Stochastic design of a global cascade reuse supply chain: Planning and managing the reverse network at Fuji Xerox

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Abstract
We develop and study a dynamic stochastic model of the production, collection, disassembly and remanufacture of photocopiers produced and sold in Japan and Thailand. We consider the inventory requirements and costs of saleable products as well as capacity requirements and costs in production, collection, disassembly and remanufacture in both countries.

Keywords: Cascade reuse, Closed loop supply chains, Stochastic demands.

Introduction

Japan's Fuji Xerox Co., Ltd. is a global company that sells photocopiers to the Asia Pacific region. It is a leader in manufacturing/remanufacturing techniques. Since December, 2004, Fuji Xerox has collected end-of-use product, and operated a 'resource circulation system' that functions independently in different countries. Returned products can be reused directly, disassembled and subassemblies and components reused, or materials can be recovered after crushing. When high-grade products are collected and reused, they are usually re-sold as used products or disassembled and individual parts re-used.

Individual parts that are re-used can either be used in a product with the same specification as the returned product, or they can be used in a product with a lower specification. This is the concept of 'cascade reuse', Kainuma et al. (2011) and Takata (2013). For example, a high capacity, high speed printer cartridge returned from the marketplace could be remanufactured into either a high capacity, high speed cartridge or downgraded into a low capacity, low speed cartridge, as it is simply over-engineered. However, a low capacity, low speed cartridge return may only be recycled into a similar low capacity, low speed cartridge as is not robust enough to be upgraded. Our aim is to study this cascade reuse system.

The structure of our paper is as follows. We first provide a description of the operation of Fuji Xerox's cascade reuse supply chain between Japan and Thailand. Then we define our discrete time stochastic model of the Fuji Xerox operations and derive expressions for the variance of the system states in the model. From this we identify the costs of operating this reverse supply chain network with a numerical analysis of our model. Finally we conclude.

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The closed loop supply chain of Fuji Xerox

The cascade reuse system is thought to be the best approach for resource circulation system in Asia Pacific area because of the big income disparities in the Asia Pacific countries. Makiya (2008) proposed an international resource circulation to supplement domestic resource circulation. In 2012, Fuji Xerox shifted from a system which performed recycling locally to a cascade reuse system in Japan, China, Korea, Australia, New Zealand. To this aim Fuji Xerox established four guiding principles:

- Prevent illegal dumping by undertaking the collection of recoverable materials.
- Do not allow waste to enter the recycling system.
- Do not impose an environmental impact on the import country/area.
- Return profits due to the environmental load reduction to the import country/area.

We investigate Fiji Xerox's cascade reuse system from an economic viewpoint. One option is to continue with the global cascade reuse supply chain, the other is to perform recycling locally. For simplicity we assume that our model only consists of Japan and Thailand.

Figure 1 shows the outline of global closed loop supply chain of Fuji Xerox where some of products that are manufactured, consumed and collected in Japan are disassembled, checked and remanufactured into components in Japan. Remanufactured products are marketed as new products. New products are manufactured only to meet the demands that remanufactured products can't supply. Collected products that are not disassembled and checked in Japan are stored in containers, which when full, are transported to Thailand. In Thailand, they are disassembled and checked. The collected products are then turned into components for remanufactured products. After remanufacturing, these products go back into the marketplace.

Stochastic model of the Fuji Xerox closed loop supply chain

Our model operates on a discrete time basis where each integer unit of time represents a month. Monthly demand in both Japan and Thailand is a normally distributed i.i.d. random variable. We assume that the demand in Japan is uncorrelated to the demand in Thailand. The demand in month t, at location i ($i = 1$ for Japan and $i = 2$ for Thailand) is given by

$$d_{t,i} \in N\left(\mu_i, \sigma_i\right). \tag{1}$$

Demand at both locations is satisfied from inventory. The inventory balance equation satisfies the following relationships in location i, see (2).

$$ns_{t,i} = ns_{t-1,i} - d_{t,i} + q_{t-1,i} + p_{t-1,i} \tag{2}$$

In (2), $ns_{t,i}$ is the net stock in time period t at location i. $d_{t,i}$ is the demand in period t, location i. $q_{t-1,i}$ is the number of products that the remanufacturer started to turn into as good as new products in the period $t-1$, at location i. $p_{t-1,i}$ are the production requests started in period $t-1$, at location i. As both the production lead-time and the remanufacturing lead-time is less than one month, both those products are available in inventory to satisfy demand in the next period (month). That is, both the production and the remanufacturing lead-time is one period long (which includes the sequence of events delay).

A proportion k_i of the products sold to the market are returned to a collection centre for remanufacturer into as good as new products. The proportion $\left(1-k_i\right)$ of products sold to the

Figure 1 – Map of the operations in the Fuji Xerox Co. closed loop supply chain
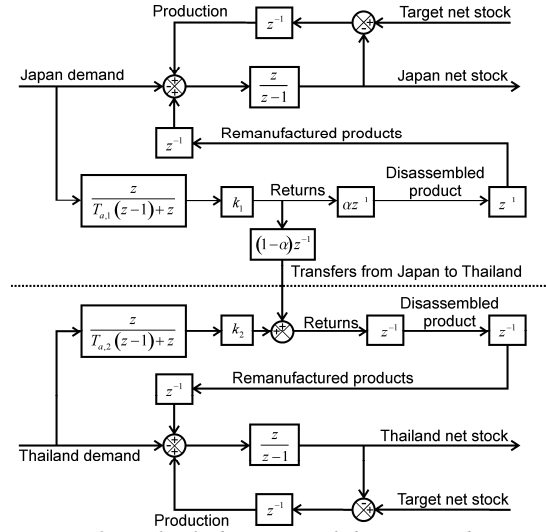

Figure 2 – Block diagram of the Cascade reuse supply chain

market are disposed of in a land-fill (or otherwise exit the system). Products stay in the market place for an exponentially distributed amount of time, with an average time in the market place of $T_{a,1}$ time periods. This type of random lead-time can be modelled at a discrete time, first order lag (Zhou and Disney, 2006) and is given by,

$$\left. \begin{aligned} \hat{d}_{t,i} &= \hat{d}_{t-1,i} + \tfrac{1}{1+T_{a,i}}\left(d_{t,i} - \hat{d}_{t-1,i}\right) \\ r_{t,i} &= k_i \hat{d}_{t,i} \end{aligned} \right\} \tag{3}$$

where $\hat{d}_{t,i}$ is number of products exiting the marketplace after an exponentially distributed amount of time and $r_{t,i}$ is the proportion of products returned to the collection centre. At the end of each month the collected products, $r_{t,i}$ are sent to be disassembled. A proportion of the products $(1-\alpha)$, $0 \leq \alpha \leq 1$ that are collected in Japan are sent via boat to Thailand. The disassembly activity is conducted on an 'as required basis', thus

$$\left. \begin{aligned} a_{t,1} &= \alpha r_{t-1,1} \\ a_{t,2} &= \left(1-\alpha\right) r_{t-1,1} + r_{t-1,2} \end{aligned} \right\}. \tag{4}$$

After disassembly, again with a lead-time of one month, the disassembled products are remanufactured into as good as new products as soon as possible. The number of products remanufactured each time period t in each location i is given by $q_{t,i} = a_{t-1,i}$. Finally, to maintain the inventory levels around safety stock targets the following equations, based on the Order-Up-Up policy, Dejonckheere et al. (2003), are used to set production targets for new products. Thus,

$$p_{t,1} = \left(1-k_1\right)\mu_1 + \alpha k_1 \mu_1 + tns_1 - ns_{t,1} \quad \text{and} \quad p_{t,2} = \left(1-k_2\right)\mu_2 - \left(1-\alpha\right)k_2 \mu_2 + tns_2 - ns_{t,2}. \tag{5}$$

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The Target Net Stock (tns_i) is a time invariant decision variable that should be set to minimise the inventory holding and backlog costs.

Variance ratio analysis

In this section we will obtain the necessary variance expressions in each of the two locations that we require in our economic analysis.

Variance of the net stock levels

The expected inventory holding and backlog costs require us to know the variance of the net stock levels over time. The variance of the net stock levels in Japan can be obtained from the following transfer function that can be found by rearranging the block diagram in Figure 2 using standard control theory methods. We refer interested readers to Nise (2004) for information on this method.

$$ns_1(z)\big/d_1(z) = k_1\alpha\left(z^2\left(T_{a,1}(z-1)+z\right)\right)^{-1} - 1. \tag{6}$$

Taking the inverse z-transform allows us to obtain the time domain impulse response,

$$ns_{t,1} = \alpha k_1 T_{a,1}{}^{t-3}\left(T_{a,1}+1\right)^{2-t}\left(1-h[2-t]\right) - h[-t] \tag{7}$$

where $h[x]$ is the Heaviside Step function, $h[x]=0$ if $x\le 0$, 1 otherwise. By Tsypkin's (1964) relationship, (Disney & Towill, 2003) we can sum the squared impulse response to obtain the variance of the net stock position as follows,

$$\sigma_{ns,1}^2 = \sigma_1^2\sum_{t=0}^{\infty}\left(\alpha k_1 T_{a,1}{}^{t-3}\left(T_{a,1}+1\right)^{2-t}\left(1-h[2-t]\right)-h[-t]\right)^2 = \sigma_1^2\left(1+\alpha^2 k_1{}^2\big/\left(2T_{a,1}+1\right)\right), \tag{8}$$

which is increasing in $\{\alpha, k_1\}$ and decreasing in $T_{a,1}$. In Thailand, the net stock levels are influenced by both the demand in Japan and the demand in Thailand, thus the variance of the net stock levels requires us to consider both $NS_2(z)\big/\varepsilon_1(z)$ and $NS_2(z)\big/\varepsilon_2(z)$ transfer functions.

$$\frac{ns_2(z)}{d_1(z)} = \frac{k_1(1-\alpha)}{z^2(z-2)(z+T_{a,1}(z-1))} \quad\text{and}\quad \frac{ns_2(z)}{d_2(z)} = \frac{k_2 - z^2\left(T_{a,2}(z-1)+z\right)}{z^2\left(T_{a,2}(z-1)+z\right)} \tag{9}$$

which can be obtained by manipulating the block diagram in Figure 2. Taking the inverse z-transform again yields the following two impulse responses,

$$ns_{t,2,1} = k_1 T_{a,1}{}^{t-4}\left(1-\alpha\right)\left(1+T_{a,1}\right)^{3-t}\left(1-h[3-t]\right) \tag{10}$$

and

$$ns_{t,2,2} = k_2 T_{a,2}{}^{t-3}\left(1+T_{a,2}\right)^{2-t}\left(1-h[2-t]\right) - h[-t] \tag{11}$$

to the demand processes in Japan and Thailand respectively. The variance of the inventory level

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in Thailand is then easily obtained by the sum of the squared impulse responses,

$$\sigma_{ns,2}^2 = \begin{pmatrix} \sigma_1^2 \sum_{t=0}^{\infty} \left(k_1 T_{a,1}^{t-4} (1-\alpha)(1+T_{a,1})^{3-t} (1-h[3-t]) \right)^2 + \\ \sigma_2^2 \sum_{t=0}^{\infty} \left(k_2 T_{a,2}^{t-3} (1+T_{a,2})^{2-n} (1-h[2-t]) - h[-t] \right)^2 \end{pmatrix} = \begin{pmatrix} \sigma_1^2 \dfrac{k_1^2 (1-\alpha)^2}{1+2T_{a,1}} + \\ \sigma_2^2 \dfrac{(1+k_2^2+2T_{a,2})}{1+2T_{a,2}} \end{pmatrix}. \tag{12}$$

Equation (12) is decreasing in $\{\alpha,\ T_{a,1},\ T_{a,2}\}$ and increasing in $\{k_1,\ k_2\}$.

Variance of the returns in Japan and Thailand

Departing from the transfer function of the returns, $R_i(z)/d_i(z) = z k_i / (T_{a,i}(z-1)+z)$, we use the same procedure to obtain the variance of the returns in each location. That is, we take the inverse z-transform and sum its square to infinity. This yields the expression

$$\sigma_{r,i}^2 = k_i^2 \sigma_i^2 / (1+2T_{a,i}), \tag{13}$$

which we will recognize as a scaled variance of the exponential smoothing forecast. This should be no surprise as the exponentially distributed delay has the same structure as the exponential smoothing forecast. Equation (13) shows us that k_i has no influence on stability, smaller k_i's reduce the variance of the returns, as do larger $T_{a,i}$'s. $-0.5 < T_{a,i} < \infty$ is required for stability, although $T_{a,i} < 0$ have no practical meaning in our modelling scenario as products cannot be returned from the marketplace before they are sent.

Variance of the disassembly and remanufacturing processes

As the remanufacturing step simply processes the output of the disassembly stage, the variance of the disassembly and remanufacturing process are identical. In Japan this is given by

$$\sigma_{a,1}^2 = \sigma_{u,1}^2 = k_1^2 \alpha_1^2 \sigma_1^2 / (1+2T_{a,1}). \tag{14}$$

In Thailand this is given by

$$\sigma_{a,2}^2 = \sigma_{u,2}^2 = k_1^2 (\alpha-1)^2 \sigma_1^2 (1+2T_{a,1})^{-1} + k_2^2 \sigma_2^2 (1+2T_{a,2})^{-1}. \tag{15}$$

The variance of the disassembly process and the remanufacturing process is increasing in k_i and decreasing in $T_{a,i}$ at both locations. However, it is increasing in α in Japan and decreasing in α in Thailand.

Variance of the production levels of new products

The transfer functions for the production of new products is given by

$$\frac{P_1(z)}{d_1(z)} = \frac{k_1 \alpha}{z^2 (T_{a,1}(z-1)+z)} - 1 = -\frac{NS_1(z)}{d_1(z)} \tag{16}$$

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which we notice is the negative of the inventory levels. Thus, the variance of the Japanese production is the same as its inventory levels. That is,

$$\sigma_{p,1}^2 = \sigma_1^2 \sum_{t=0}^{\infty} \left(-\alpha k_1 T_{a,1}^{t-3} \left(T_{a,1}+1 \right)^{2-t} \left(1-h[2-t] \right) + h[-t] \right)^2 = \sigma_1^2 \left(1 + \alpha^2 k_1^2 \left(2T_{a,1}+1 \right)^{-1} \right) = \sigma_{ns,1}^2. \quad (17)$$

Equation (17) shows that this supply chain always produces the bullwhip effect because $\sigma_{p,1}^2/\sigma_1^2 > 1$ as $\{k_1, \alpha, T_{a,1}\} \in \mathbb{R} > 0$. In Thailand the variance of the order levels require us to consider both the $p_2(z)/d_1(z)$ and the $p_2(z)/d_2(z)$ transfer functions. These are

$$\frac{p_2(z)}{d_1(z)} = \frac{k_1(\alpha-1)}{z^2(z-2)(z+T_{a,1}(z-1))} \quad \text{and} \quad \frac{p_2(z)}{d_2(z)} = \frac{z^2\left(T_{a,2}(z-1)+z\right)-k_2}{z^2\left(T_{a,2}(z-1)+z\right)}. \quad (18)$$

The same 'negative' effect can be seen in the variance of the Thai production, as it is also a reflection of the Thai inventory levels. Therefore, we can simply obtain the variance of the Thai production using

$$\sigma_{p,2}^2 = \begin{pmatrix} \sigma_1^2 \sum_{t=0}^{\infty} \left(k_1 T_{a,1}^{t-4} (\alpha-1)\left(1+T_{a,1}\right)^{3-t} \left(1-h[3-t]\right) \right)^2 + \\ \sigma_2^2 \sum_{t=0}^{\infty} \left(-k_2 T_{a,2}^{t-3} \left(1+T_{a,2}\right)^{2-n} \left(1-[2-t]\right)+h[-t] \right)^2 \end{pmatrix} = \begin{pmatrix} \sigma_1^2 \dfrac{k_1^2(1-\alpha)^2}{1+2T_{a,1}} + \\ \sigma_2^2 \dfrac{\left(1+k_2^2+2T_{a,2}\right)}{1+2T_{a,2}} \end{pmatrix} = \sigma_{ns,2}^2. \quad (19)$$

From (19), we see that $\sigma_{p,2}^2 > \sigma_2^2$. The relationship between $\sigma_{p,2}^2$ and σ_1^2 is more complex.

Mean values of the system states
The mean values of the systems states are relatively easy to determine by inspection and are detailed in Table 1. These mean values are also the initial conditions used in a simulation model that we have developed in Excel to verify our analytical results.

Economic consequences of the cascade reuse
We consider the case where the following incomes, costs and taxes are incurred.

$$T = \begin{pmatrix} \left(1-\text{Tax}_1\right)\begin{pmatrix} \mu_1\left(\text{Sales Price}_1\right)-I_{\$,1}^*-P_{\$,1}^*-A_{\$,1}^*-Q_{\$,1}^* - \\ \mu_{r,1}\left(\text{Collection cost}_1\right)+\mu_t\left(\text{Transfer Price}\right) \end{pmatrix} + \\ \left(1-\text{Tax}_2\right)\begin{pmatrix} \mu_2\left(\text{Sales Price}_2\right)-I_{\$,2}^*-P_{\$,2}^*-A_{\$,2}^*-Q_{\$,2}^* - \\ \mu_{r,2}\left(\text{Collection cost}_2\right)+\left(1-\text{Import Duty}\right)\mu_t\left(\text{Transfer Price}\right) \end{pmatrix} \end{pmatrix} \quad (20)$$

Here T is the expected income per period after tax, import duty and costs. The terms $\{I_{\$,i}^*, P_{\$,i}^*, A_{\$,i}^*, Q_{\$,i}^*\}$ will now be explained in greater detail; the other terms are straightforward.

Table 1 – Mean values in the Fiji Xerox cascade re-use supply chain model

System State	Location	Mean value
Returns	Japan	$\mu_{r,1} = \mu_1 k_1$
	Thailand	$\mu_{r,2} = \mu_2 k_2$
Disassembled and remanufactured products	Japan	$\mu_{a,1} = \mu_{q,1} = \mu_1 k_1 \alpha$
	Thailand	$\mu_{a,2} = \mu_{q,2} = \mu_2 k_2 + \mu_1 k_1 (1-\alpha)$
Production	Japan	$\mu_{p,1} = \mu_1 (1 - k_1 \alpha)$
	Thailand	$\mu_{p,2} = \mu_2 (1 - k_2) - \mu_1 k_1 (1-\alpha)$
Net Stock	Japan	tns_1
	Thailand	tns_2
Transfers	From Japan to Thailand	$\mu_t = \mu_1 k_1 (1-\alpha)$

Inventory costs

The expected per period inventory holding and backlog costs, $I_\$$, are given by

$$I_{\$,i} = \mathrm{E}\left[h_i \left(ns_{t,i} \right)^+ + b_i \left(-ns_{t,i} \right)^+ \right]. \tag{21}$$

Here h is the unit holding cost to store one unit of inventory for one month, b is the unit penalty cost for backlogging one unit for one month and $(x)^+ = \max(x,0)$ is the maximum operator, and $\mathrm{E}[x]$ is the expectation operator. We will recognise that (21) has the same structure as the newsboy problem, Hosoda and Disney (2006). This means that we should set tns_i to

$$tns_i = \sigma_{NS,i} z_i; \ z_i = \Phi^{-1}\left[b_i / (b_i + h_i) \right], \tag{22}$$

to minimise the expected inventory holding and backlog costs. $\Phi^{-1}[x]$ is the inverse of the cumulative distribution function of the normal distribution, evaluated at x. The minimised inventory holding and backlog costs are given by,

$$I_{\$,i}^* = \sigma_{NS,i} \left(b_i + h_i \right) \varphi[z_i]. \tag{23}$$

$\varphi[x]$ is the standard normal probability density function evaluated at x (Disney et al., 2012).

Production costs

We assume the production costs are driven by the following cost function,

$$P_{\$,i} = \mathrm{E}\left[u_i \left(S_i + \mu_i \right) + w_i \left(p_{t,i} - \left(S_i + \mu_i \right) \right)^+ \right]. \tag{24}$$

Here, workers are guaranteed, in each month, a certain amount of work, $(S + \mu)$, at a cost of u_i per unit of work. Production above the guaranteed work is met with overtime at a cost of w_i. The

optimal amount of 'slack' capacity, S_i, above or below the mean production levels, μ_i, at location i is given by

$$S_i^* = \sigma_{p,i} z_i; \; z_i = \Phi^{-1}\left[\left(w_i - u_i\right)/w_i\right]. \tag{25}$$

When an optimal capacity exists, the minimised production costs per period are

$$P_{\$,i}^* = u_i \mu_i + w_i \sigma_{p,i} \varphi\left[z_i\right]. \tag{26}$$

The only aspect left now is to specify the unit labor cost in Japan and Thailand, $\{u_1 = 8, \; u_2 = 7\}$ and the unit over-time cost in Japan and Thailand, $\{w_1 = 10, \; w_2 = 10.5\}$ respectively. The unit costs were based on actual case study information. Over-time regulations in Japan and Thailand were used to set the over-time costs, (Wikipedia (2014a); Panwagroup (2014)). It is customary in Japan to pay a 25% extra for additional work over the 8 hour day, Thailand pay 50% extra.

Remanufacturing and disassembly costs
In much the same way as the production costs, the remanufacturing costs are given by

$$Q_{\$,i} = \mathrm{E}\left[u_{q,i}\left(S_{q,i} + \mu_{q,i}\right) + w_{q,i}\left(q_{t,i} - \left(S_{q,i} + \mu_{q,i}\right)\right)^+\right], \tag{27}$$

where $u_{q,i}$ in the unit cost of remanufacture within the normal capacity of guaranteed hours of work $\left(S_{q,i} + \mu_{q,i}\right)$ at location i. $w_{q,i}$ is the unit cost of remanufacture in over-time operation. $S_{q,i}^*$ is the optimal slack capacity, above or below the $\mu_{q,i}$ mean remanufacturing rate at location i. $S_{q,i}^* = \sigma_{q,i} z_{q,i}; \; z_{q,i} = \Phi^{-1}\left[\left(w_{q,i} - u_{q,i}\right)/w_{q,i}\right]$. When the optimal amount of remanufacturing capacity is in place the following expression for the remanufacturing costs at location i exists,

$$Q_{\$,i}^* = u_{q,i} \mu_{q,i} + w_{q,i} \sigma_{q,i} \varphi\left[z_{q,i}\right]. \tag{28}$$

The cost of disassembly, $A_{\$}^*$, is determined in much the same way. With only the necessary change in notation, the optimal slack capacity, above or below the mean return rate, $\mu_{a,i}$, is $S_{a,i}^* = \sigma_{a,i} z_{a,i}; \; z_{a,i} = \Phi^{-1}\left[\left(w_{a,i} - u_{a,i}\right)/w_{a,i}\right]$ and the minimised disassembly cost is

$$A_{\$,i}^* = u_{a,i} \mu_{a,i} + w_{a,i} \sigma_{a,i} \varphi\left[z_{a,i}\right]. \tag{29}$$

Numerical investigations
The following numerical settings were obtained from our case study with Fuji Xerox (which have been suitably normalised for commercial reasons). We will now investigate the impact of these costs parameters on the economic performance of the cascade reuse system. Unless otherwise stated these cost parameters remain unchanged.

First we study the impact of the transfer rate, α on the economic performance of the cascade reuse system. By varying α, the proportion of returns remanufactured in Japan, we can produce Figure 3. Here $\alpha = 0$ implies that all Japanese returns are remanufactured in Thailand

Table 2 – Example cost parameters and other numerical settings

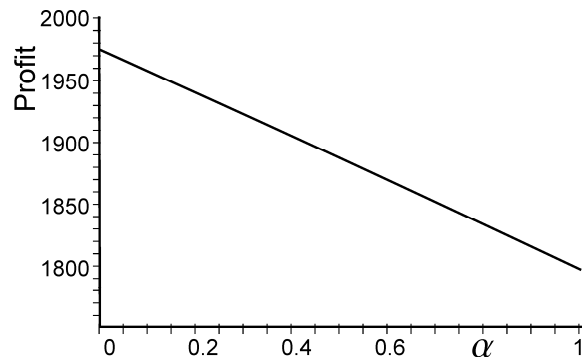| Cost Parameter	Japan $(i = 1)$	Thailand $(i = 2)$	Cost Parameter	Japan $(i = 1)$	Thailand $(i = 2)$
Disassembly cost	10	5	Transfer price	2	n/a
Variance of demand, $\sigma_{d,i}^2$	200	64	Mean demand, $\mu_{d,i}$	100	100
Return rate, k_i	0.5	0.4	Tax rate	40%	40%
Proportion of Japanese returns set to Thailand, α	0.9	n/a	Over-time remanufacturing cost	8.75	7.5
Normal remanufacturing cost	7	5	Time in marketplace, $T_{a,i}$	9	6
Over-time disassembly cost	12.5	7.5	Over-time production cost	10	10.5
Normal production cost	8	7	Selling price	30	25
Collection cost	2	1	Inventory holding cost	1	2.5
Inventory backlog cost	2.5	22.5	Import duty	n/a	5%

Figure 3 – Impact of the transfer rate (α) on the profit of the cascade re-use system
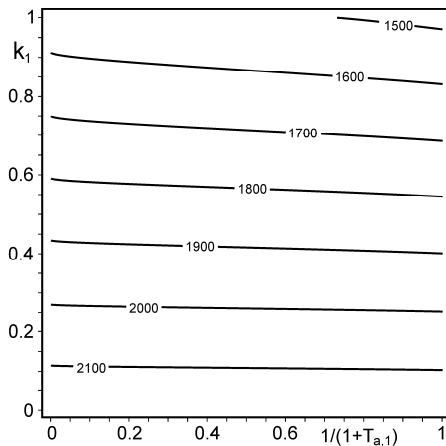

Figure 4 – Impact of the Japanese market demand parameters on the economic performance of the Cascade reuse system
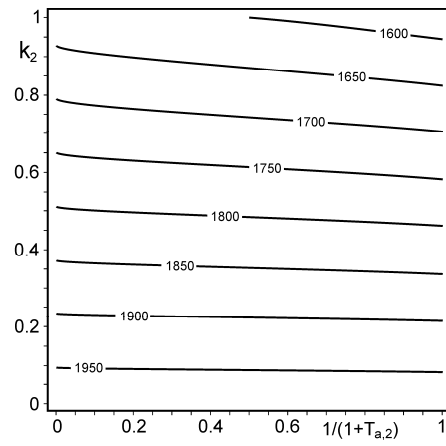

Figure 5 – Impact of the Thai market demand parameters on the economic performance of the Cascade reuse system

and $\alpha = 1$ implies that all Japanese returns are remanufactured in Japan. See from Figure 3, we can see that the profit, T, given by (20) is very nearly linear in α over the valid region of $0 \le \alpha \le 1$ (it is easy to show that $\tilde{T} = 2012.89 - 178.5\alpha$ is accurate to within an error of 0.05%). Figure 3 shows that is currently most economical to remanufacture all of the products in Japan and not to ship them to Thailand.

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Consider the impact of the Japanese market demand parameters on economic performance. Keeping $\alpha = 0.9$, we vary the proportion of products returned from the market place, k_1, and the mean of the exponentially distributed delay, $T_{a,1}$. Figure 4 shows that higher return rates (k_1) actually reduce the economic profit, but surprisingly longer times in the marketplace ($T_{a,1}$) increase profit. Figure 4 highlights the role of the Thai market demand parameters on the economic performance. Again we see that higher return rates (k_2) decrease profit and longer lead times in the marketplace ($T_{a,2}$) increase profits.

Concluding remarks

We have studied a two product cascade reuse case study. Assuming i.i.d. demand, each product spends an exponentially distributed amount of time in the market place before being returned to be remanufactured into a good as new product. We found that inventory levels are more tightly controlled with a longer average lead time in the market place. The longer lead time in the market place also created more profit in the numerical investigation. Whilst this finding is somewhat counter-intuitive a similar results was also found in Hosoda et al., (2015) albeit for a different closed loop supply chain structure. The higher the proportion of products transferred from Japan to Thailand was also found to decrease inventory levels in both Japan and Thailand, but economic performance was enhanced by smaller proportions of transfers. Our model could be easily extended to include both correlation over time and cross correlation between locations, by considering the Vector Autoregressive (VAR) demand process as in Boute et al. (2012).

References

Boute, R.N., J. Dejonckheere, S. M. Disney, W. Van de Velde. 2012 Bullwhip in a multi-product production setting. *Tijdschrift voor Economie en Management* **57**(3): 351–377.

Dejonckheere, J., S. M. Disney, M. R. Lambrecht, D. R. Towill. 2003. Measuring and avoiding the bullwhip effect: A control theoretic approach. *European Journal of Operational Research* **147**(3): 567–590.

Disney, S.M., G. Gaalman, T. Hosoda. 2012. Review of stochastic cost functions for production and inventory control. *Pre-prints of the 17th International Working Seminar of Production Economics*, Innsbruck, Austria, February 20 – 24, **1**: 117–128.

Disney, S.M., D. R. Towill. 2003. On the bullwhip and inventory variance produced by an ordering policy. *OMEGA: The International Journal of Management Science* **31**(3): 157–167.

Hosoda, T., S. M. Disney. 2006. The governing dynamics of supply chains: The impact of altruistic behavior. *Automatica* **42**(4): 1301–1309.

Hosoda, T., N. Gavirneni, S. M. Disney. 2015. Dynamics of closed loop supply chains. *5th International Conference on Industrial Engineering and Operations Management,* Dudai, United Arab Emirates, March 3 – 5.

Kainuma, Y., K. Ahsan, N. Tawara. 2011. Development of the cascade reuse hybrid manufacturing/remanufacturing system. *21st International Conference on Production Research*, July 30 – August 4, Stuttgart, Germany, 5 pages.

Kainuma, Y., S. M. Disney. 2013. Stochastic design of a global closed loop supply chain: Planning and managing the reverse network at Fuji Xerox. *22nd International Conference on Production Research*, July 28 – August 1, Iguassu Falls, Brazil. 7 pages.

Makiya, K. 2008. Collaboration towards Sustainable Collaboration towards Sustainable International Resource Circulation. http://www.env.go.jp/recycle/3r/en/ asia_0803/12/pdf, Accessed October 13, 2014.

Nise, N.S. 2004. *Control Systems Engineering*. New Jersey: John Wiley & Sons.

Panwagroup, 2014. http://www.panwagroup.net/business/index2.html, Accessed October 3, 2014.

Takata, S. 2013. Maintenance-centered Circular Manufacturing. *Procedia CIRP*, **11**(2): 3 – 31.

Tsypkin, Y. Z. 1964. *Sampling System Theory*. New York: Pergamon Press.

Wikipedia, (2014) http://en.wikipedia.org/wiki/Japanese_labour_law, Accessed October 3, 2014.

Zhou, L., S. M. Disney. 2006. Bullwhip and inventory variance in a closed loop supply chain. *OR Spectrum* **28**(1): 127–149.