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## A Study of Theory of Constraints Supply Chain Replenishment System

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### Abstract

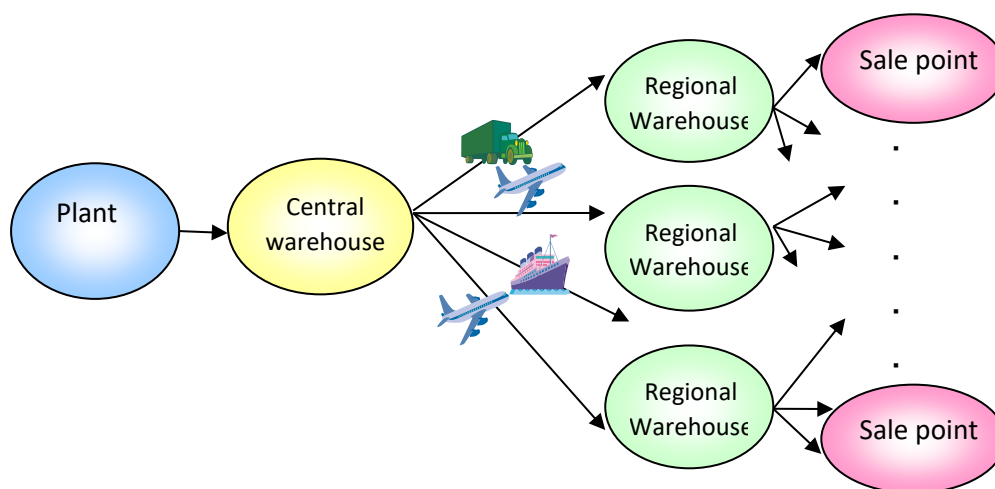
An effective inventory replenishment method implemented in the supply chain is one of the key success factors to achieve low inventory while maintaining high customer delivery performance. The Theory of Constraints (TOC) Supply Chain Replenishment System (TOC-SCRS) is one of the solutions to get this improvement in a multi-echelon supply chain. The TOC-SCRS is a replenishment method of the TOC supply chain solution. The TOC is a global managerial methodology that helps the manager to concentrate on the most critical issues. The TOC-SCRS is based on the following two strategies to decouple the bullwhip effect (or excess inventory in each node) and maintain the inventory availability to consumers (next nodes): (1) each node holds enough stock to cover demand during the time it takes to reliably replenish; (2) each node only needs to replenish what was sold. The TOC-SCRS is now being implemented by a growing number of companies. The performance reported by the implemented companies includes reduction of inventory level, lead-time and transportation costs and increasing forecast accuracy and customer service levels. However, the exploration of TOC-SCRS is lack in the literature. In this study, the concept and method of TOC-SCRS is first reviewed and modeled. A virtual supply chain case is secondly designed to show the behavior of the TOC-SCRS. A three factorial experiment, i.e., fluctuation of demand, time of replenishment and frequency of replenishment, is then presented to explore the feasibility and effectiveness of TOC-SCRS. A simulation model is designed to complete the experiment.

**Keywords:** Supply Chain Management, Inventory Replenishment, Theory of Constraints, TOC Supply Chain Replenishment System

### Introduction

The concept and method applying to the implementation of supply chain, theory of constraints (TOC) was firstly introduced in the best-selling novel written by Dr. Goldratt, *It's Not Luck* in 1994, namely TOC supply chain solution, for such solution is considered as a win-win solution in terms of conflicts on the supply chain inventory management mainly (Goldratt,

1994). This study will briefly talk about the conflicts and the solution in the following first. As for a company, its' supply chain basically consists of three major parts: plant, distribution or regional warehouse, and retailers/sale points, as shown in Figure 1. The plant is responsible for raw materials purchase and production, and products are to be stored in the plant (the central warehouse) once they are finished, and then they are delivered to a distribution warehouse where the retailer/sale point can proceed with its service, and after that products are sold to customers by the retailer/sale point. Generally, a distribution/regional warehouse is a company-owned branch, but not necessarily for retailer/sale point. But regardless whether members of these three parts belong to the same company, the so-called efficient "sales" must be the products sold to the main customers by the retailer/sale points to be considered as the real sales, otherwise they are just the inventory within the supply chain (even they are noted to be sold to downstream companies, chances that the surplus inventory may be returned still exist).



**Figure 1. The network graph of supply chain**

In terms of the maximized profit on the supply chain, we must first ensure the main customers are able to purchase goods they desired, and in order to avoid the main customers being unable to buy goods they wish to have, we must place the inventory at places where can reach them easily (such as retailers/sale points), and to prepare as large inventory as possible in order to meet the peak of demand that may occur occasionally, as shown in Figure 2. In other words, factories should produce products and deliver them to the retailer/sale point as fast as they could in order to meet the main customers' needs, as shown in the upper part of Figure 2. However in the current market that is intense and competitive, customer requirements are getting harsher and harsher and the product life cycle is unable to grasp, in order to avoid large inventories causing loss and damages (such as products being returned due to decreasing sales, waste, specifications or quality failed to meet the requirements, etc), therefore inventories must be stored at the sources of places (namely factories), and to deliver the smallest inventory to the retailer/sale point in order to prevent loss due to demand changes in the market. In other words, the plant shall try its best to delay production and delivery, and deliver its smallest inventory to the retailer/sale point, as shown in the lower part of Figure 2. Hence the conflict graph shown in Figure 2 shows the two difficulties and conflicts the supply chain management and inventory management within each sale point confronts.

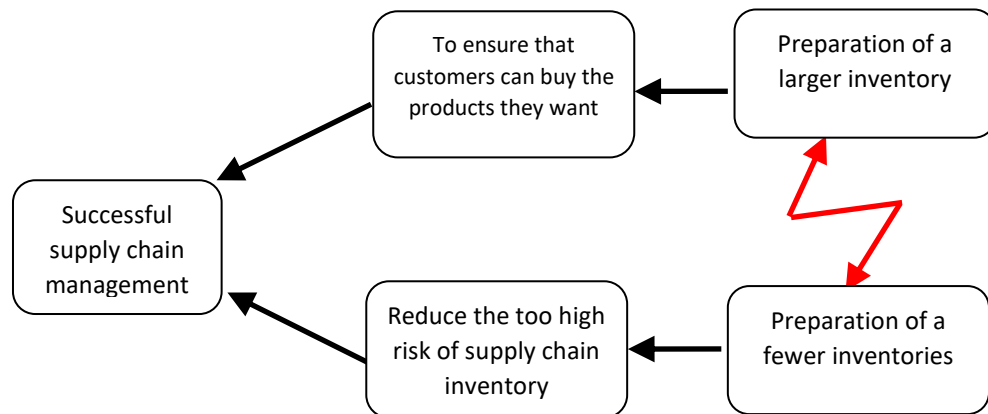


Figure 2. The conflict graph of supply chain management (Goldratt, 1994)

Generally in the face of the conflict on the supply chain, it is an ability to enhance the response capability of supply chain via a technology aiming at strengthening the market forecast and speed of information feedback, for example, to push the original plant prediction forward into the management mode of retailer/sale point, and then change it into the retailer prediction, and again to move to the management mode of plant cargo through rapid information response. Although such change can mitigate the above-mentioned conflict, but the conflict itself is remained unsolved, and even can get worse. For example, the accuracy of a retailer's forecast of future sales is found to be lower than that of a distribution warehouse's forecast, and it is due to the sales of distribution warehouse is the sum of sales of sale points, and hence the accuracy is no doubt to be higher than individual forecast conducted by each sale point; likewise plant sales is the sum of all distribution warehouse sales, therefore the accuracy on overall sales forecast conducted by the plant is of course higher than the forecast of each distribution warehouse sales. In this conflict, its very nature is not to determine which forecast is better than others (please note that forecast itself consists of risks and it is not always reliable), but it is about the inventory should be placed within the supply chain, as well as how each sale point deals with its replenishment, accounted for the reasonable issues. Therefore, the TOC has proposed the following solutions accordingly:

(1) The inventory should be placed within the source of supply chain (namely the plant). Therefore do not deliver the products to the downstream companies right away by the time they are finished; and distribution warehouses should not deliver the products to the downstream companies as soon as products from upstream companies arrived.

(2) Each sale point only needs to store enough inventory needed for such replenishment period. For example, if it takes three days for replenishment and according to the previous sales record, the maximum demand for consecutive three days is 300, and then there should be only 300 in the sale point's inventory.

(3) Each sale point should make up the replenishment in accordance with its sales, by replenishing how much it has sold.

(4) To monitor the sudden abnormal condition via the Buffer Management (BM) mechanism in order to prepare for any contingency. Such as the sudden increase in the sales resulting in low inventories, then BM can detect it right away and send out a signal for replenishment need.

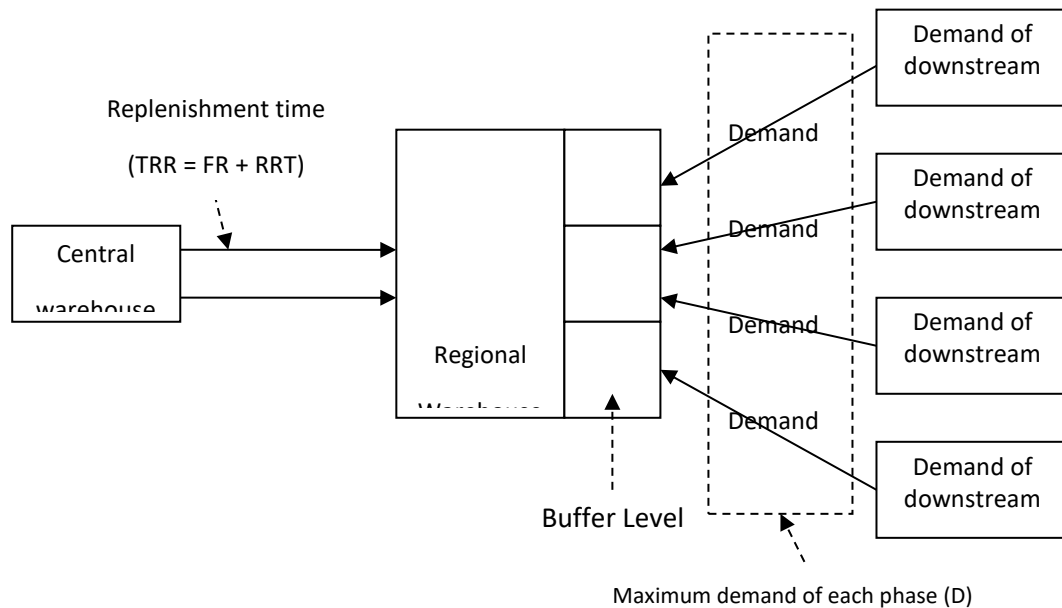
The above is the main content of the theory of constraints in terms of the supply chain solution. Among which the first point belongs to the new theory of supply chain management,

and the second and third points are referred to a brand new inventory replenishment mechanism, namely the TOC supply chain replenishment system (TOC-SCRS), and as for the fourth point, it is the monitoring mechanism of inventory. The focus of this study lies in the discussion of TOC-SCRS; therefore, regarding the TOC-SCRS implementation, please refer to the related documents (Holt, 1999; Perez, 1997; Simatupang *et al.*, 2004; Smith, 2001; Yuan *et al.*, 2003).

Under the TOC-SCRS mechanism, each sale point has stored the largest inventory that was occurred during the replenishment period, and the volume lies in the sales quantity between the two replenishment periods, hence we can be certain that the sale point has the lowest inventory. And under the BM mechanism, impacts caused by unexpected situations are to be determined, and request of emergency replenishment will be alerted if necessary, as a result, out of stock can be avoided. According to common reactions of various companies (Belvedere and Grando, 2005; Blackstone, 2001; Hoffman and Cardarelli, 2002; Novotny, 1997; Patnode, 1999; Sharma, 1997; Waite *et al.*, 1998; Watson and Polito, 2003) towards the TOC-SCRS, the benefit lies in the reduction of inventory substantially, enhancement of service quality, reduction in expired products (or reduction in the out rate), and more rapid reaction in terms of market changes, etc. However, the exploration of TOC-SCRS is lack in the literature. In this study, the concept and method of TOC-SCRS is first reviewed and modeled. A virtual supply chain case is secondly designed to show the behavior of the TOC-SCRS. A three factorial experiment, i.e., fluctuation of demand, time of replenishment and frequency of replenishment, is then presented to explore the feasibility and effectiveness of TOC-SCRS. A simulation model is designed to complete the experiment.

### **The Model of TOC-SCRS**

Figure 3 shows the basic concept of TOC-SCRS. This mechanism explains the replenishment mechanism that each sale point (namely plant, warehouse, or retailer) in the supply chain must be applied to (Cole and Jacob, 2002; Wu *et al.*, 2010; Wu *et al.*, 2011), and under the circumstances that sales of each period (the daily or weekly sales of a sale point or the sum of total demand or total purchase from the downstream companies) is determined, such mechanism contains three kinds of parameters, they are respectively the replenishment time, maximum inventory level, and replenishment quantity, details are described in the following:



$TRR(r_i)$  = Time to Reliably Replenish for product  $i$ .;  $RRT(l_i)$  = Reliable Replenishment Time for product  $i$ .

$FR(f_i)$  = Frequency of Replenishment (FR) for product  $i$ .

Figure 3. The replenishment mechanism of TOC-SCRS (Cole and Jacob, 2002)

(1) Replenishment time: The sum of replenishment frequency and the lead time it requires.

- Replenishment frequency is the how long to replenish once, which is the time interval from the previous replenishment order to the current replenishment order.

- Replenishment lead time: How long does it take from replenishment order is released until products are delivered to the destination, and such time may include the production time the upstream companies need, or the delivery time between downstream companies and the sale point, etc.

(2) Maximum inventory level: The maximum inventory quantity within consecutive replenishment time is estimated in accordance with the length of replenishment time based on the record of the previous sales. For example, if the replenishment time is 3 days, and the maximum value of the consecutive 3-day sales according to the previous sales record is defined as the maximum inventory quantity of the sale point. In other words, the maximum inventory quantity is determined in accordance with the replenishment time and previous sales, therefore the relationship can be presented in the following formula (1), and the detailed formula and application example will be shown in Figure 4.

Maximum inventory quantity =  $f$  (replenishment time, sales of each phase)

(1)



- $I$ : The total product types.
- $i$ : The product index,  $i= 1,2,\dots,I$ .
- $J$ : The total periods.
- $j$ : the period index,  $j= 1,2,\dots,J$ .
- $d_{i,j}$ : The consumption of product  $i$  during period  $j$ .
- $f_i$ : Frequency of replenishment for product  $i$ , i.e., the time period between delivers, such as two days.
- $l_i$ : The lead time required to reliably process and transfer product  $i$  from next node to our node.
- $r_i$ : The time to reliably replenish product  $i$ ,  $r_i = f_i + l_i$ .
- $t_{i,j}$ : The total consumption of product  $i$  during period  $j - r_i + 1$  to period  $r_i$ .
- $S_i$ : The buffer level of product  $i$  (Decision variable).

Based on the concept of TOC-SCRS as shown in Figure 3, each node holds enough stock to cover demand during the time it takes to reliably replenish. In other word, the buffer level of a product  $i$  in a node is determined by the maximum expected usage or consumption during the time to reliably replenish. That is, given a product  $i$ , the consumption of product  $i$  in the last some periods (i.e.,  $J$  periods) must first be collected to determine the buffer level of product  $i$ . Then the total consumption (i.e.,  $t_{i,j}$ ) of product  $i$  during the time to reliably replenish (i.e.,  $r_i$ ) must be evaluated during the last  $J$  periods as shown in (2).

$$t_{i,j} = \sum_{x=j-r_i+1}^{r_i} d_{i,x} \quad , \quad j = r_i, r_i + 1, \dots, J \quad , \quad i = 1, 2, \dots, I. \tag{2}$$

Ultimately, the buffer level ( $S_i$ ) is determined the maximum  $t_{i,j}$ , or using (3).

$$S_i = \text{Max} \left[ \sum_{x=j-r_i+1}^{r_i} d_{i,x} \quad , \quad j = r_i, r_i + 1, \dots, J \right] \quad , \quad i = 1, 2, \dots, I. \tag{3}$$

An example in the following table is utilized to demonstrate the determination of the buffer level of a product  $i$ . The consumptions during the last twenty periods are collected first and are shown in the second row in the following table. For example, the consumption in the 5<sup>th</sup> period is 8 pieces. Suppose the replenishment frequency of product  $i$  is 2 periods and its replenishment lead time is one period. Therefore, the time to reliably replenish product  $i$  is then 3 periods. Using (2), the total consumption during 3 periods can be evaluated from 3<sup>rd</sup> period to 20<sup>th</sup> period, which are shown in third row in the following table. For example, for 5<sup>th</sup> period, the total consumption during 3 period (i.e., from 3<sup>rd</sup> period to 5<sup>th</sup> period) is 13 pieces (=3+2+8). Because the maximum total consumption in 3 periods is 28 pieces for 16<sup>th</sup> period, the buffer level is 28 pieces using (3).

Period ( $j$ )	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Consumption( $d_{i,j}$ )	4	7	3	2	8	5	12	7	4	9	1	4	7	11	8	9	1	11	7	5
Consumption in 3 periods ( $t_{i,j}$ )	-	-	14	12	13	15	25	24	23	20	14	14	12	22	26	28	18	21	19	23

Figure 4. The Model of Buffer Level

(3) Replenishment quantity: The volume of each replenishment order is the total sales of the sale point from the previous replenishment order to the current replenishment order, namely to replenish how much is used, for example, if the replenishment frequency is once in two days, and then the replenishment quantity is the sales of the recent two days. In other words, the replenishment quantity is determined by the replenishment frequency and the sales within the period, therefore the relationship can be presented in the following formula (4), and the detailed formula and application example will be shown in Figure 5.

$$\text{Replenishment quantity} = f(\text{replenishment frequency, sales of each phase}) \tag{4}$$

$Q_{ij}$ : The replenishment quantity for product  $i$  during period  $j$ .

$R_{ij}$ : The quantity of receipt for product  $i$  during period  $j$ .

$V_{ij}$ : The inventory level of product  $i$  in the end of period  $j$ .

The replenishment quantity of a product  $i$  in a node is determined by the quantity of consumption between two replenishments. Therefore the replenishment quantity of a product  $i$  in a period  $j$  can be represented as (5).

$$Q_{i,j} = \begin{cases} \sum_{w=j-f_i+1}^j d_{i,w} & , \text{ if } \text{mod}((j-\alpha)/f_i) = 0 \\ 0 & , \text{ else} \end{cases} \quad (5)$$

Where  $\alpha$  is a selected integer parameter and  $0 < \alpha < f_i$ .

An example in the following table is utilized to demonstrate the determination of the replenishment quantity of a product  $i$ . The consumptions during the future twenty periods are supposed to show in the second row in the following table. For example, the consumption in the 5<sup>th</sup> period is 5 pieces. Suppose the replenishment frequency of product  $i$  is 2 periods and its replenishment lead time is one period. And  $\alpha$  is assumed to be zero. Therefore, Using (5), the quantity of replenishment for each period are shown in third row in the following table. For example, the replenishment quantity in 5<sup>th</sup> period is zero for  $\text{mod}(5/2)$  is not equal to zero. And the replenishment quantity in 6<sup>th</sup> period is 14 pieces (=5+9) for  $\text{mod}(6/2)$  is equal to zero. In order to further illustrate the receipt or inventory level variation, we assume that the goods of a replenishment order which is released in period  $j - l_i$  will be delivered (or arrived at) at  $j$  period (i.e., after  $l_i$  periods). And the quantity of receipt is equal to the replenishment quantity. Therefore, the quantity of receipt in period  $j$  can be represented as (6).

$$R_{i,j} = Q_{i,j-l_i} \quad (6)$$

Therefore, the inventory level in the end of period  $j$  is equal to the inventory level of previous period minus the consumption in period  $j$  and plus the quantity of receipt in period  $j$ , as shown in (7).

$$V_{i,j} = V_{i,j-1} - d_{i,j} + R_{i,j} \quad (7)$$

Using (6), the quantity of receipt in each period is shown in 4<sup>th</sup> row in the following table. And using (7), the inventory level in the end of each period is also shown in 5<sup>th</sup> row in the following table.

Period ( $j$ )	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Consumption ( $d_{ij}$ )	8	3	11	7	5	9	4	8	6	10	4	9	5	3	8	7	11	6	6	8
Quantity of replenishment ( $Q_{ij}$ )		11		18		14		12		16		13		8		15		17		14
Quantity of receipt ( $R_{ij}$ )	7*		11		18		14		12		16		13		8		15		17	
Inventory level ( $V_{ij}$ )**	27	24	24	17	30	21	31	23	29	19	31	22	30	27	27	20	22	18	29	21

\*: the arriving quantity in the first period is supposed to have been replenished in previous period.

\*\* : The initial inventory level is supposed to be 28 pieces.

Figure 5. The Model of Replenishment Quantity

Among the above three parameters, the replenishment time and replenishment frequency must be determined in accordance with needs by the user, but TOC stresses that unless environmental and technical constraints are found, such as sailing schedule or route change, otherwise the shorter the replenishment frequency the better the performance (like one day). As for the maximum inventory level and replenishment quantity, are determined by the known demand of each phase and replenishment time (frequency).

Secondly, in terms of impacts caused by unexpected situations, the TOC-SCRS couples with the BM mechanism system. The BM is basically an inventory monitoring mechanism that is applied to each sale point, mainly aiming at monitoring the impacts caused by unexpected situations in the supply chain, such as the delay of trucks or sudden increase in sales, etc, for



it is as well an estimation method for evaluating the level of impact. Its concept of application is similar to the buffer management mechanism collocated with the production management and drum-buffer-rope (DBR) (Schragenheim and Ronen, 1991). However, the buffer management mechanism that goes along with the DBR is the buffer time, but over here what the buffer management mechanism monitors in terms of inventory is the inventory quantity. A buffer management mechanism of monitoring is needed for each commodity and the size of the largest buffer (inventory) is the maximum inventory level, the three areas represent the three inventory monitoring areas, derived from the maximum inventory level division, and they are respectively the action, warning, and safe areas. When the inventory is more than  $2/3$  (inclusive) of buffer, it means the stock is abundant, for we do not need to pay attention, thus such area is called the safe area; when the inventory is more than  $1/3$  (inclusive) or less than  $2/3$  of buffer, it means the stock is not very abundant, for it is not up to the state of shortage, hence we only need to be alerted and pay attention to the subsequent changes, no actions are needed to be done so far, hence this area is called the warning area; when the inventory is consumed fully and less than  $1/3$  of buffer, it means it may be out of stock at any time, so we must immediately request an emergency replenishment from upstream companies, hence this area is called the action area. Through the buffer management monitoring mechanism of inventory, unexpected situations or variations that may cause a shortage can be avoided.

### **Characteristics and Problems of the TOC-SCRS**

According to the above descriptions, the TOC-SCRS basically contains the following characteristics:

(1) In general, according to the inventory theory, the inventory mechanism is divided into successive (or quantitative) replenishment, such as  $(s, S)$ , and fixed period replenishment, such as  $(R, S)$  (Silver *et al.*, 1998), and so, the TOC-SCRS is considered as a fixed period replenishment method.

(2) The determination of TOC-SCRS replenishment quantity and maximum inventory level varies from the general fixed period replenishment method. The general fixed period replenishment methods, such as  $(R, S)$  or  $(R, Q)$ , the replenishment quantity  $(Q)$  and the maximum inventory level  $(S)$  are determined by Economic Order Quantity (EOQ),  $Q = \text{EOQ}$  or  $S = s + \text{EOQ}$  (Silver *et al.*, 1998). Therefore, the replenishment frequency and the length of replenishment time have no direct impacts on the replenishment quantity or the maximum inventory level. As for the replenishment quantity of TOC-SCRS, it is determined by the replenishment frequency and the sales between two replenishment periods, it is similar to Lot-for-Lot (L4L) of material requirement planning (MRP), hence the shorter the replenishment frequency, the smaller the replenishment quantity. And the maximum inventory level is determined by the replenishment time and sales within such time, hence the shorter the replenishment time, the smaller the maximum inventory level. In other words, the length of replenishment frequency and replenishment time is the key factor to determine the replenishment quantity and the maximum inventory level of TOC-SCRS. This point (how it determines the replenishment quantity and the maximum inventory level) shows the biggest difference in the TOC-SCRS compared to general fixed period replenishment mechanisms.

(3) Because the replenishment quantity and the maximum inventory level of TOC-SCRS are determined by the replenishment frequency and replenishment lead time; therefore, how managers control the inventory level and make adjustments in accordance with changes in sales is more direct and more efficient. And as long as we can improve the replenishment

frequency and replenishment time, the inventory level can thus be reduced, and most importantly, we may avoid shortages caused by lower inventories. This is one of the reasons why the TOC-SCRS is widely accepted by practitioners.

(4) Will the number and cost of delivery increase followed by the reduction in the replenishment quantity? According to the actual case report (Kendall, 2006), there will not be any increases. A delivery of 10 commodities, 50 of each (three-month supply) and a delivery of 50 commodities, 10 of each (three-week supply), both shares the same delivery frequency, hence no extra delivery frequency or cost will be occurred.

Due to the key determinant of the replenishment quantity and the maximum inventory level of TOC-SCRS lies in the length of replenishment frequency and replenishment time, and such characteristic (how it determines the replenishment quantity and the maximum inventory level) explains how the TOC-SCRS varies from general replenishment mechanism, therefore we will be looking at the impacts on the inventory caused by different replenishment frequency and replenishment time.

### Impacts on the Inventory in Terms of Different Replenishment Time

#### *Impacts on the Buffer Level in terms of the size of TRR*

According to the TOC, the buffer level is the biggest demand within the TRR. Take the past 24-day sales of Product A shown in Table 1 as example, when the TRR= 4, we can then find out the successive sales of the previous 4 days starting from the fourth day, and so, there is a total of 21 values; and we may obtain the maximum,  $Buffer_a = \text{Max} \{(32 + 36 + 35 + 22), (36 + \dots + 26) \dots, (32 + \dots + 31)\} = 127$ . When the TRR= 8, the inventory level is to be calculated starting from the eighth day and we may obtain the maximum of sales of successive 8 days,  $Buffer_a = \text{Max} \{(32 + 36 + \dots + 27), \dots, (36 + \dots + 35)\} = 242$ , the daily successive buffer calculation is as shown in Table 1, and we can find that the demand of each phase and the length of TRR determine the Buffer Level.

Table 1. The inventory buffer in terms of different TRR<sub>a</sub>

Period (day)	1	2	3	4	5	6	7	8	9	10	11	12
Sales quantity	32	36	35	22	26	24	21	27	35	24	30	34
Successive 4-day sales				125	119	107	93	98	107	107	116	123
Successive 8-day sales								223	226	214	209	221
Period (day)	13	14	15	16	17	18	19	20	21	22	23	24
Sales quantity	26	35	25	33	30	24	30	29	32	29	35	31
Successive 4-day sales	114	125	120	119	123	112	117	113	115	120	125	<b>127</b>
Successive 8-day sales	221	232	236	242	237	237	237	232	238	232	<b>242</b>	240

*Impacts on the inventory in terms of different replenishment frequency and replenishment lead time*

Because the purchase quantity is generated within the length of each replenishment frequency time, therefore  $Q_{i,j}$  is as the demand of each order period and  $FR_i$  is the factor that determines the purchase quantity; as for the replenishment quantity is generated within the length of each replenishment lead time for  $R_{i,j}$  is as the purchase quantity, therefore  $RRT_i$  is the factor that determines the purchase timing. The time to reliably replenishment (TRR) is composed of the frequency of replenishment (FR) and reliable replenishment time (RRT), so let's use TRR= 8 as example, as the maximum FR is  $FR= TRR - 1$  and the minimum is  $FR= 1$ , how does it affect the inventory. Take the demand of successive 20-day shown in Tables 2 and 3 as example, when  $FR= 1$ ,  $RRT= 7$ , and  $FR= 7$ ,  $RRT= 1$ , the ending inventories shown on Tables 2 and 3 are very different, and further discussions will continue in the next section.

*Table 2. Changes in the inventory when FR = 1, RRT = 7*

Period (day)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Demand quantity	23	33	29	35	38	28	38	37	28	31	31	27	38	27	27	26	36	33	27	26
Order quantity	23	33	29	35	38	28	38	37	28	31	31	27	38	27	27	26	36	33	27	26
Purchase quantity								23	33	29	35	38	28	38	37	28	31	31	27	38
Ending inventory	35	32	29	25	22	19	15	14	14	14	14	15	14	15	16	17	16	16	16	17
	5	2	3	8	0	2	4	0	5	3	7	8	8	9	9	1	6	4	4	6

*Table 3. Changes in the inventory when FR = 7, RRT = 1*

Period (day)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Demand quantity	23	33	29	35	38	28	38	37	28	31	31	27	38	27	27	26	36	33	27	26
Order quantity							22							21						
							4							9						
Purchase quantity								22							21					
								4							9					
Ending inventory	35	32	29	25	22	19	15	34	31	28	25	22	18	15	35	32	28	25	22	20
	5	2	3	8	0	2	4	1	3	2	1	4	6	9	1	5	9	6	9	3

**Experimental Design and Analytical Results**

*5.1. Environment and parameter settings*

Because main factors that can affect the inventory level contain the average daily demand, demand standard deviation, and TRR, therefore this study has established 36 combinations by using high, medium, low average daily demands; high, medium, low demand standard deviations, long, short TRR values, and long, short FR values, etc. According to different combination of factors based on different levels, take a certain product as example, the average daily demands are 100, 300, and 500, demand standard deviations are 5%, 10%, and 20%, the TRR values are 5 and 10, and FR and RRT are 1, 4 and 1, 9 days respectively, as shown in Table 4. This experiment used the EXCEL software for stimulation, the average daily demand was normally distributed, and the initial Buffer rate was known; the  $3 \times 3 \times 2 \times 2 = 36$  of experiments were implemented by using different factor parameters, and a 200-day experimentation was applied to each group of parameters in order to obtain the representative data. At the beginning state, the inventory was generated based on the previous demand, therefore the 200-day can be considered as the steady-state situation. Finally, this study used the experimental results of the stimulated 36 groups, coupling with the average inventory and inventory stock standard deviation to explore and discuss the impacts on the inventory in terms of TRR, RRT, and FR.

Table 4. Parameter settings

Name of variable	Parameter value	
Average daily demand	Average daily demand: 100, 300, 500	
Demand standard deviation	Percentage of average daily demand: 5%, 10%, 20% as for standard deviations are: 100×0.05, 100×0.1, 100×0.2; 300×0.05, 300×0.1, 300×0.2; 500×0.05, 500×0.1, 500×0.2	
TRR (day)	TRR= 5	FR= 1, RRT= 4 (TRR= FR + RRT)
		FR= 4, RRT= 1
	TRR= 10	FR= 1, RRT= 9
		FR= 9, RRT= 1

**Experimental Results**

The experiment was implemented based on the parameters in Table 4, when each demand distribution is the same and TRR is larger, the maximum buffer level and maximum inventory value are higher as well. So we know the length of TRR determines the maximum buffer level value and the maximum inventory value within the system, as shown in Figure 6. When the average daily demand and standard deviation are distributed similarly, and the TRR are long and short values, the maximum of inventory buffer level of the former is larger, the beginning inventory level is as well higher, therefore the ending inventory level is expected to be higher accordingly; conversely, the average inventory level is found to be low, as shown in Figure 7.

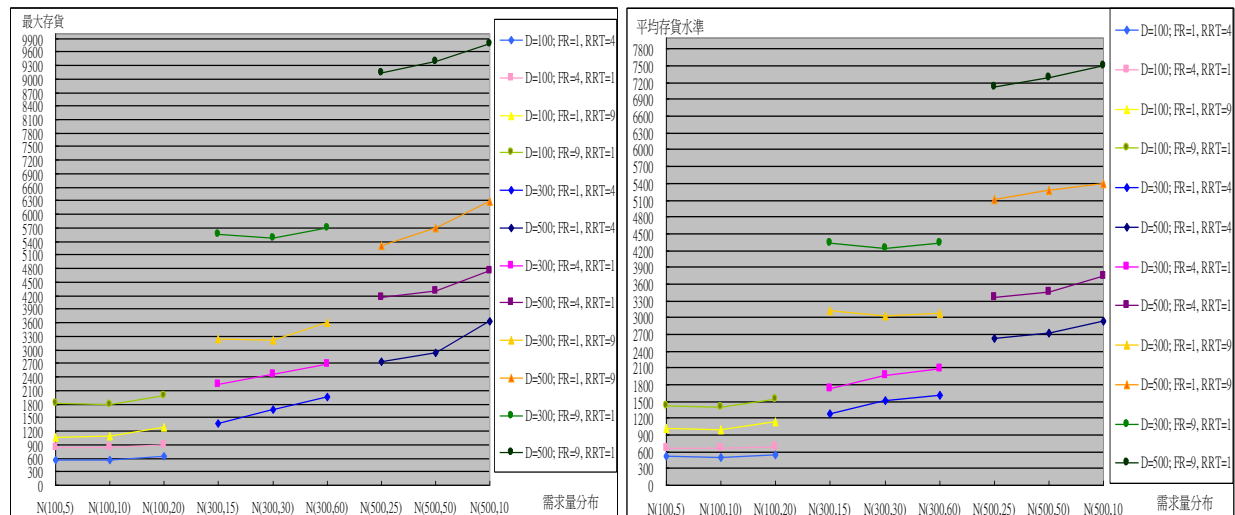


Figure 6: Distribution of the maximum ending inventory Figure 7: Distribution of the average inventory level

As for when the TRR is a fixed value, and FR and RRT values are different, how do they relate to the average inventory level? When the TRR is shorter and FR are large and small values, the average inventory level of the later is higher than which of the former; when the TRR is longer and FR are large and small values, a significant different can be found in the average inventory level of the later; as the daily demand and standard deviation increase, the average inventory level increases accordingly as well. Therefore, when the TRR is fixed and FR is a large value, the average inventory level is higher than when the FR is a small value, the higher the FR the more impacts it has on the inventory level, as shown in Figure 7.

As for the standard deviation of inventory, when the average daily demand and standard deviation are similarly distributed, TRR are large, small values, and FR is small value, no significant impacts can be found on the standard deviation of ending inventory level; when the FR is a large value, the standard deviation of ending inventory level will become larger as the FR value becomes larger. So we know when the average daily demand is fixed, no direct impacts can be found on the standard deviation of inventory as the TRR is higher; but as the TRR is higher and the FR is large value, the standard deviation of inventory level gets higher as well; conversely, no significant differences can be found. As changes in the average daily demand and standard deviation are larger or when they are both similarly distributed, and the TRR is higher, the FR value is large, the difference in the standard deviation of ending inventory level is more significant, as shown in Figure 8.



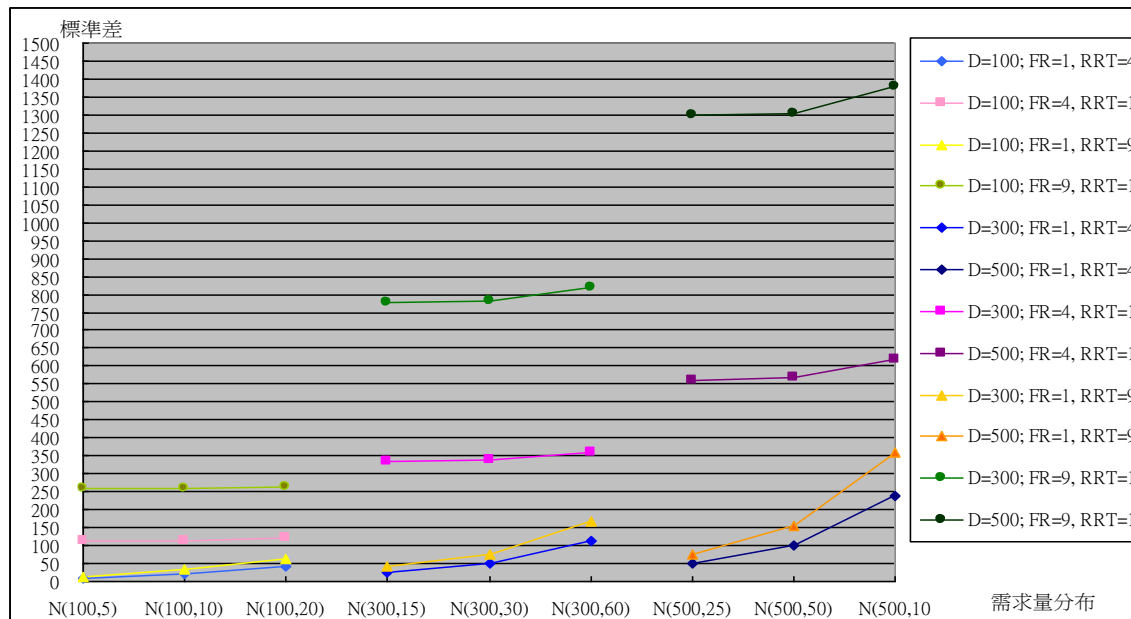


Figure 8. Distribution of the standard deviation of the ending inventory

### Conclusions

The TOC supply chain solution was firstly introduced by Dr. Goldratt in his book, *It's not luck*, and various studies aiming at such concept conducted by scholars began to take place later on. This study established a model in accordance with TOC supply chain mechanism, used the EXCEL software to run the stimulation and analysis based on three factors including average daily demand, demand standard deviation, and TRR. The results showed that in the situation when the average daily demand and demand deviation are distributed similarly and the TRR are in different values, as the TRR value gets higher, the inventory level system gets higher as well, and no significant differences are found in the standard deviation; and as the TRR values are fixed, the larger the FR value the higher the average ending inventory level and standard deviation of inventory level, and along with changes in the average daily demand and standard deviation are larger, the average ending inventory level within the system and standard deviation get higher as well. Therefore we know the TRR and FR determine the inventory level within the system.

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