A Synchronized Supply Chain for Reducing Decoupling Stock

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Abstract: Decoupling stock is required when inventory decision-making is carried out independently in different units in a supply chain. In this research we formulate the function for calculating decoupling stock, and analyze the key factors for reducing decoupling stock through synchronization.

Key words: Inventory reduction, Information sharing, System Dynamics

Introduction

The importance of information sharing has been emphasized in the supply chain management. However, it is not easy to make good use of the shared information in practice. A survey on the information sharing on Point of Sale (POS) data was conducted in 14 major sale companies in Japan in 2013 by the Distribution Economics Institute of Japan. It can be found that all of these 14 sales are sharing the POS data with their suppliers by web including the single item data, daily POS data, store's POS data, 52 week POS data. However, the inventory information had seldom been shared between sales and makers and between logistics and makers. How to share the inventory information in supply chain needs to be emphasized and further examined. The key factors impacting the effect of information sharing in supply chain were analyzed. It was found that on key factor is the difference between the replenishment cycle time and the lead time. A new approach was proposed as synchronization for making good use of the shared information. The effect of inventory reduction and shortage were compared between information sharing and synchronization based on system dynamic simulation.

The remainder of this paper is organized as follows. In the second section, the literatures on the inventory reduce based on information sharing in supply chain are reviewed. The third section describes the inventory models and the proposal of synchronization model in supply chain. The fourth section describes the simulation analysis. The results are reported and discussed in the last section.

Literature Review

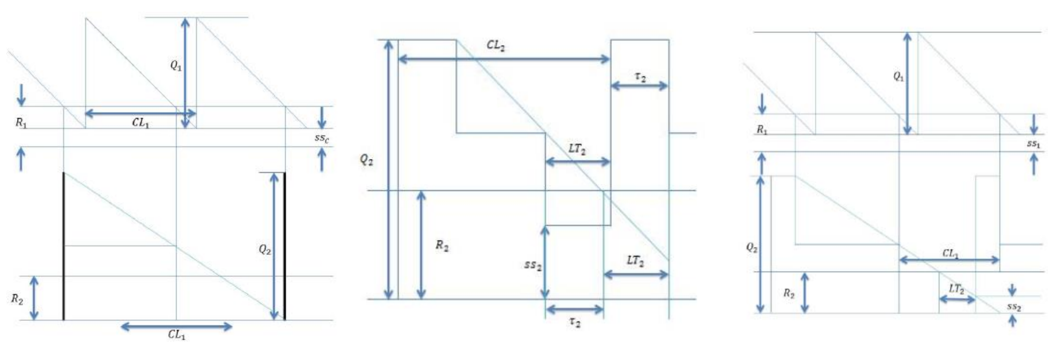
The effect of information sharing in the inventory system of multi-echelon supply chain has been examined in many studies, for example, the bullwhip effect in supply chain (Lee, et al. 1997), the value of information in supply chain (Lee. et al. 2000), and the inventory reduction (Tsao and Schvaneveldt 2001). In the inventory management systems in the multi-echelon supply chain, there may be two echelons, three echelons, or four echelons (Pan and Nagi 2012; Fu et al. 2014). Three echelons including manufacturers, logistics, and sales have often been regarded. This paper also focuses on this type. Usually, the inventory reduction in the supply chain can be effected by the structures of supply chain, i.e. the series or the arborescent inventory systems. This paper focuses on the series system. In order to assess the performance of the decisions in the inventory systems, there are some measurement scales including cost, inventory level, lead time reduction, shortage risk, service level (Costantino et al. 2014), etc. The inventory level and the shortage rate were included in this study. The demand in the nearest echelon to customers has often been regarded as being random with the normal distribution (Tsao and Schvaneveldt 2001). Recent researches regarded the demand with some special characteristics, i.e. the covariance-stationary autoregressive moving average demand (Kovtun et al. 2014; Fu et al. 2014). On the examination methods, numerical analysis has been widely adopted in the inventory system analysis. For the random demand, the numerical analysis can only show the tendency, but difficult to examine the changing scope. In this paper, through the simulation analysis based on the system dynamical models, more characteristics on the inventory reduction and shortage rate in the multi-echelon supply chain were to be analyzed.

Besides of the above selections in the inventory systems in the multi-echelon supply chain system, two other key variable affecting the information usage are the stock type and the decision structure. Usually, three types of stock have often been examined in the multi-echelon supply chain, i.e., lot size stock, echelon stock, and decoupling stock. 1) Lot size stock: the stock generated by the procurement lot size with considering the scale economics; 2) Echelon stock: the summary of the stock in one echelon and the stock passed by the echelon (Clark and Scarf 1960); 3) Decoupling stock: “the stock used a multi-echelon situation to permit the separation of decision making at the different echelons” (Silver et al. 1998). The decoupling stock is generated mainly because of the information distortion during transferring the demand forecasting information from the downstream to the upstream in supply chain. Since the conception of decoupling stock was proposed, the quantitative research has not been widely found (Tsao and Schvaneveldt 2001). This study is targeting the quantitative research on the decoupling stock.

The decision making model is one key factor effecting the inventory reduction. The decision making model can show the collaboration approaches in the inventory systems and has been seldom examined (Costantino et al. 2014). Two types of decision models on the inventory system have often been examined, i.e. a decentralized decision model (Lee and Wang 1999; Fu et al. 2014), a centralized decision model (Tsao and Wakabayashi 2000). The difference between these models can be found in decision making process, information visibility, safety stock, etc. For example, it is better to set the safety inventory in the nearest echelon to customers in the centralized decision model (Lagodimos and Anderson 1993); in the decentralized model, every echelon may keep the safety inventory in lot size. This paper focuses on a new decision structure, the synchronized decision model.

Inventory Models

According to the researches of Tsao and Schvaneveldt (2001), the inventory management models can be found as Figure 1, i.e., the centralized decision model (1-c), the decentralized decision model (1-d), and the information sharing model (1-s). In these models, two serial echelons in the supply chain are shown. In each echelon, six parameters are defined, i.e. the order point (R_1, R_2), the procurement cycle time (CL_1, CL_2), the procurement lead time (LT_1, LT_2), the order quantity (Q_1, Q_2), the safety stock (SS_1, SS_2), the time difference between cycle time and lead time (t_1, t_2). The system inventory in these three models can be defined as I^c, I^d, I^S as shown in equation (1)-(3). The safety stock in the decentralized model and the information sharing model are defined as SS as shown in equation (4)-(5).



(1-c) (1-d) (1-s)

Figure 1-System inventory in three decision models

$$I^c = \frac{Q_n}{2} + \sqrt{\sum_{i=1}^{n} LT_i} * \mu + SS_c \tag{1}$$

$$I^d = \sum_{i=1}^{n}\left(Q_i + SS_i^d\right) - \frac{Q_n}{2} + LT_1 * \mu * I^d \quad (2)$$

$$I^s = \frac{Q_n}{2} + \sum_{i=1}^{n} LT_i * \mu + \sum_{i+1}^{n} SS_i^s \quad (3)$$

$$ss_{i+1}^d = \left[\frac{k * \sqrt{LT_{\mathrm{i+1}}}\sqrt{CL_{\mathrm{i}} - 1}}{CL_{\mathrm{i}}}\right] * \mu * CL_{\mathrm{i}} \quad (4)$$

$$SS_{i+1}^s = k * \sigma * \sqrt{LT_{\mathrm{i+1}}} \quad (5)$$

The decentralized decision model can be regarded as the reference model for comparison. For the lack of centralized decisions, the increased decoupling stock is defined as DS_1, which is equal to the difference between I^d and I^c, as following equation 6). For the lack of information sharing, the increased decoupling stock can be defined as DS_2, which is equal to the difference between I^d and I^s, as shown in equation (7). Both of model C and model S can reduce the inventory. The different decoupling stock reduction between model C and model S is defined as *DS**, which is equal to the difference between I^S and I^c. It is also equal to the difference between DS_1 and DS_2 as shown in equation (8). The reduction effectiveness of *DS* (*DSE*) is defined as the percentage of the difference between *DS* and *DS** in *DS*, as shown in equation (9).

$$DS_1 = I^d - I^c = \mu \sum_{\mathrm{i=1}}^{\mathrm{n-1}}(CL_i - LT_{i+1}) + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{ss_i^d} - \mathrm{ss_c} \quad (6)$$
$$DS_2 = I^d - I^s = \mu \sum_{\mathrm{i=1}}^{\mathrm{n-1}}(\mathrm{CL_i} - \mathrm{LT_{i+1}}) + \sum_{\mathrm{i=1}}^{\mathrm{n-1}}(\mathrm{ss_{i+1}^d} - \mathrm{ss_{i+1}^s}) \quad (7)$$

$$DS^* = I^s - I^c = k\sigma\left(\sum_{\mathrm{i=1}}^{\mathrm{n}} \sqrt{LT_i} - \sqrt{\sum_{\mathrm{i=1}}^{\mathrm{n}} LT_i}\right) \quad (8)$$

$$DSE = \frac{DS - DS^*}{DS} * 100\% \quad (9)$$

According to equations (6) -(7), the difference between the replenishment cycle time (CL) in the downstream echelon and the replenishment lead time (LT) in the upstream echelon has the direct impact on both DS1 and DS2. Therefore, the synchronization model was proposed and defined as that an information sharing model with the same replenishment lead time in the upstream echelon as the replenishment cycle time in the downstream echelon. In practice, the replenishment lead time has often been fixed and very difficult to be adjusted. On the other hand, it is easier to adjust the replenishment cycle time which may cause the replenishment cost change. Therefore, the synchronization mainly depends on the adjustment in the downstream echelon. According to the setting, it is possible to examine the effect of synchronization only based on the information of the replenishment lead time in the upstream echelon. This is helpful when it is difficult to collect the information from the downstream evolvers.

In the synchronization model, the former parts of DS_1 and DS_2 can be zero, and the value of DS_1 and DS_2 only depend on value of safety inventory. The decoupling stock reduction in synchronization ($DS_1{}'$, $DS_2{}'$) can be shown as equation (10-11).

Accordingly, *DSE1* and *DSE2* can be defined as equation (12-13).

$$DS_1' = \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{ss}_{\mathrm{i}}^{d'} - \mathrm{ss_c} = \sum_{i=1}^{n}\left[\frac{k\sqrt{LT_i}\sqrt{LT_i-1}}{LT_i}\right]\mu LT_i - k\sigma\sqrt{\sum_{i=1}^{n} LT_i} \tag{10}$$

$$DS_2' = \sum_{\mathrm{i=1}}^{\mathrm{n-1}} \mathrm{ss}_{\mathrm{i+1}}^{d'} - SS_{i+1}^{s} = \sum_{i=1}^{n-1}\left[\frac{k\sqrt{LT_{i+1}}\sqrt{LT_{i+1}-1}}{LT_{i+1}}\right]\mu LT_{i+1} - k\sigma\sqrt{\sum_{i=1}^{n-1} LT_{i+1}} \tag{11}$$

$$\frac{DS_1-DS_1'}{DS_1} = \frac{\sum_{i=1}^{n-1}\left[\mu(CL_i-LT_{i+1})+SS_{i+1}^{d}\right]-\sum_{i=1}^{n-1} ss_{i+1}^{d'}}{\sum_{i=1}^{n-1}\left[\mu(CL_i-LT_{i+1})+SS_i^{d}\right]-k\sigma(\sqrt{\sum_{i=1}^{n} LT_i}-\sqrt{LT_1})} \tag{12}$$

$$\frac{DS_2-DS_2'}{DS_2} = \frac{\sum_{i=1}^{n-1}\left[\mu(CL_i-LT_{i+1})+SS_{i+1}^{d}\right]-\sum_{i=1}^{n-1} ss_{i+1}^{d'}}{\sum_{i=1}^{n-1}\left[\mu(CL_i-LT_{i+1})+SS_i^{d}\right]-k\sigma\sum_{i=1}^{n-1}\sqrt{LT_{i+1}}} \tag{13}$$

Based on the above models, some suggestions for the inventory management in supply chain could be given out. 1) If the replenishing cycle time in the downstream echelon and the replenishment lead time in the upstream echelon can be reduced, the system inventory could be further reduced. However if only reducing the replenishment cycle time, the system inventory may be increased. This requires the synchronization. 2) The synchronization requires the less difference between the replenishment lead time in the upstream and the replenishment cycle time in the downstream echelon. The decoupling stock can be reduced because of the synchronization. In addition, if the replenishment lead time could be further cut down, the effect can be better. These suggestions are to be tested and further analyzed through simulation.

Data Simulation

Usually, the demand was regarded as a fix value, μ, in researches. In practice, the demand may be a random variable with time. In this study, the simulation models with Vensim software were founded to examine the inventory system under the random demand. Four steps were executed in the simulation analysis. In step 1, the validity of the models were examined with different parameters, such as average value of demand (μ), standard deviation of demand (σ), cycle time (*CL*), lead time (*LT*); In step 2, the inventory reduction effectiveness from information sharing was examined; In step 3, the inventory reduction effectiveness from synchronization was examined；In step 4, the cost of inventory shortage was considered in the effectiveness test.

Some assumptions are set in the simulation model: 1) The order reserved in one echelon can arrive in the echelon; 2) The inventory level in each echelon is increasing; 3)When there are needs or order (including back order), the inventory decreases; 4)Inventory level and order point are checked; 5) When inventory level lower than order point, the new order will be issued in the next upstream echelon; 6) In there is inventory in hand in the next upstream echelon, the shipping will occur in the next downstream echelon and the back order will occur if no inventory in the echelon; 7) After the replenishment lead time passed, the goods will arrive at the next downstream echelon. The basic setting in the models was shown in Table 1. There are some original settings in the simulation as the data in parameters, i.e., μ (30), σ (9), *CL1* (10), *LT1* (2), *K* (2.33). *CL2* is set as a fix ratio, α, of *CL1*; *CL3* is set as the same fix ratio, α, of *CL2*. *LT2* is set as a fix ratio, β, of *LT1*; and *LT3* is set a fix ratio, β, of *LT2*.

Table 1-The setting in models

Category	**Condition**	**Value**
Supply chain setting	Echelon quantity(1, 2, 3)	3(factory, logistics, sale)
	Average needs (μ)	30
	Standard deviation(σ)	9
	Replenishing cycle time in echelon 1 (*CL1*)	6
	Replenishing cycle time in echelon 2(*CL2*)	12
	Replenishing cycle time in echelon 3(*CL3*)	24
	A fix ratio between CL (α)	α
	Replenishing lead time in echelon 1(*LT1*)	2
	Replenishing lead time in echelon 2(*LT2*)	4
	Replenishing lead time in echelon 3(*LT3*)	8
	A fix ratio between LT (β)	β
	Safety coefficient(*SS* coefficient)	2.33
Demand setting	The end demands	Normal distribution
	Minus needs	Delete
	The starting inventory in each echelon	2 times of order quantity
	Decimal point	Delete
Simulation setting	Test period (Period Quantity)	1440
	Warming up period (Period Quantity)	240
	Test times (Times)	10

Inventory Reduction with Synchronization

The simulation results of the inventory reduction through information sharing and synchronization were reported in Table 2. The results show that with the greater changes in the customer demand, the inventory reduction resulted by information sharing may be more limited. The max effect can be always found with the longest replenishment cycle time and the shortest replenishment lead time. In the synchronization, the max effect may be increased by 2% with the changes in the last demands becoming greater, but the min effect is minus. This can be explained with the equation (10) and (11) with the parameters expect of σ to be fixed. In the equation (10), with the bigger σ, the effect of *DS1* becomes more. However, comparing the effect of the difference between *CT* and *LT* with the effect of σ, the former one is much bigger. The similar analysis can be found on *DS2*.

Table 2-Inventory reduction through information sharing and synchronization

Standard deviation in demand	**Inventory reduction through information sharing**		**Inventory reduction through synchronization**	
	Max effect	**Min effect**	**Max effect**	**Min effect**
0.1	99.65%	98.93%	77.13%	0
0.3	98.75%	96.44%	77.73%	0
0.5	97.88%	93.86%	78.34%	0
0.7	96.99%	91.04%	78.99%	0
0.9	96.12%	88.04%	79.64%	0

Shortage Rate with Synchronization

Along with the inventory reduction, the risk of shortage is increasing. The shortage rate in the inventory system is defined as the percentage of back order quantity in total issued order quantity. The back order is defined as the order issued in the downstream echelon based on the order points being rejected for the shortage in the upstream echelon and under transportation. If there are several rejected orders issued in the same replenishment cycle, these rejected order would be counted as one back order. The shortage rate in supply chain is important especially when the last demand is changing. The change rate of the last demand is defined as the percentage of the standard deviation value in the average value. The decoupling stock was analyzed with Vensim under the following settings, i.e., μ (30), (*CL1*, *CL2*, *CL3*) = (8, 12, 24), (*LT1*, *LT2*, *LT3*) = (2, 4, 8).

The impact of the changing demand was examined. The simulation results show that: 1) With the higher change rate, the shortage rate become higher, and the highest shortage rate is less than 1%; 2) The shortage rate is increasing with the increasing distance to customers and the increasing change rate. The impact of replenishment cycle time and lead time on the shortage rate was examined. The simulation results show that with the longer replenishment cycle time, the shortage rate become less; with the longer replenishment lead time, the shortage rate become higher. The simulation results on the shortage rate were shown in Figure 2. In the marks, SH means information sharing model, and SY means synchronization model; the middle numbers mean the change rate, i.e. 0.3, 0.7; the last number means the echelon, i.e., 1, 2, 3.

Some suggestions can be proposed based on the simulation results. In the information sharing model, the shortage rate is higher with the shorter of the replenishment cycle time, with the longer of the replenishment lead time, and with the higher of the change rate. This can be understood that with the shorter cycle time, the order quantity may be less. The shortage rate may be increased when the orders with big demand comes. With the longer LT, it is difficult to replenish the stock on time so as not to response the order on time. In the synchronization model, only the effect in SY-1-7 is visible. The highest shortage rate can be found with the lowest β. Figure 2 also shows that the shortage rate is changing with the change of β, but not significantly with the change of α.

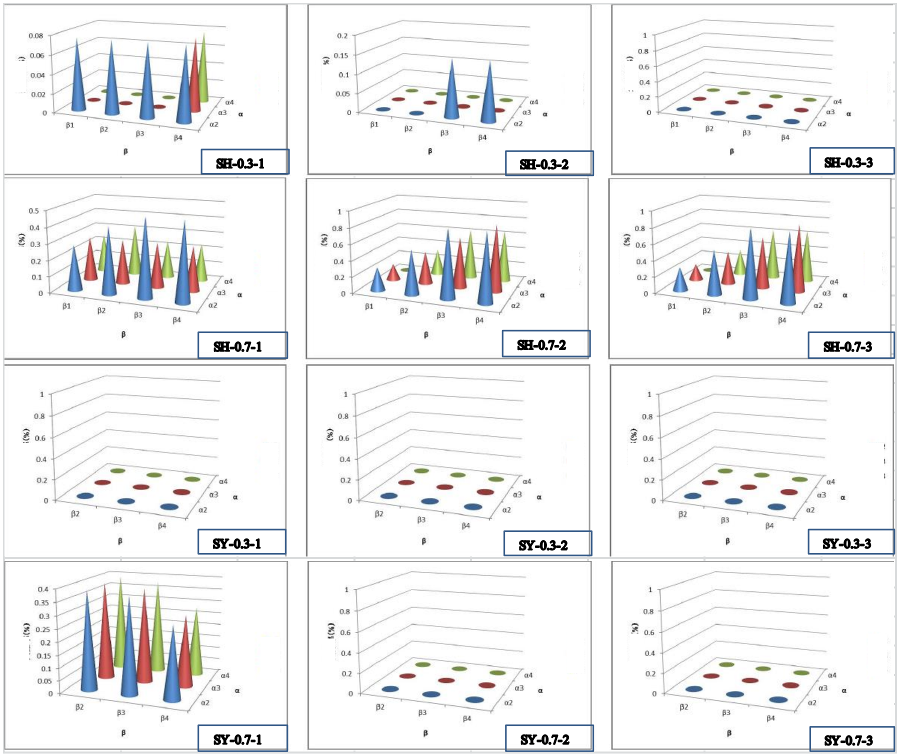


Figure 2-The simulation results on the shortage rate in different cases

In order to compare the shortage rate in these two models, the shortage rate in 1st echelon in these two models were shown as Table 3 with the change rate as 0.7. The results included the shortage rate and the max system inventory reduction in parentheses.

Table 3-The shortage rate (inventory reduction) in 1st echelon in two models

	Information sharing			**Synchronization model**		
	β2	**β3**	**β4**	**β2**	**β3**	**β4**
α2	0.41% (94.56)	0.48% (93.92)	0.48% (91.04)	0.39% (61.99)	0.38% (17.50)	0.29% (-80.99)
α3	0.28% (96.13)	0.28% (94.59)	0.28% (94.56)	0.39% (72.93)	0.38% (26.67)	0.29% (-9.83)
α4	0.23% (96.99)	0.24% (95.94)	0.24% (96.10)	0.39% (78.99)	0.38% (45.00)	0.29% (21.17)

In the information sharing model, a significant inventory reduction can be got at all cases in Table 3. The biggest effect in the inventory reduction, i.e. 96.99%, was generated with the longest cycle time and the shortest lead time. At the same status, the shortage rate was also the lowest. On the other hand, the shortage rate may increase along with the upstream echelons and even be more than 1%. In the synchronization model, the inventory reduction can only be effected by the lead time, but not by the cycle time. If the lead time in different echelons can be cut down, the inventory reduction can be realized. In the synchronization model, the lead time in the upstream echelon is equal to the cycle time in the downstream echelon. Therefore, the WIP stock in each echelon depends on the lead time. Generally, in the 1^{st} echelon, only the safety stock would be kept, but in the other echelon, both the safety stock and the lot-size stock would be kept. There is higher press in the 1^{st} echelon because of higher shortage rate, but the press becomes less in the other echelons.

Discussion and conclusion

In the inventory system in the multi-echelon supply chain, the decoupling stock is increased with the decentralized decision model. In order to reduce the decoupling stock, the most effective approach is make the decision based on the inventory information, the replenishment lead time, the last demand information in the own companies and the downstream partners. With the approach, a high effect in the inventory reduction could be achieved in whatever status of supply chains. This approach requires the upstream partners to promote the information sharing. In practice, how to share the information may be a difficulty. In addition, there is a challenge from shortage. The impact of the change in the last demand on the upstream partner is significant. In order to make a significant inventory reduction in the supply chain, it is necessary to unit all partners in the supply chain and focus on the customer satisfactions improvement.

In the case of no information sharing, a possible approach was suggested as synchronization to reduce the decoupling stock with less information sharing. In this decision model, the downstream echelon makes the decisions on the replenishment cycle time based on replenishment lead time in the upstream echelon. The inventory reduction effect may not be the same as the first approach, but it is possible to get the similar effect with the completed synchronization. This approach requires the downstream partners in the supply chain to promote the improvement. This approach may be easier to be adopted since the support condition is the cooperation from the next upstream partners which is easier to be realized than the conditions in the information sharing approach. However, the synchronization approach has a high requirement on the function of supply chain. With a lower function in supply chain, it would be easier to increase the inventory as shown in the simulation. In the second approach, the change in the last demand may have no impact on the inventory reduction effect in the upstream echelon, but the shortage may be significant in the nearest echelon to customers.

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