A Synchronized Supply Chain for Reducing Decoupling Stock

Jian Wang
Shanghai University, China, jwang@t.shu.edu.cn
Hiroaki Matsukawa
Keio University, Japan, matsukawa@ae.keio.ac.jp
Shane J. Schvaneveldt
Weber State University, U.S.A., schvaneveldt@weber.edu

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 supply chain management. However, it is not easy to make good use of the shared information in practice. For example, a recent survey on information sharing with point of sale (POS) data was conducted in 14 major retail companies in Japan by the Distribution Economics Institute of Japan (DEIJ 2013). Even though all 14 retailers shared POS data with their immediate suppliers, it was found that the data was seldom shared between retailers and manufacturers or between wholesalers and manufacturers. The question of how to share inventory information in supply chains needs further emphasis and examination. Accordingly, in this research, the key factors impacting the effect of information sharing in supply chain are analyzed. It is determined that one key factor is the difference between the replenishment cycle time and the lead time. From this, synchronization is proposed as a new approach for making good use of shared information. Using system dynamics simulation, a comparison is made of the degree of inventory reduction that is achieved through conventional information sharing and the proposed synchronization approaches.

The remainder of this paper is organized as follows. In the second section, the literature on inventory reduction based on information sharing in supply chains is reviewed. The third section describes existing inventory models and the proposed 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 chains has been examined in many studies, including the bullwhip effect in supply chains (Lee, et al. 1997), the value of information in supply chains (Lee. et al. 2000), and decoupling stock (Tsao and Schvaneveldt 2001). In the inventory management systems in multi-echelon supply chains, there may be two, three, four or more echelons (Pan and Nagi 2012; Fu et al. 2014). Three echelon supply chains (manufacturers, wholesalers, retailers) have been examined most often, and this paper also focuses on this type. Another consideration is the structure of the supply chain, i.e. series or arborescent inventory systems. This paper focuses on the series system.

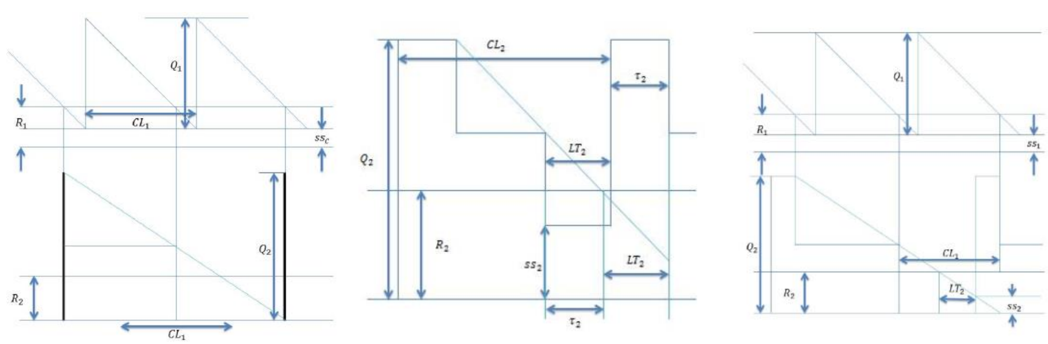
In order to assess the performance of decision-making in inventory systems, there are several important measures including cost, inventory level, lead time reduction, shortage risk, service level, and so forth (e.g. Costantino et al. 2014). Of these measures, inventory level is the focus of this study, and an examination of shortage risk is in progress as an extension of this study. As assumptions, the demand in the echelon nearest to customers has often been regarded as being random with normal distribution (Tsao and Schvaneveldt 2001). Recent studies have considered demand with certain characteristics such as covariance-stationary autoregressive moving average demand (Kovtun et al. 2014; Fu et al. 2014). Regarding analytical methods used, numerical analysis has been widely adopted in inventory system analysis. For random demand, numerical analysis can only show the general tendency and it is difficult to change the scope of examination. In this paper, through simulation analysis based on system dynamical models, it is possible to analyze the effect of more characteristics on inventory reduction in multi-echelon supply chains.

Besides the issues noted above, two other key variables influencing information usage are the stock type and the decision making structure. Three types of stock typically are considered in multi-echelon supply chains, i.e., lot size stock, echelon stock, and decoupling stock. These are defined as follows: 1) Lot size stock - the stock generated by the production or procurement lot size by considering economies of scale; 2) Echelon stock - the sum of the stock at a given stage and the stock passed on to downstream stage(s) (Clark and Scarf 1960); 3) Decoupling stock - “the stock used in a multi-echelon situation to permit the separation of decision making at the different echelons” (Silver et al. 1998). Decoupling stock arises mainly because of information distortion during transferring the demand forecasting information from downstream to upstream in supply chains. The concept of decoupling stock was proposed conceptually by Silver et al (1988), and has been examined quantitatively initially by Tsao and Schvaneveldt (2001) and further developed in the present research.

The decision making structure or model is a second key factor affecting inventory reduction. The decision making model reflects the type of collaboration approach used in the inventory system, and needs to be further examined (Costantino et al. 2014). The two types of decision models that most often have been examined are decentralized decision models (e.g. Lee and Wang 1999; Fu et al. 2014) and centralized decision models (e.g. Tsao and Wakabayashi 2000, Lagodimos and Anderson 1993). The difference between these models can be found in the decision making process, information visibility, safety stock, and so forth. For example, it is better to position the safety stock in the echelon nearest to customers in the centralized decision model (Lagodimos and Anderson 1993); in the decentralized model, every echelon may keep the safety stock in lot size. Adding to these models, this research focuses on a new decision making structure: the synchronized decision model.

Inventory Models

Based on the research of Tsao and Schvaneveldt (2001), inventory management models can be described as in Figure 1, with 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 reorder point (R_1, R_2), replenishment cycle time (CL_1, CL_2), replenishment lead time (LT_1, LT_2), order quantity (Q_1, Q_2), safety stock (SS_1, SS_2), and 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 equations (1)-(3). The safety stock in the decentralized model and the information sharing model are defined as SS^d *and* SS^s as shown in equations (4)-(5).



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

Figure 1-System inventory in three decision models

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

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

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

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

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

The decentralized decision model can be regarded as the reference model for comparison. The amount of decoupling stock arising from lack of centralized decision making is defined as DS_1, which is equal to the difference between I^d and I^c, as shown in equation (6). With regard to information sharing, the amount of decoupling stock arising from lack of information sharing can be defined as DS_2, which is equal to the difference between I^d and I^s, as shown in equation (7). Thus, model C and model S both lead to differing amounts of inventory reductions. This difference in 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 decoupling stock reduction effectiveness (*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 a direct impact on both DS1 and DS2. Consequently, this research proposes a synchronization model and define it as 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 typically is fixed and very difficult to adjust. On the other hand, it is relatively easier to adjust the replenishment cycle time, which may cause the replenishment cost to change. Therefore, synchronization mainly depends on making 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 information from the downstream stages.

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, DSE_1 and DSE_2 can be defined as equation (12-13).

$$DS_1' = \sum_{i=1}^{n} ss_i^{d'} - ss_c = \sum_{i=1}^{n} \left[\frac{k\sqrt{LT_i}\sqrt{LT_i - 1}}{LT_i}\right] \mu LT_i - k\sigma\sqrt{\sum_{i=1}^{n} LT_i} \quad (10)$$

$$DS_2' = \sum_{i=1}^{n-1} (ss_{i+1}^{d'} - SS_{i+1}^{s}) = \sum_{i=1}^{n-1} \left[\frac{k\sqrt{LT_{i+1}}\sqrt{LT_{i+1} - 1}}{LT_{i+1}}\right] \mu LT_{i+1} - k\sigma\sqrt{\sum_{i=1}^{n-1} LT_{i+1}} \quad (11)$$

$$DSE_1 = \frac{DS_1 - DS_1'}{DS_1} = \frac{\sum_{i=1}^{n-1}\left[\mu(CL_i - LT_{i+1}) + SS_{i+1}^{d}\right] - \sum_{i=1}^{n-1} ss_{i+1}^{d'}}{\sum_{i=1}^{n-1}\left[\mu(CL_i - LT_{i+1}) + SS_i^{d}\right] - k\sigma\left(\sqrt{\sum_{i=1}^{n} LT_i} - \sqrt{LT_1}\right)} \quad (12)$$

$$DSE_2 = \frac{DS_2 - DS_2'}{DS_2} = \frac{\sum_{i=1}^{n-1}\left[\mu(CL_i - LT_{i+1}) + SS_{i+1}^{d}\right] - \sum_{i=1}^{n-1} ss_{i+1}^{d'}}{\sum_{i=1}^{n-1}\left[\mu(CL_i - LT_{i+1}) + SS_i^{d}\right] - k\sigma \sum_{i=1}^{n-1} \sqrt{LT_{i+1}}} \quad (13)$$

Based on the above models, several important insights or propositions are obtained for inventory management in supply chains:

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 the replenishment cycle time is reduced, the system inventory may actually increase. Consequently, synchronization is required.

2) Synchronization requires a decrease in the difference between the replenishment lead time in the upstream echelon and the replenishment cycle time in the downstream echelon. Decoupling stock is thus reduced from this synchronization. In addition, further reductions in decoupling stock are possible through reduction in the replenishment lead time.

These propositions are tested and further analyzed through simulation.

Simulation Analysis

In past research, demand has typically been regarded as a fixed value, μ. In practice, the demand may be a random variable over time. In this study, simulation models with Vensim software were constructed to examine the inventory system under conditions of random demand. Three 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), and 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.

Several assumptions are made in the simulation model: 1) orders placed in one echelon arrive in the same echelon; 2) when orders or demand occur (including back orders), inventory decrease; 3) inventory and reorder point are monitored continuously; 4) when inventory falls below the reorder point, a new order is issued to the adjacent upstream echelon; 5) If on-hand inventory is available in the adjacent upstream echelon, shipment will be made to the adjacent downstream echelon, and if no inventory is available, a back order will occur; 6) after the replenishment lead time has passed, the items will arrive at the adjacent downstream echelon. The basic settings in the models are shown in Table 1.

The simulation model was as the data in parameters, i.e., μ (30), σ (9), *CL1* (10), *LT1* (2), *K* (2.33). *CL2* is set as a fixed ratio, α, of *CL1*; *CL3* is set as the same fixed ratio, α, of *CL2*. *LT2* is set as a fixed ratio, β, of *LT1*; and *LT3* is set as the same fixed ratio, β, of *LT2*. The equations for *CL* and *LT* are shown as equations (14)-(15). The parameter α can vary from 2 to 4; β can vary from 1 to 4.

$$CL_i=\alpha * CL_{i-1},\ \ i=2,\ 3,\ \ldots,\ n \tag{14}$$

$$LT_i=\beta * LT_{i-1},\ \ i=1,\ 2,\ 3,\ldots,\ n \tag{15}$$

Table 1- Model Settings

Category	**Condition**	**Value**
Supply chain setting	Number of echelons (1, 2, 3)	3 (factory, wholesaler, retailer)
	Average demand (μ)	30
	Standard deviation of demand (σ)	9
	Replenishment cycle time in echelon 1 (*CL1*)	6
	Replenishment cycle time in echelon 2 (*CL2*)	12
	Replenishment cycle time in echelon 3 (*CL3*)	24
	Fixed ratio between CL (α)	α
	Replenishment lead time in echelon 1 (*LT1*)	2
	Replenishment lead time in echelon 2 (*LT2*)	4
	Replenishment lead time in echelon 3 (*LT3*)	8
	Fixed ratio between LT (β)	β
	Safety coefficient (*SS* coefficient)	2.33
Demand setting	End demand	Normal distribution
	Negative demand	Delete
	Starting inventory in each echelon	2 times of order quantity
	Fractional unit of demand	Delete
Simulation setting	Test period (number of periods)	1440
	Warmup period (number of periods)	240
	Test runs (number of runs)	10

Inventory Reduction with Synchronization

The validity of the models was examined with different parameter values and showed acceptable results. The simulation results of inventory reduction through information sharing and synchronization are reported and compared in Table 2.

In the information sharing approach, greater changes in customer demand lead to more limited results for inventory reduction. The maximum effect can be always found with the longest replenishment cycle time and the shortest replenishment lead time.

In the synchronization approach, the maximum effect may be increased by 2% when changes in the most recent demand become greater, but the minimum effect is lower. This can be explained with equations (10) and (11). In equation (10), the effect of DS_1 becomes larger with larger σ. However, comparing the effect of the difference between *CT* and *LT* with the effect of σ, the former one is much larger. Similar results are found for *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

Discussion and Conclusion

In inventory systems for multi-echelon supply chains, decoupling stock is increased for the decentralized decision model. In order to reduce the decoupling stock, the most effective approach is make decisions based on the inventory information, the replenishment lead time, and the most recent demand information in one’s own company and downstream partners. With this approach, a significant inventory reduction can be achieved in whatever status of supply chain. This approach requires the upstream partners to promote information sharing. In practice, however, sharing information may be difficult to realize. Also, the impact of changes in recent demand on the upstream partner is considerable. In order to make a significant inventory reduction in the supply chain, it is necessary to align all partners in the supply chain and focus on customer satisfaction improvement.

Faced with the practical difficulties of information sharing, synchronization is proposed as a possible approach for reducing decoupling stock with less need for information sharing. In the synchronization decision model, the downstream echelon makes the decisions on the replenishment cycle time based on the replenishment lead time in the upstream echelon. While the inventory reduction effect may not be the same as with the information sharing approach, it is possible with complete synchronization to obtain nearly as great of reductions. This approach requires the downstream partners in the supply chain to lead the change. This approach may be easier to adopt since the degree of cooperation needed from the adjacent upstream partners is more limited than that required in the information sharing approach. However, the synchronization approach requires a high-performing supply chain. In the synchronization approach, the change in the last demand may have no impact on the inventory reduction effect in the upstream echelon.

Another important issue to consider is the effects on shortage rate with the synchronization approach. Research on this issue is in progress. The preliminary results indicate that the effect on shortage rate in the synchronization model may be visible only in some echelons of the supply chain. This is different from the tradeoff relationship between inventory reduction and shortage rate reduction that exists in the information sharing model.

References

Clark, A. J. and Scarf, H. 1960. Optimal Policies for Multi-echelon Inventory Problem, *Management Science*, **6**(4): 475-490.

Costantino, F., Gravio, G.D., Shaban, A., Tronci, M. 2014. The impact of information sharing and inventory control coordination on supply chain performances. *Computers & Industrial Engineering*, **76**: 292-306.

DEIJ 2013. A study on the current status and research topics on information sharing among production, delivery and sale, In: *Working group report on information sharing for improving the efficient of supply chain*. Distribution Economics Institute of Japan. (in Japanese)

Fu, D., Ionescu, C.M., Aghezzaf, E., Keyser, R. D. 2014. Decentralized and centralized model predictive control to reduce the bullwhip effect in supply chain management. *Computers & Industrial Engineering*, **73**: 21-31.

Genno, H. 2012. Proposal of a framework for analysis of supply chain management. *Kokusai Kenkyu Rongi*, **25**(2):65-85 (in Japanese).

Kovtun, V., Giloni, A., Hurvich, C. 2014. Assessing the Value of Demand Sharing in Supply Chains, *Naval Research Logistics*, **61**:515-531.

Lagodimos, A.G. and Anderson, E. J. 1993. Optimal Positioning of Safety Stocks in MRP. *International Journal of Production Research*, **31**(8): 1797-1813.

Lee, H., Padmanabhan, V., Whang, S. 1997. Information distortion in a supply chain: The bullwhip effect. *Management Science*, **43**:546-558.

Lee, H., So KutC. Tang, Christopher S. 2000. The value of information sharing in a two-level supply chain. *Management Science*, **46**: 626-643.

Lee, H. and Whang, S. 1999. Decentralized Multi-Echelon Supply Chains: Incentives and Information. *Management Science*, **45**(5): 633-640.

Pan, F., Nagi, R. 2013. Multi-echelon supply chain network design in agile manufacturing. *Omega*, **41**: 969–983.

Peterson, R. and Silver, E.A. 1985. *Decision Systems for Inventory Management and Production Planning*, 2nd Ed., pp. 60, 482, John Wiley & Sons, New York

Silver, E. A., Pyke, D. F. and Peterson, R. 1998. *Inventory Management and Production Planning and Scheduling*, John Wiley & Sons, pp.31, 471-531.

Tsao, D. B. and Schvaneveldt,S. J. 2001. A study on decoupling stock in a multiple stage inventory system. *Journal of Japan Industrial Management Association*, **52**(2): 125-132 (in Japanese).

Tsao, D.B. and Wakabayashi, K. (2000) A study on the effect of information sharing in the arborescent inventory system. *Journal of Japan Society for Management Information*, **8**(4):67-76 (in Japanese).