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Closed loop supply chain: The impact of advance notice and lead-times

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Abstract
This research investigates the impact of advance notice of the product returns on the performance of a closed loop supply chain when lead-times exist. Our closed loop supply chain consists of a manufacturer and an external remanufacturer. The market demand and the product return are stochastic and correlated with each other. A proportion of the sold products in the market are returned to an external remanufacturer. After a predetermined time period, the used products are converted into "good-as-new" products to be used to meet the market demand, together with the newly manufactured products. We quantify the benefit of the manufacturer obtaining advance notice of product returns from the remanufacturer. Furthermore, we demonstrate that the (re)manufacturing lead-times and some parameters in the product return rate can have a significant impact on the manufacturer's performance.

Keywords: closed loop supply chain, information sharing, lead-times

Introduction
Closed loop supply chains have been attracted a lot of research attention recently, due to the growth of the concern with environmental issues (see, Akçalı and Çetinkaya, 2011, for example). At the same time, the complexity of a closed loop supply chain is generally acknowledged to increase as not only the demand but also the product returns need to be considered when planning the production and distribution activities needed to maintain inventory levels. This research investigates the economic impact of the advance notice from the remanufacturer of the product return rate on the performance of a closed loop supply chain when lead-times exist. The importance of considering lead-times (or, delays) in a system is well recognized (see, Forrester, 1961, for example), when investigating dynamics of supply chains. However, there are only a few contributions that consider the impact of the lead-times explicitly in a closed loop supply chain. Similarly,

even though the importance of the value of information sharing in multi-level supply chains is well recognized (see, Lee et al., 2000, for example), not much literature addresses this issue in the field of a closed loop supply chain. Using stochastic modeling techniques, this research investigates impact of both the advance notice and the (re)manufacturing lead-times on the economic performance in a closed loop supply chain. A closed loop supply chain used herein consists of a manufacturer and an external remanufacturer. The market demand and the product return are stochastic and correlated with each other. A proportion of the sold products in the market are returned to an external remanufacturer. After a predetermined time period, the used products are converted into as-good-as-new products that are used to meet the market demand, together with newly manufactured products. In such a case, to reduce uncertainty in its supply chain, the manufacturer may want to consider not only the forecast of the market demand rate but also the product return rate that is already known to the external remanufacturer. We show how such notice can be exploited to lower the production and the inventory costs of the manufacturer. Furthermore, we demonstrate that the remanufacturing and the manufacturing lead-times and the correlation between demand and returns can have a significant impact on the manufacturer's economic performance.

Literature review

The complexity of closed loop supply chains provides a rich model to study. Minner and Kleber (2001) establish a deterministic single echelon closed loop supply chain without lead-times and then apply an optimal control theory approach to find a solution which minimises a linear cost function. Kiesmüller (2003) considers a similar situation to Minner and Kleber but incorporates lead-times into the model. It is shown that the model structure depends on the relative length of the manufacturing and remanufacturing lead-times. Using some approximations when it is necessary, Ketzenberg et al. (2006) develop analytical models to quantify the inventory cost reduction benefit in a closed loop supply chain. In their model, the benefit comes from sharing information of the market demand, the return rate, and the yield. Two analytical models are developed: a one period model and a multi-period model. The demand and the return rates are stochastic processes, and the return in one time period is correlated with the demand in the previous time period. Shi et al. (2011) consider a closed loop supply chain with multiple products using a stochastic modeling technique. In their model, uncertainty lies in the market demand and in the product return. Lagrangian relaxation is used to obtain solutions. It is shown that their model and solution approach can provide near optimal solution within a reasonable time. Kenné et al. (2012) propose a hybrid manufacturing/remanufacturing model for a closed loop supply chain network. Stochastic dynamic programming techniques are used to establish the model. In their model, the manufacturing and the remanufacturing systems are subject to random failures and repairs. A near optimal control policy is obtained using numerical methods. Using an analytical model, the game theory perspective and the newsvendor approach, Chen and Chang (2012) investigate the strategy for an original equipment manufacturer (OEM) in a closed loop supply chain consisting of an OEM and a third-party independent operator. It is concluded that for the OEM the competitive strategy could be better than the cooperative strategy under a specific conditions. van der Laan et al. (1999) consider the complexities of closed supply chains using a continuous review inventory system. A push control strategy and a pull control strategy are analyzed and compared with a traditional supply chain without remanufacturing. It shows that a pull control system results in the lower cost, thanks to the lower inventory cost. They conclude that the system-wide cost can increase as the result of involving remanufacturing process in the system. Adenso-Díaz et al. (2012) develop a supply chain simulation tool (called *the Cider Game* in their paper) based on the well-known Beer Game, in order to analyze the bullwhip effect in a closed loop supply chain. It is shown that many factors which are known as major sources of generating the bullwhip in a traditional supply chain also act as the sources of the bullwhip in a closed loop supply chain as well. A counter intuitive finding is that remanufacturing capacity and the delay time between consumption and return do not have significant influence on the level of bullwhip reduction.

In closed loop supply chains, as in traditional supply chains without returns, the importance of the value of information sharing is well recognized and investigated by many researchers. Assuming a capacitated closed loop supply chain, Ketzenberg (2009) analyses the value of information of the demand, the return, the recovery yield and the capacity utilization. The cost benefits are quantified through using heuristics and a simulation study. It is shown that information on capacity utilization can bring about the largest average benefit, though no type of information is dominant. Using a remanufacturing process, Ferrer and Ketzenberg (2004) consider the case where remanufacturing yield information is shared with an assembly line using Markov decision process. A value coming from shorter supplier's lead-time is also investigated. The product return and the remanufacturing lead-time are not considered, however. It is concluded that sharing of the yield information can bring the benefit. de Brito and van der Laan (2009) investigate the impact of imperfect information on forecast of lead-time demand under remanufacturing setting. Inventory cost is used to quantify the impact. Based on the result of analysis of four different forecasting methods, it is concluded that the most informed method is not always the lowest cost. Flapper et al. (2012) consider the benefit of having imperfect advance return information for inventory cost using a Markov decision formulation. They conclude that advance return information can reduce the inventory cost by 5% at most.

There are quite few researches considering the impact of (re)manufacturing lead-times on the performance of a closed supply chain, however. Assuming that both manufacturing and remanufacturing lead-times are stochastic, van der Laan et al. (1999) investigates the impact of lead-times on a closed loop supply chain using numerical studies. Poisson distributions are used to represent demand and return processes. To quantify the impact, inventory cost and manufacturing and remanufacturing costs are employed. One of interesting findings is that the longer remanufacturing lead-time could result in cost decrease, even though the longer manufacturing lead-time always results in cost increase. Using the continuous control theory approach, Li and Disney (2006) analyze a closed loop supply chain from the point of Bullwhip and inventory variance amplification. They quantify the impact of manufacturing and remanufacturing lead-times by comparing with traditional supply chain without returns. It is shown that shorter remanufacturing lead-time is preferable to ensure lower inventory variance.

Our research consider impact of both the value of advance notice and (re)manufacturing lead-times on the closed loop supply chain cost, assuming the demand and the return are stochastic and correlated each other. To the best of our knowledge,

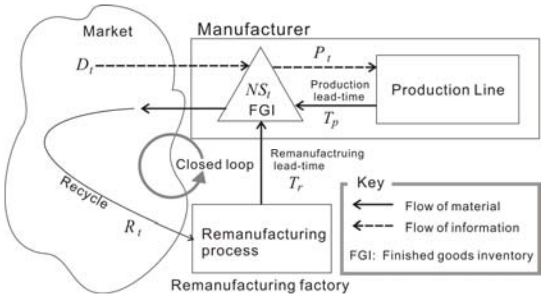

Figure 1: Schematic of our closed loop supply chain model

there are quite few researches considering both the value of information and the impact of lead-times in a closed loop supply chain setting with correlated demand and return.

Model

In this research, the following set of notation is used:

t	: time period
D_t	: market demand rate at t for the finished goods
R_t	: product return rate at t
μ_D	: mean of the market demand rate
μ_R	: mean of the product return rate
τ	: correlation time lag parameter (= 0, 1, 2, …)
ε_t	: i.i.d. error term realized at t
ζ_t	: i.i.d. error term realized at t (ε_t and ζ_t are mutually independent)
θ	: correlation coefficient
k	: non-negative scale parameter
σ_ε	: standard deviation of ε_t
σ_ζ	: standard deviation of ζ_t and $\sigma_\zeta = k\,\sigma_\varepsilon$
T_r	: remanufacturing lead-time (= 0, 1, 2, …)
T_p	: manufacturing lead-time (= 0, 1, 2, …)
P_t	: production order rate at t
NS_t	: net stock level at the end of t (negative value of NS_t represents the total backlog at t)

Fig. 1 shows the schematic of the model. For the ordering and inventory management policy, we will exploit the order-up-to policy in this research. In our model setting, both the remanufacturing and the manufacturing processes have unlimited capacities. It is assumed that there is no difference between the remanufactured products and brand-new products in terms of quality. Thus customers cannot recognize the difference between the two products. It is assumed that both the market demand rate (D_t) and the product return rate (R_t) follow a white noise processes. This white noise assumption is widely used in much of the closed loop supply chain literature (e.g. Ketzenberg et al., 2006 and Ketzenberg, 2009). It is assumed that those two processes are correlated each other, as some portion of satisfied demand in the market is returned after a certain time period. The demand and the product return rates models used herein are

$$D_t = \mu_D + \varepsilon_t \qquad (1)$$
$$R_t = \mu_R + \theta k \varepsilon_{t-\tau} + \sqrt{1-\theta^2}\zeta_t$$

where the correlation between $D_{t-\tau}$ and R_t becomes θ. This correlation represents a situation where a return rate at t is correlated with the demand rate in period $t-\tau$. We believe that this assumption is intuitively understandable in a closed loop supply chain as the part of the demand eventually becomes the input to the remanufacturing process. There are quite few research in the field of closed loop supply chain incorporating the correlation between demand and return processes, even though its importance is well recognized (Akçalı and Çetinkaya, 2011). The standard deviations of D_t and R_t are σ_ε and $k\sigma_\varepsilon$, respectively. If k is greater than unity, for example, the standard deviation of R_t becomes larger than that of D_t. Without loss of generality, it is assumed that $\mu_D \geq \mu_R$.

Sequence of events

The sequence of events in the model can be described as follows: At the beginning of t, the remanufacturing factory observes the total number of remanufacturable products, R_t that have been returned from the market place. These are then processed and delivered to the stock point of the manufacturer at the beginning of $t+T_r+1$, in order to fill partial market demand of D_t. At the beginning of t, the manufacturer receives brand-new goods from its production line, order in period t-(T_p+1), in addition to remanufacturerd products from the remanufacturer, returned in period t-(T_r+1). Next the market demand D_t is observed and filled from the on-hand inventory. If the manufacturer does not have a large enough on-hand inventory to fill the all demand, unmet demand is backlogged. At the end of t, the manufacturer places a production order P_t to meet the future demand. Therefore, NS_t, the net stock level of the manufacturer at the end of t, observes the following balance equation:

$$NS_t = NS_{t-1} + R_{t-(T_r+1)} + P_{t-(T_p+1)} - D_t \qquad (2)$$

Ordering policy

Let us use IP_t^+, the inventory position for the manufacturer at t right after P_t is determined. Thus, IP_t^+ is the net stock level at t (NS_t) plus the total of on-orders, $\{ P_{t-T_p}, \ldots, P_t \}$. The value of IP_t^+ is known to the manufacturer since all such information is local. As shown in Hosoda and Disney (2012), in a traditional supply chain setting where there is no remanufacturing, whatever ordering policy is used, we will always have the following relationship: $NS_{t+T_p+1} = IP_t^+ - \sum_{i=1}^{T_p+1} D_{t+i}$. In a closed loop supply chain, on the other hand, it is necessary to incorporate the pipeline inventory coming from the remanufacturer which will be available for the manufacturer during the time interval of (t, $t+T_p+1$]. Consequently, we have the following relationship:

$$NS_{t+T_p+1} = IP_t^+ - \sum_{i=1}^{T_p+1} D_{t+i} + PIR_t + FPIR_t, \qquad (3)$$

where

$$IP_t^+ = NS_t + P_{t-T_p} + \cdots + P_t,$$

$$PIR_t = \begin{cases} \sum_{i=T_r-T_p}^{T_r} R_{t-i} & T_r \geq T_p \\ \sum_{i=0}^{T_r} R_{t-i} & T_r < T_p \end{cases},$$

and

$$FPIR_t = \begin{cases} 0, & T_r \geq T_p \\ \sum_{i=1}^{T_p-T_r} R_{t+i}, & T_r < T_p \end{cases}.$$

PIR_t is the total pipeline inventory of remanufactured products and thus its value is already recognized by the remanufacturer at t. $FPIR_t$ represents the future pipeline inventory of the remanufactured products at t and its value is not known yet by anybody when $T_r < T_p$. Note that PIR_t is not known by the manufacturer, if there is no advance notice scheme in the supply chain. Without advance notice, the manufacturer needs to take the expected value of PIR_t, $\widehat{PIR_t}$, to determine P_t. Thus the advance notice of the product return information should have some impact on the performance of the manufacturer. Furthermore, when $T_r < T_p$, since the manufacturer must estimate the value of $FPIR_t$ as well, the magnitude of the relationship between T_r and T_p also should have impact on the performance of the manufacturer. With the knowledge of Eq. 2, we have the following relationship between IP_t^+ and IP_{t-1}^+: $IP_t^+ = IP_{t-1}^+ - D_t + R_{t-(T_r+1)} + P_t$. Thus, P_t can be written as

$$P_t = D_t - R_{t-(T_r+1)} + IP_t^+ - IP_{t-1}^+. \tag{4}$$

From Eq. 3, we can have another notation of IP_t^+ that is,

$$IP_t^+ = \sum_{i=1}^{T_p+1} D_{t+i} \quad - PIR_t - FPIR_t + NS_{t+T_p+1}. \tag{5}$$

The RHS of Eq. 5, however, includes some unknown values for the manufacturer. Thus the manufacturer may want to take the expected value of IP_t^+, which yields

$$E[IP_t^+] = \widehat{D} - \widehat{PIR_t} - \widehat{FPIR} + TNS,$$

where

$$\widehat{D} = E\left[\sum_{i=1}^{T_p+1} D_{t+i}\right] = (T_p+1)\mu_D,$$

$$\widehat{FPIR} = E[FPIR_t] = \begin{cases} 0 & T_r \geq T_p \\ (T_p - T_r)\mu_R & T_r < T_p, \end{cases}$$

$$TNS = \mathrm{E}\left[NS_{t+T_p+1}\right],$$

and TNS stands for the target net stock level and its value is predetermined by the manufacturer to minimize its inventory cost. $\widehat{PIR_t}$ is

$$\widehat{PIR_t} = \sum_{i=(T_r-T_p)^+}^{T_r} R_{t-i},$$

when the advance notice scheme is exploited. Otherwise, the value of $\widehat{PIR_t}$ becomes

$$\widehat{PIR_t} = E[PIR_t] = \begin{cases} (T_p + 1)\,\mu_R & T_r \geq T_p \\ (T_r + 1)\mu_R & T_r < T_p. \end{cases}$$

In this case $\widehat{PIR_t}$ is time independent and only depends on the values of T_r and T_p. Based on Eq. 4, we can have the order-up-to policy for a closed loop supply chain, which is

$$P_t = D_t - R_{t-(T_r+1)} + (E[IP_t^+] - E[IP_{t-1}^+]).$$

If there is no information sharing scheme in a closed loop supply chain, since the value of $E[IP_t^+]$ becomes time invariant (i.e. $E[IP_t^+] = E[IP_{t-1}^+]$), we have the following expression for P_t,

$$P_t = D_t - R_{t-(T_r+1)}. \tag{6}$$

If the advance notice is shared, P_t depends on the values of T_r and T_p,

$$P_t = \begin{cases} D_t - R_{t-(T_r-T_p)} & T_r \geq T_p \\ D_t - R_t & T_r < T_p. \end{cases} \tag{7}$$

Cost functions

In this research, the manufacturer incurs the capacity cost and the inventory cost and those costs are used to measure the performance of the closed loop supply chain. The remanufacturing cost is assumed to be a constant per unit and will be ignored in the following analysis. It is assumed that the manufacturer determines its production capacity to minimize the sum of the production related costs: the fixed production cost and the over-time production cost. The fixed production cost is the cost that the manufacturer always incurs when the production order is equal to or less than its predetermined production capacity. In this case, the amount of the fixed cost is constant, $u(\mu+s)$, where $\mu = E[P_t] = \mu_D - \mu_R$ and s is the slack capacity chosen to minimize the production cost C_p. On the other hand, if the production order is higher than the capacity, over-time is used to meet the extra demand that is above the capacity. Employees are paid at rate of w ($> u$) to produce a single unit in the overtime. Under this setting, C_p can be written as $C_p = E\ [u(\mu + s) + w(P_t - (\mu + s))^+]$. Then, as shown in Hosoda and Disney (2012), the minimum value of C_p, C_p^*, is realized when $s = z_s\sqrt{V[P]}$, where $z_s = \Phi^{-1}[\frac{w-u}{w}]$ for the standard cumulative normal distribution Φ. Then the minimized capacity cost C_p^* becomes

$$C_p^* = u\mu + w\phi[z_s]\sqrt{V[P]},$$

where ϕ is the probability density function of the standard normal distribution. The value of TNS is determined via the newsvendor approach. Every time period, the manufacture incurs the holding cost, hNS_t, when NS_t is positive at the end of t. If NS_t is negative, the manufacturer incurs the backlog cost, $-bNS_t$. In such a case, when we set $TNS = z_{NS}\sqrt{V[NS]}$ where $z_{NS} = \Phi^{-1}[\frac{b}{b+h}]$, the inventory cost is minimised. The minimised inventory cost is

$$C_{NS}^{*} = (h+b)\phi[z_{NS}]\sqrt{V[NS]}.$$

Notice that both C_P^* and C_{NS}^* are linear in $\sqrt{V[P]}$ and $\sqrt{V[NS]}$, respectively. In the next section, we will introduce analytical expressions of $\sqrt{V[P]}$ and $\sqrt{V[NS]}$.

Variances

From this section, a suffix "I" is attached to $V[\cdot]$ to represent the situation where the product return rate information is shared.

Advance notice case: From Eq. 7 with Eq. 1, the variance of P_t when the advance notice is available, $V_I[P]$, is

$$V_I[P] = \begin{cases} (1+k^2)\sigma_\varepsilon^2 & T_r > T_p \\ (1+k^2-2\theta k)\sigma_\varepsilon^2 & T_r \le T_p \wedge \tau = 0 \\ (1+k^2)\sigma_\varepsilon^2 & T_r \le T_p \wedge 0 < \tau. \end{cases} \quad (8)$$

Since the manufacturer knows the values of IP_t^+ and PIR_t in Eq. 3, the variance of the net stock levels, $V_I[NS]$, can be written as

$$V_I[NS] = \begin{cases} (T_p+1)\sigma_\varepsilon^2 & T_r \ge T_p \\ \left(1+T_p(1+k^2)+2\theta k(\tau+T_r-T_p)-T_r k^2\right)\sigma_\varepsilon^2 & T_r < T_p \wedge 0 \le \tau \le T_p - T_r - 1 \\ (T_p+1)\sigma_\varepsilon^2 + (T_p-T_r)k^2\sigma_\varepsilon^2 & T_r < T_p \wedge T_p - T_r - 1 < \tau. \end{cases} \quad (9)$$

No advance notice case: When no advance notice is given, P_t is given as Eq. 6 and its variance is

$$V[P] = (1+k^2)\sigma_\varepsilon^2. \quad (10)$$

In the RHS of Eq. 3, the manufacturer knows only the locally available information, which is IP_t^+. Thus $V[NS]$ is

$$V[NS] = \begin{cases} (1+k^2)(T_p+1)\sigma_\varepsilon^2 & T_r \ge T_p \\ \left(1+T_p(1+k^2)+2\theta k(\tau+T_r-T_p)+k^2\right)\sigma_\varepsilon^2 & T_r < T_p \wedge 0 \le \tau \le T_p - T_r - 1 \\ (1+k^2)(T_p+1)\sigma_\varepsilon^2 & T_r < T_p \wedge T_p - T_r - 1 < \tau. \end{cases} \quad (11)$$

The analytical expressions of the variances provide the following insights.

Property 1: When the return rate information is shared, the variance of net stock levels *always becomes smaller*. This property shows that the advance notice of the product return rate information will always bring about inventory cost reduction.

Property 2: When the return rate information is shared, the variance of the production order becomes smaller (i.e. $V_I[P] < V[P]$), if and only if $T_r \leq T_p$, $\tau = 0$ and θ is positive.

This property suggests that the advance notice of the product return rate information enables the manufacturer to mitigate the well-known Bullwhip Effect. However, this preferable outcome occurs only under a quite limited situation. For example, if we use the well-accepted assumption where D_t and R_t are mutually independent (i.e. $\theta = 0$), we always have $V_I[P] = V[P]$, which leads us to the conclusion that the advance notice scheme does not bring any benefit for the production cost. When $T_r \leq T_p$, $\tau = 0$, and D_t and R_t are negatively correlated, the variance of the production order can be even larger, due to the advance notice. Therefore, if the reduction of the production cost is a major concern, you should be careful about the outcome of the advance notice scheme. Managers should pay attention to the values of θ, k and τ, in addition to the relationship between T_p and T_r.

Property 3: When the return rate information is shared, the variance of the net stock levels ($V_I[NS]$) is always increasing in T_p.

This property means that reducing the manufacturing lead-times will always decrease the inventory costs. Alternatively, if the *TNS* is left unchanged, shorter manufacturing lead-times improve product availability.

Property 4: When the return rate information is shared, the variance of the net stock levels ($V_I[NS]$) is decreasing in T_r, if $T_r \leq T_p$, $0 \leq \tau \leq T_p - T_r - 1$ and $2\theta < k$.

Property 5: When the return rate information is shared and $T_r < T_p \wedge T_p - T_r - 1 < \tau$, $V_I[NS]$ is decreasing in T_r, and by setting $T_r = T_p$ (or $T_r > T_p$) the value of $V_I[NS]$ is minimized.

Property 4 and property 5 produce a counter intuitive insight: under certain condition, shorter remanufacturing lead-time (T_r) can increase the inventory cost at the manufacturer. In a serially linked supply chain, for example, it is known that shorter lead-time always reduces the inventory cost (see, Lee et al., 2000, for example). This property indicates that such an insight obtained from a serially linked supply chain setting without return may not be true in a closed loop supply chain. Using numerical analysis, van der Laan et al. (1999) report a similar finding. They show that this counter intuitive phenomenon could be observable when $T_r < T_p$. In their setting, the demand process and the return process are stochastic (i.e. $k > 0$) and independent each other (i.e. $\theta = 0$), which means that the setting used in van der Laan et al. (1999) is a special case of the contidtion required by property 4.

Property 6: When $T_r > T_p$, the value of T_r does not have any impact upon $V_I[P]$, $V_I[NS]$, $V[P]$, and $V[NS]$.

Property 6 suggests that shorter T_r does not decrease any costs as long as the relation $T_r > T_p$ holds in a close loop supply chain.

Property 7: When $T_r > T_p$ or $T_r \leq T_p \wedge 0 < \tau$, we always have $V_I[P] = V[P]$.

If it is reasonable to assume that $\tau > 0$, property 7 suggests that the advance notice cannot result in lower manufacturing cost at any values of T_p and T_r. A course of action the manufacturer can take in order to reduce the manufacturing cost, is to reduce the value of k. It might be quite difficult, however, since normally the value of k is uncontrollable value for the manufacturer. We may conclude that in a close loop supply chain reducing inventory cost is much easier than manufacturing cost.

Numerical analysis (results of numerical analysis will be shown in presentation)

Conclusion

Our findings yield the following general guideline for managers. The advance notice of the return product rate information always can reduce the inventory cost. To reduce the production cost, on the other hand, we should ensure $T_r \leq T_p$, τ =0 and a positive value of θ exist, which, however, might be quire rare in a real closed supply chain. If θ is negative, there is a possibility that the production cost will go up due to the advance notice. In addition, when $T_r \leq T_p$, reducing T_r could result in higher inventory cost. To avoid this, the values of $\{k, \theta, \tau\}$ should be carefully investigated.

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