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Optimal Order Quantities with Remanufacturing Across New Product Generations

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We address the problem of determining the optimal retailer order quantities from a manufacturer who makes new products in conjunction with ordering remanufactured products from a remanufacturer using used and unsold products from the previous product generation. Specifically, we determine the optimal order quantity by the retailer for four systems of decision-making: (a) the three firms make their decisions in a coordinated fashion, (b) the retailer acts independently while the manufacturer and remanufacturer coordinate their decisions, (c) the remanufacturer acts independently while the retailer and manufacturer coordinate their decisions, and (d) all three firms act independently. We model the four options described above as centralized or decentralized decision-making systems with the manufacturer being the Stackelberg leader and provide insights into the optimal order quantities. Coordination mechanisms are then provided which enable the different players to achieve jointly the equivalent profits in a coordinated channel.

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1. Introduction

The importance of component reuse in the saving of costs of subsequent product generations is well recognized in the literature. Reuse can reduce the number of components that need to be redesigned and ordered from new suppliers. Research on the lifecycle analysis (LCA) of multiple product generations indicates the importance of linking product design to component reuse over the product lifecycle (Lewis and Gertsakis 2001). Practical examples can be found in the electronics industry for copiers and laser printers (SCC Report 2003) and personal computers (Blazek et al. 1998). For this industry, the product lifecycle is getting shorter, while production lead-time is staying relatively stable, making remanufacturing an attractive proposition.

OEMs (original equipment manufacturers) respond differently to manage the combination of new product manufacture and remanufacturing. The organization of the closed-loop supply chain and the reuse of unsold and used products of the previous generation depend largely on the product characteristics, and industry experience (Guide and Van Wassenhove 2003). For example, in the copier industry, the manufacturer integrates used product remanufacturing in parallel with manufacturing new products (Xerox Environmental Report 1997). Hewlett-Packard controls its printer remanufacturing and refurbishing through a network of hardware recovery centers (Kumar et al. 2002). In contrast, there are a number of third-party remanufacturers who either remanufacture products in coordination with the manufacturer, or as a separate agent. Third-party remanufacture can readily be found for ink cartridges (Krazit 2003), mobile telephones (Guide et al. 2003), and components for heavy equipment. OEMs may have their own retail network, act in a coordinated fashion with their retailers, or sell products through independent retailers. McGuire and Staelin (1983) and several subsequent papers in the marketing and operations literature study coordination and independent decision-making between the retailer and the manufacturer.

In this paper, we examine the implications of the decision-making structure (OEMs, retailers and remanufacturers making their decisions jointly or independently) on the optimal ordering decision of the retailer, and the supply chain profits. We focus on cases where unsold products at the end of the period (salvages) and products returned by end-users are remanufactured into products of the original quality. We assume perfect substitution, i.e., the customer does not make a distinction between a new and remanufactured product. Typical examples are single use cameras and toner cartridges. We consider four decision-making structures: (a) the manufacturer coordinating with the retailer and the remanufacturer to obtain the optimal channel profit ordering quantity, (b) the retailer ordering independently but the manufacturer and remanufacturer coordinating their actions, (c) the remanufacturer acting independently when quoted a buyback price for remanufactured products, but the manufacturer and retailer coordinating their actions, and (d) all three parties acting independently. Channel members are independent entities maximizing an objective function dependent on the decisions of the other parties. Specifically, the research questions addressed in this paper are as follows:

(i) How are supply chain profits and optimal retailer order quantity impacted by the different decision-making structures and what are the implications on customer service levels?

(ii) What are the different factors the optimal order quantity depends on?

(iii) What are the mechanisms by which the manufacturer can achieve coordination in the decentralized systems?

The rest of the paper is organized as follows. In the following section we briefly discuss the contribution of the paper to the current literature on ordering decisions, the research on centralized vs. decentralized systems, and coordination issues. Section 3 introduces the model concept, Section 4 the model formulation and analysis, and coordination mechanisms for the decentralized systems. Insights from the models are presented in Section 5. Contributions and limitations of this paper and possible directions for future research are given in Section 6.

2. Relevant Literature

General overviews of product recovery and remanufacturing can be found in Thierry et al. (1995), Fleischmann et al. (1997), and Guide (2000). We also refer to the book, edited by Guide and Van Wassenhove (2003), from the First Workshop on Business Aspects of Closed-Loop Supply Chains.

The operational aspects of remanufacturing have received the most attention. There are numerous publications dealing with production planning and control, inventory control, and materials planning. The problem of deciding the optimal order quantity and production levels with a combination of manufacturing and remanufacturing has been studied using continuous and periodic inventory models (Mahadevan et al. 2003; van der Laan et al. 1999). This stream of literature considers a single product inventory management model, with a sufficiently short lead-time compared to the product lifecycle making the inventory management policies repetitive in nature. Mahadevan et al. (2003) consider a repetitive periodic review inventory policy with a push manufacturing system to determine the control policy for remanufacturing returned products and how many new products to manufacture each time. We model the inventory problem in the newsvendor framework since we model ordering policies for products with short lifecycles. Muckstadt and Isaac (1981) first studied inventory control policies in combination with product returns, but no remanufacturing. This paper looks at ordering policies in each period when remanufacturing unsold and used products of the previous generation lowers costs.

In a similar vein, Fleischmann and Kuik (1998) studied inventory policies under a distributed return stream over time with uncertain return and scrap rates. In contrast, we look at policies where used and unsold products are available at the end of the current product generation's lifetime. Inderfurth (1997) characterizes the disposal, remanufacturing release policy and new product manufacturing policy through a three critical number policy when the forward and reverse channels have the same lead-time. In this paper, remanufacturing lead-times are given (equal to zero) and the optimal new product manufacturing policy at the beginning of each product generation lifecycle is characterized.

There are a number of articles considering the impact of remanufacturing on product design issues. Linton and Johnston (2000) provide a decision support system to coordinate the design of future product generations with remanufacturing previous ones. The focus of this paper is on the optimal ordering policy under remanufacturing. We do not consider the implications for product design, but take that as given. Similarly, Rudi et al. (2000) provide a decision support framework to determine when to refurbish units in a medical product environment. While this paper has modeled the problem to fit the industry practice in environments with short product lifecycles and remanufacturing, it keeps an analytical focus.

Finally, Karmarkar (1981) and Karmarkar (1987) examine the multi-location multi-period problem of deciding inventory policy for a single item that can be stored in multiple locations and transferred at certain cost across locations. While this paper also deals with a multi-period problem, our focus is on reusing unsold and a fraction of used products in the next product generation. Hence, the insights obtained from this paper are of a different nature.

3. Model Description

Consider the following scenario. The manufacturer releases a new generation of products in every period, and incorporates a recovery process for previous generation products into its production system in conjunction with the manufacturing of new products. Both used and unsold products from previous generations may be considered for remanufacturing and sale in the current period. The manufacturer achieves this by interacting with a firm specializing in remanufacturing.

Assumption 1. *We assume that new and remanufactured products are perfect substitutes and that remanufacturing a product from a previous generation is less costly than manufacturing a new one.*

This assumption is supported by the empirical literature on product recovery management, which found that besides the social and environmental benefits, a lower unit variable cost is an additional benefit of remanufacturing (Guide 2000, Thierry 1997). Denote c_i as the unit variable cost of manufacturing a new product by the manufacturer, $\bar{c}_i < c_i$ the cost of remanufacturing an as-new product by the remanufacturer, and b_i the price paid by the manufacturer for a remanufactured unit in period i.

Assumption 2. *We assume the unit cost of the remanufacturer is the same for all used products as well as salvages from the previous period.*

The remanufacturer can obtain products from the previous product generation in two different ways. The remanufacturer can either remanufacture products that remained unsold in the previous period (salvages) or products that were sold, used, and then acquired from customers at the end of the period. Essentially, both used and salvaged products need to go through the same set of operations: disassembly, upgrading (e.g., software), reassembly, testing, and packaging. So the equal remanufacturing cost assumption is not unreasonable for up-gradable products with a rapid rate of technological obsolescence. If this assumption does not hold true in a certain environment, it can be relaxed easily by incorporating a yield rate on the returned product quality. Additionally, if a product acquisition management system is used, products are screened and graded before being accepted, and this greatly reduces the variability in remanufacturing costs (Guide et al. 2003).

Assumption 3. *We assume that all salvages from the previous period are available for remanufacturing* (*the recovery of salvaged units from retailers is controlled by the manufacturer*), *and of the quantity sold in the previous period, a fixed fraction α is returned by the users and available for remanufacturing in the current period.*

Our observations in industry confirm that when a higher quantity of a certain product generation is sold the returns from that generation are correspondingly higher. This assumption has also been made in previous research (Debo et al. 2005).

Assumption 4. *We assume there is a collection network in place and the marginal collection cost of a used product is negligible.*

This assumption is made for the purpose of tractability of the model. The collection cost effect of used products has been studied in Savaskan et al. (2004), and we do not focus on the collection agent, but on the quantity to order in each period.

Assumption 5. *We assume that products can be used for a limited number of future product generations.*

This limited number of reuse cycles depends on the rate of technological change, i.e., innovation, and finite product durability, i.e., wear and tear. The limited reuse assumption is consistent with previous research by Debo et al. (2005).

We model limited reuse by a factor k representing the fraction of salvaged and collected used products that can be remanufactured. The complimentary fraction (1-k) corresponds to products that have become technologically obsolete or worn out beyond recovery. Denoting sales in period i by L_i, and the unsold units salvaged at the end of the period by s_i the quantity remanufactured in period i is then given by $k(s_{i-1} + \alpha L_{i-1})$.

Note that by varying the parameters α and k, we can represent a wide variety of industrial cases. For example, setting $k = 0$ dictates the products cannot be remanufactured and used in the next generation due to a very rapid rate of technological or physical obsolescence. Conversely, setting $k = 1$ and $\alpha = 1$ corresponds to the opportunity for infinite reuse. The case $k = 0.1$ approximates the single reuse situation since even when $\alpha = 1$, the second time around, the reuse opportunity would only be 0.01 or one percent of the available salvaged and returned products. Kodak's single use cameras are designed to be reused five times, while the collection rate $\alpha = 0.6$; in this case, k is close to one.

To capture the iterative nature of the decision-making process, we model the problem as an N-period model, where, in each period, the firms have to decide the following variables: (i) The manufacturer decides the wholesale price charged to the retailer and the buyback price given to the remanufacturer, and (ii) the retailer decides how many units to order from the manufacturer. The firms have the same constant discount factor δ to account for the drop in utility of profits from one period to the next. This assumption can be relaxed easily.

We denote Qi as the order quantity for new product manufacturing in period i. This order quantity depends on the demand distribution, the costs of manufacturing and remanufacturing, the new order quantities in previous periods, and the costs, prices, and discount factor. The retailer's ordering problem is modeled using the familiar newsvendor model. We believe the newsvendor formulation best captures the short product lifecycle aspect of the applications we have observed in industry.

Following the newsvendor model, we model the demand to be uncertain (demand is denoted by the random variable x in each period) with a probabilistic distribution function (*pdf*) of $f(x)$ and a cumulative distribution function (*cdf*) of $F(x)$, known to the retailer based on historical estimates. We assume that the demand distribution f is *IGFR* (increasing generalized failure rate) to ensure the existence of the optimal solution for the decentralized channels. The retail price charged by the retailer in each period is denoted by p_i and the wholesale price charged by the manufacturer in each period w_i. We model the newsvendor with lost sales (no backorder costs), and we do not assume the existence of holding costs in each period.

Assumption 6. *We assume that the demand distribution is stationary over time, manufacturing costs drop faster than prices, specifically* $(c_i/c_{i+1}) > (p_i/p_{i+1})$, savings from remanufacturing are proportional to the manufacturing cost, i.e., $c_{i+1} - \bar{c}_{i+1} = Ac_i$, and are negligible in the last period.

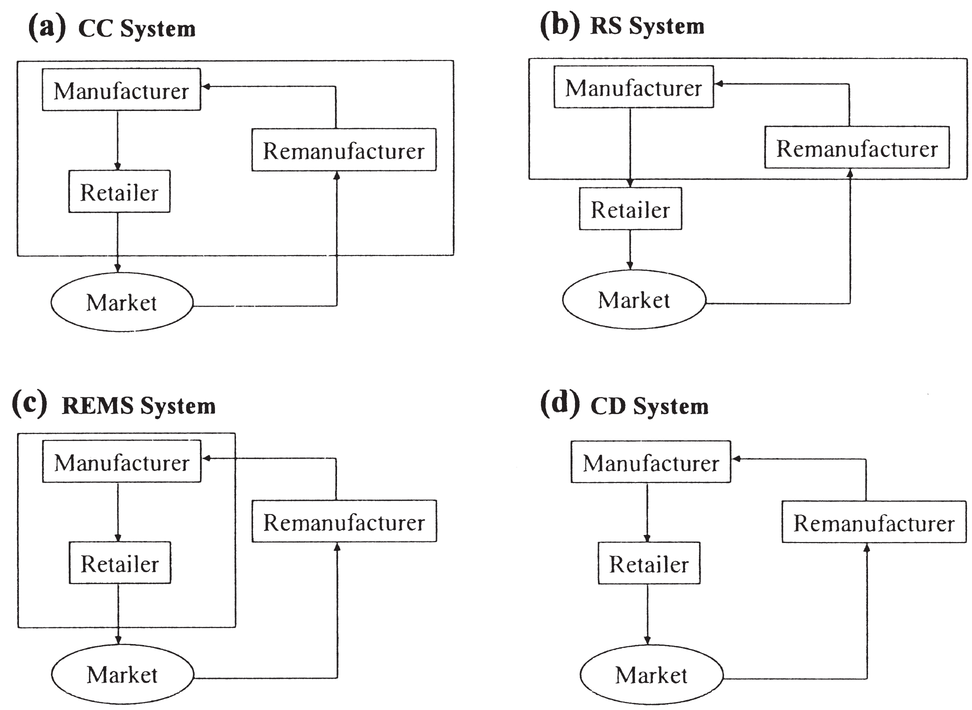
The first part of our assumption is consistent with the literature (Moorthy and Png 1992; Bhattacharya et al. 2003), which finds that high-end products (first generation) command higher margins than low-end products (later generation). The second part of the assumption reflects the fact that over time, the cost to produce a new product is going down while the cost of remanufacturing goes up due to the need to replace more components and the higher labor content in remanufacturing a product relative to manufacturing a new one. It also makes sense to assume that for the last generation, there are no longer any savings from remanufacturing, i.e., it is time to launch a completely new product. Assumption 6 also ensures that the starting inventory in period i is not greater than the order-up-to target in our newsvendor models.

The primary aim of the paper is to examine the impact of the channel structure on the ordering decision for each period, and the profits for the retailer, manufacturer and remanufacturer. We compare the order quantities in the different channel formats, assuming that each of the known variables stays the same under each channel format. The coordinated channel is the well-known channel format where a single agent acts as a profit-maximizing decision-maker for all three firms (CC system, Figure 1a). The coordinated channel acts as a benchmark case in this paper for the three decentralized cases. Presently, there are few industrial systems that behave in a purely centralized fashion. Pitney Bowes manufactures mailing systems, including postage meters, and controls the entire supply chain. The only difference being that postage meters cannot be sold by law, so Pitney Bowes leases the meters for periods ranging from 12 to 60 months, and uses returns in remanufactured and next generation meters. In Section 4, we examine coordination mechanisms with remanufacturing which achieve the profit levels of the coordinated benchmark scenario.

In the retailer-separate channel structure (RS system, Figure 1b), the manufacturer and remanufacturer coordinate their decisions, and the retailer acts independently in deciding how much to order from the manufacturer. As the remanufactured units are cheaper, the manufacturer buys all available units from the remanufacturer, and then makes from raw materials the remaining units ordered by the retailer. The RS channel structure is typical for the photocopier and single use camera industry. Complete descriptions of Xerox and Kodak's closed-loop supply chains may be found in Guide et al. (2003). In the remanufacturer-separate channel structure (REMS system, Figure 1c), the manufacturer and the retailer coordinate their decisions, and the remanufacturer acts independently of the two. The coordinated unit offers a buyback price b_i for each remanufactured product. Telecommunications firms, such as Lucent, use this type of channel structure. In the completely decentralized system (CD system, Figure 1d) all three parties act independently. Mobile telephone remanufacturing is an excellent example of this type of channel structure. A complete description of a third-party mobile telephone remanufacturer, ReCellular, Inc., is presented in Guide et al. (2005).

Assumption 7. *In determining the outcome of the games played between the manufacturer, retailer and remanufacturer, the manufacturer has sufficient channel power over the other two parties to act as a Stackelberg leader. Thus, the manufacturer uses its foresight about the*

Figure 1 **Channel decision-making structures.**



reaction functions of the other two parties in its decision-making process.

The Stackelberg structure has been used widely in the literature (Lariviere and Porteus 2001; Weng 1995). In this paper, the manufacturer acts as the central unit between the retailer and the remanufacturer, therefore it is reasonable to assume that the Stackelberg leadership rests with the manufacturer. If the retailer is the Stackelberg leader, we conjecture that the results will be in the same direction as posited in the paper. However, in this case the profits accrued to the three parties will be different.

4. Model Formulation and Analysis

In this section, we compare the channel structures with respect to the order quantity of the retailer from the manufacturer. We begin by analyzing the coordinated firm, where only the salvaged units are remanufactured. This helps us obtain a benchmark for studying the efficiency of the systems when some of the units sold in the previous period are remanufactured as well. The profit functions of the channel members can be trivially shown to be concave in the optimal order quantity from the manufacturer, so first order conditions are used throughout.

4.1. The No Recovery Case

In the coordinated channel with no recovery, the total system profits in each period are given by:

$$E(\Pi_i^{NC}) = p_i \int_0^{ks_{i-1}+Q_i} x f(x)\mathrm{d}x + p_i \int_{ks_{i-1}+Q_i}^{\infty} (ks_{i-1} + Q_i) f(x)\mathrm{d}x - ks_{i-1}\bar{c}_i - c_i Q_i$$

$I = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$

The first term corresponds to the revenues from units sold if demand is less than the total quantity available (remanufactured plus manufactured units), and the second term corresponds to revenues from units sold if demand exceeds the total quantity available. The third term represents the total cost of remanufactured units, and the fourth term reflects the total cost of newly manufactured units.

$s_{i-1} = \int_0^{ks_{i-2}+Q_{i-1}} (ks_{i-2} + Q_{i-1} - x) f(x)\mathrm{d}x$. The total system profits over N periods are given by: $E(\Pi^{NC}) = \sum_1^N \delta^{i-1} E(\Pi_i^{NC})$. We solve this dynamic program in the N^{th} period, and then solve the dynamic program backwards in each period. The quantity to be newly manufactured in each period is given by the following result:

Result 1. *The quantity to be manufactured in the last period is given by* $\bar{F}(ks_{N-1} + Q_N) = (c_N/p_N)$. *The quantity to be manufactured in the previous periods* ($i = 1,2,3,\ldots, N-1$) *is given by* $\bar{F}(ks_{i-1} + Q_i) = \{c_i - \delta k(c_{i+1} - \bar{c}_{i+1})\}/\{p_i - \delta k(c_{i+1} - \bar{c}_{i+1})\}$.

Here, $\bar{F}(y) = 1 - F(y)$. The proof of the result is in a working paper (Bhattacharya et al. 2006). We present the intuition here. The result is analogous to the newsvendor problem with salvage value. The ordering decision for the last (N^{th}) period is the same as the newsvendor one since units left unsold in the last period have no salvage value. When the salvage value is included in the one-period newsvendor model, the order quantity is given by $\bar{F}(y) = (c - s)/(p - s)$, where c is the unit cost, p the price, and s the salvage value. For periods $i = 1,2,\ldots, N-1$, if a unit is unsold at the end of the period i, depending on k, it can perhaps be remanufactured and sold as new in the next period $i + 1$. If the item is remanufactured it need not be newly manufactured in the next period $i + 1$, hence it generates a salvage value of $c_{i+1} - \bar{c}_{i+1}$, discounted by ä.

4.2. The Recovery Case

In the recovery case, we assume that in addition to the salvaged units, the remanufacturer also collects a fixed fraction α of the units that were sold in the previous period. The remanufacturer then makes new products from the total of salvaged products and used products.

4.2.1. Coordinated Channel (CC System, Figure 1a)

In the coordinated channel with recovery, the total system profits in each period are given by:

$$E(\Pi_i^{CC}) = p_i \int_0^{k(s_{i-1}+\alpha L_{i-1})+Q_i} xf(x)\mathrm{d}x$$

$$+ p_i \int_{k(s_{i-1}+\alpha L_{i-1})+Q_i}^{\infty} \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} f(x)\mathrm{d}x - k$$

$$(s_{i-1} + \alpha L_{i-1})\bar{c}_i - c_i Q_i$$

$$i = 1,2,3,\ldots, N \text{where} s_0 = Q_0 = 0.$$

The additional revenue term corresponds to the remanufactured units sold in each period, and the additional cost term to the cost of remanufacturing the used units collected in the previous period. The total system profits in N periods are given by: $E(\Pi^{CC}) = \Sigma_1^N \delta^{i-1} E(\Pi_i^{CC})$. As before, we begin by solving this dynamic program in the N^{th} period, and then solve the dynamic program backwards in each period. The quantity to be newly manufactured in each period is given by the following result:

Result 2. *In the CC system, the quantity to be manufactured in the last period is given by* $\bar{F}\{k(s_{N-1} + \alpha L_{N-1}) + Q_N\} = (c_N/p_N)$. *The quantity to be manufactured in the previous periods* ($i = 1,2,3,\ldots, N-1$) *is given by* $\bar{F}\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} = \{c_i - \delta k(c_{i+1} - \bar{c}_{i+1})\}/\{p_i - \delta(1 - \alpha)k(c_{i+1} - \bar{c}_{i+1})\}$.

The proof of the result is in the working paper. As before, when the product is more reusable (higher k), the order quantity is increasing. The denominator reflects that since remanufactured units have a salvage value of $(c_{i+1} - \bar{c}_{i+1})$,, the variable cost for these units decreases by that amount, discounted by δ. In addition the numerator also accounts for the fact that a fraction $(1 - \alpha)$ of sold units does not return.

4.2.2. Retailer-Separate Channel (RS System, Figure 1b). In the channel where the retailer acts as a separate decision-making agent, and the manufacturer and remanufacturer coordinate their decisions, the model can be set up in a similar way to Lariviere and Porteus (2001). The manufacturer provides a wholesale price to the retailer, who then places an order in that period. The manufacturer also coordinates with the remanufacturer, and decides its production level taking into account the number of remanufactured units available for the period. We first optimize the profit function of the retailer for the quantity to be ordered from the manufacturer, implicitly with respect to the wholesale price. This implicit relationship for the profit of the retailer is then substituted in the profit function of the manufacturer, who finds the optimal quantity to order. We make the same assumptions for the remanufacturer as before, i.e., he provides remanufactured units from the salvages and the fixed fraction α of the units that were used and collected in the previous period, and optimizes his profits jointly with the manufacturer. In the RS-separate system with recovery, the retailer's profits in each period are given by:

$$E(\Pi_i^{R,RS}) = p_i \int_0^{k(s_{i-1}+\alpha L_{i-1})+Q_i} xf(x)\mathrm{d}x + p_i \int_{k(s_{i-1}+\alpha L_{i-1})+Q_i}^{\infty}$$

$$\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} f(x)\mathrm{d}x - w_i\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}$$

$i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$.

The change in the profit function corresponds to the wholesale price being charged by the manufacturer for all units supplied in that period.

The manufacturer and remanufacturer profits in each period are given by:

$E(\Pi_i^{M,RS}) = (w_i - c_i)Q_i + (w_i - \bar{c}_i)k(s_{i-1} + \alpha L_{i-1})$ for $i = 1,2,3,\ldots, N$. The total retailer profits in N periods are given by: $E(\Pi^{R,RS}) = \Sigma_1^N \delta^{i-1} E(\Pi_i^{R,RS})$, and the total manufacturer and remanufacturer profits by:$E(\Pi^{M,RS}) = \Sigma_1^N \delta^{i-1} E(\Pi_i^{M,RS})$. We begin by solving this dynamic game between the retailer and the coordinated unit of the manufacturer and remanufacturer in the N^{th} period, and then solve the dynamic game backwards in each period. The quantity to be newly manufactured in each period is given by the following result:

Result 3. *In the RS system, the quantity to be manufactured in the last period is given by* $\bar{F}\{k(s_{N-1} + \alpha L_{N-1})$

$+ Q_N\} - \{k(s_{N-1} + \alpha L_{N-1}) + Q_N\}f\{k(s_{N-1} + \alpha L_{N-1}) + Q_N\} = (c_N/p_N)$. *The quantity to be manufactured in the previous periods* ($i = 1,2,3,\ldots,N-1$) *is given by*

$$\bar{F}\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} - \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}f\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} = \frac{c_i - \delta k(c_{i+1} - \bar{c}_{i+1})[\alpha + (1-\alpha)F\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}]}{p_i}$$

The proof of the result is in the working paper. We present the intuition here. The result for the last period is identical to Lariviere and Porteus (2001). Since the salvages and collected units from this period will not be reused, they do not have any value. However, in the previous periods, since salvages and collected units add value in the subsequent period through remanufacturing savings, the retailer and the manufacturer combine to order more in each period. The additional term in the numerator on the right hand side includes remanufacturing savings as before, the fixed fraction of units that are collected, as well as the third term, which reflects the savings generated from remanufacturing.

4.2.3. Remanufacturer-Separate Channel (REMS System, Figure 1c). For the channel where the remanufacturer acts as a separate agent and the manufacturer and retailer act as a coordinated unit, we model the interaction between the remanufacturer and manufacturer through a buyback price b_i for each remanufactured unit. As before, the remanufacturer makes new products from salvaged products and collected used products.

In the REMS channel with recovery, the profits of the coordinated manufacturer and retailer unit in each period are given by:

$$E(\Pi_i^{R,REMS}) = p_i \int_0^{k(s_{i-1}+\alpha L_{i-1})+Q_i} xf(x)\mathrm{d}x + p_i \int_{k(s_{i-1}+\alpha L_{i-1})+Q_i}^{\infty} \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}f(x)\mathrm{d}x - b_i k(s_{i-1} + \alpha L_{i-1}) - c_i Q_i$$

$i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$

The additional cost term corresponds to buying back the salvaged units and the used units collected in the previous period. The total manufacturer and retailer profits over N periods are given by: $E(\Pi^{M,REMS}) = \sum_1^N \delta^{i-1}E(\Pi_i^{M,REMS})$. The remanufacturer's profits in each period are given by:

$E(\Pi_i^{REM,REMS}) = (b_i - \bar{c}_i)k(s_{i-1} + \alpha L_{i-1})$ for $i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$, and the total remanufacturer profits over N periods by: $E(\Pi^{REM,REMS}) = \sum_1^N \delta^{i-1}E(\Pi_i^{REM,REMS})$. As before, we begin by solving this dynamic game between the remanufacturer and the coordinated unit of the manufacturer and retailer in the N^{th} period, and then solve the dynamic game backwards in each period. The quantity to be newly manufactured in each period is given by the following result:

Result 4. *In the REMS system, the quantity to be manufactured in the last period is given by* $\bar{F}\{k(s_{N-1} + \alpha L_{N-1}) + Q_N\} = (c_N/p_N)$. *The quantity to be manufactured in the previous periods* ($i = 1,2,3,\ldots,N-1$) *is given by the following set of implicit equations*: $\bar{F}\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} = \{c_i - \delta k(c_{i+1} - b^*_{i+1})\}/\{p_i - \delta(1-\alpha)k(c_{i+1} - b^*_{i+1})\}$, *where* $b_i^* > \bar{c}_i$ *is set by the manufacturer*.

The proof of the result is in the working paper, and the intuition is similar to Result 2. When the remanufacturer acts as a separate entity the buyback price performs the same role as the unit cost of remanufacturing, and the manufacturer-retailer coordinating unit orders the analogous quantity as the coordinated channel, with the buyback price b_i replacing the unit cost of remanufacturing, $\bar{c}_i$. Since the remanufacturer now operates as separate decision-making unit, the order quantity in total is lower. However, the manufacturer may still prefer to make more new units than before (as in the last, i.e., N^{th} period). The reason is that since the remanufactured units are now more expensive, the manufacturer has an incentive to replace some of the remanufactured units by newly manufactured units.

4.2.4. Completely Decentralized Channel (CD System, Figure 1d). For the channel where both the retailer and the remanufacturer act as separate agents, we model the interaction between the manufacturer and the retailer and remanufacturer through the same assumptions as in Sections 4.2.2 and 4.2.3.

In the CD channel with recovery, the profits of the retailer in each period are given by:

$$E(\Pi_i^{R,CD}) = p_i \int_0^{k(s_{i-1}+\alpha L_{i-1})+Q_i} xf(x)\mathrm{d}x + p_i \int_{k(s_{i-1}+\alpha L_{i-1})+Q_i}^{\infty} \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}f(x)\mathrm{d}x - w_i\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}$$

$i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$

The profits of the manufacturer in each period are given by:

$E(\Pi_i^{M,CD}) = (w_i - c_i)Q_i + (w_i - b_i)k(s_{i-1} + \alpha L_{i-1})$ for $i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$. The remanufacturer's profits in each period are given by: $E(\Pi_i^{REM,CD}) = (b_i - \bar{c}_i)k(s_{i-1} + \alpha L_{i-1})$ for $i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$. The total retailer, manufacturer and remanufacturer profits over N periods are given by: $E(\Pi^{R,CD}) = \sum_1^N \delta^{i-1}E(\Pi_i^{R,CD})$, $E(\Pi^{M,CD}) = \sum_1^N \delta^{i-1}E(\Pi_i^{M,CD})$, and $E(\Pi^{REM,CD}) = \sum_1^N \delta^{i-1}E(\Pi_i^{REM,CD})$, respectively. As before, we begin by solving this dynamic game in the N^{th} period, and then solve the dynamic game backwards in each period. The quantity to be newly manufactured in each period is given by the following result:

RESULT 5. *In the CD system, the quantity to be manufactured in the last period is given by* $\bar{F}\{k(s_{N-1} + \alpha L_{N-1}) + Q_N\} - \{k(s_{N-1} + \alpha L_{N-1}) + Q_N\}f\{k(s_{N-1} + \alpha L_{N-1}) + Q_N\} = (c_N/p_N)$. *The quantity to be manufactured in other periods* ($i = 1,2,3,\ldots, N-1$) *is given by the set of implicit equations*:

$$\bar{F}\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} - \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} f\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} = \frac{c_i - \delta k(c_{i+1} - b^*_{i+1})[\alpha + (1-\alpha)F\{k(s_{i-1} + \alpha L_{i-1}) + Q_i\}]}{p_i}$$

where $b^*_i > \bar{c}_i$ is set by the manufacturer.

The proof of the result is in the working paper, and the intuition is similar to the intuition behind Results 3 and 4. When both the retailer and the remanufacturer act as separate entities, the total order quantity decreases due to two factors: (i) in the game between the manufacturer and the retailer the risk is not shared adequately (in a coordinated effort between the manufacturer and the retailer, there is no double marginalization), and (ii) the double marginalization between the remanufacturer and the manufacturer (the buyback price is higher than the cost of remanufacturing).

4.2.5. Coordination in the Decentralized Systems. Under the assumption of complete information about cost, price and demand being shared between the three parties we first derive simple contractual forms which may be offered by the manufacturer to the retailer and the remanufacturer to induce them to coordinate their actions with the manufacturer to maximize total channel profits. The manufacturer can influence the retailer's ordering decision by specifying a contract of the type $W = [w_i, F_i]$, where w_i stands for a suitable wholesale pricing scheme in each period, and F_i is a fixed payment made by the retailer to the manufacturer in each period to distribute the efficiency gains. Similarly, the remanufacturer can influence the ordering decision of the retailer by the specification of a contract of the type $B = [b_i, G_i]$, where b_i stands for a suitable buyback pricing scheme in each period, and G_i is a fixed payment made by the manufacturer to the remanufacturer in each period to distribute the efficiency gains. Labeling this system as the *COD* system, the manufacturer's problem in each period is formulated as:

$$\underset{W,B}{Max}\ E(\Pi^{M,COD}) = \Sigma_1^N \delta^{i-1} E(\Pi_i^{M,COD})$$

where

$$E(\Pi_i^{M,COD}) = (w_i - c_i)Q_i^* + (w_i - b_i^*)k(s_{i-1} + \alpha L_{i-1})F_i - G_i$$

$i = 1,2,3,\ldots, N$ where $S_0 = Q_0 = 0$ subject to

$$\textbf{IC1}: Q_i^* = \text{argmax}_{Q_i}\{E(\Pi^{R,COD}(W, Q))\}$$

$$\textbf{IC2}: b_i^* > \bar{c}_i$$

$$\textbf{IR1}: E(\Pi^{R,COD}(W,Q)) \geq E(\Pi^{R,CD})$$

$$\textbf{IR2}: E(\Pi^{REM,COD}(B,b)) \geq E(\Pi^{REM,CD})$$

where

$$E(\Pi_i^{R,COD}) = p_i \int_0^{k(S_{i-1}+\alpha L_{i-1})+Q_i} xf(x)\mathrm{d}x + p_i \int_{k(S_{i-1}+\alpha L_{i-1})+Q_i}^{\infty} \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} f(x)\mathrm{d}x - w_i \{k(s_{i-1} + \alpha L_{i-1}) + Q_i\} - F_i$$

for $i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$; and $E(\Pi^{R,COD}(W, Q)) = \Sigma_1^N \delta^{i-1} E(\Pi_i^{R,COD}(W, Q))$. And $E(\Pi_i^{REM,COD}) = (b_i - \bar{c}_i)k(s_{i-1} + \alpha L_{i-1}) + G_i$ for $i = 1,2,3,\ldots, N$ where $s_0 = Q_0 = 0$; and $E(\Pi^{R,COD}(W, Q)) = \Sigma_2^N \delta^{i-1} E(\Pi_i^{R,COD}(W, Q))$.

The first two constraints are the incentive compatibility constraints for retailer and remanufacturer for the quantity ordered and the buyback price respectively, and the last two constraints are the individual rationality constraints for the manufacturer, making sure that the retailer and remanufacturer have the incentive to accept the W and B contracts, respectively.

RESULT 6. *The form of the optimal contract*, $W = [w_i, F_i]$, *which ensures that the retailer coordinates the order quantity with the manufacturer is given by* $w_i = \bar{c}_i$ *for the remanufactured units and* $w_i = c_i$ *for the newly manufactured units, and* $F_i = E(\Pi_i^{R,COD^*}) - E(\Pi_i^{R,CD^*})$. *The form of the optimal contract*, $B = [b_i, G_i]$, *which ensures that the remanufacturer coordinates the order quantity with the manufacturer is given by* $b_i = \bar{c}_i$, *and* $G_i = E(\Pi_i^{REM,CD^*}) - E(\Pi_i^{R,COD^*})$.

The result is analogous to other studies in the extant literature in marketing and economics that make use of a two-part tariff to overcome the problem of double marginalization in decentralized systems. If transfers between the manufacturer and the retailer and the remanufacturer and the manufacturer are made at the realized unit cost of production and remanufacturing respectively, then the coordinated channel order quantity and profit levels can be attained in the decentralized setting. In this paper, we assume, without loss of generality, all efficiency gains to be collected by the manufacturer, leaving the retailer and the remanufacturer with the same profit level as if the contract were not put in practice. This condition satisfies Pareto-optimality. The fixed payment would be seen as a franchisee fee. In practice, such agreements will have both parties sharing the gains from coordination. It can easily be shown that the contract W in isolation can coordinate the *RS* system, and the contract *B* in isolation can coordinate the *REMS* system.

5. Model Results

Based on the results obtained in the coordinated and decentralized channels in the previous section, some interesting observations can be made on the performance of the different channel structures.

PROPOSITION 1. *In all of the different channels* (*NC*, *CC*, *RS*, *REMS and CD*), *the remanufacturing option leads to a larger total quantity ordered by the retailer*. *The remanufacturing option increases the total profits of the channel members compared to identical systems with no remanufacturing*.

The advantage that the remanufacturing option has is similar in all of the five systems studied in the paper. The remanufacturing option provides an intrinsic value to the salvaged units at the end of the previous period. Therefore, as in the traditional newsvendor model with salvage value, the total quantity in each period is higher. The salvaged units and the units that are used and collected provide the manufacturer with a way of satisfying the retailer demand in a relatively inexpensive manner. Hence, the retailer has an incentive to increase the order quantity, as the downside risk is lower.

PROPOSITION 2. *The greater the difference between the cost of manufacturing* (c_i) *and remanufacturing* ($\bar{c}_i$) *in each period*, *the larger is the order quantity by the retailer from the manufacturer in each period*.

The salvage value of each unit that is unsold or used and collected from the previous period depends on the cost of newly manufacturing a product (c_i), vs. remanufacturing the product ($\bar{c}_i$). If this difference is large, the retailer has a higher incentive to order more from the manufacturer for two reasons. The first is that the manufacturer can obtain units from the remanufacturer at a lower cost, and some of these savings will be passed on to the retailer (this sharing is direct if the manufacturer and retailer make decisions in a coordinated fashion, if the two of them make decisions independently, as in the RS system and the CD system, the savings are passed on in the form of a lower wholesale price w_i). The second reason is that if this difference between c_i and $\bar{c}_i$ is high, then the salvage value is also high, hence, in the newsvendor model, the downside risk of ordering more units decreases, hence, the retailer has an incentive to order a larger number of units.

PROPOSITION 3. *The total quantity ordered in each period is related as follows in the five systems*: $\bar{Q}_i^{CC} > \bar{Q}_i^{NC}$, $\bar{Q}_i^{CC} > \bar{Q}_i^{RS}$, $\bar{Q}_i^{CC} > \bar{Q}_i^{REMS}$, $\bar{Q}_i^{RS} > \bar{Q}_i^{CD}$ and $\bar{Q}_i^{REMS} > \bar{Q}_i^{CD}$, *where for each system*, $\bar{Q}_i = k(s_{i-1} + \alpha L_{i-1}) + Q_i$.

The proof of the proposition is in the working paper, we present the intuition here. The intuition behind these relations follows directly from the results in Section 3 and Propositions 1 and 2. When comparing the *CC* system with the *NC* system, the *CC* system has a higher degree of remanufacturing, since a fraction of the used items in the previous period are collected and remanufactured for the next period. Hence, the total quantity available for sale optimally should be higher, as this provides an incentive for the retailer to order more from the manufacturer (given that some of the savings from the remanufactured items will be passed on to the retailer). The total quantity available in the *CC* system in each period is also higher than the total quantity available in each period in the *RS* system, as there is no double marginalization between the retailer and the manufacturer, the retailer has an incentive to order more in each period. Similarly, the total order quantity in the *CC* system in each period is higher than the total order quantity in each period in the *REMS* system, as in the *REMS* system, remanufactured units have a higher price ($b_i > \bar{c}_i$), hence, the manufacturer passes this on to the retailer in the form of a higher wholesale price, and the retailer has an incentive to order a smaller quantity in each period. Analogously, the order quantities in each period in the *RS* and *REMS* systems are higher than that in the *CD* system, as there is no double marginalization between the retailer and the manufacturer, the retailer has an incentive to order more in each period.

The assumptions in the paper can be relaxed in a number of cases when the underlying situations need to be modeled differently. For example, it may be less expensive to remanufacture a salvaged unit than a used one. In that case, we conjecture that (i) the firm will prefer to remanufacture fewer products than if the costs of remanufacturing of used and unused products from the previous period were equal, (ii) the total quantity ordered in each period will decrease, and (iii) there will be fewer products available in the market. If design-for-remanufacturing effects are included in the paper, i.e., if investing in reducing the cost of remanufacturing a product decreases it in a concave fashion, then the impact on the results in the paper acts in the other direction. Specifically, (i) the firm will find it optimal to remanufacture more products, (ii) the total quantity ordered for each period will

Table 1 Summary of Model Results

Factor	NC	CC	RS	REMS	CD
Quantity ordered	High	Highest	High	High	Low
Profits	High	Highest	High	High	Low
Remanufacturing	Low effect	High effect	Medium effect	Medium effect	Low effect

increase, and (iii) there will be more products available in the market. Table 1 summarizes the insights from the results of the paper.

6. Contributions, Limitations, and Future Research

One of the contributions of this paper has been to show the benefit of component reuse over multiple product generations through the cost savings of remanufacturing for products with short lifecycles. For products with short lifecycles, the newsvendor model is often appropriate, as retailers may not get the chance to order a multiple number of times. When retailers have only one chance to place an order with the manufacturer, remanufacturing can be an important source of materials, as well as cost savings due to component reuse. In this paper, we show that when remanufacturing is an option, the service level is improved because of a higher number of units being ordered by the retailer. The more reusable the product (higher k), the higher the order quantity. This higher order quantity is beneficial in two ways, as the remanufacturer adds value to products that would otherwise have been discarded, and it results in a lower number of lost sales.

It is also shown that as the difference in the unit cost between manufacturing and remanufacturing increases, the order quantity from the retailer increases because of increased salvage value. Sharing components between product generations has been known to be cost efficient because of design cost savings. In addition, this paper shows that sharing design has the added benefit of making remanufacturing a viable tool for meeting a higher demand when necessary and lowering costs. The model is a general multi-period model; hence the paper shows that the results can be applied to a general length of the planning horizon. Coordination mechanisms are also suggested to better align the goals of the manufacturer, retailer and remanufacturer by providing suitable incentives in the form of simple two-part tariffs.

In the early phase of this research, we have made a number of assumptions that must be relaxed in future research to develop a more comprehensive understanding of the benefits of component reuse across multiple product generations. If the cost of remanufacturing a used product is more than that of remanufacturing an unused product, then it can be shown that remanufacturing is a less valuable option. If the firm can invest in design-for-remanufacturing to reduce the cost of remanufacturing, then remanufacturing becomes a more valuable option. We assumed that there was no cost of transferring salvaged and used units. This can be incorporated easily into the paper by including these costs in the cost of remanufacturing by modeling the cost of transfer of used and salvaged products in lots, and then optimizing the lot sizes of the transfer. Since this was not the focus of the paper, we chose to not include the cost of transportation. As a first cut, these costs could be included on a per unit basis in the unit cost of remanufacturing if the lot size of transfer is fixed.

Another limitation of the model is the assumption that prices are set exogenously. In a competitive market, we would expect that firms engaging in remanufacturing would pass on part of their savings to the consumer by reducing the retail price of the product. Future research should consider the price set by the retailer as a decision variable in a competitive environment to determine its effect on the optimal order quantity.

We also assumed that there are no costs of collecting salvaged and used items. This is a reasonable assumption for salvaged items since they would be in the inventory of the retailer. There is a cost of collecting used items, e.g., through providing incentives to customers to return used products, and other associated costs of the reverse supply chain. This issue has been addressed separately in other research on the subject. While we did not include it in this paper as a first cut, it could be incorporated either through a higher average unit cost of remanufacturing for used items, or through a combination of a fixed cost and unit cost of collection. We also did not model variable yields in the quality of used items, as this was not a focus of the paper. We conjecture that this will reduce the overall quantity ordered by the retailer and will also lead to a higher proportion of new products to remanufactured products provided by the manufacturer. Finally, we did not model the cost of designing product generations so that components can be reused in the future.

In summary, this paper makes a contribution to the literature on remanufacturing by highlighting the importance of lowering costs in products with short lifecycles, and developing models of the trade-offs underlying different decision-making systems when remanufacturing is taken into account. The remanufacturing option can enable firms to effectively increase the service levels to their customers, as well as reducing their own costs.

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