Pricing Decision Model for Short Life-cycle Product in a Closed-loop Supply Chain with Remanufacturing

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Abstract

While there has been very few published works that attempt to model remanufacturing decisions for products with short life-cycle, we believe that there are many situations where remanufacturing short life-cycle products is rewarding economically as well as environmentally. We propose a model for determining prices that maximize the supply chain's total profit.

The system consists of a retailer, a manufacturer, and a collector of used-product under multi-period setting. Demand functions are time-dependent functions, both for new and remanufactured products; and price-sensitive. Return rate is an increasing function of the collecting price. We take pricing game approach, where manufacturer is the leader. The model is solved analytically to find optimal prices as well as analytical insights.

The results suggest that the optimal price of remanufactured product is higher during the decline phase compared to the price in previous phases. Numerical examples show that higher remanufacturing cost-savings has reduced collector's profit.

Identification: "Sustainable Supply Chain" and "Pricing and Revenue Management"

Keywords: *short life cycle product*, *remanufacturing*, *closed loop supply chain*, *pricing*, *optimization*.

JEL classification: D4 (Market structure and pricing) and C3 (Multiple or Simultaneous Equation Models; Multiple Variables)

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Introduction

Remanufacturing is a process of transforming used product into “like-new” condition, so there is a process of recapturing the value added to the material during manufacturing stage (Atasu, Guide, & Wassenhove, 2010; Atasu, Sarvary, & Wassenhove, 2008). The idea of remanufacturing used products has gained much attention recently for both economical and environmental reasons. As suggested by Gray & Charter (2008), remanufacturing can reduce production cost, the use of energy and materials. There are numerous studies on remanufacturing. However, most of the published works on remanufacturing have considered durable or semi-durable products. Very little attempt has been made to study how remanufacturing maybe applied to products with short life-cycle. In some developing countries like Indonesia, there is a large segment of society that could become potential market for remanufactured short life-cycle products like mobile phones, computers and digital cameras.

Several studies show that life-cycle for such high-technology products is getting shorter due to rapid innovation in technology (Guide, Jayaraman & Linton, 2003; Lebreton & Tuma, 2006; Wu, Aytac, Berger & Armbruster, 2006; Xianhao & Qizhi, 2007; Briano, Caballini, Giribone & Revetria, 2010; Hsueh, 2011), but there are limited number of remanufacturers for these products. In Europe and the United States, the decisions to remanufacture electronic products are encouraged by government regulations such as WEEE (2003) and RoHs (2003), and as a form of responsibility for environmental conservation (Chung & Wee, 2011). Remanufacturing is not only beneficial to the environment but also can provide economic benefits (Lee, Cho & Hong, 2010; Kaebernick, Manmek & Anityasari, 2006; and Kerr & Ryan, 2001). Considering the mounting wastes from electronic products nowadays, the potential of remanufacturing practices in reducing waste sent to the landfill, as well as in reducing production costs, we believe it is very important to study issues in remanufacturing of short life-cycle product in a closed-loop supply chain.

Pricing decision is an important task in an effort to gain economic benefit from remanufacturing practices. There are several studies focused on pricing of remanufactured products, but many of them have not considered the whole supply chain, and also only a very few concern about obsolescence of short life-cycle products. Our study will be focused on pricing decisions in a closed-loop supply chain involving manufacturer, retailer and collector of used-products, where customers have the option to purchase new or remanufactured products in the same market channel. We consider an oligopoly for single item with no constraint on the quantity of remanufacturable cores throughout the selling horizon.

Literature Review

Remanufacturing of mobile phones and electronic products has been recognized as an important practice. Helo (2004) claimed that product life-cycle has significantly shortened by rapid technological advancement, and coupled with fashionable design that attracts frequent purchases of new products, has generated pressure on and opportunities for reverse logistics. Franke, Basdere, Ciupek & Seliger (2006) suggested that remanufacturing of durable high-value products such as automobile engine, aircraft equipment, and machine tools, has been extended to a large number of consumer goods with short life-cycle and relatively low values, like mobile phones and computers. He also quoted market studies by Kharif (2002), Marcussen (Marcussen, 2003) and Directive 2002/96/EC which revealed that there is a significant potential for mobile phone remanufacturing due to the large supply market of the used mobile phones in Europe and the high market demand in Asia and Latin America.

Neto & Bloemhof-Ruwaard (2012) found that remanufacturing significantly reduces the amount of energy used in the product life-cycle, even though the effectiveness of remanufacturing is very sensitive to the life span of the second life of the product. They also proposed that the period of the life-cycle in which the product is returned to recovery, the quality of the product, the easiness to remanufacture and the recovery costs can affect whether or not remanufacturing is more eco-efficient than manufacturing. Rathore, Kota & Chakrabarti (2011) studied the case of remanufacturing mobile handsets in India. They found that used phone market is very important, even though with a lack of government regulation for e-wastes. It is also observed that there is a negative user-perception of second hand goods and that the process of remanufacturing has not been able to capture much required attention from its stakeholders. J. Wang, Zhao & Wang (2011) showed that the mobile phone market in China is growing rapidly. The above mentioned studies have affirmed our intuitive proposition that there is a high potential for remanufacturing short life cycle products.

Motives for deploying reverse chain can be for profitability or environmental impact mitigation, which either driven by regulation and/or morale. In our research, the underlying motive considered would be focused on profitability, which seems to be the suitable motive applied to industries in the absence of environment protection regulation, like in most of the developing countries. Guide & Wassenhove (2009) suggest that key activities in reverse supply chain can be categorized as (1) front end, which deals with product returns management; (2) engine, which covers remanufacturing operations issues; and (3) back end, which handles market development of remanufactured product. They believe that it is important to keep business focused in research of closed-loop supply chain for relevance to industry; hence highlight the significance of profitability, product valuation, pricing and marketing issues. In terms of marketing strategy, Atasu et al. (2010) concluded that remanufacturing does not always cannibalize the sales of new products. He proposed that managers, who understand the composition of their markets and use the proper pricing strategy, should be able to create additional profit. In a similar manner, Souza (2013) points out that introducing remanufactured product to the market alongside with the new product has two implications, namely market expansion effect and cannibalization effect; which makes pricing of the two products is critical. Therefore, pricing decision is an important task in an effort to gain economic benefit from remanufacturing practices.

There are several studies that discuss pricing strategies involving remanufactured products, obsolescence, and nonlinear demand function. However, none has considered the situation that we address in this paper. Table 1 shows the review result and where our proposed model stands.

TABLE 1. LITERATURES ON PRICING MODELS

	Supply Chain members involved	**Differen-tiating New & Reman**	**Planning Horizon**	**Demand Function**	**Decision variables**	**Objective**	**Consi-dering obsoles-cence**	**Remark**
Guide et al. (2003)	remanu-facturer	only reman product	single period	Dr known	price of * reman * core	max profit	no	consider several quality classes of cores

	Supply Chain members involved	**Differentiating New & Reman**	**Planning Horizon**	**Demand Function**	**Decision variables**	**Objective**	**Considering obsolescence**	**Remark**
Bakal & Akcali (2006)	remanufacturer	only reman product	single period	linear in price	price of * reman * core	max profit	no	consider effect of recovery yield
Ferrer & Swaminathan (2006)	manufacturer	no (Pn = Pr)	* infinite * two period * multi period	linear in price	* price * quantity	max profit	no	consider monopoly & duopoly
Vadde et al. (2006)	product recovery facility	only reman product	selling horizon	function of price and obsolescence	* price	max profit	yes	consider 2 types of obsolescence * gradual * sudden
Mitra (2007)	retailer	reman & refurbish products	selling horizon	two cases: * linear in price * non-linear	price of * reman * refurbish	max revenue	no	consider the availability of product
Atasu et al. (2008)	manufacturer	yes (Pn ≠ Pr)	two period	linear in price	* price * quantity	max profit	no	consider green segment, market diffusion, competition with other OEM
Qiaolun et al. (2008)	* manufacturer * retailer * collector	no (Pn = Pr)	selling horizon	linear in price	price of * retail *wholesale * collecting	max profit	no	manufacturer is the Stackelberg leader
Li et al. (2009)	remanufacturer	only reman product	single period	stochastic, function of price	price of * reman *core	max utilization	no	consider random yield and random demand
Liang et al. (2009)	remanufacturer	only reman product	single period	none	price of core	high return on investment	no	consider selling price follows GMB, and core price follows option principles
Ferrer & Swaminathan (2010)	manufacturer	yes (Pn ≠ Pr)	* infinite * two period * multi period	linear in price	* price * quantity	max profit	no	consider monopoly & duopoly
Ovchinnikov (2011)	manufacturer	yes (Pn ≠ Pr) Pn fixed	selling horizon	Dn known & constant Dr function of price	* price * quantity of reman	max profit	no	also study customers' switching behavior $\alpha(Pr) \in [0,1]$
Shi et al. (2011)	manufacturer	no (Pn = Pr)	single period	stochastic, linear in price	* price * quantity of new & reman	max profit	no	consider understocking & overstocking risks
Vadde et al. (2011)	product recovery facility	no new products	single period	deterministic	prices	max revenue min cost	no	consider several types of used products

	Supply Chain members involved	**Differentiating New & Reman**	**Planning Horizon**	**Demand Function**	**Decision variables**	**Objective**	**Considering obsolescence**	**Remark**
Wei & Zhao (2011)	* manufacturer * retailer	no (Pn = Pr)	single period	linear in price	price of * retail *wholesale * collecting	max profit	no	consider two competing retailers
Pokharel & Liang (2012)	consolidation center	only cores	single period	Dr is known	* core price * quantity of cores	min cost	no	consider stochastic return quantity and quality
Wu (2012a)	* OEM * remanufacturer	yes (Pn ≠ Pr)	two period	linear in price	prices * new * reman	max profit	no	consider level of interchangeability
Wu (2012b)	* OEM * remanufacturer	yes (Pn ≠ Pr)	* two period * multi period	linear in price	prices * new * reman	max profit	no	consider degree of disassemblability
Chen & Chang (2013)	manufacturer	yes (Pn ≠ Pr)	* static * 2-period * multi periods over life-cycle	*linear in price, with substitutable coefficient *dynamic (over time)	price of * new * reman for each period	max profit	no	*static unconstrained *dynamic pricing - constrained * consider system of manufacturing only & hybrid settings
Jena & Sarmah (2013)	*remanufacturer *retailer	only reman product	single period	random	cores price	max profit	no	consider 3 schemes of collection: direct, indirect, coordinated
Xiong et al. (2013)	manufacturer	only reman product	finite & infinite horizon	random	cores price	min cost	no	consider lost sales and uncertain quality of used products
proposed model	**manufacturer* ** retailer* ** collector*	*yes* *(Pn ≠ Pr)*	*selling horizon*	*function of time and price*	*price of* ** retail* **wholesale* ** collecting*	*max profit*	*yes*	

Note:
Pn = price of new product, Pr = price of remanufactured product
Dn = demand of new product, Dr = demand of remanufactured product

Problem Description

We consider a closed-loop supply chain with three members, manufacturers, retailer, and collector as depicted in Figure 1. Manufacturer acts as the leader and releases initial wholesale prices. The retailer then uses that information to find her optimum retail prices.

Finally, manufacturer updates the prices to find the optimum ones. The other members then follow that policy and maintain a balanced quantity along the supply chain.

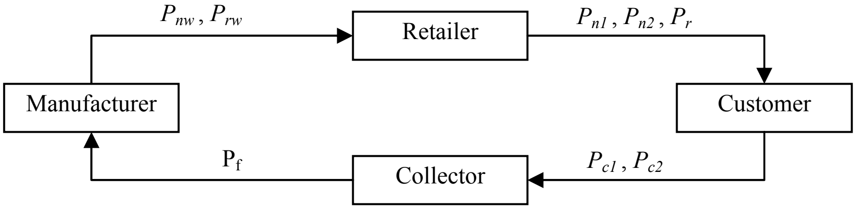

FIGURE 1. FRAMEWORK OF THE CLOSED-LOOP PRICING MODEL

The product considered in this model is single item, short life-cycle, with obsolescence effect after a certain period. Demand functions are time-dependent functions which represent the short life-cycle pattern along the entire phases of product life-cycle, both for new and remanufactured products; and linear in price. The market demand capacity is adopted from Wang & Tung (2011), that was constructed based on Verhulst's population model and extended to cover the obsolescence period, where the demand decreases significantly.

Let the selling horizon be [0, T]. Demand of the remanufactured product starts to appear at $t_1 \in [0, \mu]$, when some of the products have reached their end-of-use. The cores used for remanufacturing during [t_1, t_3] are collected from the returns of new products sold during [0, μ]. During [t_3, T], there are only remanufactured products offered, and the cores come from new products sold during [μ, t_3]. Figure 2 represents the demand pattern over time. The demand functions for new and remanufactured products can be formulated as follows:

$$D_n(t) = \begin{cases} D_{n1}(t) = U / \left(1 + ke^{-\lambda U t}\right) & ; 0 \le t \le \mu \\ D_{n2}(t) = U / \left(\lambda U (t - \mu) + \delta\right) & ; \mu \le t \le t_3 \end{cases} \qquad where \quad \begin{aligned} k &= U / D_0 - 1 \\ \delta &= 1 + ke^{-\lambda U \mu} \end{aligned}$$

$$D_r(t) = \begin{cases} D_{r1}(t) = V/\left(1+he^{-\eta V(t-t_1)}\right) & ;t_1 \le t \le t_3 \\ D_{r2}(t) = V/\left(\eta V(t-t_3)+\varepsilon\right) & ;t_3 \le t \le T \end{cases} \qquad where \quad \begin{array}{c} h = V/D_{r0}-1 \\ \varepsilon = 1+he^{-\eta V(t_3-t_1)} \end{array}$$

where U is a parameter representing the maximum possible demand, μ is the time when the demand reaches its peak U level, D_0 is the demand when t=0, and λ is the speed of change in the demand as a function of time. A parallel definition is applicable for V, t_3, D_{r0}, and η respectively for the remanufactured products.

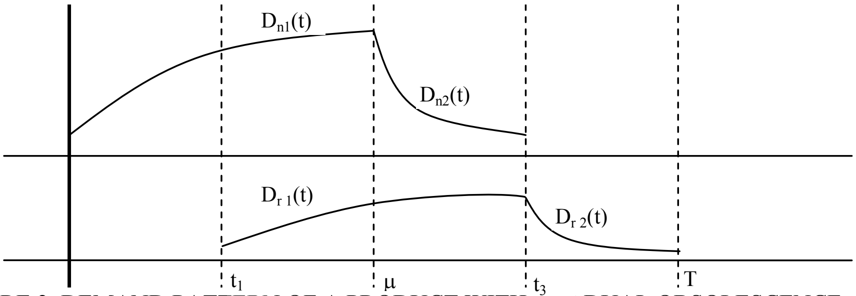

FIGURE 2. DEMAND PATTERN OF A PRODUCT WITH GRADUAL OBSOLESCENCE, OVER TIME

The new product is sold at retail price P_{n1} during [0, μ], and P_{n2} during [μ, t_3]. P_m is the maximum price, known and fixed, poses as the upper limit, at which demand would be zero. Remanufactured product are sold at retail price P_r during [t_1, T], and the maximum price is P_{n2}, since customer would choose to buy new product rather than remanufactured one when the remanufactured product price is as high as P_{n2}. Therefore, demand of new product during [0, μ] is $D_{n1}(t)(1 - P_{n1}/P_m)$, demand of new product during [μ, t_3] is $D_{n2}(t)(1 - P_{n2}/P_m)$; demand of remanufactured product during [t_1, t_3] is $D_{r1}(t)(1 - P_r/P_{n2})$, and demand of remanufactured product during [t_3, T] is $D_{r2}(t)(1 - P_r/P_{n2})$.

The demand function information is shared to all members of the supply chain, and retailer decides the retail prices (P_{n1}, P_{n2}, P_r), manufacturer decides the wholesale prices for new product (P_{nw}) and remanufactured product (P_{rw}), while collector determines collecting price P_{c1} and P_{c2} for cores collected from new products sold during $[0, \mu]$ and $[\mu, t_3]$ respectively. Since the product has short life-cycle, remanufacturing process is only applied to cores originated from new products. Return rate (τ) is an increasing function of the collecting price. We use the function proposed by Qiaolun et al. (2008), $\tau_1 = \gamma_1 P_{c1}^{\theta 1}$ and $\tau_2 = \gamma_2 P_{c2}^{\theta 2}$, where $\gamma_1, \gamma_2, \theta_1, \theta_2 \in [0,1]$. It is assumed that collector only accepts cores with a certain quality grade, and all collected cores will be remanufactured. Unit raw material cost for new product (c_{rw}), unit manufacturing cost (c_m), unit remanufacturing cost (c_r), and unit collecting cost (c) are known and constant, while transfer price P_f is a given value in the model. The objective of the proposed model is to find the optimum prices that maximize total profit of the supply chain using pricing game approach.

Optimization

After manufacturer releases initial wholesale prices (P_{nw}, P_{rw}), retailer optimizes the retail prices P_{n1}, P_{n2}, and P_r. The profit function can be formulated as follows:

$$\begin{aligned}
\Pi_R &= \int_0^{\mu} \frac{U}{1+ke^{-\lambda U t}}\left(1-\frac{P_{n1}}{P_m}\right)\left(P_{n1}-P_{nw}\right)dt + \int_{\mu}^{t_3} \frac{U}{\lambda U(t-\mu)+\delta}\left(1-\frac{P_{n2}}{P_m}\right)\left(P_{n2}-P_{nw}\right)dt \\
&\quad + \int_{t_1}^{t_3} \frac{V}{1+he^{-\eta V(t-t_1)}}\left(1-\frac{P_r}{P_{n2}}\right)\left(P_r-P_{rw}\right)dt + \int_{t_3}^{T} \frac{V}{\mu V(t-t_3)+\varepsilon}\left(1-\frac{P_r}{P_{n2}}\right)\left(P_r-P_{rw}\right)dt \\
&= d_1\left(1-\frac{P_{n1}}{P_m}\right)\left(P_{n1}-P_{nw}\right)+d_2\left(1-\frac{P_{n2}}{P_m}\right)\left(P_{n2}-P_{nw}\right)+\left(d_3+d_4\right)\left(1-\frac{P_r}{P_{n2}}\right)\left(P_r-P_{rw}\right) \qquad \text{........ (1)}
\end{aligned}$$

where

$$d_1 = \frac{1}{\lambda}\ln\left(\frac{\delta}{(1+k)e^{-\lambda U\mu}}\right) \qquad d_2 = \frac{1}{\lambda}\ln\left(\frac{\lambda U(t_3-\mu)+\delta}{\delta}\right)$$

$$d_3 = \frac{1}{\eta}\ln\left(\frac{\varepsilon}{(1+h)e^{-\eta V(t_3-t_1)}}\right) \qquad d_4 = \frac{1}{\eta}\ln\left(\frac{\eta V(T-t_3)+\varepsilon}{\varepsilon}\right)$$

The objective is to maximize profit (1), and consequently it needs to satisfy the first derivative condition. Hence,

$$P_{n1}{*} = \left(P_m + P_{nw}\right)/2 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (2) \;; \qquad P_r{*} = \left(P_{n2} + P_{rw}\right)/2 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (3)$$

$$-\frac{2}{P_m} d_2 \left(P_{n2}{*}\right)^3 + \left(d_2\left(1 + \frac{P_{nw}}{P_m}\right) + \frac{d_3 + d_4}{4}\right)\left(P_{n2}{*}\right)^2 - \frac{\left(d_3 + d_4\right)\left(P_{rw}\right)^2}{4} = 0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (4)$$

It is expected that $P_{n2}*$ is lower than $P_{n1}*$ to increase demand rate at the decline stage, however the model allows $P_{n2}*$ to attain higher value than $P_{n1}*$, which in turns is not attractive for customers. Our preliminary investigation showed that P_{n2} has a tendency to attain higher value than P_{n1}, which is also consistent with Ferrer & Swaminathan's finding (Ferrer & Swaminathan, 2006). Therefore, we impose a constraint where $P_{n2} \le P_{n1}$.

In the collector's optimization model, the objective function is

$$\text{Max} \quad \Pi_C = \gamma_1 P_{c1}{}^{\theta_1} d_1 \left(1 - \frac{P_{n1}}{P_m}\right)\left(P_f - P_{c1} - c\right) + \gamma_2 P_{c2}{}^{\theta_2} d_2 \left(1 - \frac{P_{n2}}{P_m}\right)\left(P_f - P_{c2} - c\right) \;\ldots\ldots\ldots\ldots\ldots (5)$$

However, since we assume balanced quantity throughout the supply chain, collector should only collect as much as the demand of the remanufactured product, which consequently determines collecting prices based on the following equations:

$$P_{c1}{**} = \left(\frac{\gamma_1 d_1 \left(1 - \dfrac{P_{n1}}{P_m}\right)}{d_3 \left(1 - \dfrac{P_r}{P_{n2}}\right)}\right)^{(1/\theta_1)} \;\ldots\ldots\ldots\ldots\ldots\; (6) \;; \; P_{c2}{**} = \left(\frac{\gamma_2 d_2 \left(1 - \dfrac{P_{n2}}{P_m}\right)}{d_4 \left(1 - \dfrac{P_r}{P_{n2}}\right)}\right)^{(1/\theta_2)} \;\ldots\ldots\ldots\ldots\ldots\; (7)$$

This approach is supported by Guide, Teunter, et al. (2003). When collecting prices are set, the maximization problem has shifted to a matter of determining the transfer price, which is a compromise between Collector and Manufacturer. We propose remanufacturing cost saving (*s*) as a parameter for determining transfer price P_f, such that unit cost for remanufacturing is $(1-s)$ of unit cost for manufacturing. This approach is logical because we believe that savings from remanufacturing would be an appropriate incentive for the manufacturer to remanufacture a product. After transfer price is agreed upon, manufacturer will determine the wholesale prices for both the new (P_{nw}) and the manufactured products (P_{rw}) in order to maximize her profit which is expressed in the following function:

$$\Pi_M = \left[d_1\left(1-\frac{P_{n1}}{P_m}\right) + d_2\left(1-\frac{P_{n2}}{P_m}\right)\right]\left(P_{nw}-c_{rw}-c_m\right) + \left(d_3+d_4\right)\left(1-\frac{P_r}{P_{n2}}\right)\left(P_{rw}-P_f-c_r\right) \quad \ldots\ldots\ldots(8)$$

First derivative conditions for optimizing manufacturer's profit are

$$\begin{aligned}\frac{\partial \Pi_M}{\partial P_{nw}} &= d_1\left(1-\frac{P_{n1}}{P_m}\right) + d_2\left(1-\frac{P_{n2}}{P_m}\right) - \frac{d_1}{2P_m}\left(P_{nw}-c_{rw}-c_m\right) \\ &\quad -\left[\frac{d_2}{P_m}\left(P_{nw}-c_{rw}-c_m\right) + \left(\frac{d_3+d_4}{P_{n2}}\right)\left(\frac{1}{2}-\frac{P_r}{P_{n2}}\right)\left(P_{rw}-P_f-c_r\right)\right]\frac{\partial P_{n2}}{\partial P_{nw}} = 0\end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

$$\begin{aligned}\frac{\partial \Pi_M}{\partial P_{rw}} &= \left(d_3+d_4\right)\left(1-\frac{P_r}{P_{n2}}\right) - \left(\frac{d_3+d_4}{2P_{n2}}\right)\left(P_{rw}-P_f-c_r\right) \\ &\quad -\left[\frac{d_2}{P_m}\left(P_{nw}-c_{rw}-c_m\right) + \left(\frac{d_3+d_4}{P_{n2}}\right)\left(\frac{1}{2}-\frac{P_r}{P_{n2}}\right)\left(P_{rw}-P_f-c_r\right)\right]\frac{\partial P_{n2}}{\partial P_{rw}} = 0\end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

where
$$\frac{\partial P_{n2}}{\partial P_{nw}} = \frac{d_2 P_{n2}}{6d_2P_{n2} - 2d_2P_{nw} - P_m\left(2d_2+d_3+d_4\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

$$\frac{\partial P_{n2}}{\partial P_{rw}} = \frac{\left(d_3+d_4\right)P_mP_{rw}}{-12d_2P_{n2}^{\ 2} + 4d_2P_{n2}\left(P_m+P_{nw}\right) + 2P_mP_{n2}\left(d_3+d_4\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

By solving equations (9) and (10), the optimum wholesale price P_{nw}^* and P_{rw}^* can be found. However, with these optimum wholesale prices, retailer's profit can decrease significantly when the previous retail prices are maintained, because manufacturer's profit model overlooks the demand rate. Therefore, we propose an alternate model where manufacturer considers demand rate to be influenced by the wholesale prices. In this case, retailer's margin rate is assumed, namely m_1, m_2, and m_3 for products sold at P_{n1}, P_{n2}, and P_r respectively. These margins are treated as parameters to the model. The modified profit function becomes

$$\Pi_{M2} = \left[d_1\left(1 - \frac{m_1 P_{nw}}{P_m}\right) + d_2\left(1 - \frac{m_2 P_{nw}}{P_m}\right)\right]\left(P_{nw} - c_{rw} - c_m\right) + \left(d_3 + d_4\right)\left(1 - \frac{m_3 P_{rw}}{m_2 P_{nw}}\right)\left(P_{rw} - P_f - c_r\right) \quad \text{……………………………..(13)}$$

The first derivatives are

$$\frac{\partial \Pi_{M2}}{\partial P_{nw}} = -\left(\frac{m_1 d_1 + m_2 d_2}{P_m}\right)\left(P_{nw} - c_{rw} - c_m\right) + \left[d_1\left(1 - \frac{m_1 P_{nw}}{P_m}\right) + d_2\left(1 - \frac{m_2 P_{nw}}{P_m}\right)\right] + \left(d_3 + d_4\right)\left(\frac{m_3 P_{rw}}{m_2 P_{nw}^{\;2}}\right)\left(P_{rw} - P_f - c_r\right) = 0 \quad \text{…………..(14)}$$

$$\frac{\partial \Pi_{M2}}{\partial P_{rw}} = \left(d_3 + d_4\right)\left[\left(1 + \frac{m_3}{m_2 P_{nw}}\right)\left(P_{rw} - P_f - c_r\right) + \left(1 - \frac{m_3 P_{rw}}{m_2 P_{nw}}\right)\right] = 0 \quad \text{……………………..(15)}$$

Solving (14) and (15) will result in the optimum wholesale prices P_{nw}** and P_{rw}**. Manufacturer applies the wholesale prices to the demand rate provided by retailer. This recalculation might decrease the total profit of supply chain members since increasing retail price would decrease the demand rate.

Numerical Example

In this numerical example, let assume that new product's demand capacity parameters are U=1000, D_0=90, λ=0.01, and remanufactured product's demand capacity parameters are

V=500, D_{r0}=50, η=0.01. Selling horizon is divided into four time periods where t_1=1, μ=2, t_3=3, and T=4. The unit raw material cost for new product c_{rw}=1500, unit manufacturing cost c_m=1000, unit remanufacturing cost c_r=800, and unit collecting cost c=100. Maximum price is P_m=12000, and remanufacturing cost saving is 20%. Return rate parameters are $\gamma_1 = \gamma_2$ =0.01, and $\theta_1 = \theta_2$=0.7. Manufacturer's assumption for Retailer's margins are $m_1 = m_2 = m_3 =$ 120%. Table 2 shows the numerical example results.

It is observed that P_{n2} is higher than P_{n1} which forced the system to adjust so that P_{n2} does not exceed P_{n1}. It appears that the rapid decrease in demand for the new product during [μ, t_3] could not be compensated by giving a price discount. Mathematically it is understandable that when there is a rapid decline in demand and reducing price does not lead to a significant increase in demand, the only way to maintain profit is to set the retail price high. However, from business perspective it does not make good sense to increase the retail price when a product is entering a decline stage. We also observed that collector profit is much lower than retailer's and manufacturer's, because collector only gains from remanufactured product. This result is consistent with Qiaolun et al. (2008).

TABLE 2. NUMERICAL EXAMPLE RESULTS

Demand		**Retailer**	**Collector**	**Manufacturer**
d_1= 381.75	**Prices**	P_{n1}= 9,395.96	P_{c1}= 295.69	P_{nw}= 6,791.92
d_2= 52.04		P_{n2}= 9,395.96	P_{c2}= 634.91	P_{rw}= 4,395.96
d_3= 204.82		P_r= 6,895.96	P_f = 1200.00	
d_4= 47.66	**Profit**	1,760,806.07	186,905.17	2,466,723.19
	TOTAL PROFIT = 4,414,434.42			

The impact of remanufacturing cost saving (s) on the optimum results

Remanufacturing cost saving obviously has an impact on collector's and manufacturer's profit, and it affects the total profit. By varying *s* from 10%, 20%, 30% and 40%, we find that the total profit is increasing along with higher *s*. This relations can be explained as follows. When higher s is used, the remanufacturing variable cost is lower, hence the margin for each remanufactured product is higher. Hence, the ratailer could set lower retail price for remanufactured products. As Table 3 shows, with higher *s* values, the optimum value of P_r decreases which then creates higher demand for remanufactured products. However, collector's profit diminishes as *s* increases, so a limit should be posted according to both parties agreement.

TABLE 3. THE EFFECT OF REMANUFACTURING COST SAVINGS ON OPTIMUM RESULTS

s	P_{n1}	P_{n2}	P_r	P_{nw}	P_{rw}	P_f	P_{c1}	P_{c2}
10%	9,388.99	9,388.99	6,951.49	6,777.99	4,513.99	1,450.00	284.40	610.67
20%	9,395.96	9,395.96	6,895.96	6,791.92	4,395.96	1,200.00	295.69	634.91
30%	9,402.06	9,402.06	6,839.56	6,804.12	4,277.06	950.00	307.05	659.30
40%	9,407.31	9,407.31	6,782.31	6,814.63	4,157.31	700.00	318.47	683.83

s	Π_R	Π_C	Π_M	Total
10%	1,736,138.56	247,339.24	2,418,447.40	4,401,925.20
20%	1,760,806.07	186,905.17	2,466,723.19	4,414,434.42
30%	1,787,044.42	123,222.75	2,516,268.80	4,426,535.97
40%	1,814,838.07	56,282.42	2,567,095.30	4,438,215.79

Conclusion and Future Research Opportunities

In this study we have developed pricing model for short life-cycle with remanufacturing. The study fills the gap in remanufacturing literature which to date has been mostly dominated by durable products. For some short life-cycle products, remanufacturing is a sensible activity to do, but the speed of collecting and remanufacturing the used products should be quick as the demand for the product is diminishing fast. The lack of coordination in making the pricing decision has led the model to set too high retal prices and hence the demand potential is not well exploited. We initially thought that the retail price should be reduced when the product is entering a decline phase, but from the results it is apparent that lowering the price does not help increasing the profit during that period. This is also understandable because as the demand is sharply declining, the only way to obtain higher profit is to set a high price, so getting a very few customers that are buying the product with high price results in higher revenue rather than discounting the price, but the demand only increases slightly. However, from business point of view, it is not sensible to increase the price during the decline period. Numerical examples show that higher remanufacturing cost-savings has reduced collector's profit, which means retailer or manufacturer should take over the collection activities under high remanufacturing cost-savings cases.

Future research may be directed toward development of models that consider different demand processes, multiple objective functions, and the case when balanced quantity is not the case. It may be possible that the collector is not able to collect at the quantity desired by the manufacturer. It is also possible that the manufacturer has a certain capacity constraint where not all demand can be satisfied. In such as case it is important to take into account the service level.

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