Research on lead-time reduction of two-stage supply chain based on Stackelberg game

Hao-ran Shi[1, 3], Kejian Liu[2]*

[1]*School of Energy and Environment, Xihua University, 610039, Chengdu, P.R.China*

[2]*School of Mathematics and Computer Engineering Xihua University, 610039 Chengdu, P.R.China*

[3]*School of Transportation and Logistics, Southwest Jiaotong University, 610031, Chengdu, P. R. China*

Received 12 June, 2014, www.tsi.lv

Abstract

In the two-stage supply chain, under the model of lead time reduction management cost shared by upstream and downstream based on Stackelberg Game, when suppliers have the priority of decision right rather than retailers, it is more advantageous to reduce the cost and the lead time and can reach the maximum profit for the whole supply chain.

Keywords: Supply chain, Lead time, Decision order, Cost sharing

1 Introduction

Lead time refers to the interval from ordering to receiving goods in the downstream delivered by suppliers in the upstream. This is also called inventory replenishment lead time. Those in the downstream hope suppliers to reduce the lead time so as to reduce inventory and cost. To reduce the lead time, suppliers usually needs some extra investment, for example, buy new equipment, improve or set up new information system or upgrade inventory equipment. However, many enterprises can't afford such a huge investment and have to shift the cost to those in the downstream. When the cost is on buyers in the downstream, some suppliers take it for granted that buyers should shoulder all cost for reducing the lead time. If buyers are willing to do so, then they are granted with the right to reduce the lead time and decide the length of it.

When suppliers decide the length of inventory lead time, there are usually two decision orders: one is that retailers decide how many goods to order and inform it of suppliers, and leave it to suppliers to decide the length of the lead time; the other is that suppliers decide the time of arrival and retailers decide when to order and how many to order based on the delivery situation.

Suppliers are facing the following questions: when to decide the lead time, before retailers' order or after? What is the best lead time for ordering so as to reduce the cost as much as possible? What will be the influence on the cost if the decision order between the upstream and the downstream is exchanged?

2 Literature review

Many researchers have focused on the importance of reducing the lead time from several perspectives. Perry, M. Ben-Daya and Zhang describe the random and swift response model [1-3].

Swift response model is necessary when orders are given at the same time [4]. In two recent articles, some researchers propose an effective qualitative model for the supply chain [5-7]. Many researches study the ordering lead time decision [8-11]. They suppose that those in the downstream decide the ordering lead time and shoulder the cost for reducing the lead time. Moreover, researchers also study the lead time decision made by retailers for the maximum profit. However, although suppliers have shifted the cost for reducing the lead time to retailers, it doesn't mean that cost of suppliers is free from the influence of retailers' decision on ordering. It is because under the condition that suppliers have the priority to decide the length of the lead time, the cost for reducing it will be affected by the cost of ordering and further, the quantity of ordering which may lead to a drop of profit for suppliers. Thus, suppliers do not favour such strategy. To move a step further, if retailers cannot afford the cost alone, they will give up reducing the lead time.

3 Model description and establishment

3.1 STACKELBERG GAME MODEL

Suppose there are two producers who take the turn to decide the production in a two-stage Stackelberg Game. In the first stage, producer 1 as the leader takes the priority to plan for the production. In the second stage,

**Corresponding author* e-mail: liukejian@gmail.com

producer 2 as the follower plans for the production under the principle of obtaining the maximum profit after learning about the yield level of the leader. Suppose the marginal costs of two producers are the same, $c_1 = c_2 = c$, the market demand function is $D = a-(q_1+q_2)$, in which $a>0$, a is a constant. q_i is the production of producer i, $i=1,2$. This function is known by two producers.

By the backward induction, we consider the second stage first. Suppose the production of producer 1 is q_1, the optimal production $\overset{s}{q}_1$ of producer 2 is: $\overset{s}{q}_1 \in \arg gMax_{q_2}\{\pi_2(q_1,q_2)=[a-(q_1+q_2)-c]q_2\}$

Based on the first order condition, we can get the optimal reaction function for producer 2: $q_2 = R_2(q_1) = \dfrac{a-q_1-c}{2}$

Then, we consider the first stage and predict the reaction function for producer 2 $q_2 = R_2(q_1) = \dfrac{a-q_1-c}{2}$.

The optimal production $\overset{s}{q}_1$ of producer 1 is

$$\overset{s}{q}_1 \in \arg gMax_{q_2}\{\pi_2(q_1,q_2)=[a-(q_1+R_2(q_1))-c]q_1$$
$$=[a-(q_1+\frac{a-q_1-c}{2})-c]q_1$$

By the first order condition, we can get the optimal production $\overset{s}{q}_1 = \dfrac{a-c}{2}$ of producer 1. So, $\overset{s}{q}_2 = R_2(\overset{s}{q}_1) = \dfrac{a-\overset{s}{q}_1-c}{2} = \dfrac{a-c}{4}$. Thus, the result of Stackelberg Game is $\overset{s}{q} = \overset{s}{q}_1 + \overset{s}{q}_2 = \dfrac{3(a-c)}{4}; D^s = a-\overset{s}{q} = \dfrac{a+3c}{4}$. The profits of two producers are: $\begin{cases}\pi_1^s = (D^s-c)\overset{s}{q}_1 = \dfrac{(a-c)^2}{8} \\ \pi_2^s = (D^s-c)\overset{s}{q}_2 = \dfrac{(a-c)^2}{16}\end{cases}$.

However, in actual economic activities, producers cannot know exactly about the market demand function but only estimate it. Nevertheless, such estimation varies from person to person. Here we suppose that every producer takes it for granted that the estimation of his counterparts is the same as his.

Suppose the market demand function estimated by producer 1 is $D = a_1-(q_1+q_2)$, and that he thinks producer 2 estimates the same.

The market demand function estimated by producer 2 is $D = a_2-(q_1+q_2)$, and that he thinks producer 1 estimates the same. Here $a_i, i=1,2$, which are above 0.

Under such circumstances, we divide the Stackelberg Game Model into two stages as the conventional way. And apply it to backward induction method. First we consider the second stage, set the production of producer 1 is q_1, as producer 2 thinks the market demand function to be $D = a_2-(q_1+q_2)$. If producer 2 produces q_2, producer 2 thinks that his profit is expected to be $\pi_2(q_1,q_2) = [a_2-(q_1+q_2)-c]q_2$, from the first order condition, we can get the optimal reaction function of producer 2 is $q_2 = R_2(q_1) = \dfrac{a_2-q_1-c}{2}$.

Let's be back to the first stage, as producer 1 estimates the market demand function is $D = a_1-(q_1+q_2)$, and thinks that the production of producer 2 will be q_2 in the second stage, then the profit is $\pi_2(q_1,q_2) = [a_1-(q_1+q_2)-c]q_2$. From the first order condition, we can get the optimal reaction function of producer 2 estimated by producer 1: $q_2 = R_2(q_1) = \dfrac{a_2-q_1-c}{2}$. In this case, producer 1 thinks his profit is $\pi_1(q_1,q_2) = [a_1-(q_1+R_2(q_1))-c]q_1$. From the first order condition, producer 1 thinks that his optimal production is $q_1 = \dfrac{a_1-c}{2}$, in which q1=a1-c2. $q_2 = R_2(q_1) = \dfrac{a_2-q_1-c}{2}$.

Let's be back to the second stage. As the production of producer 1 is, producer 2 thinks that his optimal reaction function is:

Thus, producer 2 thinks that his optimal production is: $q_2 = \dfrac{a_2-q_1-c}{2} = \dfrac{2q_2-a_1-c}{2}$

The actual market demand function is $D = a-(q_1+q_2)$, so the market price will be: $p = a-(q_1+q_2) = a-[\frac{q_1-c}{2}+\frac{2a_2-a_1-c}{4}] = \frac{4a-a_1-2a_2+3c}{4}$.

Therefore, the profits of two producers are:

$$\begin{cases}\pi_1 = (D-c)q_1 = \dfrac{(q_1-c)(4a-a_1-2a_2-c)}{8} \\ \pi_2 = (D-c)q_2 = \dfrac{(2a_2-a_1-c)(4a-a_1-2a_2-c)}{16}\end{cases}.$$

3.2 INVENTORY MODEL BASED ON (Q,r) STRATEGY

(Q,r) inventory strategy is a common inventory management strategy, in which the warehouse manager checks the inventory with continuity. When the existing inventory drops to the replenishment point r, the manger will order Q goods from suppliers in the upstream.

Those goods will arrive after the lead time L. The variation of inventory under (Q,r) strategy is shown in Figure 1.

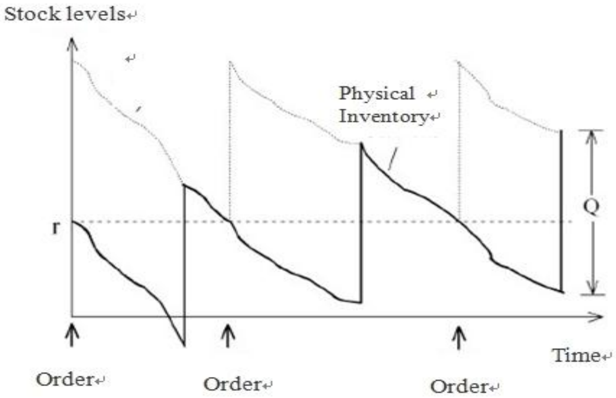

FIGURE 1 The variation of inventory

Here we discuss the replenishment cost with fixed lead time. D^L is the aggregate demand during the lead time, then function $G(y)$ is expressed as: $G(y)=E[h(y-D^L)^+ + g(D^L-y)^+]$

D is the demand per unit time. It is a random variable. λ refers to the demand rate of market; R refers to fixed ordering cost; g / (piece·per unit time) refers to replenishment cost; h / (piece·per unit time) refers to holding cost; the replenishment lead time is L. λ, R, g, h, L are all constants.

When the demand is reached in the way that the demand grows stably and randomly and keeps such growth, under such condition, if inventory y is subject to the even distribution of $(r, r+Q]$ (when the demand is discrete, y is subject to the even distribution of $\{r, r+1,\cdots,r+Q\}$)

When the demand is a continuous variable, the average cost per unit time is expressed as: $C(Q,r)=\dfrac{R\lambda+\int_r^{r+Q}G(y)dy}{Q}$.

When the demand is a discrete variable, the average cost per unit time is expressed as: $C(Q,r)=\dfrac{R\lambda+\sum_r^{r+Q}G(y)}{Q}$.

3.3 MODEL ESTABLISHMENT

We have studied the two-stage supply chain consisting of suppliers and retailers with single product. The ordering lead time L refers to the interval between ordering and receiving. It can be divided into n separated parts. Part i has the minimum interval a_i and the standard time b_j. If $L_o=\sum_{j=1}^{n}b_j$ is used to express the initial ordering lead time of the supply chain, L_i is to express the minimum length of ordering lead time of part $1,2,\ldots,i$, then there is:

$$L_i=\sum_{j=1}^{i}a_j+\sum_{j=i+1}^{n}b_j=\sum_{j=1}^{i}a_j+\sum_{j=i}^{n}b_j-\sum_{j=1}^{i}b_j=\sum_{j=i}^{n}b_j-\sum_{j=1}^{i}(b_j+a_j)$$
$$=L_o-\sum_{j=1}^{i}(b_j+a_j) \quad (1)$$

The ordering lead time L can be shortened by adding some cost. Therefore, it is controllable. Suppose the cost for reducing a unit time for part i is C_i, and $c_1\le c_2\le\cdots\le c_n$ refers to the cost of the ordering lead time as well as the cost for reducing the ordering lead time. Then, there is:

$$K(L)=c_i(L_{i-1}-L)+\sum_{j=1}^{n}C_j(b_j-a_j), L\in(L_i,L_{i-1}), \quad (2)$$

$$K(L_0)=0, K(L_n)=\sum_{j=1}^{n}C_j(b_j-a_j). \quad (3)$$

The cost of suppliers and retailers and the cost of ordering constitute the cost of inventory. The cost of ordering and that of the lead time management are shouldered by suppliers. The aggregate ordering cost per unit time is $\prod_m(L,Q)$. There is:

$$\prod_m(L,Q)=\frac{D}{Q}C_m+\frac{Q}{2}P_m h+\theta\frac{D}{Q}K(L). \quad (4)$$

D is the average demand per unit time; Q is the quantity of orders; h is the inventory holding cost rate; C_m is the cost of a single supplier; p is the purchasing price of the supplier; θ is the ratio of cost for reducing the ordering lead time shouldered by suppliers. Given that (Q,r) strategy is very common in researches and actual situations, this paper also employs this strategy as the inventory strategy. Suppose retailers are faced with the natural distribution of demand during the lead time, averaging LD and the standard variation to be $\sigma\sqrt{L}$. Then we can know the average inventory level per unit time is $I_p\cong\frac{Q}{2}+K\sigma\sqrt{L}$. K is the inventory security coefficient. The ordering cost of suppliers consists of average inventory cost, ordering cost, and the lead time management cost. The aggregate ordering cost per unit time is $\prod_m(L,Q)$. Then there is:

$$\prod_r(L,Q)=\frac{D}{Q}C_r+(\frac{Q}{2}+K\sigma\sqrt{L})P_r h+(1-\theta)\frac{D}{Q}K(L). \quad (5)$$

C_r is the ordering cost of a single retailer. P_r is the purchasing price of retailers. $(1-\theta)$ is the ratio of cost for reducing the lead time shouldered by retailers.

Usually, the ordering process is that the upstream decides the arrival time of goods and the downstream decides the quantity of goods. This paper compares two cases: one is that the upstream decides the ordering lead time first, the other is retailers decide the quantity of goods first.

4 Comparison of different decision orders

Usually, the ordering process is that the upstream decides the arrival time of goods and the downstream decides the quantity of goods. This paper compares two case: one is that the upstream decides the ordering lead time first, the other is retailers decide the quantity of goods first.

4.1 THE OPTIMAL MODEL OF SUPPLIERS' PRIORITY DECISION

Suppose suppliers are equipped with relevant information of retailers, such as the ordering cost and inventory cost. Suppliers have the priority to decide the ordering lead time and then leave it to retailers to decide the quantity of ordering. Obviously, in this Stackelberg Game, suppliers stand as leaders while retailers as the followers.

First, we consider the optimal ordering quantity of retailers under the condition that the ordering lead time L is given. The optimal decision mode of retailers is:

$$\min \prod_r (L,Q) = \frac{D}{Q}C_r + (\frac{Q}{2} + K\sigma\sqrt{L})P_r h + (1-\theta)\frac{D}{Q}K(L) . \quad (6)$$

Calculate the derivatives of Q in the cost function and equal it to 0.

$$\frac{d\prod_r (L,Q)}{dQ} = \frac{D}{Q^2}[C_r + (1-\theta)\frac{D}{Q}K(L)] + \frac{P_r h}{2} = 0 , \quad (7)$$

$$\frac{d^2\prod_r (L,Q)}{dQ^2} = \frac{dD}{Q^3}[C_r + (1-\theta)K(L)] = 0 . \quad (8)$$

As $L \in (L_i, L_{i-1})$, $\prod_r (L,Q)$ is the concave function about Q, then the optimal quantity is:

$$Q^* = \sqrt{\frac{2D[C_r + (1-\theta)K(L)]}{P_r h}}, L \in (L_i, L_{i-1}), \quad (9)$$

$$\frac{dQ^*}{dL} = -(1-\theta)\frac{DC_i}{P_r h}\{\sqrt{\frac{2D[C_r + (1-\theta)K(L)]}{P_r h}}\} = -(1-\theta)\frac{DC_i}{P_r h Q^*} . \quad (10)$$

Thus, $\frac{dQ^*}{dL} < 0$. The ordering quantity of retailers will increase along with the reduction of the lead time. When suppliers can predict the quantity decided by retailers based on formula (9), there is:

$$\min \prod_m (L,Q) = \frac{D}{Q}C_m + \frac{Q}{2}P_m h + \theta\frac{D}{Q^*}K(L) . \quad (11)$$

For each (L_i, L_{i-1}), we can get the derivatives of $\prod_m (L,Q^*)$ to L.

$$\frac{d\prod_m (L,Q)}{dL} = -\frac{D}{Q^{*2}}[C_m + \theta K(L)]\frac{dQ^*}{dL} - \frac{DC_i}{Q^*}\theta + \frac{P_m h}{2}\frac{dQ^*}{dL} . \quad (12)$$

Substitute (9) to (12) and get:

$$\frac{d\prod_m (L,Q)}{dL} = \{-\frac{C_m + \theta K(L)p_r h}{2[C_r + (1-\theta)K(L)]} + \frac{\theta P_r}{1-\theta} + \frac{P_m h}{2}\}\frac{dQ^*}{dL} . \quad (13)$$

Because $\frac{d\prod_m (L,Q^*)}{dL} = 0$, it is easy to get:

$$\frac{C_m + \theta K(L)}{C_r + (1-\theta)K(L)} = \frac{2\theta}{1-\theta} + \frac{P_m}{P_r} . \quad (14)$$

When $K(L) > 0$, we can get:

$$\frac{d\prod_m (L,Q^*)}{dL}|L = L_t = -\frac{p_r C_i[(1-\theta)C_m - \theta C_r]}{2[C_r + (1-\theta)K(L)]^w}\frac{dQ^*}{dL} > 0 . \quad (15)$$

Thus, when $K(L_t) \in [0, K(L_n)]$, the optimal ordering lead time of suppliers is $L^* = L_t$. If $K(L_t) > K(L_n)$, then $L^* = L_n$; If $K(L_t) < 0$, then, $L^* = L_0$. Thus the optimal ordering quantity is $Q^* = \sqrt{\frac{2D[C_r + (1-\theta)K(L)]}{P_r h}}, L \in (L_i, L_{i-1})$. L^* and Q^* are the equilibrium of the Stackelberg Game with suppliers as leaders. Compare this result and the original ordering lead time and quantity, there is: $\prod_m (L^*, Q^*) \le \prod_m (L_0, Q_0)$.

4.2 THE OPTIMAL MODEL OF RETAILERS' DECISION PRIORITY

Suppose retailers first decide the ordering quantity and leave it to suppliers to decide the ordering lead time. Obviously, such decision order is featured by retailers' decision priority in the Stackelberg Game.

First we assume that suppliers make the decision of the ordering lead time after they know about the ordering quantity Q. For them, there is the following model:

$$\min \prod_m (L,Q) = \frac{D}{Q} C_m + \frac{Q}{2} P_m h + \theta \frac{D}{Q} K(L) , \quad (16)$$

$$\frac{d \prod_m (L,Q)}{dL} = -\frac{DC_i}{Q} \theta < 0 . \quad (17)$$

Thus, in this case, the optimal ordering lead time is L_0 and $K(L_0) = 0$. When retailers predict that the ordering lead time is L_0 and when $L \in (L_i, L_{i-1})$, $\prod_r (L,Q)$ is the concave function about Q. the optimal ordering quantity of retailers is:

$$Q_0 = \sqrt{\frac{2DC_r}{p_r h}} . \quad (18)$$

L_0 and Q_0 are the equilibrium of the Stackelberg Game with retailers as leaders. Whatever the ordering quantity is, for suppliers, the ordering lead time is L_0. Retailers' decision does not affect the lead time.

Comparing the situations in which suppliers and retailers serve as leaders respectively. When suppliers are leaders, the ordering lead time L^* is smaller or equals to that when retailers are leaders. Thus, in the supply chain, suppliers' priority of decision helps reduce the ordering lead time. In the Stackelberg Game, suppliers have the right of priority of decision and the arrival time is: $\prod_m (L^*, Q*) \le \prod_m (L_0, Q_0)$. Compare to the situation in which retailers decide the ordering quantity first and suppliers decide the lead time later, suppliers are more willing to take the initiative to decide the length of the lead time and then leave it to retailers to decide the ordering quantity.

However, are retailers willing to decide the ordering quantity after suppliers' decision of the lead time? Suppose $\Delta\Pi$ is to express the optimal cost respectively when suppliers and retailers serve as leaders, there is:

$$\begin{aligned} \Delta\Pi &= \Pi_m (L^*, Q^*) - \Pi_m (L_0, Q_0) \\ &= (\frac{D}{Q^*} - \frac{D}{Q^0}) C_r + (\frac{Q^*}{2} - \frac{Q^0}{2}) p_r h \\ &+ (\sqrt{L^*} - \sqrt{L_0}) p_r hk\sigma + \frac{R}{Q^*}(1-\theta) K(L^*) \\ &= (Q^* - Q^0) p_r h + (\sqrt{L^*} - \sqrt{L_0}) p_r hk \end{aligned} , \quad (19)$$

$$\begin{cases} \dfrac{d\Delta\Pi}{dL_0} = -\dfrac{1}{2} L_0^{\frac{1}{2}} p_r hk\sigma < 0 \\ \dfrac{d\Delta\Pi}{dL_0} = (\sqrt{L^*} - \sqrt{L_0}) p_r hk < 0, L^* \ne L_{0r} \\ \dfrac{d\Delta\Pi}{dk} = (\sqrt{L^*} - \sqrt{L_0}) p_r hk\sigma < 0, L^* \ne L_0 \end{cases} . \quad (20)$$

With the increase of the standard deviation R of customer demand, the cost difference G of retailers of the original security coefficient k and the arrival time L0 will decrease for sure, no matter who is the leader. The fluctuation of the demand is more significant to retailers when suppliers take the priority to decide the lead time. Whether willing or not, under the original condition, the decision of suppliers will affect the fluctuation of customer demand, the service of retailers and the arrival time.

5 Data analysis

We calculate the aggregate ordering cost $\prod_m (L^*, Q*)$ and $\prod_m (L_0, Q_0)$ under two different cost ratio θ, and conclude that the cost of ordering lead time decided by suppliers first is smaller than or equals to the cost of ordering quantity decided by retailers. Thus, suppliers wish to take the priority to replenish the inventory.

With the increase of the standard deviation of customer demand faced by retailers, or to say, the uncertainty of the demand, the cost difference varies between the priority of decision of suppliers and retailers. This indicates that when the demand fluctuates, retailers are more willing to let suppliers decide the ordering lead time first. If the fluctuation is small, then it may not favour the retailers in that the cost function $\prod_r (L^*, Q^*)$ is bigger than the static Game cost function $\prod_r (L_0, Q_0)$ when retailers are exposed to full information.

When the cost sharing ratio θ is given, the cost of suppliers' priority of decision is smaller than or equals to that of suppliers' following decision. That is to say, suppliers are prone to take the priority to decide the lead time.

Under different cost ratio θ, we calculate the cost of suppliers, the cost of customers in the downstream, the aggregate cost of the supply chain and the cost of the optimal lead time. The results show than when the cost sharing ratio is $\theta = 0.3$, the cost of suppliers, the cost of customers in the downstream and the aggregate cost of the supply chain are smaller than that shouldered by retailers for reducing the lead time. This indicates that when the sharing cost is given, leaving suppliers to take the priority of decision and shoulder some cost for reducing the lead time is advantageous both to supplier and retailers. Suppliers can choose a proper ratio to decide the cost of the lead time and the operation.

6 Conclusion

This paper considers the cost sharing for reducing the lead time. It studies the decision order of the ordering lead time which is common but overlooked. Under the Stackelberg Game Model, suppliers take the initiative to decide the lead time and retailers, the quantity of goods. This paper analyses the ordering order in which retailers decide the quantity of goods after suppliers decide the lead time. It points out that this way helps to reduce the lead time in the two-stage supply chain as well as the cost of suppliers. If the demand is uncertain, then suppliers' priority of decision on the lead time is advantageous to themselves, retailers and even to the whole supply chain. This paper provides a new idea to supply chain management.

Acknowledgments

The paper was supported by National Natural Science Foundation of China (61271413) and Academic Cultivation Project of Key Laboratory of Fluid and Power Machinery Engineering, Xihua University (Grant No. SBZDPY-11-10).

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Authors

Hao ran Shi, born on November 1, 1973, Da Zhou country, Si Chuan Province, China

Current position, grades: Xihua University, Master
University studies: Logistics Engineering
Professional interests: Operational Research

Kejian Liu, born on June 1, 1974, Hubei, China

Current position, grades: associate professor
University studies: Xihua University
Scientific interest: Computer Network, Database and Information System.