The Development of the Distribution/VMI Game Based on Theory of Constraints

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Abstract

As the flourish of today's supply chain, the traditional model of replenishment will cause accumulation of excessive inventory to the retailers and customers, or cause shortages and inability to meet the demands. To solve this problem, Theory of Constraints (TOC) proposed the replenishment model of demand-pull, combined with the establishment of factory-warehouse to achieve performance improvement. In the absence of empirical research, this study applied the Bean Game developed by Dr. Goldratt to design a supply chain system for different scenarios, in order to allow players and managers better understanding and supporting the TOC replenishment method through the operations of the game.

Key Words: Theory of Constraints, Supply Chain, Demand-Pull, Factory-Warehouse

1. Introduction

In the traditional supply chain system, the ideal state to the upstream suppliers or manufacturers is to meet customer's demand and reduce the inventory to the minimum. While the ideal state to the customers or retailers is that the suppliers deliver the goods on time and with zero defects. Therefore, the retailers would conduct forecast based on the customers' historical demands, and send the forecast results to suppliers or wholesalers. After the wholesalers collect and arrange all the data, they place the orders at the factories. The factories

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manufacture and send the products to various wholesalers and suppliers, and then they are sent to retailers or customers. The above process is called the traditional "push-type production." If the retailers' forecast is inaccurate, the error demand would snowball, and result in a "bullwhip effect." It is also the core issue existing in the supply chain: the dilemma of inventory amount. Too much inventory would increase the cost, while insufficient inventory would lead to poor customer services (see Figure 1).

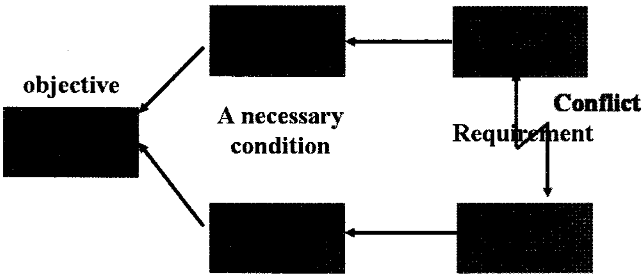

Figure 1. Schematic diagram of inventory conflict

In response to this conflict, the traditional solution is to ask customers for more transparent information on their demands, or find a more accurate method to forecast. The results have been unsatisfactory. Based on theory of constraints (TOC) developed by Dr. Goldratt (Yuan, 2004), the reasons that companies could not meet customer's demand with low inventory include: the replenishment time is too long, suppliers are not reliable, and forecasts are inaccurate. Thus, a good solution must be able to meet customer's demand with low inventory under the above three factors. TOC suggested that companies must adopt the replenishment approach of demand-pull to establish the inventory target and replenishment frequency, as well as adjusting the objective inventory, changing the original "push-type production" to "pull-type production", using the idea of small batch replenishment according to the customer's orders, and vacating an appropriate space to build warehouse, so that the replenishment time can be shortened to transportation time only (warehouse of the factory can separate production lead time and transportation time, the regional warehouse can separate the transportation time from the factory to the regional warehouse). In addition, in case of "inaccurate forecast", TOC Insight suggested that if the concept of aggregation is used in the distribution system, the fluctuations are reduced after evenly distributed (Goldratt and Goldratt, 2005), as shown in Figure 2.

According to Figure 2, the accumulation of individual statistical variation is much greater than the overall statistical variation, so the supply point of related to demand point is more reliable. Therefore, TOC though that the variation of overall demand forecast generated in the manufacturing end is much small than the one of individual forecast generated in retail side. And when the downstream retail points are more, this phenomenon will become more pronounced. In addition, in order to avoid too high or out-of-stock inventory, TOC advocated placing most inventories in the focus point (Source of supply) and the location with most accurate forecast. In this way, it can operate under the most accurate forecast; also significantly reduce the replenishment time and increase reliability and flexibility of replenishment. However, in the current supply chain, there are still many enterprises and companies doubt greatly whether the replenishment approach of demand-pull is appropriate. Because enterprises and companies often believe that the reason for poor performance is mainly due to the inaccurate forecast. But Dr. Goldratt did not think so, he maintained that: the main reason for poor performance in enterprises and companies was no exact implementation of the replenishment method for Demand-pull. Although Dr. Goldratt (2006) has put forward this view, it is still lack of potent arguments to prove that and bring more profits. So in the absence of empirical research, Bean Game presented by Goldratt and Goldratt (2005) and Excel VBA were used in this study, combined with the concepts of "warehouse" and "aggregation" to design this game, expected to prove Dr. Goldratt's doctrine in a more substantive way.

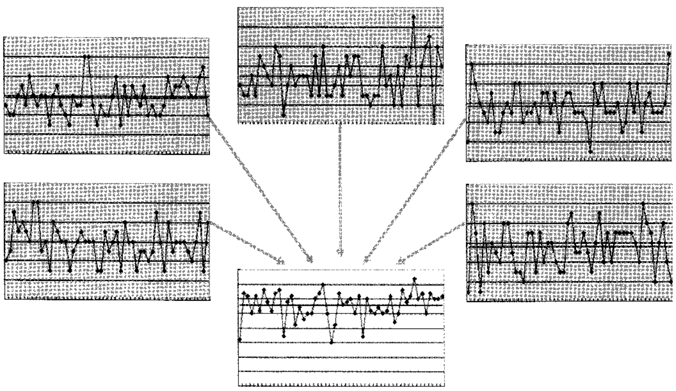

Figure 2. Demand fluctuation shrinks due to aggregation

2. Literature Review

2.1 The traditional replenishment mechanism

The operation of traditional supply chain: when the upstream suppliers get a certain number of orders from retailers, after a period of operating time, the goods are delivered to retailers. And retailers sell them to more downstream customer. But because the upstream suppliers do not know the demand situation at the end of the supply chain, they also don't know sufficiently whether the original quantity of orders meet the downstream customers (Robert *et al.*, 1999). In order to increase response rate to strain the downstream customer's changes in actual demand, usually their inventories will be enhanced and hope to protect output through demand forecast, so as to avoid Out of Stock (OOS). So this phenomenon spread to various levels in supply chain: retailers want to predict customers' demand state, wholesalers want to forecast retailers' demand state, and suppliers want to forecast wholesalers demand state. At every level of forecast, the error generated in the upper level will be calculated into, so the upstream of supply train has larger forecast error, resulting in the so-called "bullwhip effect."

Tsai *et al.* (1998) proposed that: the formation of the bullwhip effect will cause a vicious circle in the entire supply chain. And it will bring following adverse results: (1) customers often can not buy the products they want; (2) to enhance customer satisfaction, hold an excessive high inventory, causing goods rejected, dead stocks or scraps; (3) storage or distribution center often do not send the products ordered by retailers on time; (4) best sellers are often stock out in the warehouse or distribution center frequently, and non-best sellers have too high inventories; (5) the products supplied to distribution or warehouse center by factory are often not consistent with the actual demand of the market (customers). Lee *et al.* (1997a/b) also pointed out that when the upstream supply chain have gradual amplification, it will result in the most bad phenomenon in supply chain, such as: (1) Lost or Low Sales; (2) High Inventories; (3) Unresponsiveness. From the views of above scholars, we can know the consequences brought by bullwhip effects, which will cause a great loss to factories or companies. Therefore, how do people avoid the generation of bullwhip effect, the replenishment mechanism appears to be quite important. In the following chapters of this study, the scholars' solutions targeted at traditional replenishment mechanism will be proposed.

2.2 TOC replenishment mechanism

On how to avoid the occurrence of bullwhip effect, Lin (2006), Li (2005), Yuan (2004) and Weng (2004) summarized several keys and ways from the previous studies: (1) reduce uncertainty to forecast a more accurate future demand; (2) reduce unnecessary price fluctuations; (3) reduce replenishment lead times effectively; (4) establish Strategic Partnership to increase supplier's reliability, hereinto, it can let every member in the supply chain fully understand and access to reliable and complete information of customer demands through the aggregation of information. In this way, the uncertainty caused by surmising end-user demands simply through downstream orders can be eliminated. So the demands of every level in supply chain will be forecast more accurately. In order to reduce the drastic seasonal fluctuations of customer demands during the promotional period, it is necessary to reduce unnecessary price fluctuations, also replace the fixed sales promotion with the strategy of

EDLP (Everyday Low Price). Through the IT like Electronic Data Interchange (EDI), the processing time of orders can be effectively reduced, thereby reducing lead times of downstream manufacturers' ordering to increase the accuracy of forecasts (Lee *et al.*, 1997b/2000), and then effectively reduce replenishment lead times. And the strategic partnership can be established through the Vendor Managed Inventory (VMI) or Continuous Replenishment Planning (CRP), so the suppliers can grasp sales information and inventory initiatively as the direction of market demand forecasts and automatic replenishment (Achabal *et al.*, 2000).

2.3 The establishment of warehouses

Goldratt and Goldratt (2005) mentioned why did they improve management performance in supply chain through the establishment of warehouses as follows: (1) the longer the replenishment time is, the higher inventory customers should be prepared and a higher Out-of-stock at the same time; (2) Even if the production lead time is reduced, the problem remains serious; (3) In many cases, the delivery time from the factory to the customer is very long. Based on the above-mentioned possible problems, TOC thought that the establishment of warehouses will enable replenishment time to shorten significantly. They also mentioned that, when the warehouse had a right inventory, the replenishment time could be decreased to the original order lead time, production lead times and transportation lead times were reduced and only left the latter. Hereinto, the warehouse of factory can separate production lead times and transportation time, and regional warehouses can separate the transportation time from factory to the regional warehouse. Therefore, companies or factories must arrange suitable space to build the warehouses. Lin (2006) also compared the traditional and TOC practices, as shown in Table 1:

Table 1. Comparison between traditional and TOC practices

	Traditional practices	TOC practices
Warehouse settings	Only set local warehouse	Set center and local warehouses
Inventory	The demands in the whole replenishment time	Center warehouse: the whole demands during the production time. Local warehouse: the demands sent from center warehouse to local warehouse.
Replenishment time	Order time + production time + transportation time	Transportation time

From the above table it can know that, the establishment of warehouses can indeed predict future demand more accurately, shortening the replenishment time and increase the reliability of suppliers. Additionally, the control and management of warehouse is also very important. When the warehouse holds too high inventory, it is very easy to form a backlog of company's cash; while the warehouse holds too less inventory, it will cause poor service to the customers. TOC pointed out that, the right quantity of inventory was equivalent to the average usage in the replenishment time multiplying by the variation factors. Therefore, how to make company with a least target inventory in warehouse provide sufficient service for customers, it is the biggest issue which the management level must face to.

2.4 Aggregation

In the supply chain, when a supply point must also fulfill various consumption points, if the concept of aggregation is used, the fluctuations will be averaged to become shrinking. At the same time, the demand variation of upstream supply points is far less than the total variations arose from downstream consumption points. Also, when the consumption points are more and larger, the effect reflected will be more obvious, as shown in the following three scenarios orderly:

Scenario 1. One supply point provides for four consumption points (Figures 3, 4)

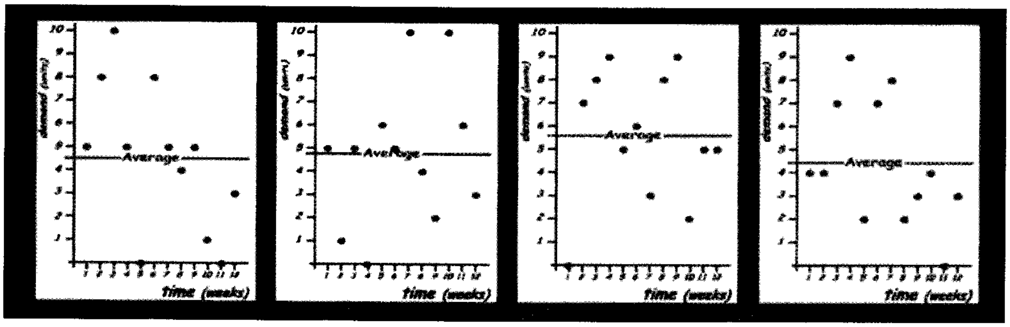

Figure 3. Consumption points (Goldratt and Goldratt, 2005)

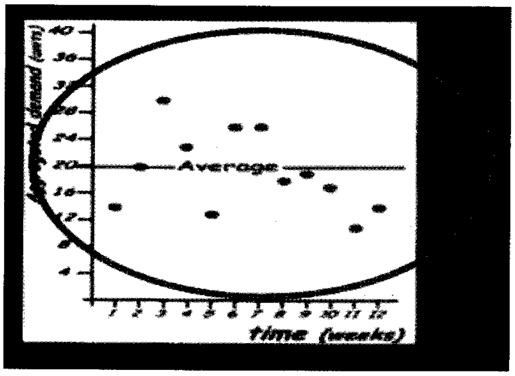

Figure 4. Supply points (Goldratt and Goldratt, 2005)

Scenario 2. One supply point provides for ten consumption points (Figures 5, 6)

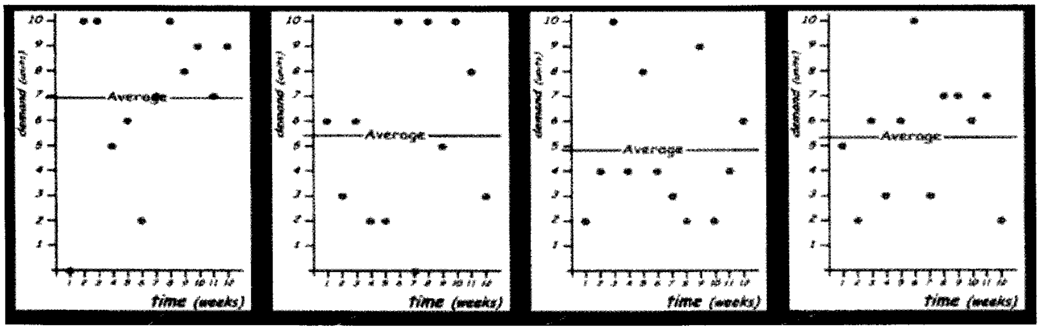

Figure 5. Consumption points (Goldratt and Goldratt, 2005)

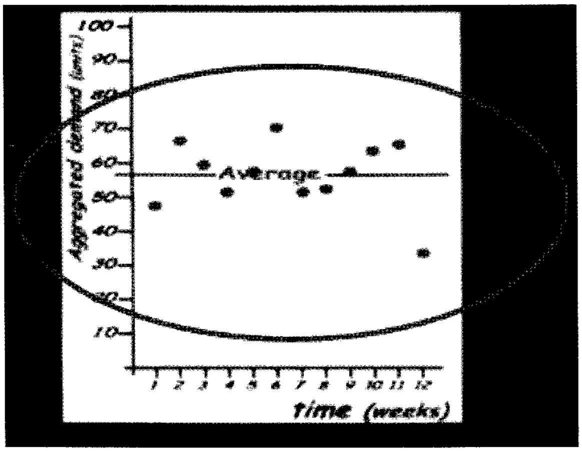

Figure 6. Supply points (Goldratt and Goldratt, 2005)

Scenario 3. One supply point provides for one hundred consumption points (Figures 7, 8)

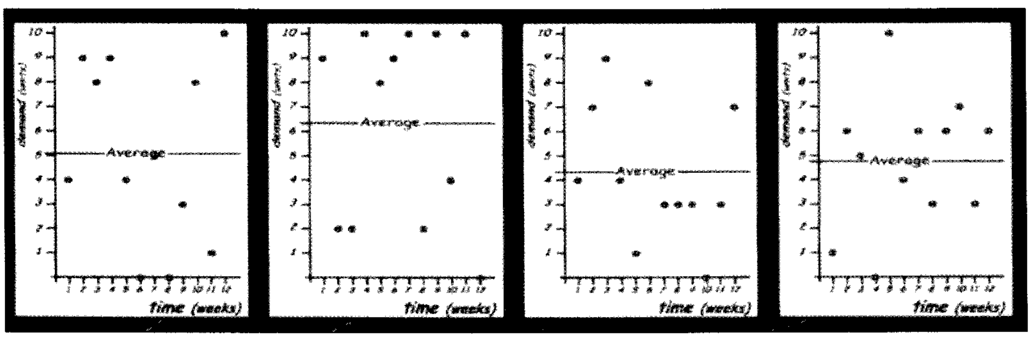

Figure 7. Consumption points (Goldratt and Goldratt, 2005)

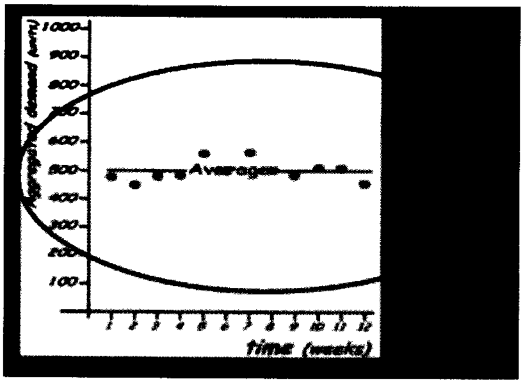

Figure 8. Supply points (Goldratt and Goldratt, 2005)

Based on the diagrams of above three scenarios, it is obvious that no matter the consumption points are four, ten or one hundred; there is no significant change in variation of consumption end. However, when the consumption points are only four, the variation of supply points is still great, and when the consumption points are ten, the variation of supply points shrinks largely; and finally, when the consumption points are one hundred at the same time, the variation in the supply end is actually so stable (Figure 8). Therefore, in the distribution system, the supply point related to demand point is more reliable.

2.5 Replenishment mechanism

The phenomena often happen in the supply chain, such as replenishment time is too long, the supplier is not reliable and forecasts are inaccurate, which will usually cause a great loss to the company or factory. In view of this, the possible causes and solutions analyzed by TOC are as follows:

1. Replenishment time is too long: as large bulking has a large discount and no needs to spend too much time deciding ordering quantity, enterprises often issue orders until the inventory reaching the ordering point, which prolongs the replenishment time. TOC proposed to take small quantities of order to shorten the time for replenishment.
2. Supplier is not reliable: if the supplier is not reliable, enterprises can choose to replace it or train the existing suppliers, so as to enhance the supplier's reliability. But sometimes these methods are not useful for the emergent enterprises, so they often take the most direct way, which is to hold a large quantity of inventory to cope with.
3. Forecast is inaccurate: Forecast System can only forecast trends, but it can not predict the actual demands. When the predictive value is higher than the actual demands, it will cause the inventory phenomenon; on the contrary, it would cause OOS. However, as the cognition of the enterprises, the OOS is more serious than inventory, so they prefer to hold higher inventories to avoid OOS.

Hereinto, TOC's opinion was to increase the frequency of replenishment with small quantities of ordering, which was generally the so-called demand-pull of supply chain management model. This method placed the majority of inventories in the focus point (the supply source), and the target inventory of each product at each focus point was decided according to the formula. Customer points inform factories of daily consumption, the factories would regularly replenish customers' daily actual consumptive quantity with the fastest speed (more frequent replenishment). In addition, the factory must replenish the consumptive quantity at the focus point regularly (Figure 9):

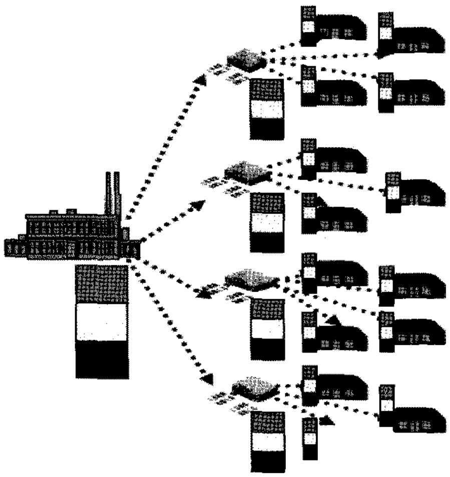

Figure 9. Replenishment mechanism of demand-pull (Li, 2007)

The downstream retail end makes an order according to actual output, while the upstream manufacturing end will cyclically produce based on actual sales. And the center warehouse is the Buffer for the entire distribution system; its replenishment method complies with the one of Drum-Buffer-Rope (DBR). Hereinto, TOC divides inventory into three parts, green part symbolizes excessive high inventory, yellow part symbolizes moderate inventory, and red part symbolizes shortage of inventory. And the size of each part depends on the setting service level. Unless there were exceptional demands, the three parts are with the same size. When the inventory is located in the green part for a long time, managers should take action, namely revise the target inventory downward, don't replenish until the inventory is reduced to a new target inventory; on the contrary, when the inventory is located in the red part for a long time, managers should revise the target inventory upward. At this time, the current amount of orders will increase, including the increments of current demands and target inventory. After that, it is required to do continuous observation until the system become more stable.

3. Research Methodology

3.1 Settings of supply chain

The supply chain system of Dr. Goldratt's Bean Game was targeted at in this study to conduct experimental games. The scenarios are as follows: (1) assumed a factory produces four kinds of products and they are sent to six customers (other factories or retailers); (2) Each customer has different demands every day; (3) Customers make orders to the factory based on replenishment frequency; (4) The factory manufactures products to meet each customer's orders, the information of the Games is shown in Figure 10:

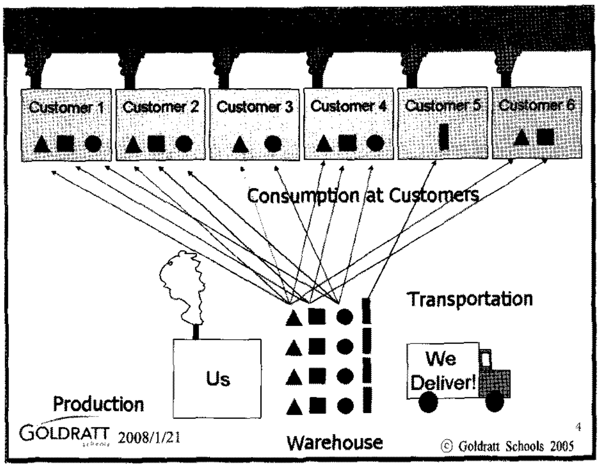

Figure 10. Schematic diagram of Bean Game

With regard to the work assignment in the game, one people is needed to lead the game; and each customer station needs 1~2 people to make orders in accordance with their experiences and the current inventory; one person is needed to do factory scheduling, which decides the order of production and the size of batch; one people is needed to analyze the financial position of the factory, and send the results to the CEO. Finally, two people are needed to decide the production of factory; they are responsible for the factory's daily production capacity, and this production capacity is regarded as the inventory.

3.2 Basic assumptions and limitations

A total of three scenarios of these games are carried out to analyze the differences and improvement of each performance. The three scenarios respectively are: (1) Traditional replenishment model (replenishment based on historical data and experience); (2) Demand-pull but without the factory's; (3) Demand-pull with warehouse of factory. In addition, as the game executes, take into account the convenience for those participants and implementers during operation, as well as the fluency of implementing the game, many complex situations in the supply chain are simplified, also added the following assumptions and limitations for a more rigorous manner to play this game, so as to achieve the purposes of this study: (1) a single producer, a number of customers; (2) factories and customers are in short supply and no replenishment; (3) Don't consider ordering costs and transport costs. Based on the design of scenarios, the ordering costs and transport costs were not considered in this study. The unit product price, unit inventory costs, unit OOS costs and operating expenses set in this study are as shown in Table 2:

Table 2. Table for cost and price settings of each item

	Unit product price	Unit inventory costs	Unit OOS costs	Operating expenses
Factory	20 NT$/piece	1 NT$/piece	500 NT$/piece	2000 NT$/week
Customer	20 NT$/piece	1 NT$/piece	500 NT$/piece	-

3.2.1 Customers' daily demands are the known parameters

Hereinto, each customer's demand parameters are different, their daily demands from 0 to 6 as shown in Table 3 to Table 8 below:

Table 3. Table for demand parameters of Customer 1

Roll	Blue	Yellow	Red
1	0	1	1
2	0	1	2
3	0	2	3
4	4	2	4
5	5	3	5
6	6	3	6

Table 4. Table for demand parameters of Customer 2

Roll	Blue	Yellow	Red
1	1	2	1
2	2	2	2
3	3	2	3
4	0	5	4
5	0	5	5
6	0	5	6

Table 5. Table for demand parameters of Customer 3

Roll	Blue	Red
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6

Table 6. Table for demand parameters of Customer 4

Roll	Blue	Yellow	Red
1	1	1	0
2	1	1	0
3	2	1	4
4	2	6	5
5	3	6	6
6	3	6	6

Table 7. Table for demand parameters of Customer 5

Roll	White
1	5
2	5
3	5
4	6
5	6
6	6

Table 8. Table for demand parameters of Customer 6

Roll	Blue	Yellow
1	1	1
2	1	1
3	2	2
4	2	2
5	3	3
6	3	3

3.2.2 Assumed the capacity of manufacturer (factory) is unlimited

According to different scenarios in the game, the factory will have daily different production capacities. The distribution of the factory's parameters is as shown in Table 9:

Table 9. Table for factory's capacity parameter

	Average capacity	Max capacity	Min capacity
Scenario 1 and Scenario 2	52.5	90	15

As Scenario 3 has established as warehouses of factory, its average, max and min capacities are not considered. So only the capacity parameters in Scenario 1 and Scenario 2 are listed in Table 9.

3.2.3 If the factory use mass production, it is necessary to reproduce every four days

In Scenario 1 and Scenario 2, the factory takes mass production in accordance with the production order from the left (Blue) to the right (White). The size of the batch is as shown in Table 10:

Table 10. Table of factory's production batch

	Blue	Yellow	Red	White
Size of batch	70	50	65	30

Additionally, the lead time of transportation and ordering frequency for factory and customer are as shown in Table 11:

Table 11. Table for settings of lead time

	Lead time of transportation	Ordering frequency (Scenario 1)	Ordering frequency (Scenario 2)	Ordering frequency (Scenario 3)
Factory	1 day	-	-	-
Customer	1 day	Each week	Each week	Each day

According the table above, the lead time for transportation of factories and customers are both one day. The customer's ordering frequency in Scenario 1 and Scenario 2 are each "week"; Scenario 3 is each "day." At the end of experimental game, it is required a clear indicator for assessment of performance to the results of each executive. Performance indicators are as follows: (1) the total profits; (2) Average inventory; (3) OOS amount

(Expressed as a percentage); (4) the times of OOS (expressed as a percentage).

3.3 Management scenario of each round in the game

In this study, the management model of TOC supply chain combined with Demand-pull as a complementary was used, to discuss the difference in performance between the traditional model (Scenario 1) and non-traditional model (Scenarios 2 and 3). In addition, this game let the players experience the improving results of TOC management model without too many complicated operations; the game was divided into three scenarios and each scenario can be executed continually.

3.3.1 Scenario 1 traditional replenishment model

Based on historical data and experiences, customers forecast and decide the ordering quantity of "each week" by themselves; while the factories distribute in accordance with their own capacities. In addition, at the beginning of period, customers must order "opening inventory" for each product by themselves; while there is no opening inventory in the factories.

3.3.2 Scenario 2 Demand-pull without warehouse of factory

In view of TOC, customers used replenishment method of Demand-pull, which replenishes according to the using amount "each week"; the factories are still based on production capacity to do self-distribution. Similarly, at the beginning of period, customers must order "opening inventory" for each product by themselves; while there is no opening inventory in the factories.

3.3.3 Scenario 3 Demand-pull with warehouse of factory

Also in view of TOC, customers used replenishment method of Demand-pull. However, due to the factory establishes warehouses, the replenishment frequency is changed from "each week" of above two scenarios to "each day", replenishing with small quantities. Customers' daily target inventory of each product is also the max demand of the product. There is opening inventory in the factory, its quantity is "twice of total max demand" of customers. As shown in the Blue part, the factory's opening inventory is $2 \times (6+3+6+3+0+3) = 42$.

3.4 Record table and operational instruction of the game

Convenient for operators recording the situations of inventory and ordering, as well as rapid operating inventory and costs, Bean Game used Excel to produce exclusive record table. Detailed instruction and operating procedures are attached with the operation manual of the game. The operation manual can be used to play the game and make a direct statement to the players.

4. Empirical Validation

The game of this study had a total of six experimental groups (A~F), there was one factory and six customers in each group. The game complies with the scenarios and parameters set in this chapter, Scenario 1 carried out the so-called traditional replenishment model; While Scenario 2 used the method of Demand-pull for replenishment; And Scenario 3 not only used replenishment method of Demand-pull, but also established a warehouse. The experimental results of each scenario are shown as follows orderly.

4.1 Experimental results and analysis of Scenario 1

First Scenario 1 was analyzed; its experimental result is as shown in Table 12:

Table 12. Experimental data of each group in Scenario 1

	Average daily total inventory	Average weekly total OOS quantity (%)	Average weekly total OOS times (%)
Group A	113.8	6.92%	10.6%
Group B	**140**	4.86%	3.45%
Group C	104.5	3.78%	6.35%
Group D	98.8	5.86%	4.86%
Group E	119.5	**11.14%**	**12.10%**
Group F	102.3	8.80%	9.12%

According to the above table, in Scenario 1, average daily total inventory of Group B is the largest; while the average weekly total OOS quantity and times of Group E are the most of all groups. In succession, Group B and E are targeted to do the further discussion for the main season of poor performance. Table 13 shows the average daily inventory for each group of customers and factories as follows:

Table 13. Average daily inventories of customers and factories in Scenario 1

	Average daily total inventory	Average daily inventory of customer	Average daily inventory of factory
Group A	113.8	21.5	92.3
Group B	**140**	**28.7**	**111.3**
Group C	104.5	21.5	83
Group D	98.8	21.4	77.4
Group E	119.5	25.2	94.3
Group F	102.3	16.3	86

From the data in above table, average daily inventories of customers and factories in Group B are the highest of all groups. There is no doubt that its total inventory is also the highest. Then further observe the average daily inventory of customer as shown in Table 14:

Table 14. Average daily inventory of customers in Group B

	Average daily inventory
Customer 1	14.7
Customer 2	33
Customer 3	15.4
Customer 4	**50.3**
Customer 5	**44.3**
Customer 6	14.4

As shown in above table, it is obvious that the Customer 4 and 5 are the main reason for the worst performance in Group B, the average daily inventory is respectively **50.3** and **44.3**, which are higher than many other customers. Hereinto, through in-depth observation of this study, the reason for such high inventories of Customer 4 and 5 is due to the "opening stock" is ordered too high. The opening inventories ordered by each customer are as shown in Table 15:

Table 15. Opening inventory ordered by each customer in Group B

	Blue	**Yellow**	**Red**	**White**
Customer 1	15	12	21	0
Customer 2	48	46	45	0
Customer 3	30	0	30	0
Customer 4	**80**	**80**	**80**	**0**
Customer 5	0	0	0	**72**
Customer 6	30	33	0	0

It can see from the above table clearly that, the opening inventories of Customer 4 and 5 are 80 and 72 respectively. So it is sure that the main reason for poor performance of Customer 4 and 5 is bad order of "opening inventory." In addition, as the opening inventories of Customer 4 and 5 are ordered too high, their ordering amounts are much smaller compared to other groups. In this way, the distribution quantity of factory is relatively small, thus the inventory is much higher (as shown in Table 13). This also indirectly points out that the entire supply chain system is closely linked with each other. And then back to Table 12, aim at Group E in Scenario 1 to analyze the reason why its average daily total

OOS quantity and times are the worst. Table 16 refers to OOS quantity of customers and factories in each group:

Table 16. Conditions of OOS quantity in each group

	Average weekly OOS quantity of customers (%)	Average weekly OOS quantity of factories (%)	Average total OOS quantity (%)
Group A	1.94%	4.98%	6.92%
Group B	4.86%	0%	4.86%
Group C	1.8%	1.98%	3.78%
Group D	2.53%	3.33%	5.86%
Group E	4.25%	**6.89%**	**11.14%**
Group F	3.96%	4.84%	8.80%

Based on the above table, the reason for the highest average total OOS quantity of Group E is due to the OOS quantity of factory is too much (6.89 %). For the further observation of factory replenishment in Group E, see Table 17:

Table 17. Conditions of customers and factories in Group E

	Blue		**Yellow**		**Red**		**White**	
	Total order quantity	**Total inventory**	**Total order quantity**	**Total inventory**	**Total order quantity**	**Total inventory**	**Total order quantity**	**Total inventory**
Week 1	85	140	**102**	**100**	**118**	**76**	30	30
Week 2	86	195	**96**	**78**	**122**	**119**	60	60
Week 3	80	220	**100**	**72**	114	130	30	60
Week 4	64	239	68	100	90	146	20	76

According to above table, the Yellow and Red products of factory show a serious state that demand exceeds supply, namely the target inventory of customer is too high. For example, the Yellow products of the third week, customers' total demand is 100, but factory inventory is only 72. Similarly, the total demand of Red product in the first week is 118, but factory inventory is only 76. As a result, the factory has serious OOS. Through the analysis results in this section, the traditional model of replenishment adopted in Scenario 1 has a lot of room for improvement in average inventory, OOS quantity and times. Therefore, the Scenario 2 in next section will use the model of Demand-pull for replenishment.

4.2 Experimental results and analysis of Scenario 2

The opening inventory of products ordered by customers in Scenario 2 is the same as that in Scenario 1. The difference lies in the customers in Scenario 2 take demand-pull model for replenishment. So the factor affecting performance in Scenario 2 are left only "opening inventory" and "factory capacity." The experimental results of each group are as shown in Table 18.

Table 18. Experimental data of each group in Scenario 2

	Average daily total inventory	Average weekly total OOS quantity (%)	Average weekly total OOS times (%)
Group A	113.2	1.72%	2.3%
Group B	**126.4**	3.02%	3.37%
Group C	96	**9.91%**	**8.93%**
Group D	102.2	5.92%	5.86%
Group E	103.1	8.95%	8.88%
Group F	110	2.34%	3.12%

According to the table, the average daily total inventory of Group B is significantly higher than other groups. Therefore, the average daily total inventory of Group B is continued to do in-depth study. Table 19 refers to inventory conditions of customers and factories in each group as below:

Table 19. Average daily inventories of customers and factories in Scenario 2

	Average daily total inventory	Average daily inventory of customer	Average daily inventory of factory
Group A	113.2	17.7	95.5
Group B	**126.4**	**28.6**	97.8
Group C	96	20.6	75.4
Group D	102.2	18.9	83.3
Group E	103.1	19.5	83.6
Group F	110	19	95

Through the above table, it is clear the reason that average daily total inventory of Group B is highest is due to too high of "Average daily inventory of customer." Also as Scenario

2 has used replenishment model of demand-pull, so it is deduced the too high "opening inventory" ordered leads to too high average daily inventory of customers in Group B. The customer's opening inventory in Group B has been mentioned in the above section in detail, it may have much to do with the results analyzed in this section. Undertaking the description in the preceding paragraph, the key factors impacting the quantity and times of OOS are still "opening inventory" and "factory capacity." Once the opening inventory is set too low, there is a great potential of causing OOS. Through Table 18, it is obvious that the average total OOS quantity of Group C is the most of all groups. Then it can know whether it is caused by improper ordering according to opening inventory ordered by customers in Group C. As shown in Table 20:

Table 20. Opening inventory ordered by customers in Group C

	Blue	**Yellow**	**Red**	**White**
Customer 1	30	40	50	0
Customer 2	**15**	**30**	**30**	0
Customer 3	**20**	0	**20**	0
Customer 4	20	40	40	0
Customer 5	0	0	0	44
Customer 6	25	21	0	0

Through the above table for opening inventory of customers in Group C, it is not difficult to find that Customer 1 and 2's opening inventories are ordered slightly low. In succession, it is very likely to cause serious OOS in Week 1 and 2. According to Figure 11 and 12, Customer 2 and 3 have large OOS dilemma in Week 2 and 3 respectively. Therefore, under normal circumstances of sufficient factory production capacity, the "opening inventory" ordered by customers play an important role.

	Total profit	**Average inventory**	**Total OOS quantity**	**Total OOS times**
Week 1	1093	12.7	0	0
Week 2	-1608	11.8	5	1
Week 3	223	15.1	1	1
Week 4	464	23.6	0	0

Figure 11. Performance of Customer 2 of Group C in Scenario 2

	Total profit	Average inventory	Total OOS quantity	Total OOS times
Week 1	-3233	7.0	9	4
Week 2	-2600	9.6	7	2
Week 3	558	23.0	0	0
Week 4	637	17.4	0	0

Figure 12. Performance of Customer 3 of Group C in Scenario 2

4.3 Experimental results and analysis of Scenario 3

Scenario 3 used TOC method and Demand-pull replenishment, and at the same time it established warehouse of factory. All the factors could lead to poor performance were eliminated, such as "opening inventory" and "target inventory" etc. Additionally, as the establishment of the warehouse, it can use daily small batch to replenish. Thus customer end is also able to order the "opening inventory" clearly. In other words, simply maintain the target inventory at the daily max demand. While in warehouse parts, in order to ensure there is no OOS, the amount of inventory, which is "twice of all customers' max demands." Table 21 refers to experimental data of each group in Scenario 3:

Table 21. Experimental data of each group in Scenario 3

	Average daily total inventory	Average weekly total OOS quantity (%)	Average weekly total OOS times (%)
Group A	98.2	0	0
Group B	98.2	0	0
Group C	98.9	0	0
Group D	98.2	0	0
Group E	98.3	0	0
Group F	98.2	0	0

Through the above table, it can see there is no OOS, and the average daily total inventory is quite stable, too. In comparison to the previous two scenarios, the average daily total inventory also becomes much smaller. When the replenishment model under above three different scenarios is finished, further analysis and comparison of these three different scenarios were done in succession.

4.4 Analysis of the executed results

The performance differences of three scenarios were compared in this study. In other words, the traditional model of replenishment (Scenario 1) and TOC replenishment model (Scenarios 2 and 3) were compared to decide which one was better. Analysis and comparison of three different scenarios were done in this section again. The experimental results of these three scenarios are shown respectively in Figures 13, 14, and 15 below:

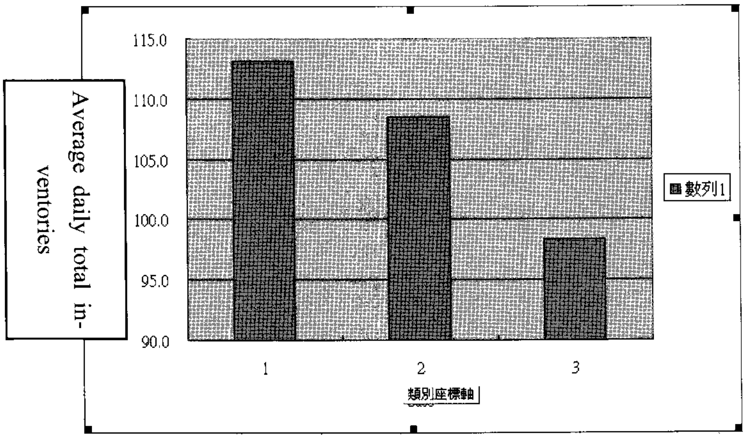

Figure 13. Average daily total inventories of three scenarios

According to Figure 13, it is clear that the average daily total inventory of Scenario 3 is obviously better than Scenario 1 and Scenario 2. But Scenario 2 is not significantly better than Scenario 1. This is due to the design of the scenario: the quantity of downstream customers is not many. As mentioned in the previous chapters, when the downstream customers are more, the benefits of aggregation will become more pronounced. But because of the scenarios designed in this study only have 6 customers in downstream, so the performance of average inventory in Scenario 2 is not significantly better than that of Scenario 1.

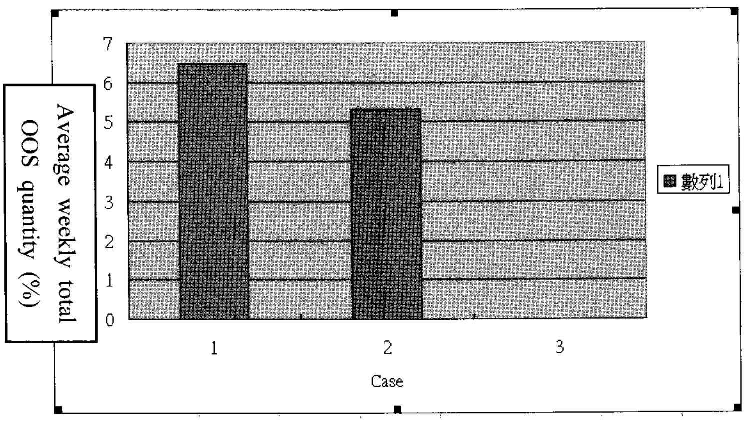

Figure 14. Average weekly total OOS quantity of three scenarios

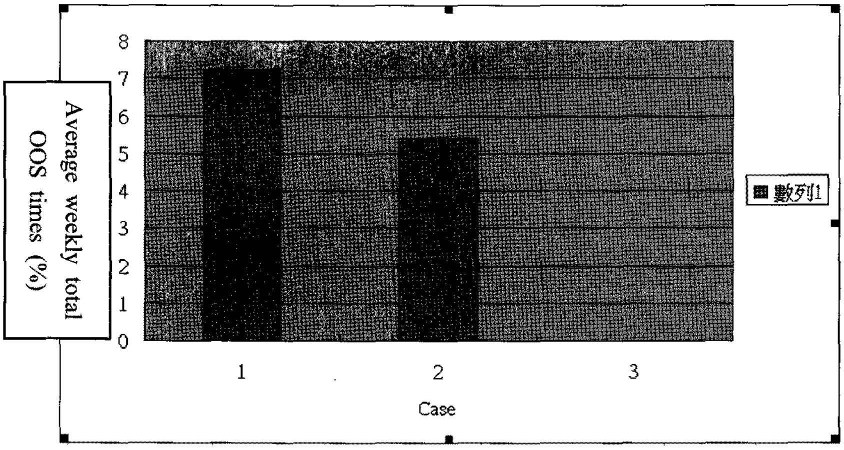

Figure 15. Average weekly total OOS times of three scenarios

According to Figure 14 and 15, it can still be found the OOS quantity and times of Scenario 3 are far better than those of Scenario 1 and Scenario 2 to well. Although Scenario 2 is better than Scenario 1, it is not significant. The reason is Scenario 2 don't order opening inventory properly. On the condition of Demand-pull replenishment model and sufficient capacity of the factory, whether the opening inventory is ordered appropriately or not, which will directly affect OOS or not. As mentioned in preceding sections, customers of certain groups improperly order opening inventory, resulting in a bad performance. Once a opening inventory is ordered properly, the performance of Scenario 2 will be significant better than that of Scenario 1. While as Scenario 3 has already ordered a proper quantity of opening inventory, coupled with the establishment of warehouses and the use of Demand-pull replenishment model, there will be no OOS. Taking all these three indicators, it proves that the use of TOC supply chain management can indeed have better performance. Also when the points of downstream side are larger, there will be more significant improvement of performance.

5. Conclusions

In this study, the supply chain system which allows many people to participate was designed, including an upstream manufacture and several downstream customers. In the game, the inventory was controlled and managed with different replenishment models. In the Scenario 1, customers used traditional replenishment model, but it could not response to market demand effectively and rapidly, resulting in too much inventory or OOS of a product. TOC thought the Demand-pull must be used for replenishment, and at the same time combined with factory-warehouse established at the most accurate place. In this way, replenishment time will be reduced from the original "Ordering lead time", "production lead time" and "transportation lead time" to only left "transportation lead time", so as to respond to market demand more quickly and operate with most accurate forecast, as well as improve the reliability and flexibility of replenishment. Therefore, the TOC replenishment method was applied in the Scenario 2 and 3 of this study. Although Scenario 2 is better than Scenario 1, it is not significant, which is due to the quantity of downstream customers is not large enough; if it is more and more, the improving effect will increase more and more significantly. As comparison between Scenario 3, Scenario 1 and Scenario 2, the performance of Scenario 3's inventory, OOS quantity and times are improved significantly. Thus, the importance of establishing warehouse is obvious. Of course the warehouse shall be established at appropriate areas, so the benefits of TOC replenishment methods can be maximized.

A game developed by Dr. Goldratt was aimed at in this study to design, but in the course of the game, in order to avoid lengthy and complicated, many settings of the scenarios were simplified to improve the fluency of playing the game, including OOS replenishment, transportation costs, ordering costs and batch discounts etc. the subsequent player can properly increase the scenario settings if necessary. Additionally, in the Scenario 3 of the game, despite the TOC logical thinking was used to order the opening and target inventories, there is still possible space for improvement in the inventory settings, so as to let the inventory be in more ideal state. In addition, as there are only six customers set in downstream customer end, so the order is used to transfer in the game. If the number of downstream customer increases, the whole network of supply chain will become more complex, it can expect to replace the delivery of orders with network. As a result, not only could save many costs and shorten the game time, but also can design a more diversified supply chain system through the opening of network. Finally, if the supply chain system combines with the other TOC methods, such as buffer management or TOC corrective indicators, it can see the effects through changing the scenarios of the game. It is believed there are other more methods on improving the performance of supply chain, which can get real performance improvements in line with the actual situation and TOC management model.

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