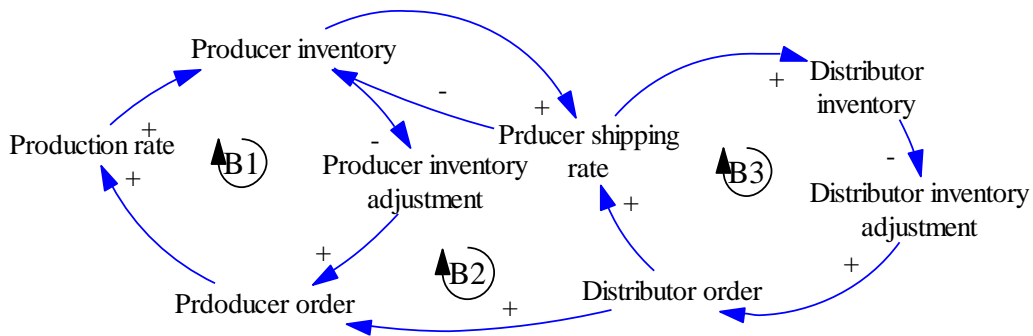
Figure 4- 1 Causal loop diagram of explanatory model with two sectors

Table 4- 1 Feedback loops of the explanatory model with two sectors

| Loop | Feedback Process | Path |
|------|-----------------|------|
| B1 | Effect of producer inventory on producer order | **Producer order** + Production rate + Producer inventory - Producer inventory adjustment + **Producer order** |
| B2 | Effect of distributor order on producer order | **Distributor order** + Producer order + Production rate + Producer inventory + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B3 | Effect of distributor inventory on distributor order | **Distributor order** + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |

B1 and B3 are similar for the various sectors in the supply chain. The same is true for the other two sectors, the wholesaler and the retailer. B1/B3 and B2 indicate the balancing impact of inventory adjustment and received orders on orders placed, respectively.

Overall, fluctuating orders can be attributed to the balancing loop over time. The balancing loop adjusts individually the state of affair for the various participants. This is because the participants' perceptions and decision making processes differ from one another and change over time.
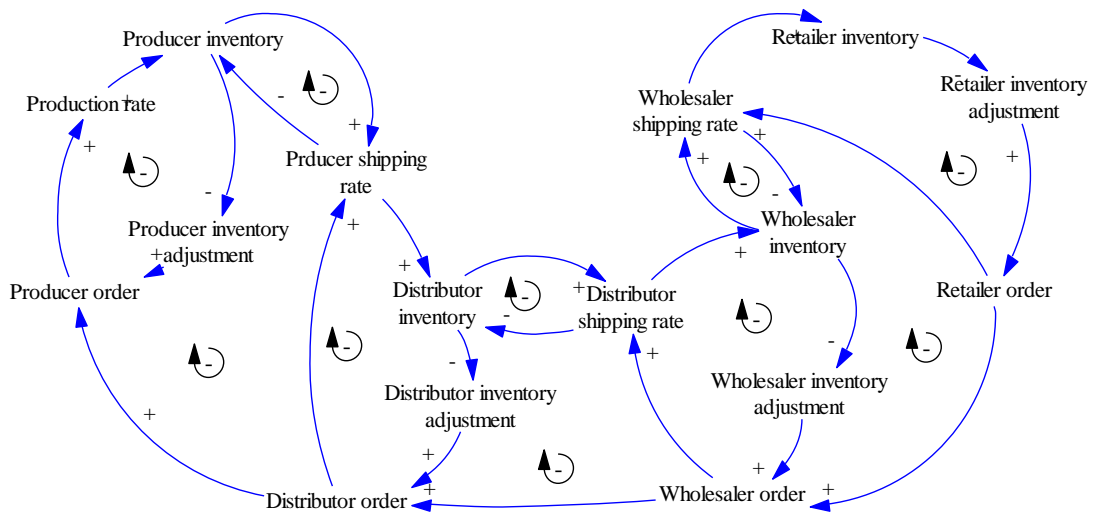
Figure 4- 2 Causal loop diagram of the beer game

*4.2.2 Stock-and-Flow Diagram*

In the thesis, the beer game is modeled using a twelve-stock diagram. The main stocks are inventory, backlog and stock of unsatisfied orders. The four sectors, i.e. the retailer, wholesaler, distributor and producer are shown with R, W, D, P in the model. The time span for the beer game experiments is 36 weeks, and the time step is set to 1. The complete model details with all the feedback loops are shown in Appendix A.

Each of the four sectors is modeled as portrayed in figure 4-3. The order placed includes two parts, i.e. the order received forecast and the adjustment of the effective inventory. The order received forecast is based on an experimental smoothing of incoming order over the recent weeks.

The inventory is influenced by the shipment rate and acquisition rate. Shipment rate decreases the inventory as well as the backlog. The effective inventory means the result of the inventory minus the backlog. The larger the gap between the effective

inventory and the desired inventory, the larger the correction order to close that gap should be.
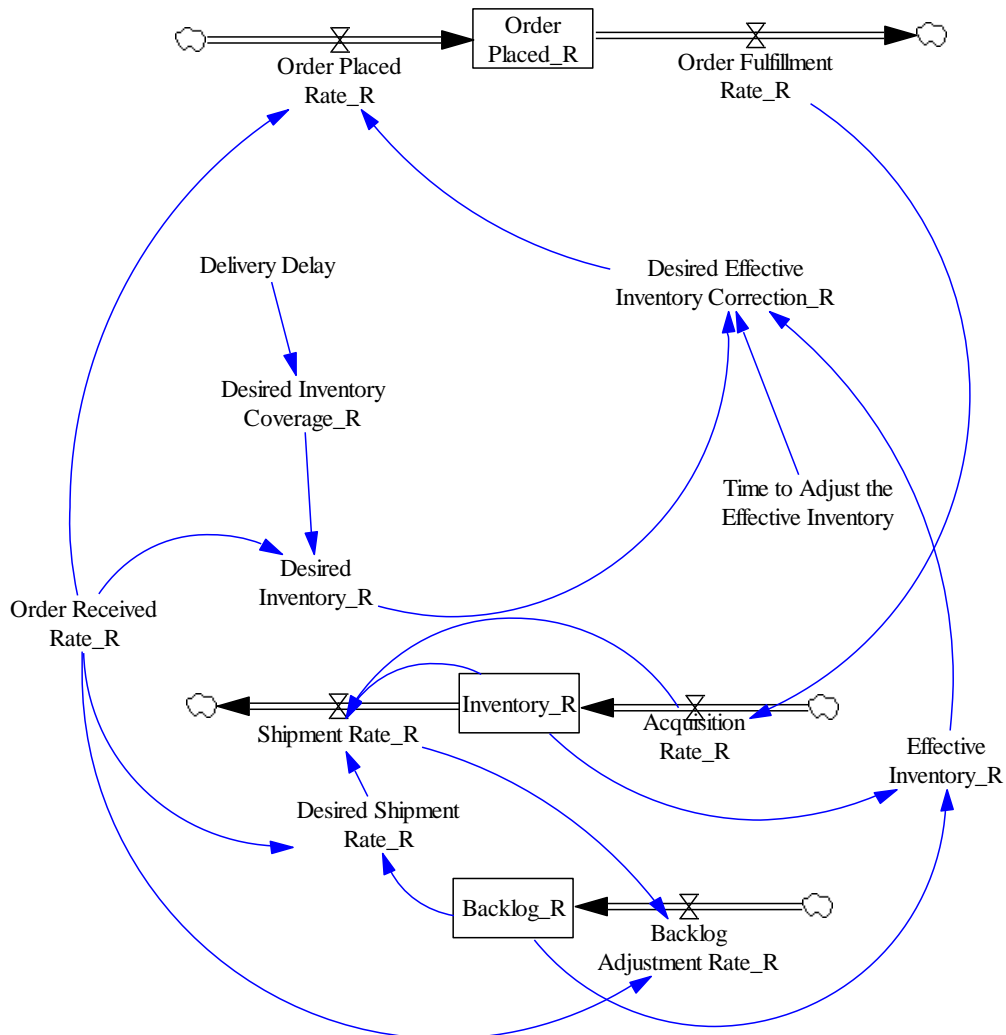


Figure 4- 3 Stock-and-Flow diagram of any sector in the basic beer game

Figure 4-3 displays the stock and flow diagram of the any sector. The basic equation of the order placed rate is as below:

$$Order\ Placed\ Rate$$
$$= MAX(Order\ Received\ Rate\ +\ Desired\ Effective\ Inventory\ Correction\ ,0)$$

# Chapter 5 Explanatory Model Validation

All models are limited or simplified representations of the real world (Sterman, 2000). However, policymakers need models to help them make decisions. The objective of model validation is to build confidence in the model. The model validations here use the same time steps and time span.

## 5.1 Extreme Condition Test

A reasonable model should be able to produce the correct behavior not only in general conditions but also in extreme conditions. Extreme condition tests are conducted under conditions that rarely occur in the real world to study whether the behavior of the model is reliable in these cases.

In the extreme condition test, we set the customer's demand equal to (4 + step (-4, 4)), which means the demand would be 0 from week 5 for the system simulation.

## Order Placed Rate



| "Order Placed Rate\_R" : 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| "Order Placed Rate\_W" : 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | |
| "Order Placed Rate\_D" : 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | |
| "Order Placed Rate\_P" : 1 | | | | | | | | |
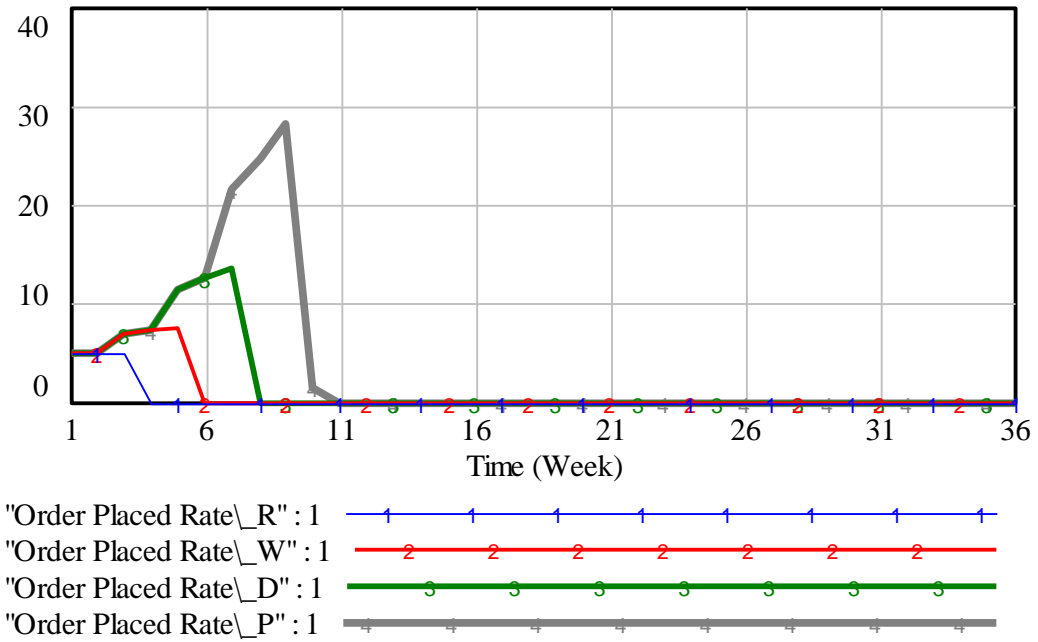
Figure 5- 1 Order placed rate under the extreme condition test

## Inventory



| "Inventory\_R" : 1 | 1 | 1 | | "Inventory\_D" : 1 | 3 | 3 |
| "Inventory\_W" : 1 | 2 | 2 | | "Inventory\_P" : 1 | | |
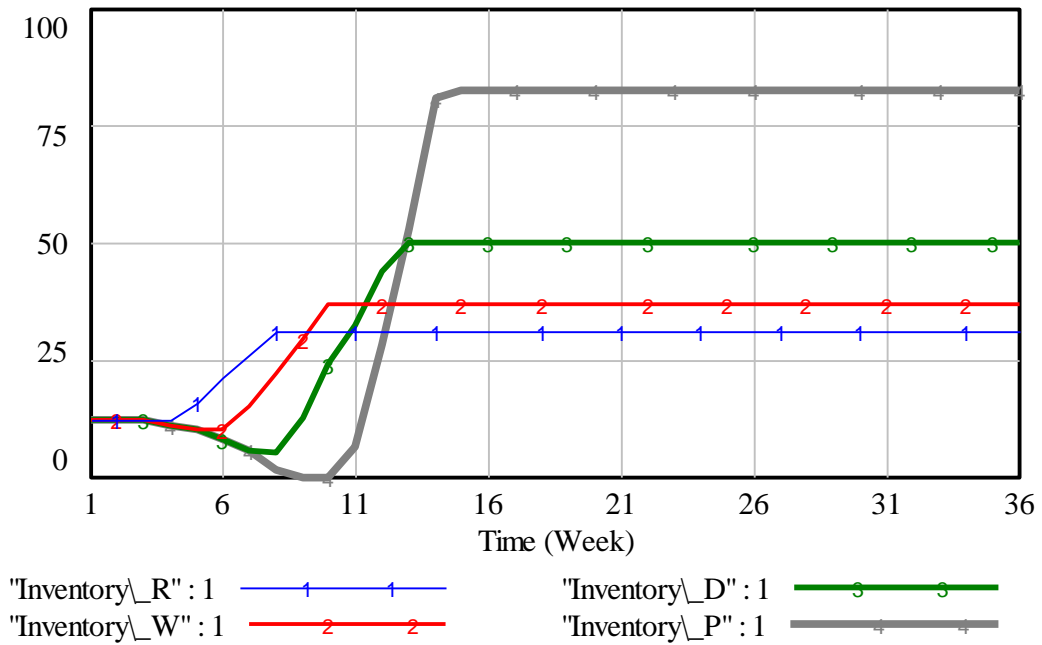
Figure 5- 2 Inventory under the extreme condition test
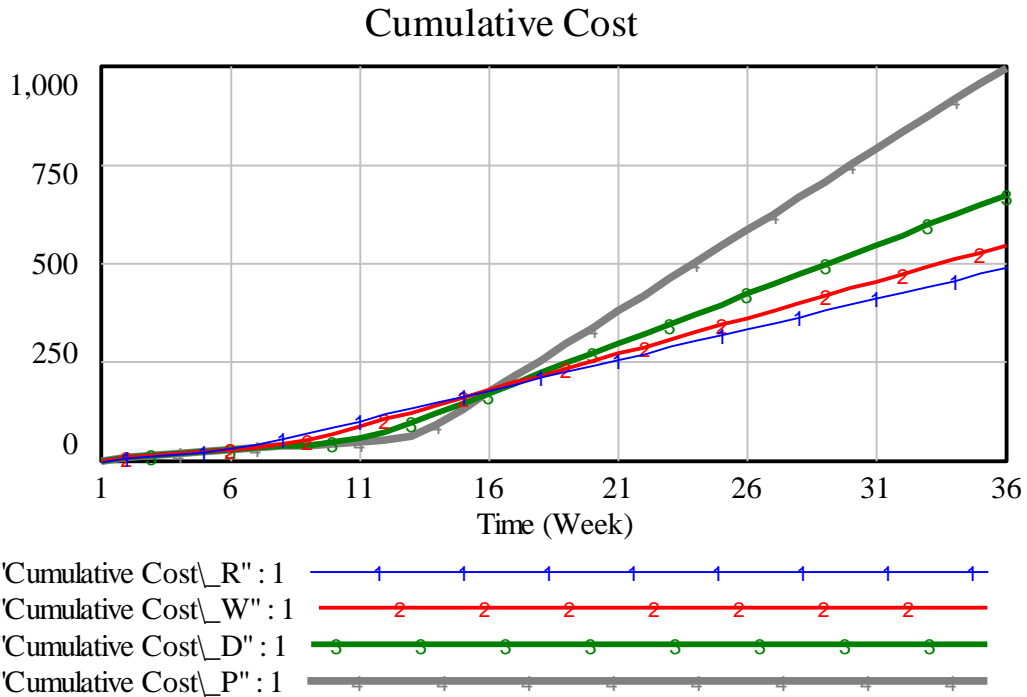
## Cumulative Cost



Figure 5- 3 Cumulative cost under the extreme condition test

As seen in the above figures, after the customer's order changes to zero, the order placed of the retailer decreases to zero first. However, due to the gap between the effective inventory and the desired effective inventory of the retailer, the order received rate of the wholesaler increases for a short time. This occurs again for the distributor and then for the producer. Nevertheless, after their order received rates become zero, the desired effective inventory is also zero. There is no need to adjust the effective inventory, and all the order placed rates decrease to zero.

This finding proves that the ordering mechanism in this model is reliable. The inventory decreases first, because the initial order placed rate is four, whereas the order received rate, which includes the effective inventory adjustment, is greater than four. The signal of the effective inventory adjustment can be transmitted upstream. Nevertheless, when the ordering and the supply line inventory are zero, the inventory is also stable.

## 5.2 Structure-Behavior Test

### 5.2.1 Sector Cut Test

Additional sectors in the supply chain increase the fluctuations in orders. The sectors are removed systematically as showed in Figure 5.4-5.6.
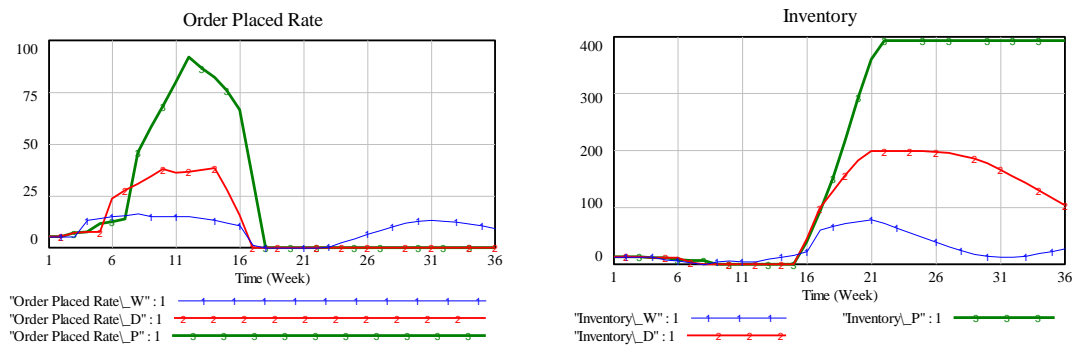


Figure 5- 4 Order placed rate and inventory of three sector supply chains
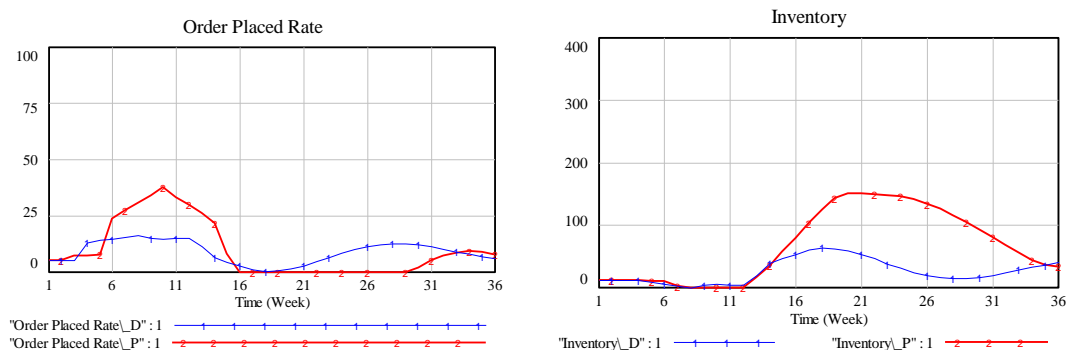


Figure 5- 5 Order placed rate and inventory of two sector supply chains
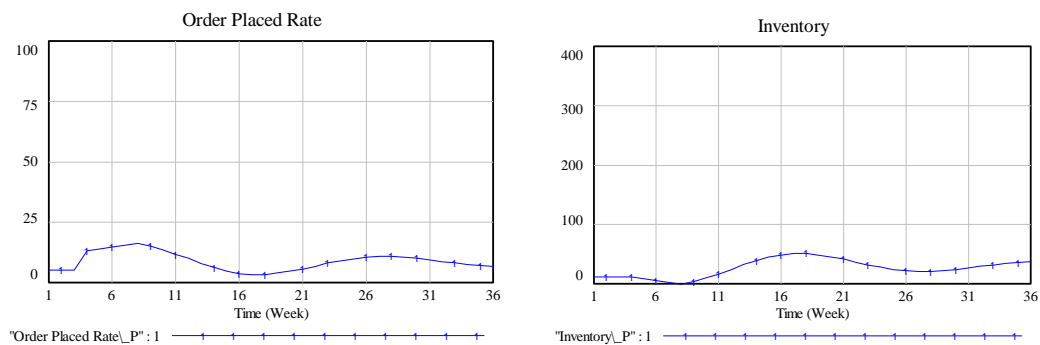


Figure 5- 6 Order placed rate and inventory of one sector supply chain

Because the producer sector is the only sector that exists in all three scenarios, for convenience of analysis, we use the order placed rate of the producer as the example (i.e., order placed rate_P). We can see that the peak value is greater than 50 in the three-sector supply chain, greater than 25 in the two-sector supply chain, and less than 25 in the one-sector supply chain. This result is also found for the inventory of the producer. Furthermore, regardless of the number of sectors in the supply chain, the orders fluctuation is amplified from the producer to the upstream. This finding proves that this model could behavior the characteristics of the bullwhip effect.

### 5.2.2 Feedback Loops-Cut Test

In the following section, feedback loops are cut and analyzed. Because the total causal loop diagram is very large and complex, only part of the diagram is presented for clarity. However, the loops would be cut in the entire model. In the model, there are two major loops represented two kinds of relationships: the internal relationship of the sector; and the one between the sectors, in other words, the external relationship of the sector.

### B1/B3 is cut

B1/B3 is the "effect of inventory on order placed". This loop indicates the internal relationship of the sector. Once the loop is cut, the order is no longer influenced by the current inventory, but only by the received orders. In this scenario, all orders are the same but with a time delay. The gap between the desired effective inventory and the effective inventory cannot be decreased.
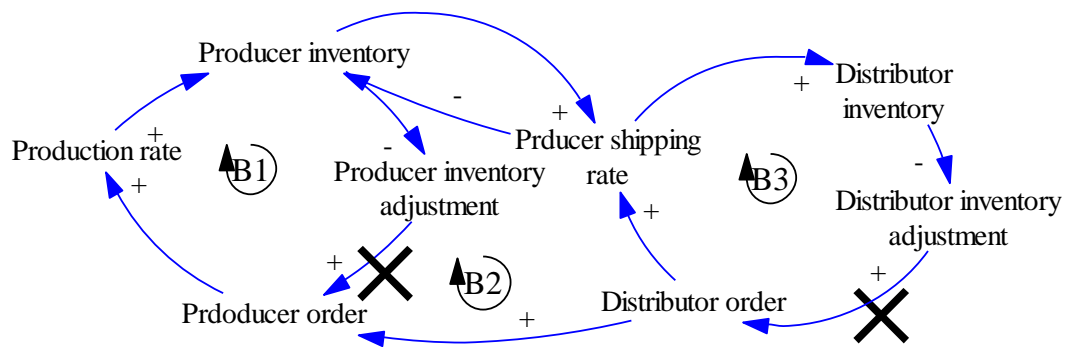
Figure 5- 7 Cutting B1/B3

In Figure 5-8, we can see that the phase lag of the order placed rate is two weeks, because it takes two weeks to transfer the information to the next sector within the beer game. Backlogs are stable after some time because the orders received and the shipments are equal to eight then.

Due to the two week information delay, the producer increases the order in week 10. However, the current inventory is insufficient for the shipment. Backlog increases from week 12 to week 14, and the number of products received by the wholesaler is very low from week 14 to week 16 because of the two weeks delivery. Increased orders are received in week 14, and the backlog of the producer is stable after week 14. For the wholesaler, the order received rate increases in week 8. Because of the same insufficient inventory, the backlog increases from week 10 to week 12 for the first time. As explained previously, the products received are very low from week 14 to week 16, so the backlog increases for the second time during this period. The pattern of the backlog of the distributor and the retailer can be explained in the same way.
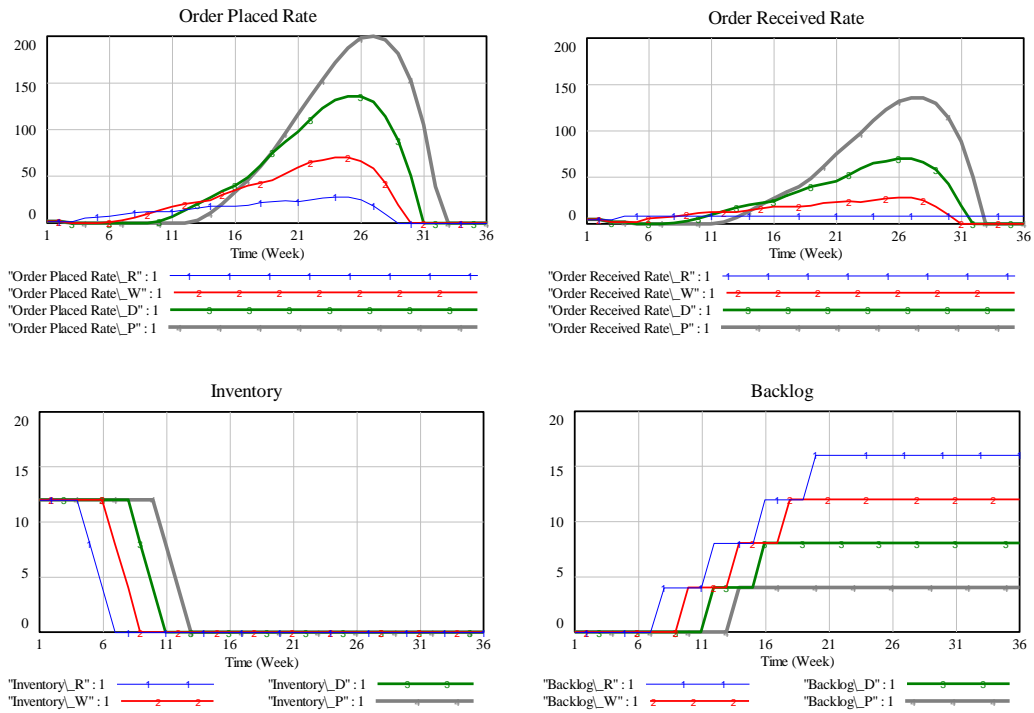
Figure 5- 8 Cutting B1/B3 simulations

***B2 is cut***

B2 is the "effect of order received on order placed". This loop indicates the relationship between the sectors.
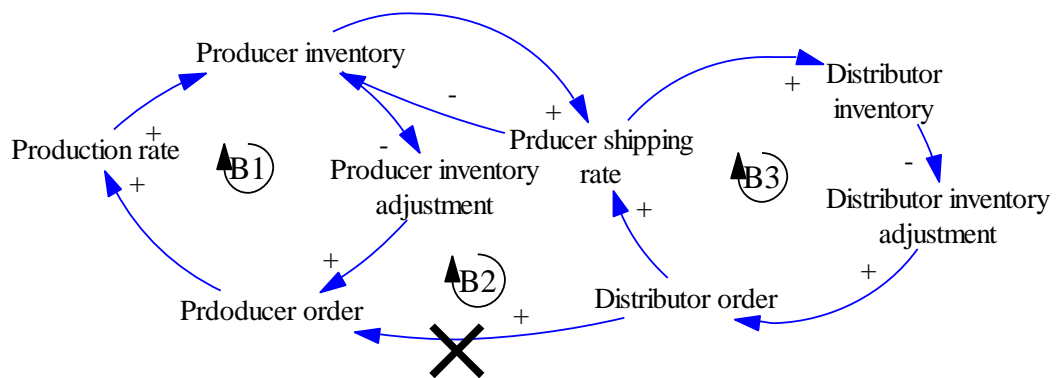


Figure 5- 9 Cutting B2

From the figure on the order received rate, we can see that participants order larger quantities and do so more aggressively. The retailer orders the least, and the effective inventory correlation of the retailer is the smallest.

Although the number of order received sent from the wholesaler is the highest, the backlog of the producer is not much higher than the others. This is because the delivery time of the producer is the shortest, and the backlog can be corrected very quickly to prevent it from becoming too large.
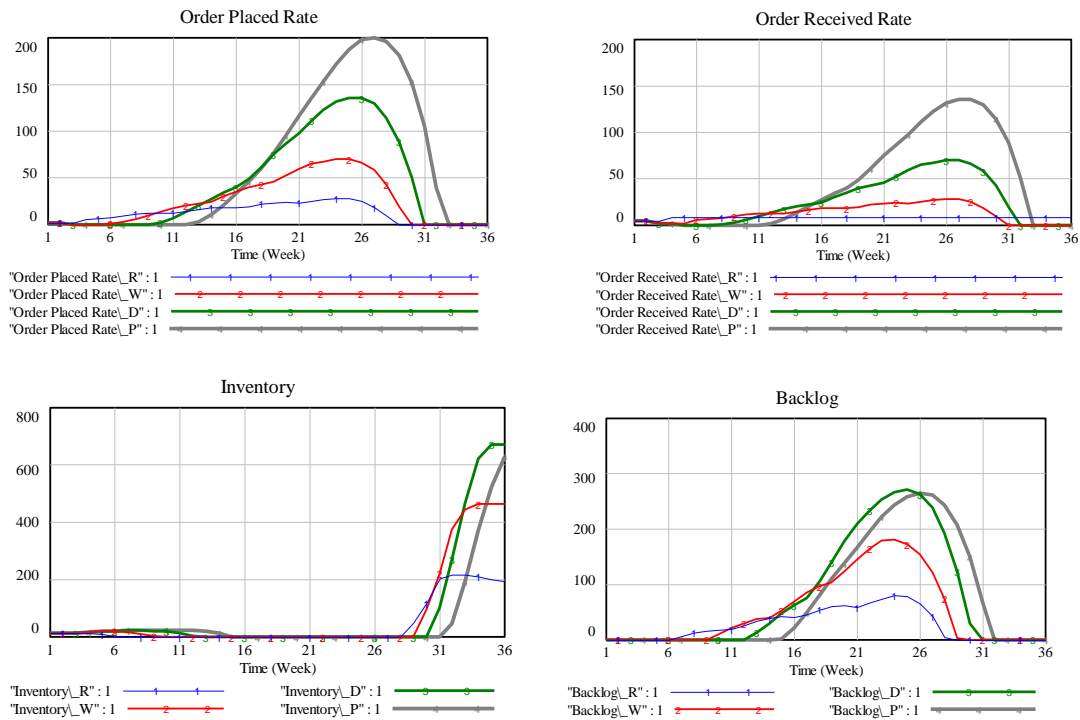


Figure 5- 10 Cutting B2 simulations

5.3 Parameter Sensitivity Test

This model was tested through the extreme condition test and the structure and behavior test. Therefore, logic of the model is reasonable, and the equations are sufficiently robust.

The sensitivity of the parameters can provide support when formulating policies. For the model on which the thesis is based, there are some parameters the participants can control by administrative methods. These methods may be potential policies to solve

the problem in the beer game. In the test, the model runs 500 times. The candidate parameters distribute normally with a standard deviation of 25%.

*5.3.1 Delivery Delay*

Delivery delay can influence the inventory adjustment. The delivery delay is four weeks. Considering the 25% change in the value of candidate parameters, the values will be set from three weeks to five weeks.
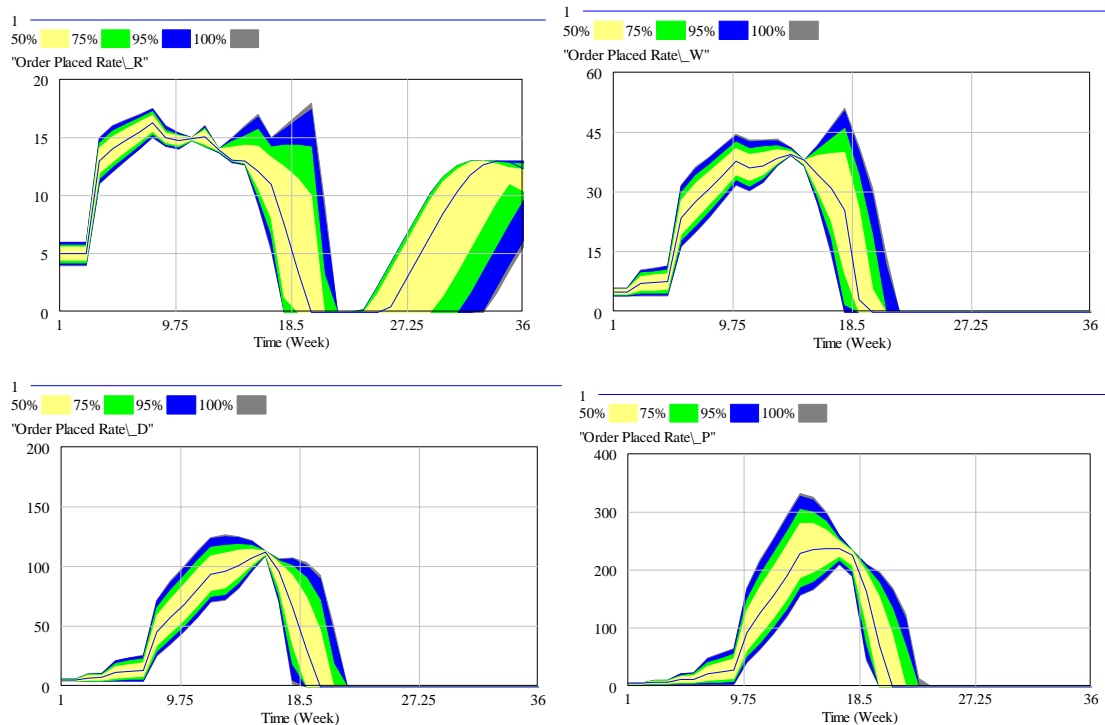


Figure 5- 11 Sensitivity test of inventory coverage

Figure 5-11 shows the test results. The figure shows the 50%, 75%, 95% and 100% confidence bounds for the order placed rate. There is a 50% chance that the order placed rate of the producer will be between approximately 200 and 280 in week 15 and a 95% chance that it will be between approximately 170 and 340.

## 5.3.2 Time to Adjust the Effective Inventory

The time to adjust the effective inventory can influence inventory adjustment. The value is four weeks. Considering the 25% change in the value of the candidate parameters, the values will be set from three weeks to five weeks.
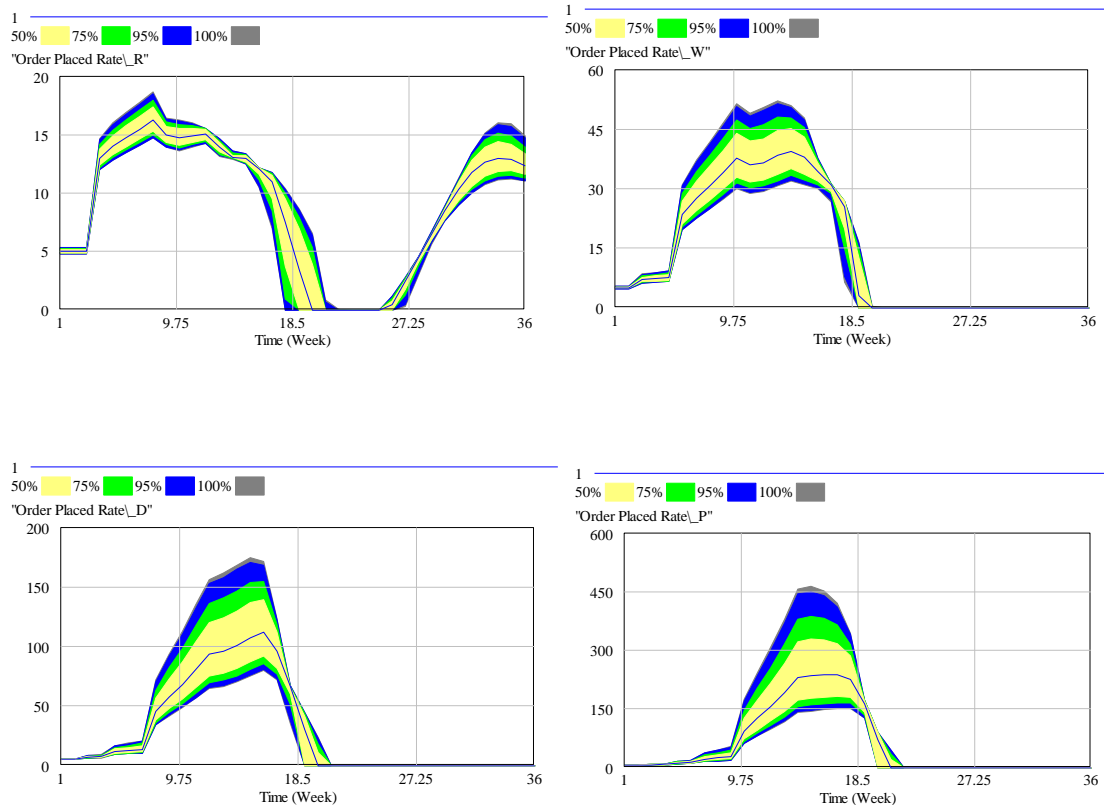


Figure 5- 12 Sensitivity test of delivery delay

Figure 5-12 shows the test results. We can compare the same sector in the same week. There is a 50% chance that the order placed rate of the producer will be between approximately 170 and 320 in week 15 and a 95% chance that it will be between approximately 140 and 460. Small changes in the delivery delay lead the balancing loop of the inventory adjustment to yield increasingly differences along the supply chain.

In summary, this model has passed the extreme condition, structural behavior, and sensitivity test. Thus, the model is reliable. In the following chapter the explanatory

model would be expanded to simulate the beer game experiments.

# Chapter 6 Modeling and Analysis of Supply Line Information Policy

There are three scenarios in the beer game experiments: the group with basic information; the group with in-transit stock information; and the group with supply line information. The explanatory model, proposed in chapter 4, has passed the tests and in this chapter the other two scenarios will be modeled based on that explanatory model.

In the beer game experiments, two performance indicators are assessed, the amplification ratio and the cumulative cost. The amplification ratio indicates the stability of the supply chain. Taking the supply chain as a whole, earnings are the retailer's sales, which in the beer game, is the predetermined customer order. Therefore, the cumulative cost is a good criterion to measure the performance of the supply chain. The lower the cumulative cost, the higher is the profit of the supply chain.

6.1 In-transit Model

In the experimental group of the first and second beer game experiments, the participants had information on the in-transit stock. The results show that, with this policy, their performance was better than that of the control group, which had the basic information. Compared to the basic causal loop diagram, new loops (B4, B5) for the in-transit stock are added.

Figure 6- 1 Causal loop diagram of the in-transit inventory with two sectors

Table 6- 1 Feedback loops of the in-transit inventory with two sectors

| Loop | Feedback Process | Path |
|------|------------------|------|
| B1 | Effect of producer inventory on producer order | **Producer order** + Production rate + Producer inventory - Producer inventory adjustment + **Producer order** |
| B2 | Effect of distributor order on producer order | **Distributor order** + Producer order + Production rate + Producer inventory + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B3 | Effect of distributor inventory on distributor order | **Distributor order** + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B4 | Effect of producer in-transit inventory on producer order | **Producer order** + Production rate + Producer in-transit stock – **Producer order** |
| B5 | Effect of distributor in-transit inventory on distributor order | **Distributor order** + Producer shipping rate + Distributor in-transit stock - **Distributor order** |

The stock-and-flow diagram is expanded based on the explanatory model. The in-transit stock of the retailer is the sum of the wholesaler's shipment rate this week and last week.
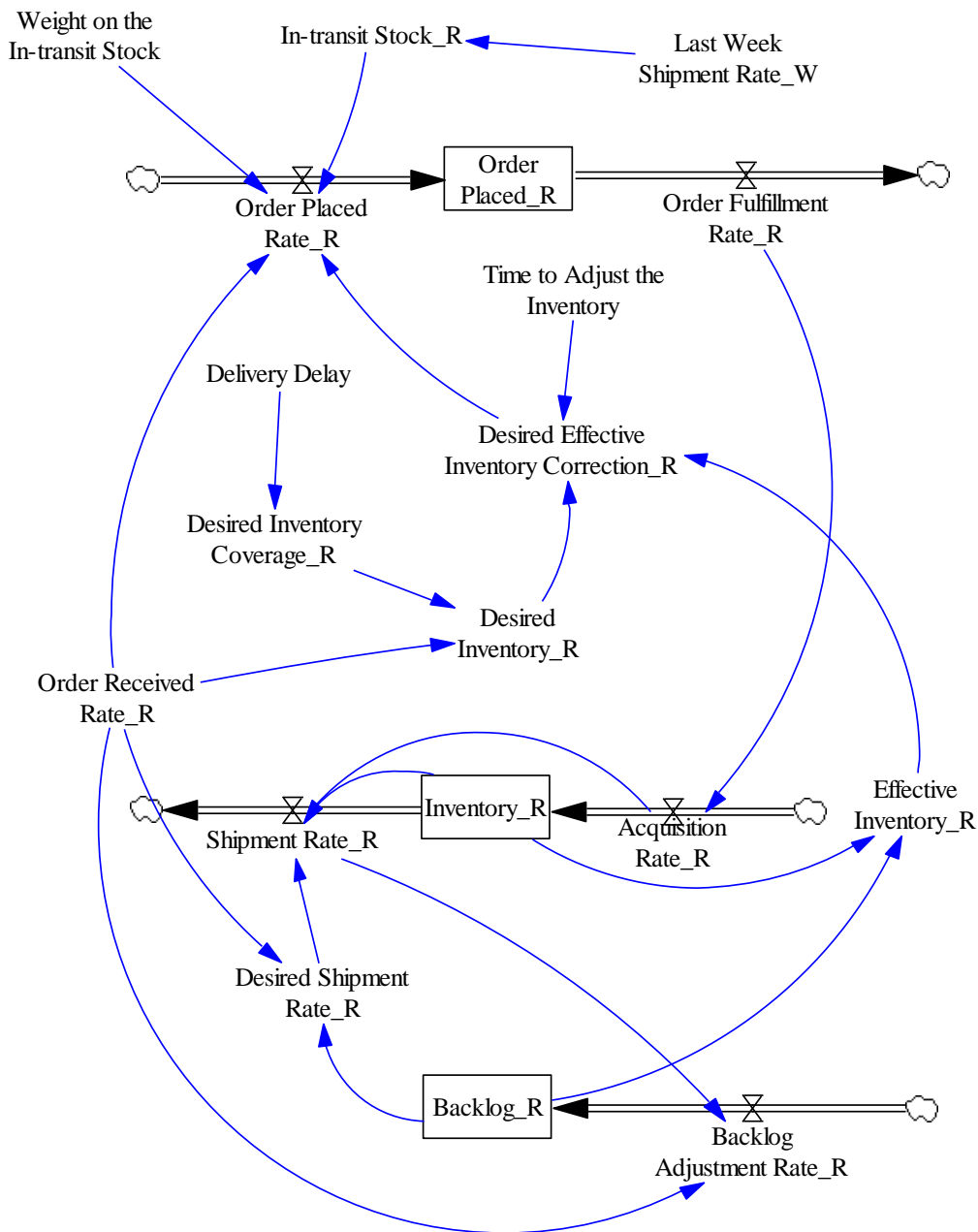
Figure 6- 2 Stock-and-Flow diagram of the retailer with in-transit information

Now the function of the order placed rate is changed as follows.

$Order\ Placed\ Rate$

$= MAX(Order\ Received\ Rate\ +\ Desired\ Effective\ Inventory\ Correction$

$-\ Weight\ on\ the\ Intransit\ Stock\ *\ Intransit\ Stock, 0)$

The parameter "Weight on the In-transit Stock" may be interpreted as the fraction of the in-transit stock taken into account by the participants. It is influenced by the participants' degree of sensitivity on the in-transit stock information. The subjects fully recognize the in-transit stock and do not double-order if the weight is 1. The in-transit inventories are forgotten if the weight is 0. The simulation results are shown as follows.

Table 6- 2 Amplification ratios of five scenarios in supply line simulations

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Weight on the In-transit Stock = 0 | 1 | 3 | 8.875 | 27.125 | 58.25 |
| Weight on the In-transit Stock = 0.25 | 1 | 5 | 13.375 | 28.625 | 44 |
| Weight on the In-transit Stock = 0.5 | 1 | 5.5 | 13.75 | 33.5 | 72 |
| Weight on the In-transit Stock = 0.75 | 1 | 5.5 | 13 | 29 | 60.5 |
| Weight on the In-transit Stock = 1 | 1 | 5.5 | 11.875 | 25.625 | 53.25 |

## Cumulative Cost
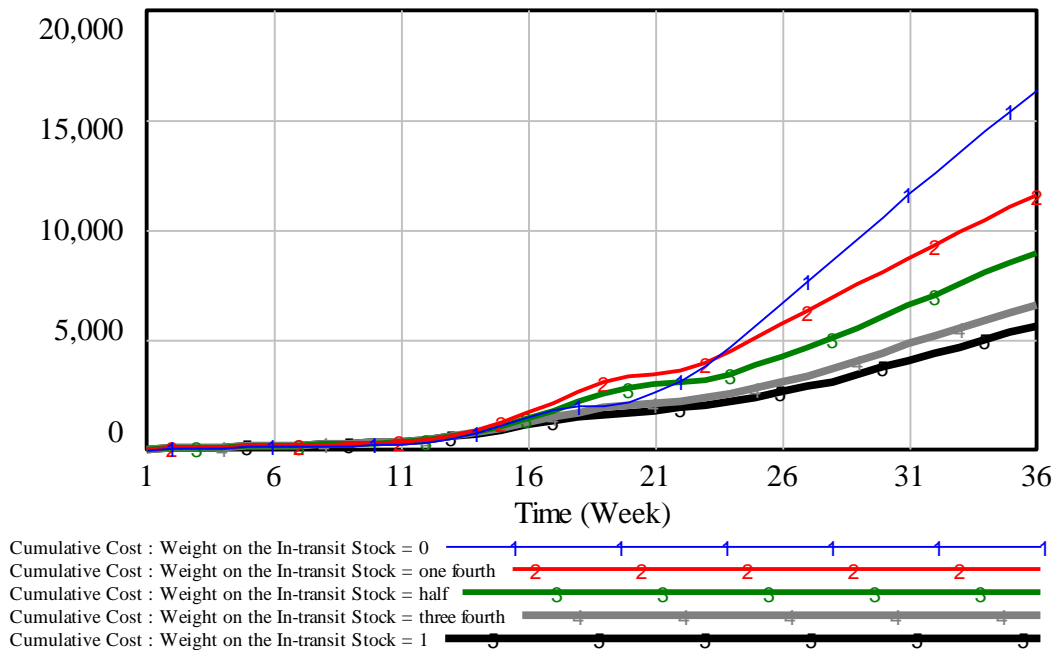


Figure 6- 3 Cumulative cost of different weight in simulations with in-transit stock information

From the simulation results we can see that, the amplification ratio is the highest for all four sectors when the "Weight on the In-transit Stock" is 0.5. The impact of different value is much larger on the upstream participants than on the downstream participants. Despite the amplification ratio results of the scenario "Weight on the In-transit Stock = 0" and the scenario "Weight on the In-transit Stock = 1" are more or less the same, there is a large gap between their cumulative costs. The cumulative cost of the scenario "Weight on the In-transit Stock = 0" is the highest. Generally, we can draw two conclusions: 1) The bullwhip effect could be weakening if the in-transit information is available; 2) Higher degree of sensitivity on the in-transit stock information could decrease both the instability and the cumulative cost significantly.

## 6.2 Supply Line Model

As the third experiment suggests, the participants' performance in the beer game would be much better if they considered the inventory on the supply line. The supply

line products are the products ordered that have not been received. The larger the gap between the desired supply line inventory and the actual supply line inventory, the larger the order should be to correct this gap.

Compared to the causal loop diagram of the explanatory model, different loops (B4, B5) of the supply line inventory are added.
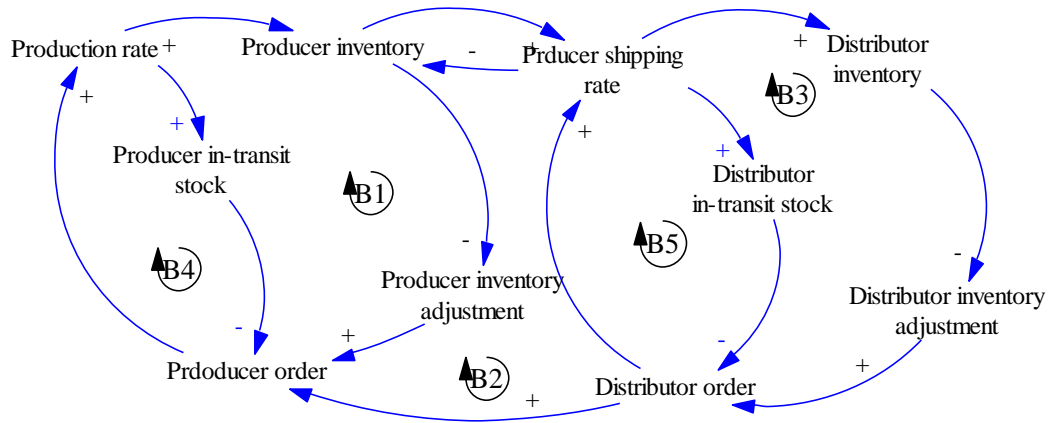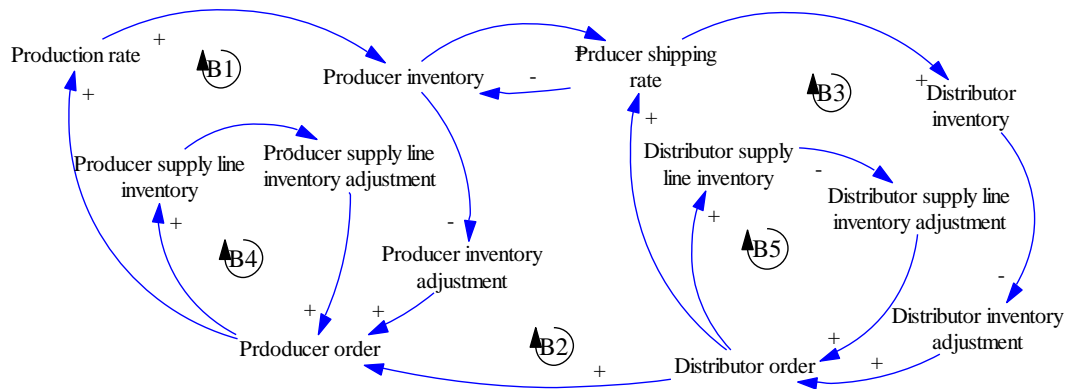


Figure 6- 4 Causal loop diagram of the supply line inventory with two sectors

Table 6- 3 Feedback loops of the supply line inventory with two sectors

| Loop | Feedback Process | Path |
|------|-----------------|------|
| B1 | Effect of Producer inventory on Producer order | **Producer order** + Production rate + Producer inventory - Producer inventory adjustment + **Producer order** |
| B2 | Effect of Distributor order on Producer order | **Distributor order** + Producer order + Production rate + Producer inventory + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B3 | Effect of Distributor inventory on Distributor order | **Distributor order** + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B4 | Effect of Producer supply line | **Producer order** + Producer supply line inventory – |

| | | |
|---|---|---|
| | inventory on Producer order | Producer supply line inventory adjustment + **Producer order** |
| B5 | Effect of Distributor supply line inventory on Distributor order | **Distributor order** + Distributor supply line inventory - Distributor supply line inventory adjustment + **Distributor order** |

Now the function of the order placed rate is changed.

$$Order\ Placed\ Rate$$
$$= MAX(Order\ Received\ Rate\ +\ Desired\ Effective\ Inventory\ Correction$$
$$+\ Weight\ on\ Supply\ Line\ *\ Desired\ Supply\ Line\ Correction, 0)$$
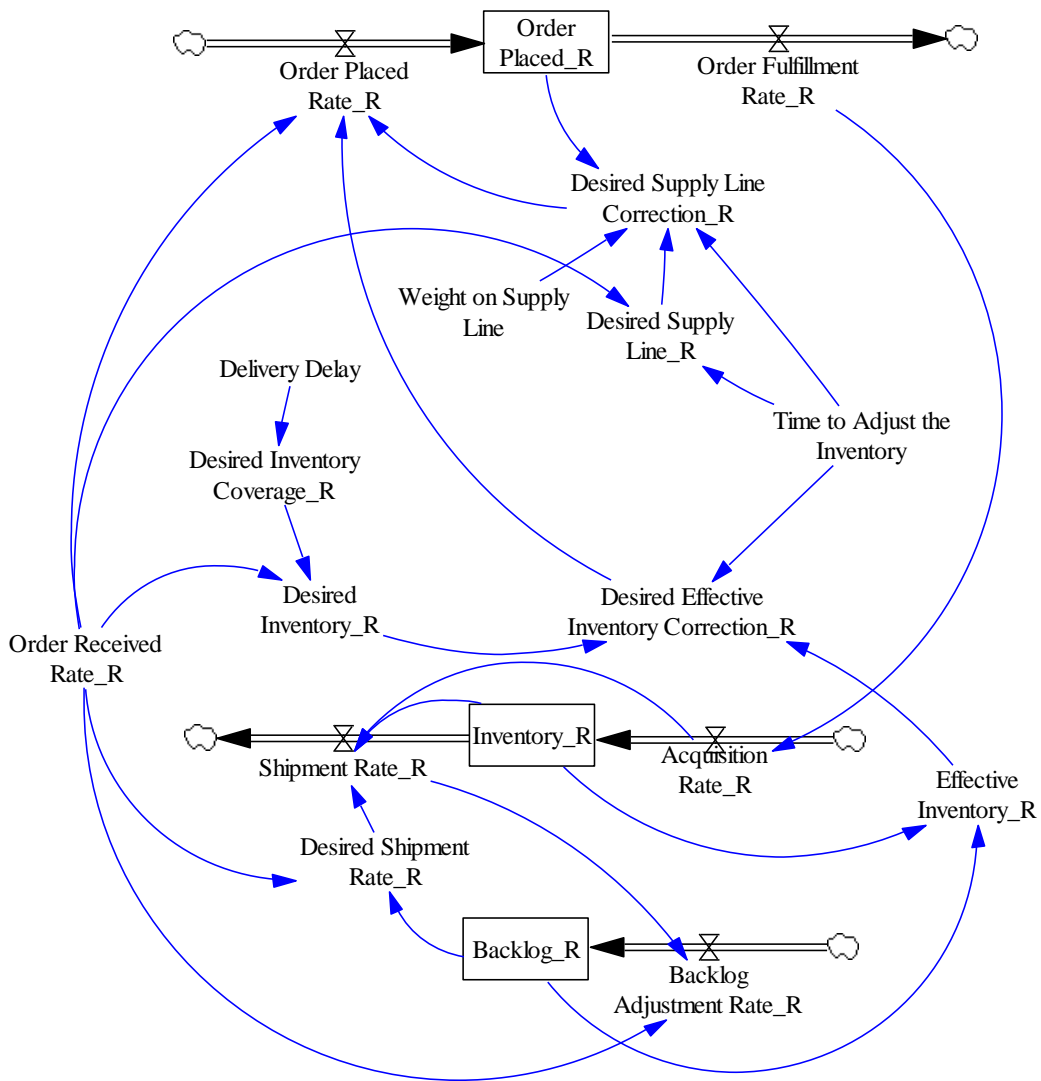
Figure 6- 5 Stock-and-Flow diagram of the retailer with supply line information

The parameter "Weight on Supply Line" may be interpreted as the fraction of the supply line taken into account by the participants. It is influenced by the participants' degree of sensitivity on the supply line information. The subjects fully recognize the supply line and do not double-order if the weight is 1. The supply line inventories are forgotten if the weight is 0.The simulation results are shown as follows.

Table 6- 4 Amplification ratios of five scenarios in supply line simulations

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Weight on Supply Line = 0 | 1 | 3.125 | 8.875 | 27.125 | 58.25 |
| Weight on Supply Line = 0.25 | 1 | 2.75 | 6.75 | 16.875 | 41.25 |

| Weight on Supply Line = 0.5 | 1 | 2.75 | 6.75 | 16.625 | 40.875 |
| Weight on Supply Line = 0.75 | 1 | 2.875 | 7.875 | 21.125 | 56.875 |
| Weight on Supply Line = 1 | 1 | 3.125 | 9.125 | 26.875 | 79 |

## Cumulative Cost
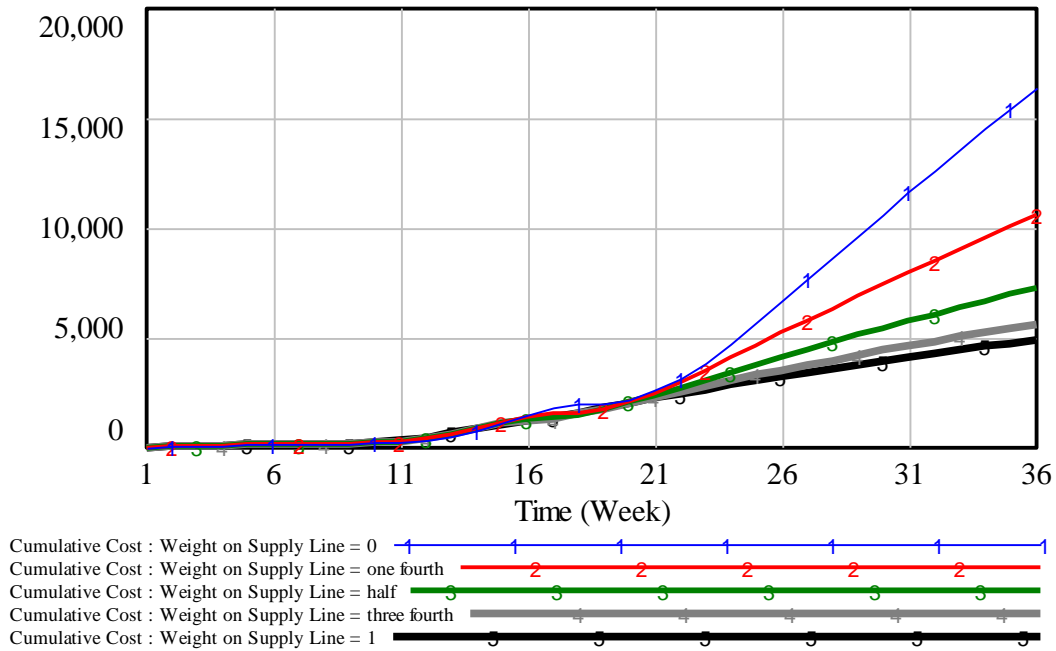


Figure 6- 6 Cumulative cost of different weight in simulations with supply line information

We find a trade-off between stability and costs so that the optimal weight on supply line is moderate. The amplification ratio is the lowest for all four sectors when the "Weight on Supply Line" is 0.5, while the lowest cumulative cost appears in the scenario "Weight on Supply Line = 1".

We can draw three conclusions: 1) The bullwhip effect could be weakening if the supply line information is available; 2) Higher degree of sensitivity on the supply line information could decrease the cumulative cost significantly; 3) The instability will increase if the supply line stock being considered in a too large weight.

6.3 Performance Comparison

As proved above, both the two kinds of information can weaken the bullwhip effect. Here we compare the performance of the three scenarios with the same range together, to test our hypothesis 1 ("Additional supply line information may weaken the bullwhip effect, and the entire supply line information is more effective than a portion of it (in-transit information)." again.

The scenario "Weight on the In-transit Stock = 1" has the best performance both in instability and the cumulative cost. For the simulation with supply line information, the gap of the cumulative cost between the scenario "Weight on Supply Line = 0.75" and the scenario "Weight on Supply Line = 1" is not so significant, while the simulation results of the amplification ratio of the formal scenario is much better, so we choose the scenario "Weight on Supply Line = 0.75" to represent the optimal simulation here.
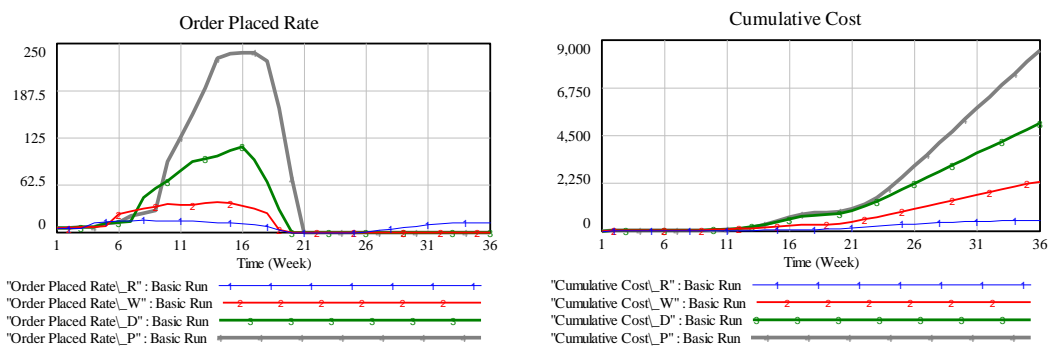


a. Simulation result of the basic run
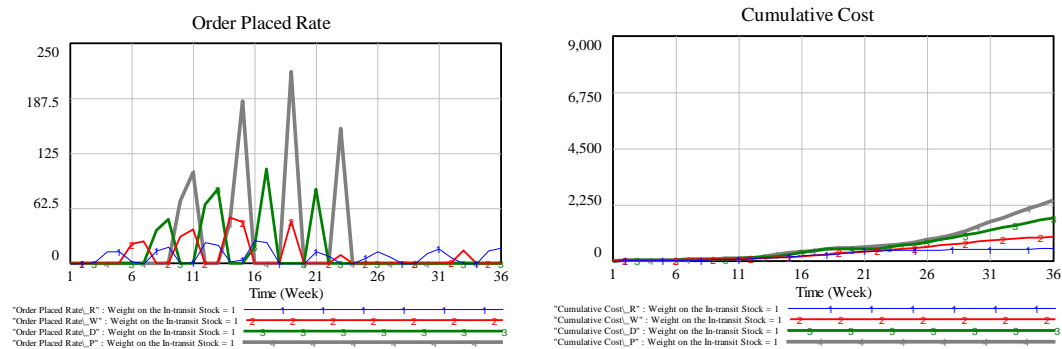


b. Simulation result of the in-transit model (Weight on the In-transit Stock = 1)
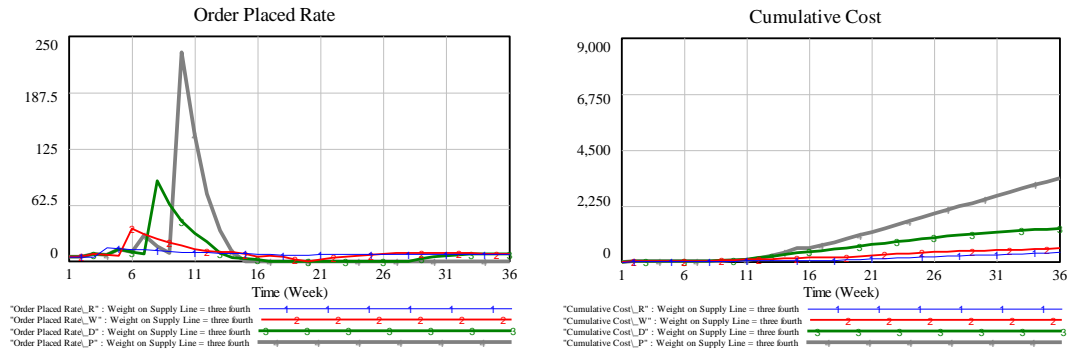
c. Simulation result of the supply line model (Weight on Supply Line = 0.75)

Figure 6- 7 Simulation results of three information scenarios

Table 6- 5 Amplification ratios of three scenarios in simulations

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| Explanatory Model | 1 | 3.125 | 8.875 | 27.125 | 58.25 |
| In-transit Information | 1 | 5.5 | 11.875 | 25.5 | 53.25 |
| Supply Line Information | 1 | 2.875 | 7.875 | 21.125 | 56.75 |

Table 6- 6 Cumulative costs of three scenarios in simulations

|  | Cumulative Cost |
|---|---|
| Explanatory Model | 16373 |
| In-transit Information | 5589 |
| Supply Line Information | 5580 |

From those three figures and tables above, we can see that the cumulative cost does decrease if the participants have access to more information and utilize that information indeed effectively in their decision making. The performance of the model where information about the supply line is made available and the best, and its orders are more stable than the other two models. This result is totally in line with the conclusion of the experiments. It also proves that the model is a reliable representation of the Beer Game.

The conclusion that different values of the weight have different simulation results suggests that different perceptions with different degree of sensitivity of the same kind of information have different impact. Based on this and the conclusion in the

beer game analysis, the policies governing how the information is utilized would be analyzed in the following chapters.

# Chapter 7 Modeling of the Perceived Delivery Delay Policy

7.1 Desired Inventory Coverage

From the previous chapters we know that the supply line inventory information policy is an effective means to improve the performance of the supply chain. However, participants who have the access to this kind of information do not achieve such a good performance in the experiments as in the simulations. The participants know that the delivery delay is four weeks when they play the game. Due to upstream stock-out in the short run, however, it may take more than four weeks to receive the products after ordering, when the system exhibits a transient behavior. The participants are aware of this situation, but they do not know how the delivery delay will vary. They typically would make their ordering decision based on their current perception of the delivery delay. This apparently rational decision-making process unintentionally increases the bullwhip effect. To reflect this process in our model, new variable "Perceived Delivery Delay" is proposed.
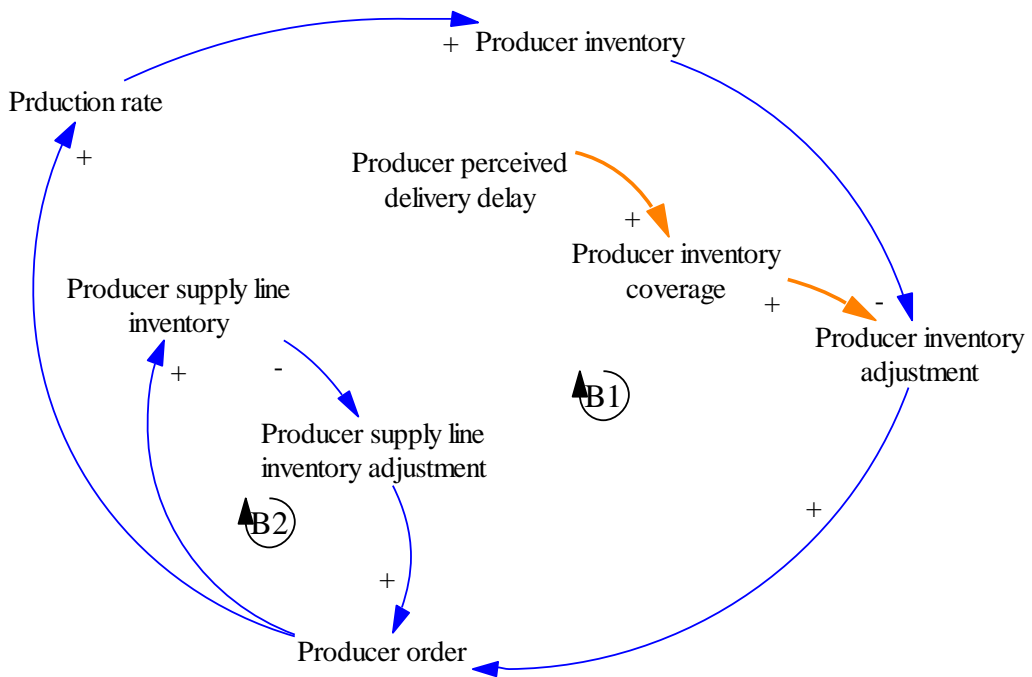
Figure 7- 1 Causal loop diagram of the retailer with perceived delivery delay

The stock-and-flow diagram is expanded based on the supply line inventory model.
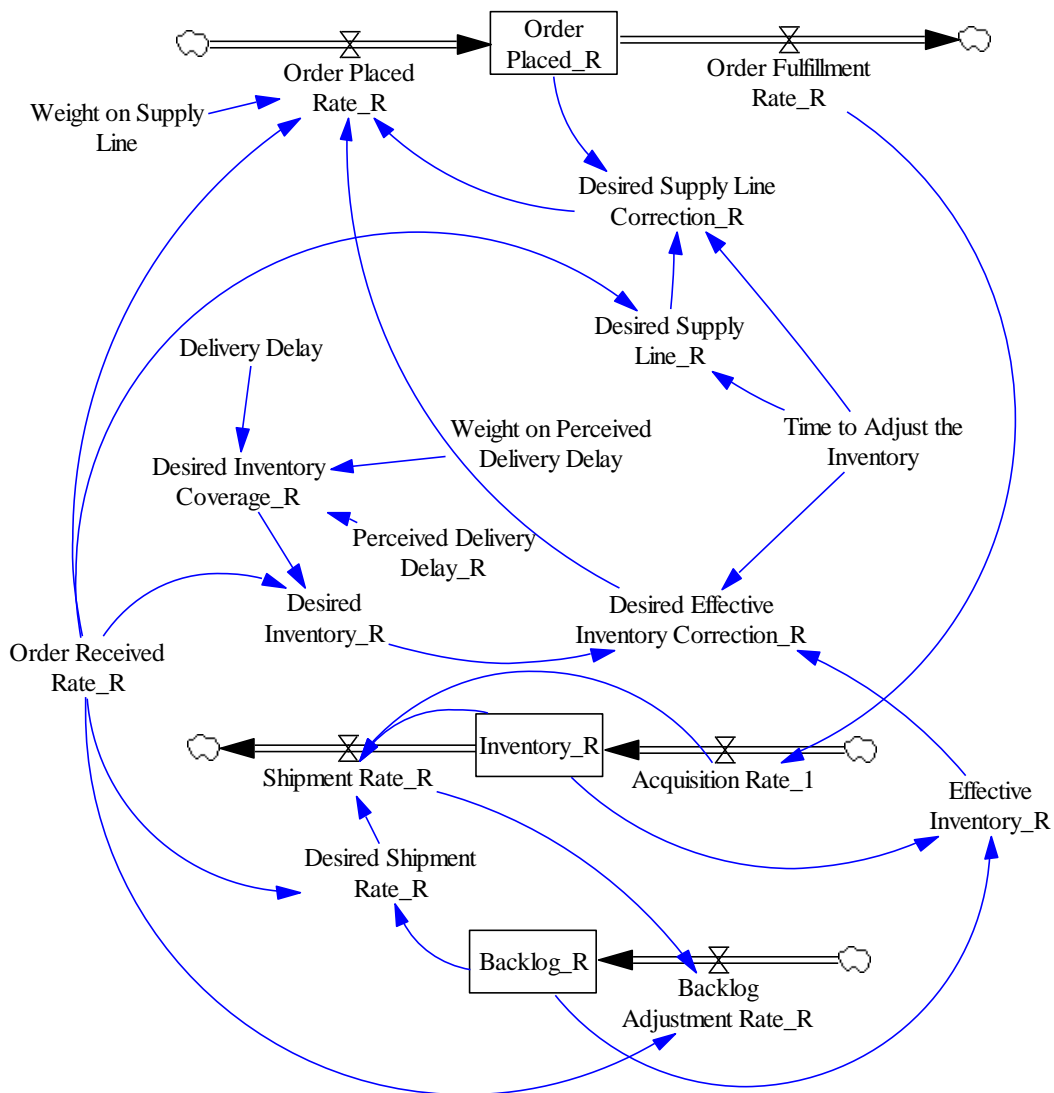
Figure 7- 2 Stock-and-Flow diagram of the retailer with perceived delivery delay

## 7.2 Perceived Delivery Delay

The delivery delay is perceived based on the inventory on the supply line and the order received rate. Larger order received rate can make the participants feel that the delivery rate is faster, in other words, bring down the perceived delivery rate. To reflect this process in our model, two policy feedback loops are proposed, i.e. R1 and B3.
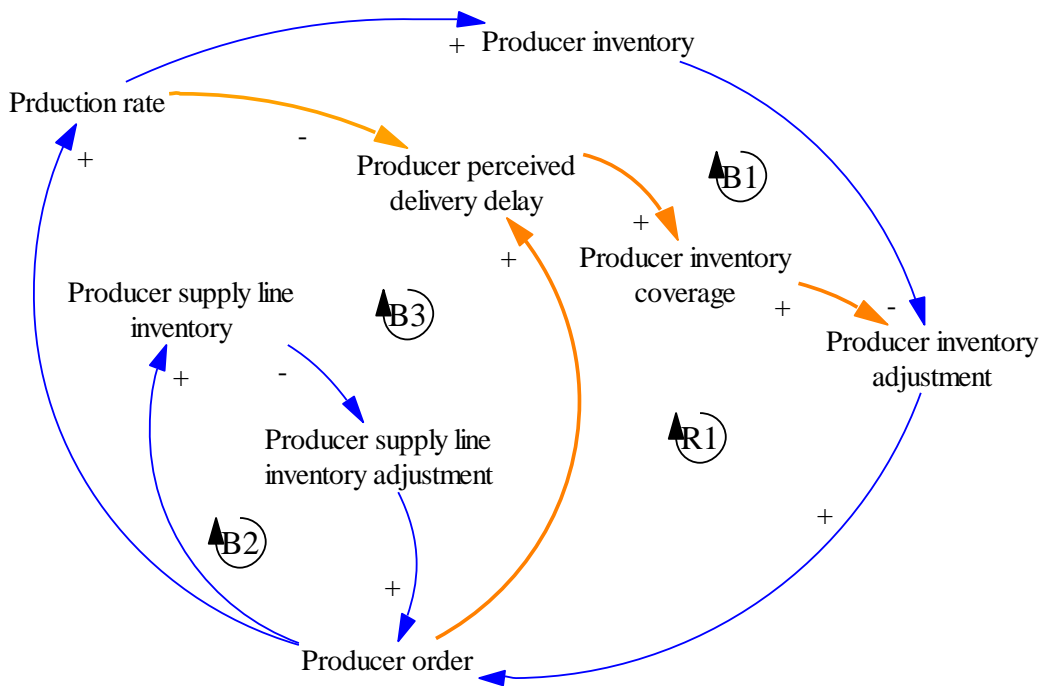
Figure 7- 3 Causal loop diagram of the retailer with perceived delivery delay policy

Table 7- 1 Feedback loops of the retailer with perceived delivery delay policy

| Loop | Feedback Process | Path |
|------|------------------|------|
| R1 | Effect of Producer perceived delay on Producer order | **Distributor order** + Producer shipping rate + Distributor inventory - Distributor inventory adjustment + **Distributor order** |
| B1 | Effect of Producer inventory on Producer order | **Producer order** + Production rate + Producer inventory - Producer inventory adjustment + **Producer order** |
| B2 | Effect of Producer supply line inventory on Producer order | **Producer order** + Producer supply line inventory - Producer supply line inventory adjustment + **Producer order** |
| B3 | Effect of Producer perceived delay on Production rate | **Production rate** - Producer perceived delivery delay + Producer inventory coverage + Producer inventory adjustment + Producer order + **Production rate** |
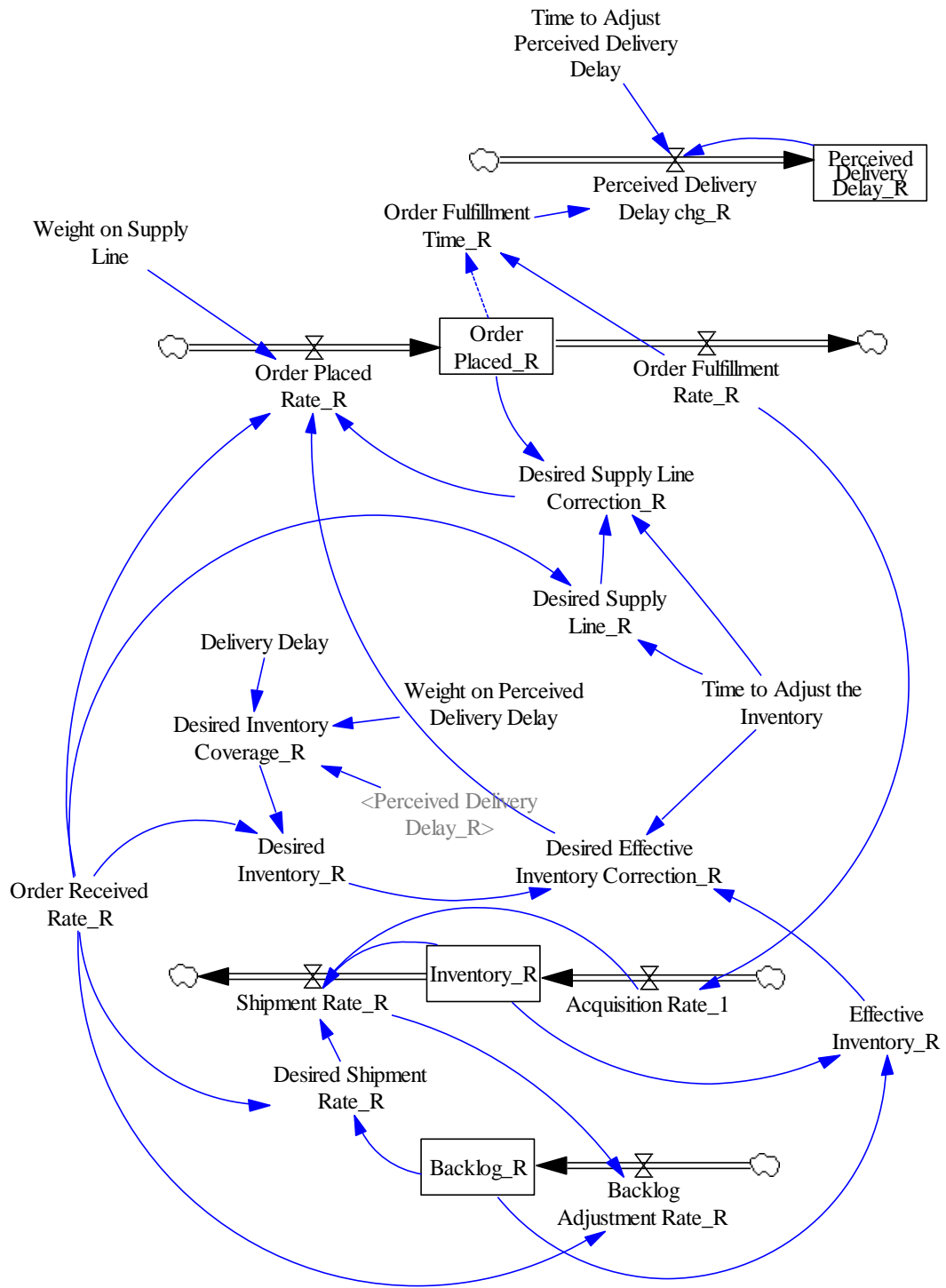
Figure 7- 4 Stock-and-Flow diagram of the retailer with perceived delivery delay policy

The stock means that the perceived delivery delay would be decided on based up on an exponential smoothing of the order fulfillment time. By smoothing the order fulfillment time, the perceived delivery delay could be more stable, so as to reduce the bullwhip effect.

In the beer game, placing the order is the only decision that participants need to make. Perceived delivery delay is the participants' perception about the delivery delay based on the supply line inventory information. The desired inventory coverage is the way they transform this perception into the ordering decision.

It takes time from the order is placed until the order is received. After placing significantly, the perceived delivery delay would increase first, and decrease when the order placed has been received later. Although there is a balancing loop between the perceived delivery delay and the production rate, it takes time to receive the beer after ordering. Especially for the downstream participants, the time could be much longer than the production time in case of stock-outs in some sectors. So the problem is that, on one hand, the players' backlog and perceived delivery delay are increasing rapidly and they are gradually losing their patience, which could make them feel that the delivery delay is longer than expected. So they would order considerably more than they actually need, which is called as phantom orders (Sterman, 2000). This balancing loop would eventually causes players to receive their ordering beer. The more beer they receive, the shorter they perceive the delivery delay to be. As a consequence, they would decrease their order significantly afterward in the realization that the supply line does not have to be as massive as expected. This mental thinking and decision-making process is the reason for such a broad range of fluctuation in the order placed rate.

# Chapter 8 Analysis of the Perceived Delivery Delay Policy

As the results presented in previous Chapter demonstrate, the participants vary in their mental perception and decision making process even though they know that the equilibrium delivery delay is 4 weeks. So here the desired inventory coverage is set as the weighted trade-off of the perceived delivery delay (in the short run) and fixed delivery delay (in the long run) with different weight. The equation of the desired inventory coverage is as below:

Desired Inventory Coverage

$= Weight\ on\ Perceived\ Delivery\ Delay * Perceived\ Delivery\ Delay$

$+ (1 - Weight\ on\ Perceived\ Delivery\ Delay) * Delivery\ Delay$

If the desired inventory coverage is equal to the perceived delivery delay, i.e. the weight is equal to 1, then, the delivery delay has no impact on the desired inventory coverage.

Assume a parameter α to replace the "Weight on Perceived Delivery Delay" (0≤α≤1), then,

Desired Inventory Coverage = α * Perceived Delivery Delay + (1 - α) * Delivery Delay

α is the weight we assign to the perceived delivery delay in the desired inventory coverage. The larger α is, more aggressively the participant is in delivery delay adjustment. In the following part we test different values of α, to find the optimal range.

# Cumulative Cost
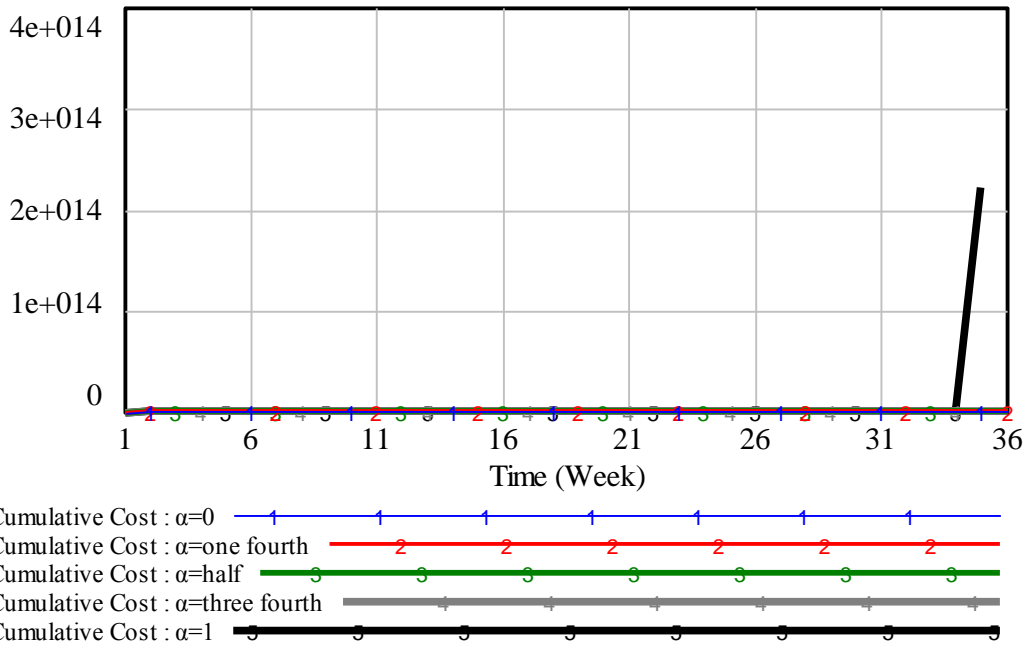


a. Extremely large cumulative cost in scenario "α = 1" compared to the other four scenarios

# Cumulative Cost
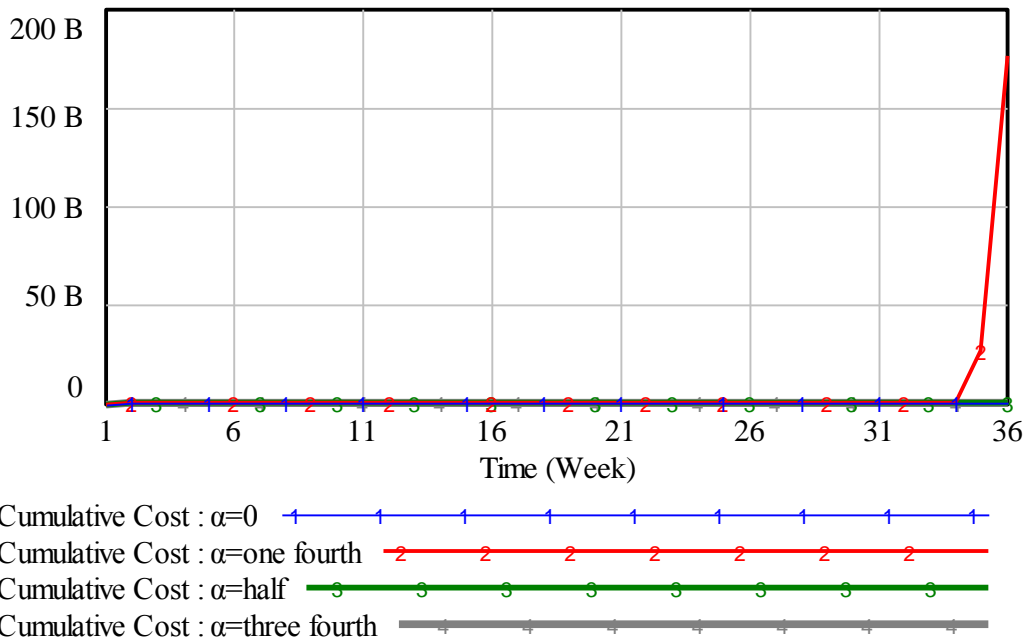


b. Relatively large cumulative cost in scenario "α = one fourth" compared to the other three scenarios

## Cumulative Cost
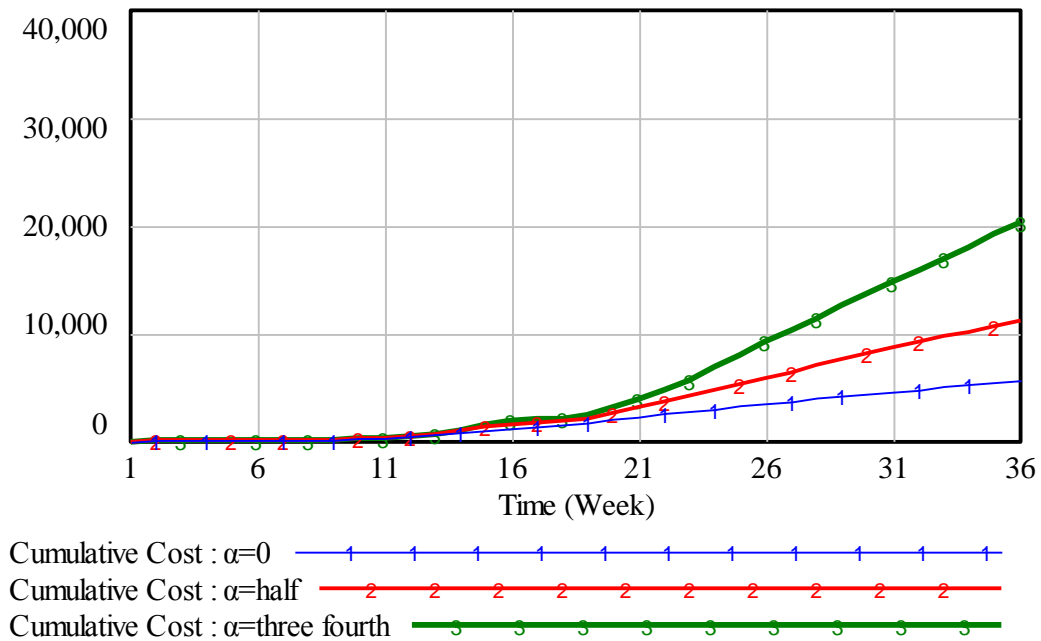
c. Acceptable cumulative cost in three scenarios

Figure 8- 1 Cumulative costs of different values of α

We can see that the scenario "α = 0" has the lowest cumulative cost. "α=0" means that the inventory coverage is exactly equal to the fixed delivery delay, i.e. four weeks. However, in real life, the delivery delay may change. It is not feasible to consider the delivery delay as a constant number in the decision-making process. Furthermore, as we find in the beer game experiments, participants cannot be so rational. Their perceived delivery delay will influence their decision, though they know the exact delivery delay is four weeks.

The cumulative cost in scenario "α = 1" is extremely large, which indicates that too aggressive inventory coverage adjustment will increase the cost. Figure 8-1 b shows that the cumulative cost in scenario "α = one fourth" is also quite large. This finding shows that too conservative decision can also bring very large cost. The optimal weight assigned to the perceived delivery delay in the desired inventory coverage should be neither too small nor too large. In the following analysis we choose four values of α: 1/2, 11/20, 3/5, and 7/10.

Table 8- 1 Amplification ratios of four different values of α

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| α=half | 1 | 2.875 | 8.25 | 22.5 | 70.25 |
| α=eleven twentieth | 1 | 2.75 | 8.25 | 22.125 | 62.75 |
| α=three fifth | 1 | 2.875 | 8.25 | 24.625 | 96.75 |
| α=seven tenth | 1 | 3 | 8.5 | 30 | 129.875 |

## Cumulative Cost
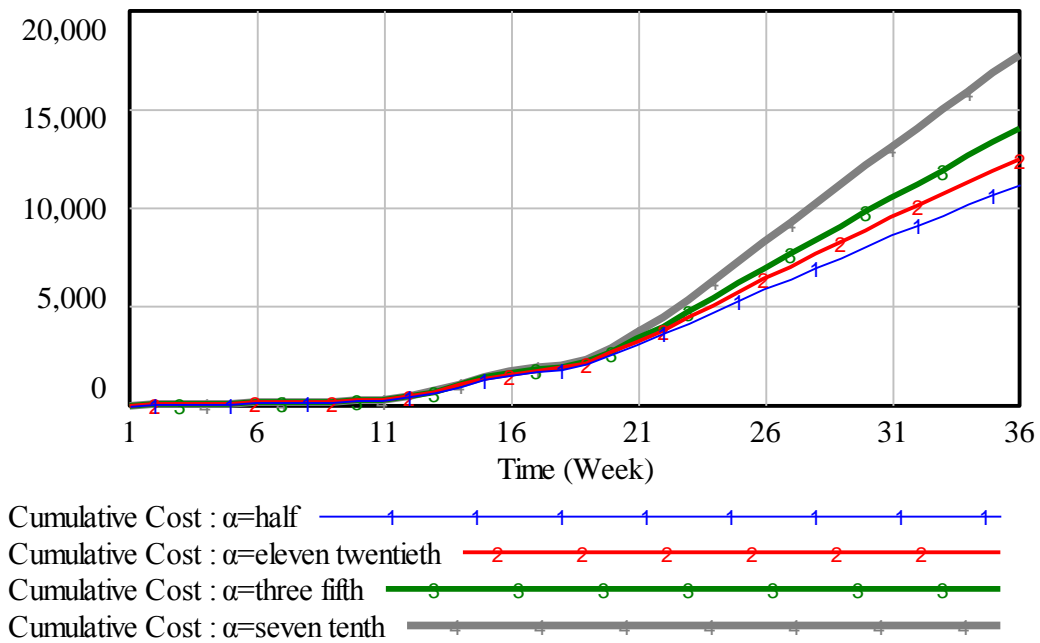


Figure 8- 2 Cumulative costs of four different values of α

From the simulation results above, we can see that in this case, scenario"α=half" has the lowest cumulative cost. This suggests that the weight on the perceived delivery delay should not too large. Too aggressiveness will lead decision-maker to change their inventory coverage based on their perception of the delivery delay in the short run, and influence the upstream participants' order received estimation significantly, and finally increase the cost of the entire supply chain.

From "α=half" and "α=eleven twentieth" scenarios, we find a trade-off between the stability and costs, though those two values of α are both moderate. Over the 36 weeks, "α=half" scenario achieve the lowest cost, while "α=eleven twentieth" scenario has the lowest amplification ratio. This suggests that to eliminate the bullwhip effect, if possible, may be not an economic solution.

The equation of the perceived delivery delay is as below:

Perceived Delivery Delay$_t$ = Perceived Delivery Delay$_{t-1}$ + Perceived Delivery Delay chg * Time Step

While

Perceived Delivery Delay chg = (Order Fulfillment Time - Perceived Delivery Delay$_{t-1}$) / Time to Adjust Perceived Delivery Delay

So that,

Perceived Delivery Delay$_t$ = Perceived Delivery Delay$_{t-1}$ + (Order Fulfillment Time - Perceived Delivery Delay$_{t-1}$) / Time to Adjust Perceived Delivery Delay * Time Step

Assume a parameter β to replace "(Time Step / Time to Adjust Perceived Delivery Delay)", then

Perceived Delivery Delay$_t$ = (1 - β) * Perceived Delivery Delay$_{t-1}$ + β * Order Fulfillment Time

So then,

Desired Inventory Coverage = α * ((1 - β) * Perceived Delivery Delay$_{t-1}$ + α * β * Order Fulfillment Time) + (1 - α) * Delivery Delay

In the process forming the perception of delivery delay, players may act either aggressively or cautiously in response to changes in the actual delivery delay. B is the weight we assign to the order fulfillment time. The larger β is, the more aggressive the participant is. It could be changed to reflect decision maker's mental state of affair.

## Cumulative Cost
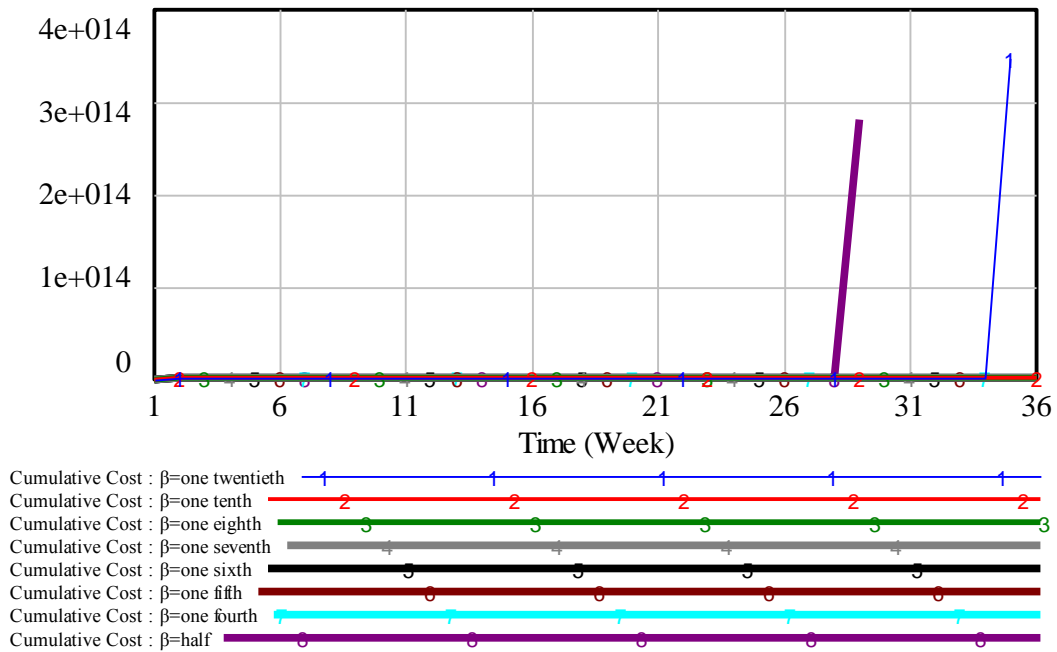
a. Extremely large cumulative costs in scenarios "β= half" and "β=one twentieth" compared to other scenarios
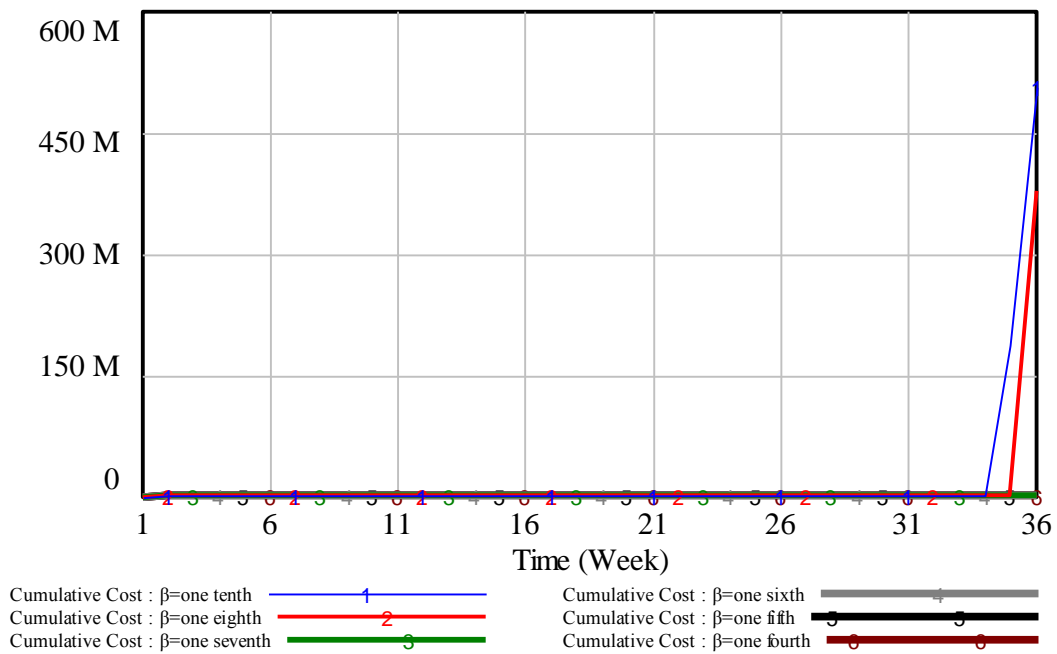


## Cumulative Cost

b. Relatively large cumulative costs in scenarios "β= one tenth" and "β=one eighth" compared to other scenarios
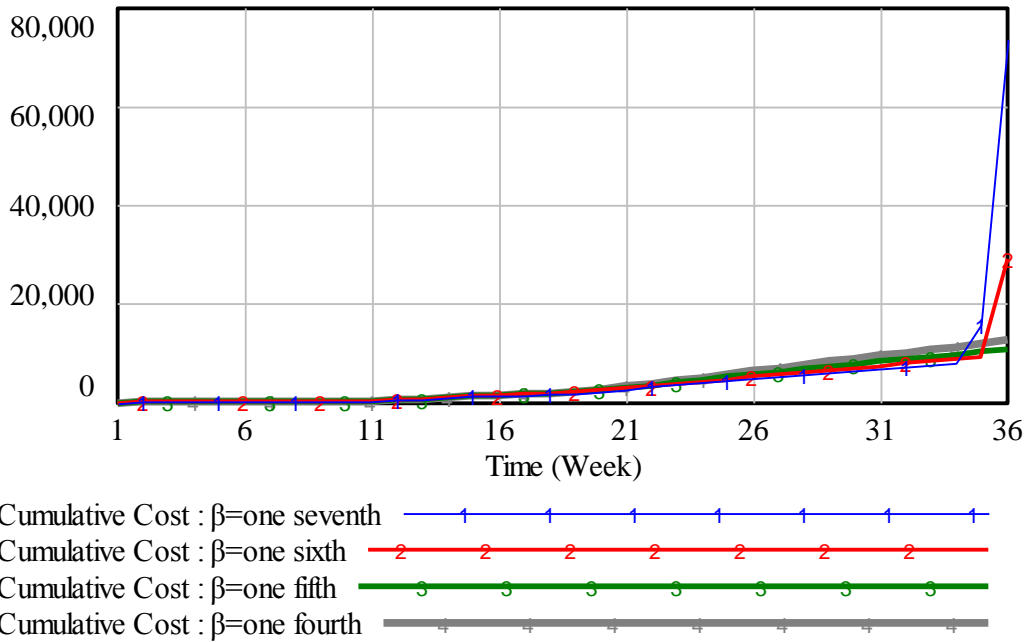
## Cumulative Cost



c. Acceptable cumulative cost in four scenarios

Figure 8- 3 Cumulative costs of different values of β

From figure 8-3 we find that, too cautious decision in delivery delay perception will also increase the cost in the long run. This may because of the cumulative backlog. We will come back to this in the following analysis, in which we choose four values of β: 1/3, 1/4, 1/5, and 1/6.
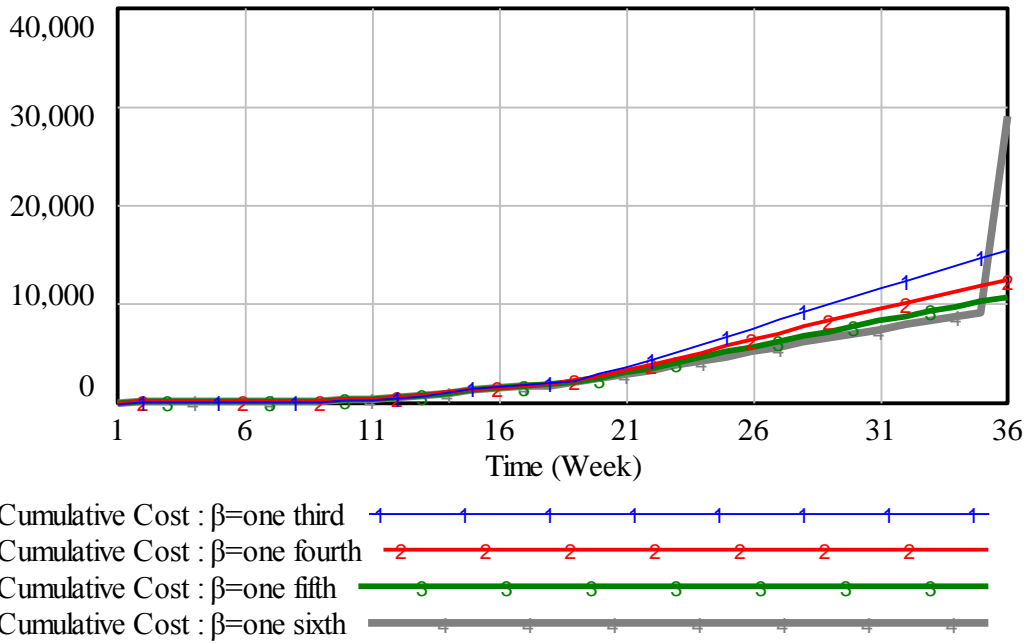
a. Cumulative costs of different values of β over 36 weeks
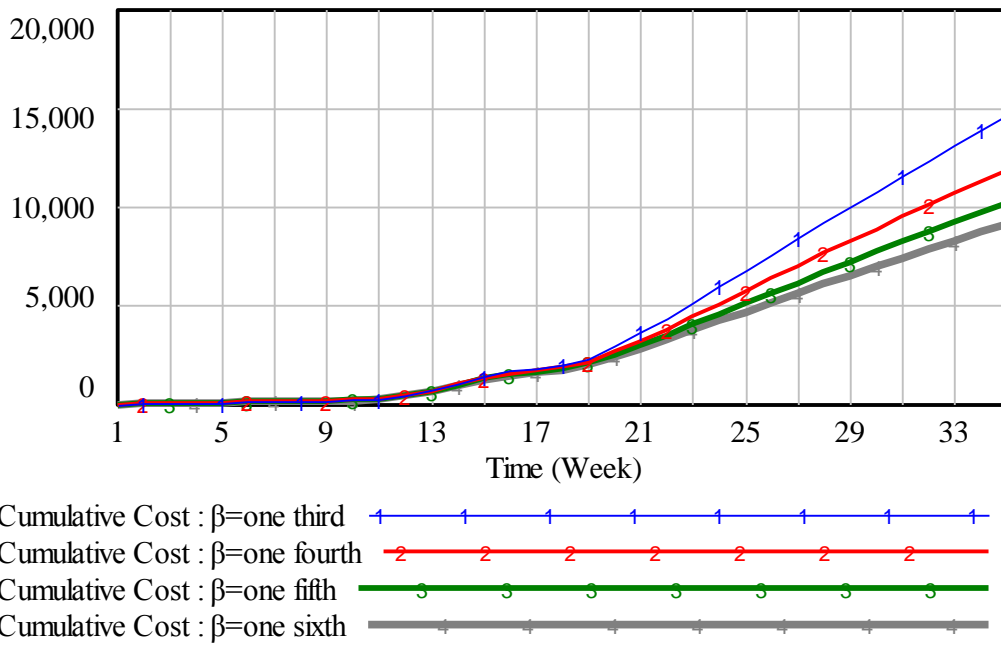


b. Cumulative costs of different values of β over 35 weeks

Figure 8- 4 Cumulative costs of different values of β

Table 8- 2 Amplification ratios of different values of β

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| β=one third | 1 | 3 | 8.375 | 28.75 | 120.75 |

| | | | | | |
|---|---|---|---|---|---|
| β=one fourth | 1 | 2.875 | 8.25 | 22.625 | 82.75 |
| β=one fifth | 1 | 2.875 | 8.25 | 22.375 | 61.75 |

Note: the amplification ratio of scenario "β=one sixth" is extremely large from week 31, so we remove it in this comparison.

Table 8- 3 Amplification ratios of different values of β over 31 weeks

| | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| β=one third | 1 | 3 | 8.375 | 28.75 | 120.75 |
| β=one fourth | 1 | 2.875 | 8.25 | 22.625 | 82.75 |
| β=one fifth | 1 | 2.875 | 8.25 | 22.375 | 61.75 |
| β=one sixth | 1 | 2.875 | 8.125 | 22.125 | 60.375 |

The results of the simulation show that the cumulative cost decreases when β decreases from one third to one fifth, indicating that by being more cautious could result in changing the perceived delivery delay, lower the cumulative cost. However, when β further decreases to one sixth, the cumulative cost increases. Again, we find the trade-off between short run performance and long run performance here. This is because the participants would not change their orders placed rate to make the inventory/backlog respond effectively to the change in demand. If the demand situation is really changed, the entire supply chain would not be efficiently sensitive. The resulting increase in backlog would bring up the cumulative cost, and even cause the customers to leave and search for other suppliers. This indicates that neither too aggressive nor too cautious is not a smart choice for the decision-maker.

These two conclusions above suggest that the degree of aggressiveness has significant impact on the information perception, as well as the degree of sensitivity. Decision makers should not be too aggressive in changing either the perceived delivery delay or the desired inventory coverage during the information utilization process. By relying on intermediate delivery delay values resulting from a system in transition, the corresponding decision making may cause inefficiency in that the orders exhibit significant fluctuation that decreases the overall profit. On the other hand, too

cautious policy will bring in significant backlog in the long run. Moreover, our finding supports the existing of the trade-off between stability and costs. This suggests that maybe the bullwhip effect should be allowed to exist to some extent.

# Chapter 9 Modeling and Analysis of other Information

# Transformation Policies

9.1 Estimated Order Received

Based on the supply line inventory information, the perception of the delivery delay will be transformed into the inventory coverage, and into the ordering decision-making finally. Besides, there are some other information transformation mechanisms which also have impact on the ordering. Demand forecast is determined based on the information of the order received rate. The order received rate could change suddenly, and this would influence the ordering significantly and probably unrealistically much. By smoothing the demand forecast, the corresponding order placed rate could be more stable, so as to reduce the bullwhip effect. The estimated order received rate means the demand forecast would be made based on an exponential smoothing of the order received rate. The sector of the estimated order received rate is modeled as below:
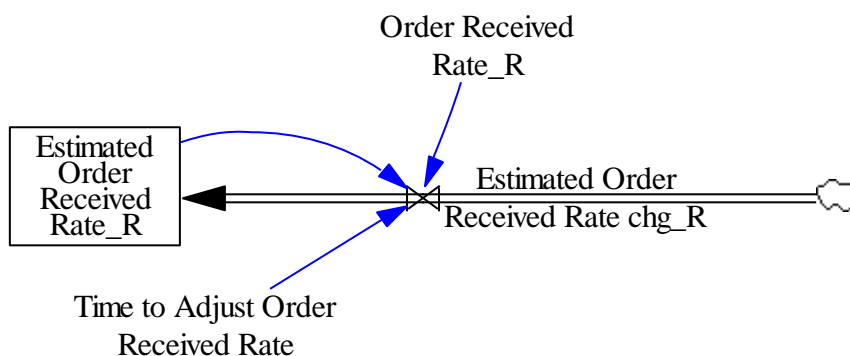
Figure 9- 1 Sector of the estimated order received rate
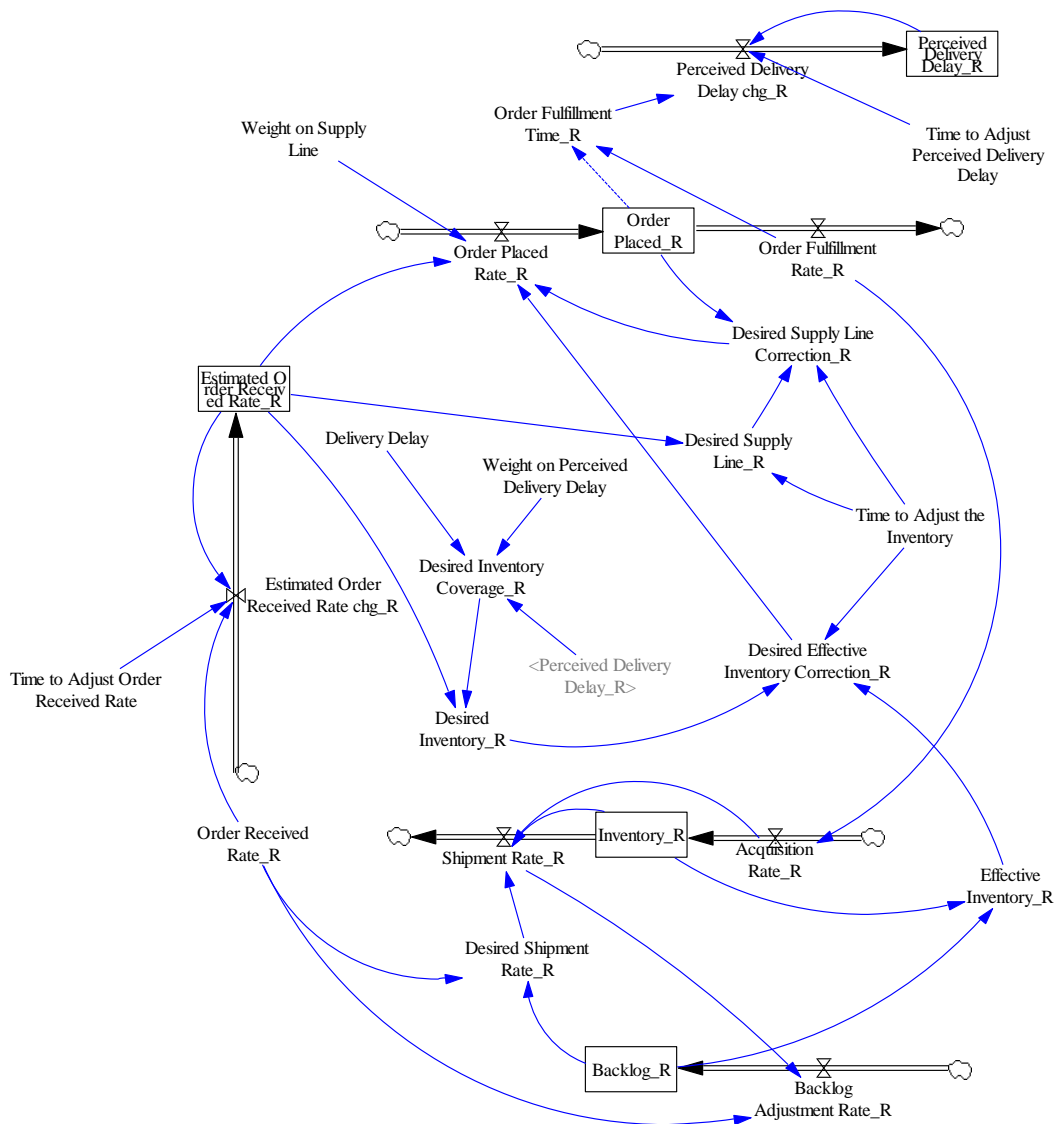
Figure 9- 2 Stock-and-Flow diagram of the retailer with estimated order received rate

The equations of the estimated order received rate are as below:

Estimated Order Received Rate$_t$ = Estimated Order Received Rate$_{t-1}$ + Time Step * Estimated Order Received Rate chg

Estimated Order Received Rate chg = (Order Received Rate - Estimated Order Received Rate$_{t-1}$) / Time to Adjust Order Received Rate

So,

Estimated Order Received Rate$_t$ = Estimated Order Received Rate$_{t-1}$ + Time Step * (Order Received Rate - Estimated Order Received Rate $_{t-1}$) / Time to Adjust Order

Received Rate

Set the "Time Step / Time to Adjust Order Received Rate" as γ, then,

Estimated Order Received Rate$_t$ = (1 − γ) * Estimated Order Received Rate$_{t-1}$ + γ *

Order Received Rate

γ is the weight we assign to the current value of the order received rate. Thus a larger weight assigned to the order received rate when γ is larger. The larger γ is, more aggressively the participant adjusts the estimated order received rate. The scenario "γ=1" means the estimated order received rate is exactly equal to the current order received rate, in other words, there is no policy on the estimated order received rate at all.

Table 9- 1 Amplification ratios of different values of γ

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| γ=one twentieth | 1 | 1.75 | 2.75 | 4 | 5.375 |
| γ=one tenth | 1 | 1.875 | 3.25 | 5.625 | 9 |
| γ=one sixth | 1 | 2 | 4 | 7.625 | 13.375 |

Note: the amplification ratio of scenarios "γ=one fourth", "γ=half", and "γ=1" are extremely large, so we remove these in this comparison.

## Cumulative Cost
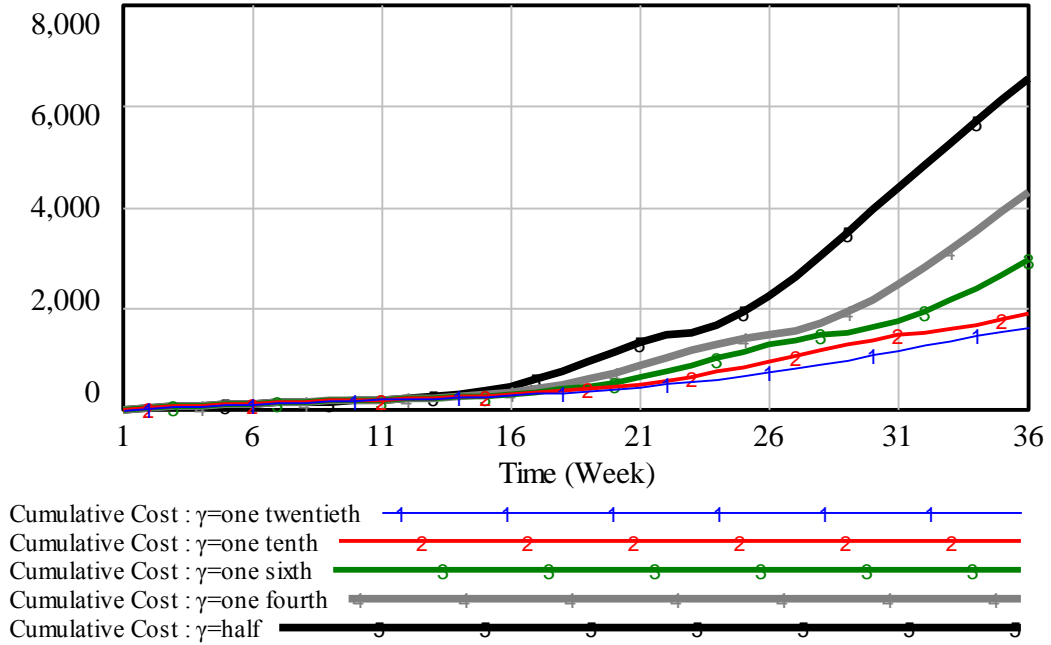


a. Cumulative costs of six different values of $\gamma$

## Cumulative Cost
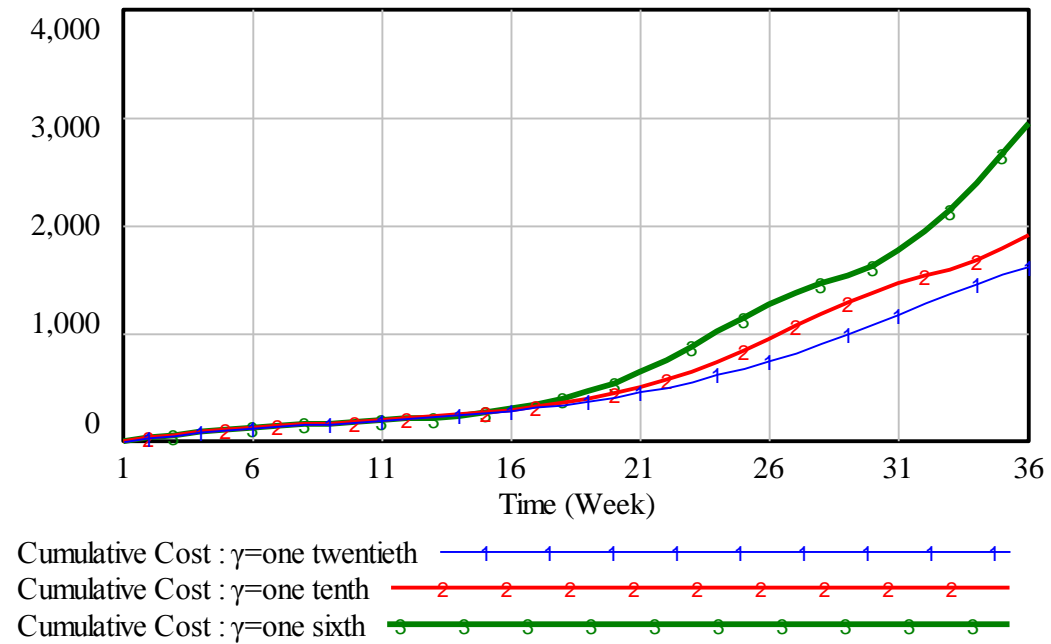


b. Cumulative costs of three different values of $\gamma$

Figure 9- 3 Cumulative costs of different values of $\gamma$

From the simulation we can see that a smaller $\gamma$ would yield a smaller amplification ratio. In other words, the bullwhip effect would be smaller. Furthermore, the smaller $\gamma$

is, the lower is the cumulative cost. This suggests that by smoothing the estimation of the incoming order rate could decrease both the amplification ratio and the total cost. Participants should not forecast the demand only based on the current order received rate. The historic data of the order received rate are also very important for making a highly effective decision.
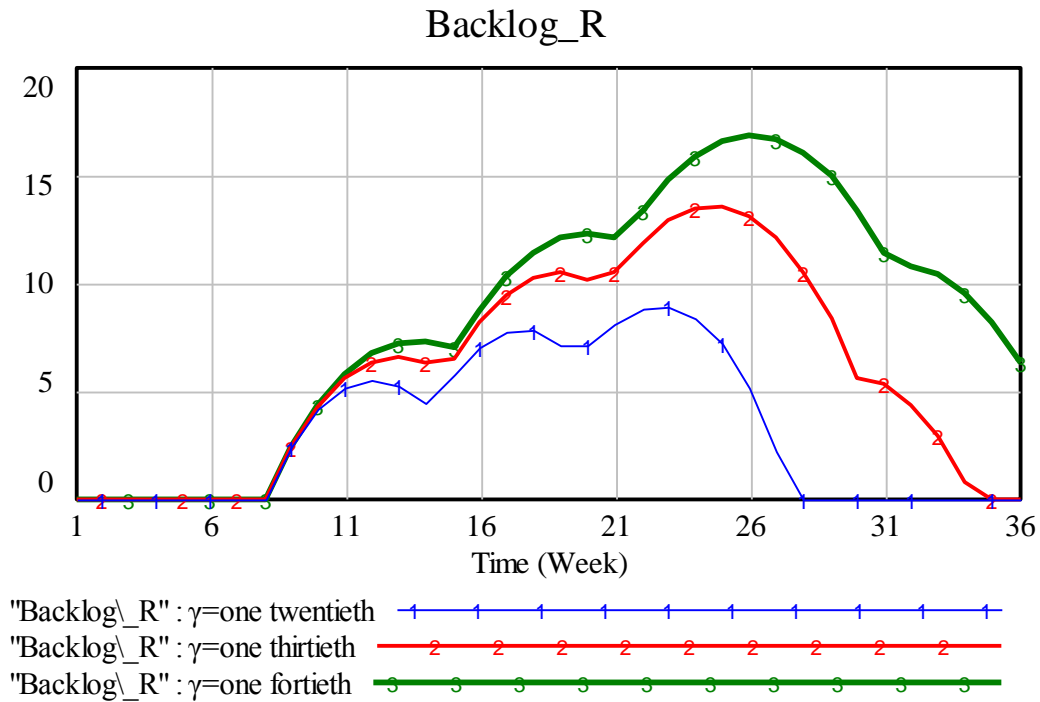


Figure 9- 4 Backlog of different values of γ

However, if γ is too small as shown in figure 9-4, the backlog will be very high. This is because the participants would not change their orders placed rate to make the inventory/backlog respond effectively to the change in demand. The entire supply chain would not be efficiently sensitive to the really changed customer demand. On the other hand, more aggressive policy can bring in a lower backlog. This also supports the finding that there is a trade-off between the short run performance and long run performance.

9.2 Time to Adjust Inventory

From the model we can see that, the ordering is determined by two factors in the transformation process: inventory adjustment and demand forecast. The inventory adjustment can be influenced by both inventory coverage determination and adjustment time. From the previous analysis we find that, the participants' degree of the aggressiveness does have significant impact on both inventory coverage determination and demand forecast. "Time to Adjust the Inventory" (defined as $\delta$ here) will be analyzed here to investigate whether it could be influenced by the degree of aggressiveness as well.

The amplification ratio achieve the lowest in scenario "$\delta=10$", which indicates that the adjustment should be neither too aggressive nor too cautious).

Table 9- 2 Amplification ratio of different value of $\delta$

|  | Customer | Retailer | Wholesaler | Distributor | Producer |
|---|---|---|---|---|---|
| $\delta=3$ | 1 | 2.5 | 5.875 | 8.375 | 11.5 |
| $\delta=6$ | 1 | 1.75 | 2.75 | 4 | 5.375 |
| $\delta=10$ | 1 | 1.625 | 2.375 | 3.25 | 4.25 |
| $\delta=20$ | 1 | 1.625 | 2.5 | 3.375 | *3.875* |
| $\delta=40$ | 1 | 1.75 | 2.75 | 3.5 | *3.875* |

Note: the amplification ratios of the producer in scenarios "$\delta=20$" and "$\delta=40$" are lower than the amplification ratio in scenario "$\delta=10$". This is because of the very large value of $\delta$ (a very long time to adjust the inventory), that the order placed rate of the producer has not reached to the highest value in the 36 weeks.

## Cumulative Cost
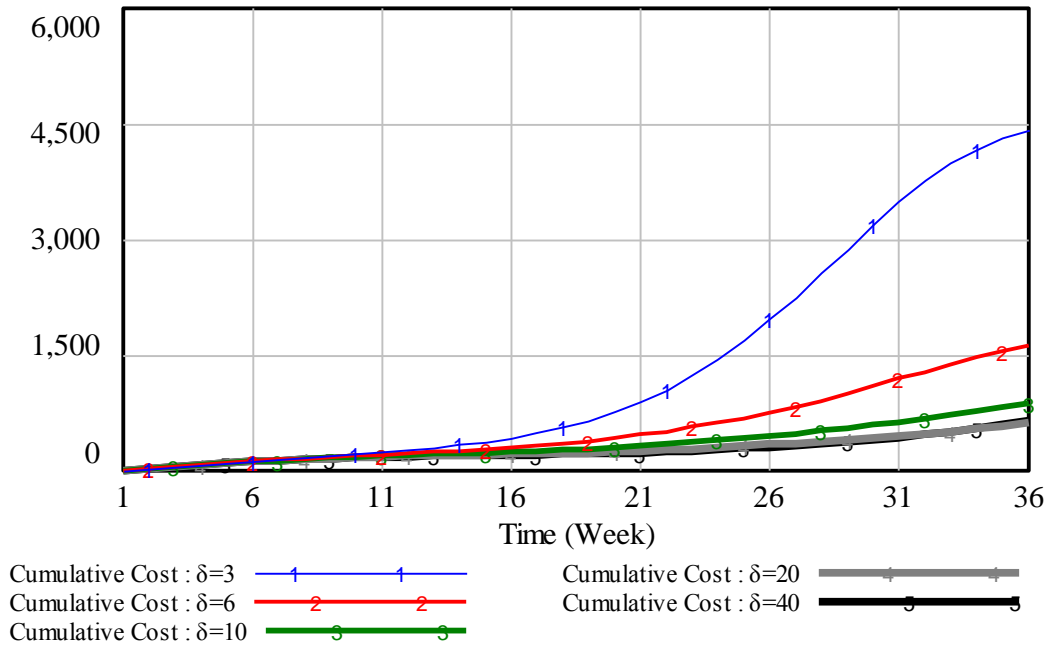


Figure 9- 5 Cumulative cost comparison of different value of δ
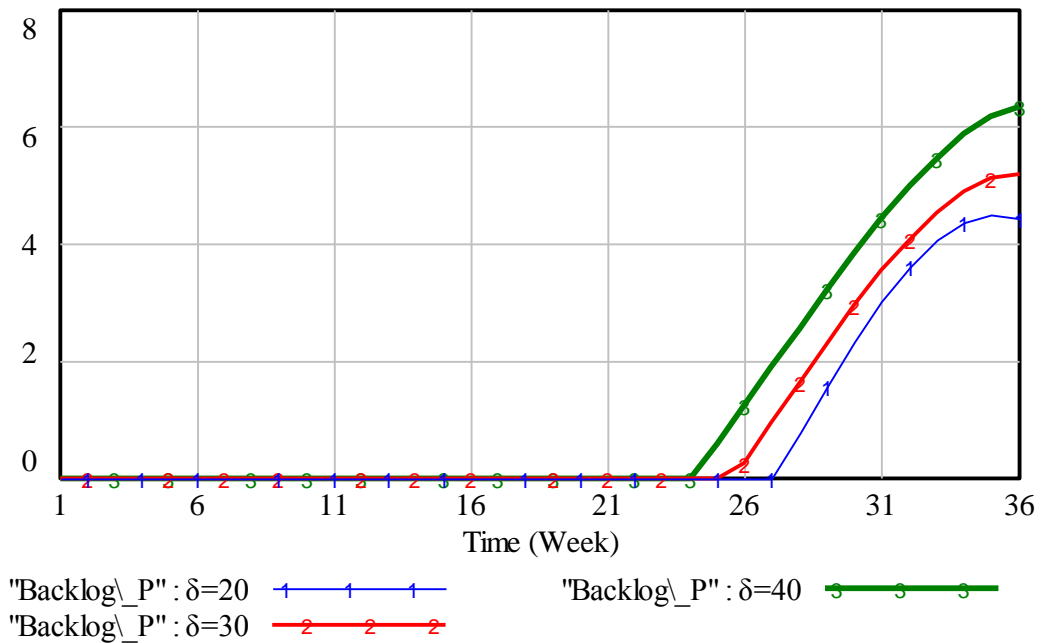
## Backlog_P



Figure 9- 6 Backlog of different values of δ

From 3, via 6, to 10 scenarios, we can see that both the amplification ratio and the cost decreases when the value of δ increases. However, from 10, via 20, to 40

scenarios, we can see that the cost is decrease when the value of δ increases. On the other hand, the amplification ratio increases when the value of δ increases. Again, we find the trade-off between short run performance and long run performance so that the optimal adjustment time is moderate. In a word, the participants' degree of aggressiveness has significant impact in both two factors (i.e. inventory adjustment and demand forecast) in the information transformation process, and plays an important role in the ordering ultimately.

# Chapter 10 Conclusions

10.1 Conclusion

This thesis further investigates the formation mechanism of the bullwhip effect from the mental viewpoint. Three experiments have been done both played online and physically with participants from different countries with diverse ages, so as to minimize the impact of culture and background factors. A framework of human decision making process with four steps is proposed. The feedback causal relationship structure of the beer game is offered. Corresponding three different information scenarios have been modeled. The criteria of the performance are set as the amplification ratio of the order placed rate and the cumulative cost.

Three beer game experiments indicate strongly that the hypotheses are correct. Additional supply line information helps a lot. Moreover, the perception of the available information has a significant impact on the performance, while people may have imperfect interpretation based on different degree of sensitivity and degree of aggressiveness. Furthermore, People can gradually learn to interpret the given information effectively, but they may have different ways of transformation that into a decision when they are presented the same kind of information. They may have different degree of aggressiveness with the same perception which will result in different responses and decisions to the information they perceived.

Two groups of policies have been analyzed. For the information availability policies, four conclusions have been found: 1) With more information does help the participants improve their performance; 2) Different information has different effectiveness, and the supply line information is superior to the in-transit stock

information (i.e, a portion of the supply line information); 3) Higher degree of sensitivity on the in-transit stock information could decrease both the instability and the cumulative cost significantly; 4) Higher degree of sensitivity on the supply line information could decrease the cumulative cost significantly, but the instability will increase if the supply line inventory being considered in a too large weight. In other words, there is a trade-off between stability and costs.

The information utilization policies consist of information perception policies and information transformation policies. For the information perception policies, the result of the simulation suggests that either too aggressive or too cautious is not optimal during the process of the delivery delay perception. Perceived delivery delay is the participants' perception about the delivery delay based on the supply line inventory information. Too cautious perception will bring up the cumulative cost, and even cause the customers to leave and search for other suppliers. On the other hand, by relying on intermediate delivery delay values resulting from a system in transition, the corresponding decision making may cause inefficiency in that the orders exhibit significant fluctuation that decreases the overall profit.

For the information transformation policies, we find a trade-off between short run performance and long run performance so that the demand estimation is moderate. The simulation shows that, by smoothing the estimation of the incoming order rate could help to decrease both the amplification ratio and the total cost. But too cautious estimation will bring in larger backlog and increase the costs in the long run.

Again, in the inventory adjustment, there is a trade-off between short run performance and long run performance. Too radical inventory coverage will finally increase the cost of the entire supply chain, while too cautious decision will decrease the stability. The simulation also shows that either too small or too large time to adjust the inventory would have some side effect.

Two trade-offs are being found in the process of information utilization: 1) the one between short run performance and long run performance. Different degree of sensitivity in the information perception phase and different degree of aggressiveness both in information perception and information transformation phases could influence the performance of the supply chain significantly; 2) the one between stability and costs. The simulation suggests that the goal of weakening the bullwhip effect and the goal of decreasing the cost is conflicting sometimes. Our goal should be minimize the cumulative cost by weakening the bullwhip effect, rather than seeking to eliminate it. In real life decision makers have different personalities, and their decision making styles are also diverse, and this does aggravate the bullwhip effect.

10.2 Limitations and Further Researches

More criteria could be created to measure the bullwhip effect, such as the mean and the variance of the order placed rate changes, the actual lead time, the variance of the backlog and so on. In this way, not only the cumulative cost, but also the structure of the cost could be known in details, so that decision makers could have more ideas about the supply chain.

The capacity of production has not been considered in this model. It would be interesting to test different scenarios, for instance, the upper limit of order received rate of the producer, the decision of whether make investment in production capacity based on the demand forecast. Shipment capacity is also worthy to be studied.

Patience of downstream players is also an interesting field if their perceived delay is too long, due to upstream players' stock-out or capacity problem. What will happen if they go to find other suppliers and what's the different result for the current supplier in a perfectly competitive market and monopolistic competitive market are also needed to be studied.

In this thesis, the degree of aggressiveness is set to be the same value within all sectors in the supply chain. However, participants are different in real. Different value of these parameters could be tested, to investigate the consequences of combinations with different degrees of aggressiveness in a supply chain. This could provide a clue for business men to choose their partners.

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# Appendix A: Complete Model
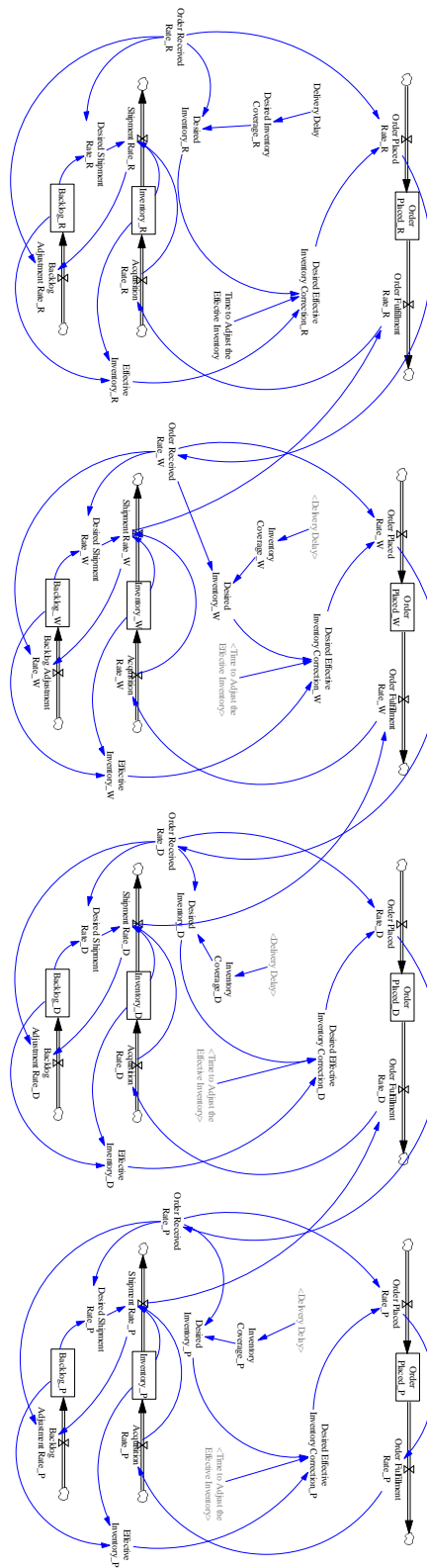
# Appendix B: Complete Policy Model
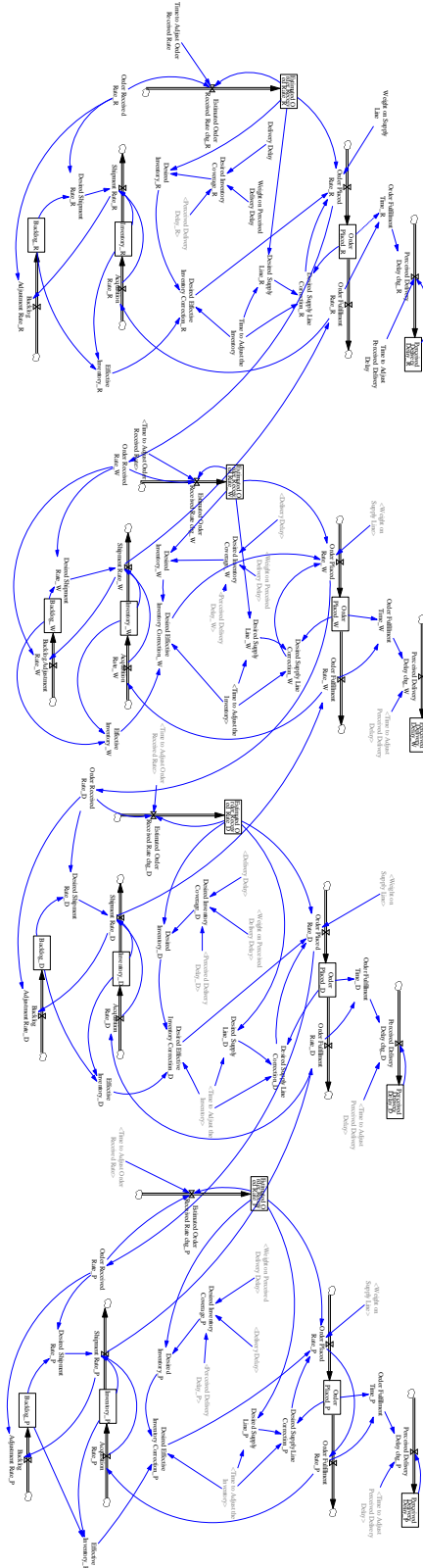
## Appendix C: List of Policy Model Equations

(001)    "Acquisition Rate\_D"=

   "Order Fulfillment Rate\_D"

  Units: **undefined**


(002)    "Acquisition Rate\_P"=

   "Order Fulfillment Rate\_P"

  Units: **undefined**


(003)    "Acquisition Rate\_R"=

   "Order Fulfillment Rate\_R"

  Units: **undefined**


(004)    "Acquisition Rate\_W"=

   "Order Fulfillment Rate\_W"

  Units: **undefined**


(005)    "Backlog Adjustment Rate\_D"=

   "Order Received Rate\_D"-"Shipment Rate\_D"

  Units: **undefined**


(006)    "Backlog Adjustment Rate\_P"=

   "Order Received Rate\_P"-"Shipment Rate\_P"

  Units: **undefined**


(007)    "Backlog Adjustment Rate\_R"=

"Order Received Rate\_R"-"Shipment Rate\_R"

Units: **undefined**


(008)    "Backlog Adjustment Rate\_W"=

"Order Received Rate\_W"-"Shipment Rate\_W"

Units: **undefined**


(009)    "Backlog\_D"= INTEG (

"Backlog Adjustment Rate\_D",

0)

Units: **undefined**


(010)    "Backlog\_P"= INTEG (

"Backlog Adjustment Rate\_P",

0)

Units: **undefined**


(011)    "Backlog\_R"= INTEG (

"Backlog Adjustment Rate\_R",

0)

Units: **undefined**


(012)    "Backlog\_W"= INTEG (

"Backlog Adjustment Rate\_W",

0)

Units: **undefined**


(013)    Cumulative Cost=

"Cumulative       Cost\_R"+"Cumulative       Cost\_W"+"Cumulative

Cost\_D"+"Cumulative Cost\_P"

Units: **undefined**


(014)    "Cumulative Cost chg\_D"=

         "Inventory\_D"*0.5+"Backlog\_D"

     Units: **undefined**


(015)    "Cumulative Cost chg\_P"=

         "Inventory\_P"*0.5+"Backlog\_P"

     Units: **undefined**


(016)    "Cumulative Cost chg\_R"=

         "Inventory\_R"*0.5+"Backlog\_R"

     Units: **undefined**


(017)    "Cumulative Cost chg\_W"=

         "Inventory\_W"*0.5+"Backlog\_W"

     Units: **undefined**


(018)    "Cumulative Cost\_D"= INTEG (

         "Cumulative Cost chg\_D",

             0)

     Units: **undefined**


(019)    "Cumulative Cost\_P"= INTEG (

         "Cumulative Cost chg\_P",

             0)

     Units: **undefined**


(020)    "Cumulative Cost\_R"= INTEG (

         "Cumulative Cost chg\_R",

0)

Units: **undefined**


(021)    "Cumulative Cost\_W"= INTEG (

"Cumulative Cost chg\_W",

0)

Units: **undefined**


(022)    Delivery Delay=

4

Units: **undefined**


(023)    "Desired Effective Inventory Correction\_D"=

("Desired Inventory\_D"-"Effective Inventory\_D")/Time to Adjust the

Inventory

Units: **undefined**


(024)    "Desired Effective Inventory Correction\_P"=

("Desired Inventory\_P"-"Effective Inventory\_P")/Time to Adjust the

Inventory

Units: **undefined**


(025)    "Desired Effective Inventory Correction\_R"=

("Desired Inventory\_R"-"Effective Inventory\_R")/Time to Adjust the

Inventory

Units: **undefined**


(026)    "Desired Effective Inventory Correction\_W"=

("Desired Inventory\_W"-"Effective Inventory\_W")/Time to Adjust the

Inventory

Units: **undefined**


(027)    "Desired Inventory Coverage\_D"=

Weight    on    Perceived    Delivery    Delay*"Perceived    Delivery
Delay\_D"+(1-Weight on Perceived Delivery Delay

)*Delivery Delay

Units: **undefined**


(028)    "Desired Inventory Coverage\_P"=

Weight    on    Perceived    Delivery    Delay*"Perceived    Delivery
Delay\_P"+Delivery Delay

Units: **undefined**


(029)    "Desired Inventory Coverage\_R"=

Weight    on    Perceived    Delivery    Delay*"Perceived    Delivery
Delay\_R"+(1-Weight on Perceived Delivery Delay

)*Delivery Delay

Units: **undefined**


(030)    "Desired Inventory Coverage\_W"=

Weight    on    Perceived    Delivery    Delay*"Perceived    Delivery
Delay\_W"+(1-Weight on Perceived Delivery Delay

)*Delivery Delay

Units: **undefined**


(031)    "Desired Inventory\_D"=

"Desired Inventory Coverage\_D"*"Estimated Order Received Rate\_D"

Units: **undefined**


(032)    "Desired Inventory\_P"=

"Desired Inventory Coverage\_P"*"Estimated Order Received Rate\_P"

Units: **undefined**


(033)    "Desired Inventory\_R"=

"Desired Inventory Coverage\_R"*"Estimated Order Received Rate\_R"

Units: **undefined**


(034)    "Desired Inventory\_W"=

"Desired Inventory Coverage\_W"*"Estimated Order Received Rate\_W"

Units: **undefined**


(035)    "Desired Shipment Rate\_D"=

"Order Received Rate\_D"+"Backlog\_D"

Units: **undefined**


(036)    "Desired Shipment Rate\_P"=

"Order Received Rate\_P"+"Backlog\_P"

Units: **undefined**


(037)    "Desired Shipment Rate\_R"=

"Order Received Rate\_R"+"Backlog\_R"

Units: **undefined**


(038)    "Desired Shipment Rate\_W"=

"Order Received Rate\_W"+"Backlog\_W"

Units: **undefined**


(039)    "Desired Supply Line Correction\_D"=

("Desired Supply Line\_D"-"Order Placed\_D")/Time to Adjust the Inventory

Units: **undefined**

(040)    "Desired Supply Line Correction\_P"=

         ("Desired Supply Line\_P"-"Order Placed\_P")/Time to Adjust the Inventory

    Units: **undefined**


(041)    "Desired Supply Line Correction\_R"=

         ("Desired Supply Line\_R"-"Order Placed\_R")/Time to Adjust the Inventory

    Units: **undefined**


(042)    "Desired Supply Line Correction\_W"=

         ("Desired   Supply   Line\_W"-"Order   Placed\_W")/Time   to   Adjust   the

Inventory

    Units: **undefined**


(043)    "Desired Supply Line\_D"=

         "Estimated Order Received Rate\_D"*Time to Adjust the Inventory

    Units: **undefined**


(044)    "Desired Supply Line\_P"=

         "Estimated Order Received Rate\_P"*Time to Adjust the Inventory

    Units: **undefined**


(045)    "Desired Supply Line\_R"=

         "Estimated Order Received Rate\_R"*Time to Adjust the Inventory

    Units: **undefined**


(046)    "Desired Supply Line\_W"=

         "Estimated Order Received Rate\_W"*Time to Adjust the Inventory

    Units: **undefined**

(047)      "Effective Inventory\_D"=

        "Inventory\_D"-"Backlog\_D"

    Units: **undefined**


(048)      "Effective Inventory\_P"=

        "Inventory\_P"-"Backlog\_P"

    Units: **undefined**


(049)      "Effective Inventory\_R"=

        "Inventory\_R"-"Backlog\_R"

    Units: **undefined**


(050)      "Effective Inventory\_W"=

        "Inventory\_W"-"Backlog\_W"

    Units: **undefined**


(051)      "Estimated Order Received Rate chg\_D"=

        ("Order Received Rate\_D"-"Estimated Order Received Rate\_D")/Time to

Adjust Order Received Rate

    Units: **undefined**


(052)      "Estimated Order Received Rate chg\_P"=

        ("Order Received Rate\_P"-"Estimated Order Received Rate\_P")/Time to

Adjust Order Received Rate

    Units: **undefined**


(053)      "Estimated Order Received Rate chg\_R"=

        ("Order Received Rate\_R"-"Estimated Order Received Rate\_R")/Time to

Adjust Order Received Rate

    Units: **undefined**

(054)   "Estimated Order Received Rate chg\_W"=

   ("Order Received Rate\_W"-"Estimated Order Received Rate\_W")/Time to

Adjust Order Received Rate

   Units: **undefined**


(055)   "Estimated Order Received Rate\_D"= INTEG (

   "Estimated Order Received Rate chg\_D",

      4)

   Units: **undefined**


(056)   "Estimated Order Received Rate\_P"= INTEG (

   "Estimated Order Received Rate chg\_P",

      4)

   Units: **undefined**


(057)   "Estimated Order Received Rate\_R"= INTEG (

   "Estimated Order Received Rate chg\_R",

      4)

   Units: **undefined**


(058)   "Estimated Order Received Rate\_W"= INTEG (

   "Estimated Order Received Rate chg\_W",

      4)

   Units: **undefined**


(059)   FINAL TIME   = 36

   Units: Week

   模拟的最后时间

(060)    INITIAL TIME   = 1

    Units: Week

    模拟的初始时间


(061)    "Inventory\_D"= INTEG (

       "Acquisition Rate\_D"-"Shipment Rate\_D",

         12)

    Units: **undefined**


(062)    "Inventory\_P"= INTEG (

       "Acquisition Rate\_P"-"Shipment Rate\_P",

         12)

    Units: **undefined**


(063)    "Inventory\_R"= INTEG (

       "Acquisition Rate\_R"-"Shipment Rate\_R",

         12)

    Units: **undefined**


(064)    "Inventory\_W"= INTEG (

       "Acquisition Rate\_W"-"Shipment Rate\_W",

         12)

    Units: **undefined**


(065)    "Order Fulfillment Rate\_D"=

       DELAY FIXED("Shipment Rate\_P",2,4)

    Units: **undefined**


(066)    "Order Fulfillment Rate\_P"= DELAY FIXED (

       "Order Placed Rate\_P",4,4)

Units: **undefined**

(067)     "Order Fulfillment Rate\_R"=

DELAY FIXED("Shipment Rate\_W",2,4)

Units: **undefined**

(068)     "Order Fulfillment Rate\_W"=

DELAY FIXED("Shipment Rate\_D",2,4)

Units: **undefined**

(069)     "Order Fulfillment Time\_D"=

"Order Placed\_D"/("Order Fulfillment Rate\_D"+1)

Units: **undefined**

(070)     "Order Fulfillment Time\_P"=

"Order Placed\_P"/("Order Fulfillment Rate\_P"+2)

Units: **undefined**

(071)     "Order Fulfillment Time\_R"=

"Order Placed\_R"/("Order Fulfillment Rate\_R"+1e-005)

Units: **undefined**

(072)     "Order Fulfillment Time\_W"=

"Order Placed\_W"/("Order Fulfillment Rate\_W"+1e-005)

Units: **undefined**

(073)     "Order Placed Rate\_D"=

MAX("Estimated Order Received Rate\_D"+"Desired Effective Inventory

Correction\_D"

+"Desired Supply Line Correction\_D"*Weight on Supply Line,0)

122

Units: **undefined**

(074)    "Order Placed Rate\_P"=

MAX("Estimated Order Received Rate\_P"+"Desired Effective Inventory

Correction\_P"

+"Desired Supply Line Correction\_P"*Weight on Supply Line,0)

Units: **undefined**


(075)    "Order Placed Rate\_R"=

MAX("Estimated Order Received Rate\_R"+"Desired Effective Inventory

Correction\_R"

+"Desired Supply Line Correction\_R"*Weight on Supply Line,0)

Units: **undefined**


(076)    "Order Placed Rate\_W"=

MAX("Estimated Order Received Rate\_W"+"Desired Effective Inventory

Correction\_W"

+"Desired Supply Line Correction\_W"*Weight on Supply Line,0)

Units: **undefined**


(077)    "Order Placed\_D"= INTEG (

"Order Placed Rate\_D"-"Order Fulfillment Rate\_D",

16)

Units: **undefined**


(078)    "Order Placed\_P"= INTEG (

"Order Placed Rate\_P"-"Order Fulfillment Rate\_P",

16)

Units: **undefined**

(079)    "Order Placed\_R"= INTEG (

       "Order Placed Rate\_R"-"Order Fulfillment Rate\_R",

         16)

    Units: **undefined**


(080)    "Order Placed\_W"= INTEG (

       "Order Placed Rate\_W"-"Order Fulfillment Rate\_W",

         16)

    Units: **undefined**


(081)    "Order Received Rate\_D"=

       DELAY FIXED("Order Placed Rate\_W",2 ,4)

    Units: **undefined**


(082)    "Order Received Rate\_P"=

       DELAY FIXED("Order Placed Rate\_D",2 ,4)

    Units: **undefined**


(083)    "Order Received Rate\_R"=

       4+STEP(4,4)

    Units: **undefined**


(084)    "Order Received Rate\_W"=

       DELAY FIXED("Order Placed Rate\_R",2 ,4)

    Units: **undefined**


(085)    "Perceived Delivery Delay chg\_D"=

       ("Order Fulfillment Time\_D"-"Perceived Delivery Delay\_D")/Time to

Adjust Perceived Delivery Delay

    Units: **undefined**

(086) "Perceived Delivery Delay chg\_P"=

("Order Fulfillment Time\_P"-"Perceived Delivery Delay\_P")/Time to
Adjust Perceived Delivery Delay

Units: **undefined**


(087) "Perceived Delivery Delay chg\_R"=

("Order Fulfillment Time\_R"-"Perceived Delivery Delay\_R")/Time to
Adjust Perceived Delivery Delay

Units: **undefined**


(088) "Perceived Delivery Delay chg\_W"=

("Order Fulfillment Time\_W"-"Perceived Delivery Delay\_W")/Time to
Adjust Perceived Delivery Delay

Units: **undefined**


(089) "Perceived Delivery Delay\_D"= INTEG (

"Perceived Delivery Delay chg\_D",

4)

Units: **undefined**


(090) "Perceived Delivery Delay\_P"= INTEG (

"Perceived Delivery Delay chg\_P",

4)

Units: **undefined**


(091) "Perceived Delivery Delay\_R"= INTEG (

"Perceived Delivery Delay chg\_R",

4)

Units: **undefined**

(092)    "Perceived Delivery Delay\_W"= INTEG (

   "Perceived Delivery Delay chg\_W",

      4)

   Units: **undefined**


(093)    SAVEPER   =

         TIME STEP

   Units: Week [0,?]

   输出存储频率


(094)    "Shipment Rate\_D"=

   MIN("Desired Shipment Rate\_D","Inventory\_D"+"Acquisition Rate\_D")

   Units: **undefined**


(095)    "Shipment Rate\_P"=

   MIN("Desired Shipment Rate\_P","Inventory\_P"+"Acquisition Rate\_P")

   Units: **undefined**


(096)    "Shipment Rate\_R"=

   MIN("Desired Shipment Rate\_R","Inventory\_R"+"Acquisition Rate\_R")

   Units: **undefined**


(097)    "Shipment Rate\_W"=

   MIN("Desired Shipment Rate\_W","Inventory\_W"+"Acquisition Rate\_W")

   Units: **undefined**


(098)    TIME STEP   = 1

   Units: Week [0,?]

模拟的时间步长

(099)    Time to Adjust Order Received Rate=

20

Units: **undefined**


(100)    Time to Adjust Perceived Delivery Delay=

5

Units: **undefined**


(101)    Time to Adjust the Inventory=

6

Units: **undefined**


(102)    Weight on Perceived Delivery Delay=

0.55

Units: **undefined**


(103)    Weight on Supply Line=

0.75

Units: **undefined**