Channel Choice and Coordination in a Remanufacturing Environment

Abstract

The importance of the reuse of components and materials from post-consumer products has been widely recognized in the literature and in practice. In this paper, we address the problem of choosing the appropriate channel structure for the recollection of post-consumer products from customers. Specifically, we consider a manufacturer who has three options for collecting such products: (a) she can undertake the recollection effort herself, (b) she can provide suitable incentives to an existing retailer (who already has a distribution channel) to undertake the recollection effort, and (c) she can subcontract the recollection effort to a third party. Based on our observations in the industry, we model the three options described above as decentralized decision-making systems with the manufacturer being the Stackelberg leader. When considering decentralized channels, we find that *ceteris paribus*, agencies that are closer to the customer, e.g. retailers, are the most effective undertakers of the recollection effort for the manufacturer. Coordination mechanisms are then characterized which enable the different players to achieve profits that are equivalent to the profits in a coordinated channel.

1 Introduction

The importance of the environmental performance of products and processes for the operation of the overall business is increasingly being recognized. One of the central themes which has emerged from the current legislation introduced in Europe, North America and Japan is that producers should assume the responsibility of their products from the cradle to the grave. The corporate response to the evolving environmental performance requirements has been proactive in a large number of cases. For example, car manufacturers, including DaimlerChrysler (Automotive News, 1999) and BMW (Thierry 1997, BMW Environmental Report 1997) are beginning to insist that their suppliers abide by the same strict environmental guidelines that they have set for themselves. Recently, joint ventures for research and development on recovery processes have been set up, eg., the one by BMW, Renault and Fiat (Chemical Marketing reporter, 1994), who agree to recover and process each other's cars abroad for recovery. Other examples of such product categories are one-time use cameras (Kodak), copy and print cartridges (Xerox, Canon and Accutone), and copiers (Agfa Gevaert, Océ and Xerox). In all these cases, product recovery activities and decisions about product recovery management are perceived as an integral part of the product development and original manufacturing process of the products (Thierry et al. 1995).

The organization of product take-back systems and the reuse of old products varies largely depending on the product characteristics, the structure of the supply chain, and industry experience. For example, in the electronics industry, product take-back activities are managed by the equipment manufacturers in parallel with the distribution of new products (Xerox Environmental Report 1997). Xerox has been a leader in reusing their high value, end of lease copiers in the manufacturing of new copiers which meet the same strict quality standards. The company reports that the green manufacturing program saves the company $200 million a year through the reuse of parts and materials (Fiona 1993). In a similar vein, Hewlett-Packard encourages customers to return their used computers or peripherals to any HP offices from where the products are later sent to one of HP's hardware recycling centers in the UK, France or Germany for refurbishing, remanufacturing or recycling. In the automotive industry in the US and Europe, joint ventures for used car recovery have been established between the manufacturers and the existing network of dismantlers. Vehicle recycling research partnerships among the big car manufacturers such as the one managed by Ford, GM and DaimlerChrysler (Fortune 1995) provide relevant auto recycling technologies to dismantlers to achieve a high return on investment and recyclability from vehicle recovery[1].

Most consumer products such as one-time use cameras (Kodak), and print and copy cartridges (Xerox, Canon and Accutone) are directly returned from the retailers or from the customers to the manufacturer, to be fed into the original supply stream. Kodak collects cameras back from large retailers who also develop films for customers. The company recovers seventy-six percent of the weight of a disposed camera in the production of a new one. Each time a camera is returned to Kodak, the retailer is reimbursed both a fixed fee per camera and the transportation costs. Print and copy cartridges, which are largely distributed through manufacturer outlets (Xerox and Canon), are directly collected back from the customers using prepaid mail boxes provided by the manufacturer. Similar to the one-time use cameras, they are disassembled and remanufactured into new products of the original quality.

In this paper, our goal is to examine the implications of the manufacturer's reverse channel decision on the supply chain profits. We focus on the cases where the used products which are collected back from the consumers are remanufactured into products of the original quality. Based on observations from current practice and the literature on reverse logistics channels, we consider three product take-back channel structures: (a) manufacturer undertaking the collection directly from the customers (b) manufacturer contracting the collection activity to the retailer (c) manufacturer contracting the collection activity to a third party. We consider channel members to be independent entities, maximizing some form of an objective function which is dependent on the performance of reverse channel activities. Specifically, the research questions that we address in this paper are as follows:

(a) What are the implications of different reverse channel structures on the supply chain profits? How does the incentive to invest in product take-back change under each reverse channel structure and what are its implications for the pricing decisions of the manufacturer and of the retailer?

(b) How can the manufacturer achieve coordination in the distribution channel when product

[1]Some of the recently established joint ventures are: Volkswagen-Evert Heeren (Germany); Volvo and AB Gotthard Nilson and Stena Bilfragmentering AB and Bildemontering AB (Sweden); Renault-BMW-Fiat and 100 licenced dismantlers (Europe).

take-back activity is managed by the retail outlet or by a third party?

The rest of the paper is organized as follows. In the following subsection, we briefly discuss the contribution of our paper to the current literature on supply chain management, and the research on distribution channel design and coordination issues. Section 2 is devoted to the conceptualization of the model and Section 3 to the model formulation. Following the development of the model, the analytical results for the optimal reverse channel structures are presented in Section 4. Section 5 examines channel coordination mechanisms with product recovery. We outline the limitations of this work and possible directions for future research in Section 6.

1.1 Extant Literature

Reverse logistics channels have been of interest to researchers in both operations management and marketing. At a broad level, Fleischmann et al. (1997) review the current research in the quantitative analysis of reverse logistics systems. However, these studies focus on operational decisions and do not consider any incentive conflicts in decentralized channels which may exist between different reverse channel entities. Stern et al. (1996) describe the role and the function of each channel member in different reverse logistics structures. However, this stream of research has largely been exploratory or descriptive and lacks a quantitative basis for comparing different channel structures.

Distribution channel design and coordination mechanisms between forward channel partners have been an extensively evolving area of research. The analytical marketing literature on channel choice follows two streams with the first group of articles concentrating on equilibrium channel structures and the second group on coordination mechanisms. McGuire and Staelin (1983) model a channel of two manufacturers selling competing but differentiated products through a single outlet. They investigate under what conditions a manufacturer may want to place an intermediary between itself and the next level in the channel. Coughlan (1985) extends this research to a generalized demand function and tests its implications empirically. Similarly, Choi (1991) examines an industry context with two manufacturers and a single retailer for both linear and non-linear product demand functions. Lee and Staelin (1997) generalize the above work to a competitive environment with two manufacturers and two retailers. They look at an uncoordinated channel structure, and analyze the vertical strategic interactions between the manufacturers and the retailers. However, none of these articles explicitly consider reverse channel design from the manufacturer's point of view. The second group of articles deals with the design of mechanisms to enhance coordination between the channel members' decisions. Jeuland and Shugan (1983) show that profit sharing and more specifically, quantity discounts can be a useful tool for coordination of price and non-price decisions of a manufacturer and a retailer. Quantity discounts as coordination mechanisms have also evoked interest in the operations literature. Goyal (1977) and Weng (1995) study the topic of buyer supplier coordination and joint economic lot sizing. Corbett (1996) extends this stream of research to the asymmetric information case by comparing different discount schemes without making the assumption that the supplier or the buyer knows the other channel partner's cost. For a review of the literature on this subject, see Goyal and Gupta (1989) and Benton and Park (1996). This paper complements the existing research in distribution channel choice and coordination mechanisms by exploring the implications of assigning a dual role to a forward channel member. Specifically, we question how channel profits and the attractiveness of product take-back are affected if the retailer assumes the product's collection responsibility. We explicitly model the effect of pricing decisions of the different players on the demand, and analyze incentive conflicts within decentralized channels. Our analysis looks at coordination possibilities between the manufacturer and the retailer with product take-back.

In the supply chain management literature, flexible ordering and return policies for retailers in cases of uncertain market demand have been studied by several authors. The returns which are of interest in these studies occur at the end of a selling period due to overstocking decisions of the retailers. Pasternack (1985), Emmons and Gilbert (1996) and Donohue (1996) determine optimal product return contracts from the point of view of the manufacturer. Related to this, Padmanabhan and Png (1997) explore the impact of ordering flexibility provided by return contracts on retail level competition. In contrast, we consider products which are returned from customers and are post consumer goods which can be remanufactured into new products. We also explore how buyback payments can be incorporated into channel coordination mechanisms. Additionally, there are several papers which examine the implications of supply chain design decisions on inventory cost of products both for the manufacturer and for the distributor (Lee 1996, Lee and Tang 1997, Lee and Tang 1998). We add to the stream of research on supply chain design by modeling the implications of the manufacturer's reverse channel choice on unit production costs and furthermore examine its effect on channel pricing decisions under each product take-back structure.

There is a related stream in the economics literature on durable goods where used products would meet consumers' demand and would at the same time compete with new products. However, this stream focuses on the planned obsolescence and secondary markets (e.g. Swan 1972, Bulow 1982, Bulow 1986). More specifically, these papers address a monopolist's decision to invest in his product's durability when there is a possibility of cannibalization of new products by the old ones in the secondary market. While our interest is on the design of the systems that would enable the efficient collection of the durable products, the question of how durable a product should be is also relevant in a remanufacturing context and we identify it as a future research topic. In the next section, we conceptualize the model and elaborate on the model assumptions.

2 Model Description

Consider the following scenario. Suppose that the manufacturer has incorporated a recovery process for used products into her original production system, thereby being able to remanufacture a returned used unit into a new product. Thus, a product can be manufactured directly from raw materials, or by remanufacturing part or whole of a returned unit into a new product.We assume that producing a new product by using a returned unit is less costly than manufacturing a new one. This assumption states that savings from materials and assembly of subsystems within the new product dominate the additional costs of disassembly, inspection for reusability, and the cost of remanufacturing of a returned product[2]. Ceteris paribus, the manufacturer strictly prefers a higher product return rate to a lower product return rate from the market. Denote c_m as the unit cost of manufacturing a new product, and c_r as the unit cost of remanufacturing a returned product into a new one. c_r is assumed to be the same for all returned products. This assumption can easily be relaxed by incorporating a yield rate on returned product quality. The yield rate models the variance in reusability of post-consumer products due to different usage patterns[3]. We

[2]Kodak incorporates considerations such as part reusability, ease of disassembly and recoverability into the product design process for its single-use camera line. This enables them to easily disassemble returned cameras and thus manufacture new ones at lower unit costs by only replacing parts such as lens and battery.

[3]It can easily be shown that the uncertainty in the returned product quality reduces the incentives to invest in product take-back activities since the benefit from investing in collection effort will be lower.

characterize the reverse channel performance by the product return rate from the market. Since product take-back is a costly activity, and there are no secondary markets, the manufacturer invests in collection activities to achieve a return rate that would at most match the current demand rate for her product. This observation enables us to model the variable τ which denotes the fraction of the current demand supplied from returned products. The average unit cost of manufacturing can be written as $c = c_m(1-\tau) + c_r\tau$. Note that when all demand is satisfied from returned products (*i.e.* $\tau = 1$), $c = c_r$. If the return rate of used products is zero, then all demand will be satisfied from manufactured units and therefore $c = c_m$. If we denote unit cost savings from recovery by Δ where $\Delta = c_m - c_r$, the average unit cost can also be represented by $c_m - \tau\Delta$.

In our model, we assume that products are distributed through an independent retailer. The assumption made for the product's distribution channel structure enables us to explore the implications of assigning a dual role to a forward channel member. Specifically, if the retailer undertakes the collection effort, he not only determines the quantity demanded in the market by setting the retail price of the product, but also by his collection effort level, he influences the average manufacturing cost of the product. Even though we consider a single manufacturer-retailer structure, the manufacturer can in fact sell to different retailers if the retailers are not in direct competition. The manufacturer can also manufacture competing brands, but she does not sell competing brands to the same retailer and the brands do not share the same manufacturing process[4]. The retailer can also carry many brands but we consider only one brand for which he takes decisions independent of the other existing brands. This enables us to focus on the game between one manufacturer and one retailer in determining the optimal market characteristics. The distribution channel decision variables are simply the wholesale price of the product, w which is determined by the manufacturer and the retail price of the product, p decided by the retailer.

As stated before, the primary aim of this paper is to examine the impact of the reverse channel structure (the agent involved in the collection effort) on supply chain profits. Assuming that the cost of collection as a function of the product return rate is the same under each channel format, we compare the incentives to invest in product recovery for different agents. The cost of collection is modeled with both fixed and variable cost components, where the product return rate observed

[4]This enables us to decouple the cross-brand elasticities in recommending a suitable reverse channel to the manufacturer in different environments.

from the market is a concave function of the fixed investment in product recovery activities[5]. For instance, the fixed investment would correspond to any promotional activities that would increase awareness. Specifically, if the fixed cost of investment is given by I, $\tau = B_o\sqrt{I}$ where B_o is a scaling constant[6]. In addition, the cost of collection increases with the number of the units collected, as recovering the product from the consumer and sending it to the manufacturer would incur a cost proportional to the amount of the older products that are recovered. Specifically, we model the variable cost of collection by $A\tau D(p)$ where A is the constant unit cost of collection and $\tau D(p)$ is the total number of units taken back from the customers. Thus, the total cost of collection as a function of the fraction of products that are reused (τ) is given by: $C(\tau) = I + A\tau D(p) = B\tau^2 + A\tau D(p)$[7].

Decentralized reverse channel structures are classified into three categories: the retailer owned collection channel (RC System, Figure 1.b), the manufacturer owned collection channel (MC System, Figure 1.c), and the third party owned collection channel (TPC System, Figure 1.d).

As a benchmark case, the *Coordinated Distribution and Collection Channel* (CDC system, Figure 1.a) is used, where a central decision-making unit jointly decides on the retail price of the product p and the collection effort level τ. In section 5, we examine coordination mechanisms with product take-back which achieve the profit levels of the coordinated benchmark scenario.

In the *Retailer Owned Collection Channel (RC System, Figure 1.b)*, the retailer assumes a dual role for the manufacturer. Besides distributing the product in the market, he also engages in the collection activity of used products from the market. One characteristic of this channel format is that the ownership of used products initially rests with the retailer after the collection. In order to take the products back, the manufacturer pays a transfer price b per product returned to her from the retailer[8]. As an example of this channel structure, Kodak currently engages retailers who sell its products to take part in the collection activity of the disposed cameras. Similarly, for

[5] Hence, there are decreasing returns to investment I.

[6] Hence, the amount of investment to be made to achieve a return rate at a level of τ_o is given by $I_o = B\tau_o^2$

[7] Consider the reverse vending machines that are used to recover post consumer goods. Each customer who returns a used product to these machines receives a fixed payment per unit, which is represented by the parameter A in our model. The investments in installing these machines corresponds to I, the fixed investment in our modeling framework. Also, $B = \frac{1}{B_0}$.

[8] Based on the assumption of strictly convex collection costs and no secondary product markets, it follows that all the units collected by the retailer are finally returned to the manufacturer.

electronics products, such as television sets, home appliances, personal computers, retailers also act as collection points when products are returned to them at the moment of new sales.

Figure 1 : Reverse Channel Structures

In the *Manufacturer Owned Collection Channel* (*MC System, Figure 1.c*), the manufacturer undertakes the collection effort herself, and decides on the wholesale price w and the collection effort level, τ. An example of this form of reverse channel structure is Xerox's network for printer and copy cartridges in Europe. Specifically, Xerox provides prepaid mail boxes so that the used cartridges can be sent back to Xerox at no expense to the customers[9]. Another recent example is the Polaroid single-use instant cameras which are distributed through independent retailers. The used cameras are collected back directly from the customers by Polaroid. The company provides postage paid envelopes offering a two dollar rebate for each camera returned.

In addition, it is also not unusual to see the collection activity contracted by the manufacturer to a third party, who is engaged only in the collection of the used products from the market. In the *Third Party Owned Collection Channel (TPC System, Fig 1.d)* for a given transfer price b of a used product, the third party maximizes his profits to determine the collection effort level, τ. The third party operates as a broker between the customer and the manufacturer.

In determining the outcome of the game played between the manufacturer and the retailer, *it is assumed that the manufacturer has sufficient channel power over the retailer to act as a Stackelberg*

[9] However, it is interesting to note that in Europe, the company covers only a set of countries for free delivery of the used cartridges due to the increasing delivery costs of the product.

leader. Thus, she uses her foresight about the retailer's reaction function in her decision making. The Stackelberg structure for the solution of similar games has been widely used in the literature (McGuire and Staelin 1983, Weng 1995).

While analyzing the model, the three decentralized collection structures, where agents maximize their profits independently for a single period are compared. Although the forward and the reverse channel decisions are made in a single period setting, the model assumes the previous existence of the product in the market. Those products sold in the previous periods can be returned to the manufacturer for reuse via the reverse channel. Hence, the focus of analysis is on the average channel profits per period when similar products are introduced to the market repeatedly (eg. Kodak introduces new models of disposable cameras which can incorporate components from previous generations of cameras). By focusing on a single period setting, we avoid the implications of the existence of secondary markets for used products[10]. We compare the decentralized decision making system to a centrally controlled system to provide insights on efficiency loss under each reverse channel structure . The centrally coordinated system is used as a benchmark scenario for deriving the channel coordinating pricing scheme. The next section describes in detail the profit maximization problem of the manufacturer, the retailer and the third party in the outlined reverse channel systems.

3 Model Formulation and Analysis

In this section, we compare the channel structures with respect to the retail price of the product, the collection effort level and the total channel profits. In order to derive insights about the choice of the collection channel, we assume a linear demand curve. The specific form of the linear demand model which is analyzed in this section is given by: $D(p) = \phi - \beta p$, with ϕ and β being positive parameters, and p the price of the product. In a recent paper, Lee and Staelin (1997) show that the vertical interaction between the channel members and the optimality of the channel strategies depend on the convexity of the demand functions. Therefore, it should be pointed out that while the linear demand assumption is consistent with the literature (Bulow 1982, Weng 1995) and

[10] Our results do not change if a two-period model is used where the recovered products in the first period are reused in the second period with no secondary markets in the second period.

enables us to develop a first cut analysis of the reverse channel decision of the manufacturer, the generalizability of the results to non-linear demand functions is a question of future research[11]. The profit functions of the channel members can trivially be shown to be concave in the decision variables, so the first order conditions are used throughout to characterise the optimal decision variables. As a benchmark scenario, we first analyze the case of no-recovery.

3.1 The No Recovery Case

In the coordinated channel without recovery, the total system profits are : $\Pi_T^C = (\phi - \beta p)[p - c_m]$. The first order conditions for the optimal retail price result in $p_C^* = \frac{\phi+\beta c_m}{2\beta}$, and $\Pi_T^{*C} = \frac{(\phi-\beta c_m)^2}{4\beta}$.

In the decentralized channel without recovery, the retailer's profits are given by $\Pi_R = (\phi - \beta p)[p - w]$, from which we obtain the optimal retail price as a function of the wholesale price as $p^* = \frac{\phi+\beta w}{2\beta}$, using the first order condition. The manufacturer's profits are given by $\Pi_M = (\phi - \beta p^*)[w - c_m]$. The manufacturer assumes that the retailer is going to act optimally, and accordingly sets her wholesale price $w^* = \frac{\phi+\beta c_m}{2\beta}$, from which we obtain the manufacturer's profits to be $\Pi_M^* = \frac{(\phi-\beta c_m)^2}{8\beta}$, the retailer's profits to be $\Pi_R^* = \frac{(\phi-\beta c_m)^2}{16\beta}$ and the decentralized total system profits to be $\Pi_T^{*D} = \frac{3(\phi-\beta c_m)^2}{16\beta}$. The results of the no recovery case are summarized in Table 1[12].

	Coordinated Channel	**Decentralized Channel**
Total Profits Π_T^*	$\frac{(\phi-\beta c_m)^2}{4\beta}$	$\frac{3(\phi-\beta c_m)^2}{16\beta}$
Retail Price p^*	$\frac{\phi+\beta c_m}{2\beta}$	$\frac{3\phi+\beta c_m}{4\beta}$
Wholesale Price w^*		$\frac{\phi+\beta c_m}{2\beta}$
Manufacturer Profits π_M^*		$\frac{(\phi-\beta c_m)^2}{8\beta}$
Retailer Profits π_R^*		$\frac{(\phi-\beta c_m)^2}{16\beta}$

Table 1: Channel Results With No Recovery

[11] We conjecture that the results of the model would hold for all demand patterns with non-positive elasticities with respect to price.

[12] Note that the well-known result of efficiency being lost in a decentralized channel compared to a coordinated channel holds here, as the system profits in the decentralized channel (manufacturer + retailer) of $\frac{3(\phi-\beta c_m)^2}{16\beta}$ are less than the coordinated channel profits of $\frac{(\phi-\beta c_m)^2}{4\beta}$.

3.2 The Recovery Case

We now assess the impact of product recovery on the individual profits of the manufacturer and the retailer, and on the system profits. First, the optimal collection effort in a coordinated channel with one manufacturer and one retailer is expressed in closed form. The decentralized reverse channel structures described in Section 2 are then analyzed to find the optimal collection effort in each case, and these efforts are compared with one another to derive insights into the collection strategy for the manufacturer.

3.2.1 Coordinated Distribution and Collection Channel (CDC System, Figure 1.a)

The collection effort in the coordinated channel is computed by optimizing the joint profits (total supply chain profits) of the manufacturer and retailer. As stated in Section 2, the total cost of the collection effort has the form $C(\tau) = B\tau^2 + A\tau D(p)$, where τ is the fraction of the current demand which is to be recovered, and A and B are constants. The retailer's gross profits in this system are given by: $(\phi - \beta p)[p - w]$ and the manufacturer's gross profits are given by $(\phi - \beta p)[w - c_m + \tau\Delta]$. The net joint profits in the coordinated system are given by: $\Pi^{CDC}(p, \tau) = (\phi - \beta p)[p - w] + (\phi - \beta p)[w - c_m + \tau\Delta] - B\tau^2 - A\tau D(p)$. The optimal retail price p^{*CDC} and the collection effort τ^{*CDC} can be found by their respective first-order conditions. The simultaneous solution of the first order conditions results in $p^{*CDC} = \frac{\phi+\beta c_m}{2\beta} - \frac{1}{2}(\Delta - A)^2 \frac{\phi-\beta c_m}{4B-\beta(\Delta-A)^2}$[13] and $\tau^{*CDC} = \frac{(\phi-\beta c_m)(\Delta-A)}{4B-\beta(\Delta-A)^2}$. The demand and total profits in the coordinated distribution and collection system can be found by evaluating $D(p)$ and $\Pi^{CDC}(p, \tau)$ at p^{*CDC} and τ^{*CDC}. The results are shown in Table 2[14].

[13] The retail price charged is lower than the retail price in the centrally coordinated system without recovery (see Table 1). Part of the system profit gains from reduced unit variable costs is passed on to the customers as a lower retail price, which also enhances the demand of the product.

[14] In the CDC system, to satisfy the condition $\tau^{*CDC} \geq 0$, note that B should assume values greater than $\frac{\beta(\Delta-A)^2}{4}$. To achieve comparability across different channel structures, we will assume that the condition $B \geq \frac{\beta(\Delta-A)^2}{4}$ is satisfied for all three channel structures.

	CDC SYSTEM
Π_T^*	$\dfrac{\frac{(\phi-\beta c_m)^2}{4\beta}}{\left[1-\frac{\beta(\Delta-A)^2}{4B}\right]^2}$
p^*	$\frac{\phi+\beta c_m}{2\beta}$-$\frac{(\phi-\beta c_m)(\Delta-A)^2}{2(4B-\beta(\Delta-A)^2)}$
τ^*	$\frac{(\phi-\beta c_m)(\Delta-A)}{(4B-\beta(\Delta-A)^2)}$

Table 2: Channel Results with Recovery

Next, we characterize in a similar fashion the optimal collection efforts in the decentralized channel structures. In the rest of the paper we use the notation $\Pi_j^i(.)$ to represent the profit function of agent j[15] when agent i[16] is performing the collection activity.

3.2.2 Retailer Owned Collection Channel (RC system, Figure 1.b)

We first consider the case when the retailer undertakes the collection effort. The retailer's net profits are given by $\Pi_R^{RC}(p,\tau) = (\phi - \beta p)[p - w] + b\tau(\phi - \beta p) - B\tau^2 - A\tau D(p)$, since the number of units that are recovered equal $\tau D(p)$. The first order conditions for the optimal retail price and the collection effort are given by : $p^{*RC} = \frac{\phi+\beta[w-(b-A)\tau^*]}{2\beta}$ and $\tau^{*RC} = \frac{(b-A)}{2B}(\phi - \beta p^*)$. The manufacturer assumes that p^{*RC} and τ^{*RC} satisfy these conditions, and uses them to determine the optimal wholesale price w^{*RC}. The manufacturer's profits are given by $\Pi_M^{RC}(w) = D(p^{*RC})[w - c_m + \Delta\tau^{*RC}] - b\tau^{*RC}D(p^{*RC})$. Applying the first order condition for the wholesale price, $w^{*RC} = \frac{(\phi+\beta c_m)}{2\beta} - \frac{(\Delta-b)(b-A)(\phi-\beta c_m)}{2[4B-\beta(\Delta-A)(b-A)]}$. The optimal value of the wholesale price can then be used to compute the demand and profits for the two parties. From the non-negativity restriction of the manufacturer's profit function, it also follows that the condition $b \leq \Delta$ always holds.

3.2.3 Manufacturer Owned Collection Channel (MC system, Figure 1.c)

In this system, the retailer only engages in the distribution of the product. His profit function is given by $\Pi_R^{MC}(p) = (\phi - \beta p)[p - w]$. The first order conditions for the optimal retail price result

[15] j=R represents the retailer, j=M represents the manufacturer, j=TP represents the third party and j=T represents the total channels profits.

[16] i=RC represents the retailer owned collection channel, i=MC represents the manufacturer owned collection channel and i=TPC represents the third party owned collection channel.

in: $p^{*MC} = \frac{\phi+\beta w}{2\beta}$. The manufacturer's profits are given by $\Pi_M^{MC}(w,\tau) = D(p^{*MC})[w - c_m + \tau\Delta] - B\tau^2 - A\tau D(p^{*MC})$. Applying the first order condition for the wholesale price and the collection effort, we obtain $w^{*MC} = \frac{\phi+\beta c_m}{2\beta} - \frac{(\Delta-A)^2(\phi-\beta c_m)}{2[8B-\beta(\Delta-A)^2]}$ and $\tau^{*MC} = \frac{(\phi-\beta c_m)(\Delta-A)}{8B-\beta(\Delta-A)^2}$. The values of Π_M^{*MC}, Π_R^{*MC} and p^{*MC} are listed in Table 3.

	RC SYSTEM	MC SYSTEM	TPC SYSTEM
Π_T^*	$\frac{\frac{(\phi-\beta c_m)^2}{4\beta}}{\left[1-\frac{\beta(\Delta-A)(b-A)}{4B}\right]^2 \frac{1}{[\frac{3}{4}-\frac{\beta(b-A)(2\Delta+b-A)}{16B}]}}$	$\frac{\frac{(\phi-\beta c_m)^2}{4\beta}}{\left[1-\frac{\beta(\Delta-A)^2}{8B}\right]^2 \frac{1}{[\frac{3}{4}-\frac{\beta(\Delta-A)^2}{16B}]}}$	$\frac{\frac{(\phi-\beta c_m)^2}{4\beta}}{\left[1-\frac{\beta(b-A)(\Delta-b)}{4B}\right]^2 \frac{1}{[\frac{3}{4}-\frac{\beta(b-A)(2\Delta-3b+A)}{16B}]}}$
p^*	$\frac{[3B-\beta(\Delta-A)(b-A)]\phi+\beta Bc_m}{\beta[4B-\beta(\Delta-A)(b-A)]}$	$\frac{3\phi+\beta c_m}{4\beta}-\frac{(\phi-\beta c_m)(\Delta-A)^2}{4[8B-(\Delta-A)^2\beta]}$	$\frac{3\phi+\beta c_m}{4\beta}-\frac{(\phi-\beta c_m)b(\Delta-b)}{4[4B-\beta b(\Delta-b)]}$
τ^*	$\frac{(\phi-\beta c_m)(b-A)}{2[4B-\beta(\Delta-A)(b-A)]}$	$\frac{(\phi-\beta c_m)(\Delta-A)}{8B-\beta(\Delta-A)^2}$	$\frac{(\phi-\beta c_m)(b-A)}{2[4B-\beta(\Delta-b)(b-A)]}$
w^*	$\frac{\phi+\beta c_m}{2\beta}-\frac{(\Delta-b)(b-A)[\phi-\beta c_m]}{2[4B-\beta(\Delta-A)(b-A)]}$	$\frac{\phi+\beta c_m}{2\beta}-\frac{(\Delta-A)^2[\phi-\beta c_m]}{2[8B-\beta(\Delta-A)^2]}$	$\frac{\phi+\beta c_m}{2\beta}-\frac{(\phi-\beta c_m)(b-A)(\Delta-b)}{2[4B-\beta(b-A)(\Delta-b)]}$
Π_M^*	$\frac{\frac{(\phi-\beta c_m)^2}{8\beta}}{\left[1-\frac{\beta(\Delta-A)(b-A)}{4B}\right]}$	$\frac{\frac{(\phi-\beta c_m)^2}{8\beta}}{\left[1-\frac{\beta(\Delta-A)^2}{8B}\right]}$	$\frac{\frac{(\phi-\beta c_m)^2}{8\beta}}{\left[1-\frac{\beta(\Delta-b)(b-A)}{4B}\right]}$
Π_R^*	$\frac{(\phi-\beta c_m)^2}{16\beta}\frac{\left[1-\frac{\beta(b-A)^2}{4B}\right]}{\left[1-\beta\frac{(\Delta-A)(b-A)}{4B}\right]^2}$	$\frac{\frac{(\phi-\beta c_m)^2}{16\beta}}{\left[1-\beta\frac{(\Delta-A)^2}{8B}\right]^2}$	$\frac{\frac{(\phi-\beta c_m)^2}{16\beta}}{\left[1-\beta\frac{(\Delta-b)(b-A)}{4B}\right]^2}$
Π_{TP}^*			$\frac{\frac{(\phi-\beta c_m)^2}{16\beta}(\frac{\beta(b-A)^2}{4B})}{\left[1-\beta\frac{(\Delta-b)(b-A)}{4B}\right]^2}$

Table 3: Channel Results with Recovery

3.2.4 Third Party Owned Collection Channel (TPC system, Figure 1.d)

As in the MC system, in this channel structure, the retailer engages only in the distribution of the product. Hence, his profit function and the optimal retail price of the product are given by: $\Pi_R^{TPC}(p) = (\phi - \beta p)[p - w]$ and $p^{*TPC} = \frac{\phi+\beta w}{2\beta}$. The third party who performs the collection activity maximizes $\Pi_{TP}^{TPC}(\tau) = b\tau D(p^{*TPC}) - B\tau^2 - A\tau D(p^{*TPC})$. Thus, the optimal value of the collection effort τ^{*TPC} is given by $\frac{(b-A)}{2B}(\phi - \beta p^{*TPC})$. Given p^{*TPC} and τ^{*TPC}, the manufacturer's profit function follows as: $\Pi_M^{TPC}(w) = (\phi - \beta p^{*TPC})[w - c_m + (\Delta - b)\tau^{*TPC}]$. Using the first order conditions to find the optimal value of the wholesale price, we obtain $w^{*TPC} = \frac{(\phi+\beta c_m)}{2\beta} - \frac{(\phi-\beta c_m)}{2\beta}[\frac{\frac{\beta(b-A)(\Delta-b)}{4B}}{1-\frac{\beta(b-A)(\Delta-b)}{4B}}]$, from which the optimal retail price and profits for the three parties are calculated and tabulated in Table 3.

4 Model Results

Based on the results summarized in Table 2 and Table 3, some interesting observations are made on the performance of decentralized reverse channel structures.

Proposition 1 *In the decentralized third party owned collection channel (TPC system), the manufacturer sets* $b^* = \frac{\Delta + A}{2}$*. In the decentralized retailer-owned collection channel (RC system), the manufacturer passes on the entire savings in unit variable cost resulting from recovery to the retailer, i.e., the manufacturer sets* $b^* = \Delta$[17]*.*

Note that in the TPC system, the incentives of the third party to invest in collection is directly driven by b. Hence the manufacturer faces the following trade-off while determining the optimal value for b. If she assigns a large value to b, she observes a high level of investment in the collection effort by the third party (ie., a large τ value) but at the same time, her net savings from product recovery diminishes, (ie., $\Delta - b$ decreases) and therefore her profits decrease as b approaches Δ. We find that the direct and the indirect effects of b on the manufacturer's profits balance when $b^* = \frac{\Delta + A}{2}$.

Surprisingly, in the RC system, we find a different sort of interaction between the value of b and the manufacturer's profits. In the RC system, the manufacturer does not extract any of the direct savings from the unit variable cost, but prefers to pass them on to the retailer. There are two main driving forces to this seemingly counter-intuitive result. The first reason is that passing on all the savings to the retailer results in an increased payoff for the retailer (higher value of $b * \tau * D$). This acts as an incentive for the retailer to reduce the retail price of the product and *increase demand,* which results in an increase in profits. Also, by increasing the value of b to Δ, the collection effort τ increases, and this second order effect decreases the retail price and increases the demand even further. Consequently, the manufacturer's profits increase as a result of the expansion in the demand.

Proposition 2 *The optimal collection efforts are related as follows:* $\tau^{*CDC} \geq \tau^{*RC} \geq \tau^{*MC} \geq \tau^{*TPC}$*.*

[17]For the proofs of the propositions, please refer to the Appendix A.1 .

Note that while the total savings from collection in the TPC system are given by $(b - A)\tau D[p(w)]$, the total savings are given by $(\Delta - A)\tau D[p(w)]$ in the MC system. From proposition 1, we see that the marginal benefit of investing in τ in the TPC system is less than the marginal gains in the MC system (i.e., $(b^*_{TPC} - A) < (\Delta - A)$). Hence, the third party invests less in the recollection compared to the manufacturer in the MC system. In addition, the manufacturer can strategically set w in a way that would make product take-back more profitable and this results in a second degree effect on τ. Comparing the MC and the RC systems, we see that while both the manufacturer and the retailer face the same marginal gains from investing in τ (i.e., $b^*_{RC} - A = \Delta - A$), the retailer can directly impact the market size. The manufacturer can influence the retailer's demand only by strategically choosing the wholesale price, w (there is double marginalization), and hence the MC system has a lower level of recollection than the RC system. The centrally coordinated system leads to the highest investment level since the decisions are fully coordinated in the channel.

Proposition 3 *The retail prices with recovery in the coordinated channel and the three cases in the decentralized channel are related as follows:* $p^{*CDC} \leq p^{*RC} \leq p^{*MC} \leq p^{*TPC}$. *Consequently,* $D^{*CDC} \geq D^{*RC} \geq D^{*MC} \geq D^{*TPC}$.

The investment in recovering used products from the market benefits only the third party directly in the TPC system, and there is only a second-order effect on the retail price[18] in the form of a lower wholesale price offered by the manufacturer to the retailer. The effect on the retail price is more direct in the MC system, as the manufacturer sets a lower wholesale price to increase demand, and thereby increases her savings in the unit variable cost through recovery. The reduction in retail price in the RC system is the largest among the decentralized channels, as the retailer benefits the most by being able to directly influence demand. The price in the coordinated channel is lower than all three decentralized channels, because the gains in efficiency from the coordination effort can be effectively shared with the market to increase both demand and profits.

[18] The manufacturer lowers her wholesale price compared to the no recovery case to partially pass on the savings in unit variable cost from the collection effort to the customer through the retailer, thereby influencing demand.

Proposition 4 *The manufacturer's and retailer's profits in the decentralized channel are related as follows:* $\Pi_M^{*RC} \geq \Pi_M^{*MC} \geq \Pi_M^{*TPC}$, *and* $\Pi_R^{*RC} \geq \Pi_R^{*MC} \geq \Pi_R^{*TPC}$. *The total profits in the coordinated channel with recovery always dominate the total profits in the decentralized channel with recovery. Specifically,* $\Pi^{*CDC} \geq \Pi_T^{*RC} \geq \Pi_T^{*MC} \geq \Pi_T^{*TPC}$.

The implications of Proposition 3 form the basis of an interesting finding of the paper, viz., the closer an agency is to the market, the more efficient is the collection effort for all the parties involved in the channel. The effect of loss of efficiency in the decentralized system is mitigated in part by the ability to act more closely at influencing the underlying demand.

The implication of Proposition 4 and this section is that the ranking of the different channel structures (in terms of benefits to the manufacturer and retailer) mirrors the benefits to non-channel members as well. *The benefits to society in terms of an increased collection effort (greater reuse of products) as well as an increased ability to buy the product (greater demand) complement the increased profits for the manufacturer and retailer in the coordinated system and RC system.*

We now focus on the sensitivity of the collection effort τ to the different model parameters. Table 4 summarizes the impact of the market potential ϕ, the unit variable cost of manufacturing c_m, and the savings in the unit variable cost Δ, on the collection effort τ. The collection effort increases as the market potential ϕ increases, which has interesting implications for recovery system design. A high value of market potential implies higher demand and hence, a higher collection effort[19].

Factor	**Effect on Collection Effort τ**
Market Potential ϕ	Increasing in ϕ
Unit cost c_m [20]	Decreasing in c_m
Unit cost savings Δ[21]	Increasing in Δ

Table 4: Effect of Model Parameters on Collection Effort

[19] A high value of market potential could also result from customers finding environmentally-friendly products more attractive, thereby increasing the collection effort for such products.

[20] Δ is kept fixed

[21] c_m is kept fixed.

We also find that for a fixed Δ, the collection effort is decreasing in c_m and it is increasing in Δ when c_m is held constant. The first effect occurs from the fact that as c_m increases, the retail price also increases and, this leads to a reduction in demand. As the market size (scale) shrinks, so does the profitability of investing in product recovery, and hence we observe a lower level of investment in collection effort. As the unit cost savings increase, the marginal benefit of investing in product take-back increases and this leads to a higher investment level in the collection effort. As the return rate of used products is high, the manufacturer faces a lower average unit cost and hence the retail price decreases, resulting in an increase in market size. This also has a positive second degree effect on the investment level in τ. When unit cost savings increase proportionally with c_m (i.e. $\Delta = kc_m$ where $0 < k < 1$), we find that for low c_m and high k values, the positive and direct effect of an increase in Δ (in parallel to an increase in c_m) on τ dominates the secondary effect that the reduction in market demand has on the collection effort[22].

Figure 2: Effect of transfer price, b, on collection effort, τ

Figure 3: Fraction of units recovered τ vs. B

[22] Please see appendix 1 for analytical results.

The effect of the transfer price (b) in the RC and TPC systems on the value of τ is also interesting (Figure 2), in that while the collection effort in the RC system increases monotonically with the transfer price, the collection effort is *concave* in the TPC channel with respect to the transfer price. As the cost of the collection effort (B) increases, the value of the collection effort decreases in all three systems (Figure 3) but at varying rates. *The retailer's collection effort decreases at the fastest rate, the manufacturer's effort decreases at a modest rate, while the third party's effort reduces at the slowest rate.* Put differently, *the third party's collection effort is the lowest, but also the most robust* of the three channels to changes or mis-estimations in B.

Our observations in industry corroborate the findings of the model. We observe that in a large number of industries, retailers actually undertake the collection effort on behalf of the manufacturer, eg. Kodak (Kodak Environmental Report 1997). McCartney (1999) also provides empirical evidence to support the model findings. When the manufacturer owns the distribution channel, as in the coordinated case, the manufacturer undertakes the collection effort herself, as in the case of Xerox (Xerox Environmental Report 1997).

In the next section, we examine mechanisms which enable the manufacturer to achieve coordinated channel performance in the RC system. First, we consider an environment where all cost parameters are common knowledge to the channel members. Next, we briefly state the impact on the manufacturer when the retailer retains private information about his collection costs.

5 Coordination in the Retailer Collecting Channel

Under the assumption of complete information about cost and demand data, we first derive a simple contract form which may be offered by the manufacturer to the retailer to induce him to choose an effort level that maximizes total channel profits[23]. Following the theory of incentive contracts (see Laffont and Tirole, 1993), we take a principle-agent approach, with the manufacturer as the principal. The role of the manufacturer as the principal is consistent with the spirit of the earlier sections of this paper, which give the manufacturer the role of the leader in the Stackelberg game. The manufacturer can influence the retailer's choice of the collection effort

[23]In Appendix A.3, we also provide a similar analysis for possible coordination alternatives when the third party is the collecting agent.

level by specifying a contract of the type $W(\tau) = [w(\tau), F]$. Here, $w(\tau)$ stands for a wholesale pricing scheme contingent on the fraction of the market demand satisfied from returned products, and F is a fixed payment made by the retailer to the manufacturer which distributes the efficiency gains. Thus, the manufacturer's problem is formulated as:

$\underset{W(\tau)}{Max}\, \Pi_M^{RC} = (w(\tau) - (c_m - \Delta * \tau^*))D(p^*) - b * \tau^* * D(p^*) + F$

subject to

IC1: $\tau^* = \arg\max_{\tau} \{\Pi_R^{RC}(W(\tau), b)\}$

IC2: $p^* = \arg\max_{p} \{\Pi_R^{RC}(W(\tau), b)\}$

IR: $\Pi_R^{RC}(W(\tau), b) \geq \Pi_R^{-}$

where Π_R^{-} is the retailer's profit level realized in the decentralized channel structure, and $\Pi_R^{RC}(W(\tau), b) = [p - w(\tau)]D(p) + b * \tau * D(p) - C(\tau) - F$ is the profit function of the retailer under the contract $W(\tau)$. The first two constraints are the incentive compatibility constraints for τ and p respectively, while the last constraint is the individual rationality constraint of the manufacturer[24]. Proposition 5 states one form of the optimal contract that the manufacturer offers the retailer.

Proposition 5 *The form of the optimal contract,* $W^*(\tau) = (w^*(\tau), F^*)$, *which ensures that the retailer undertakes the coordinated effort level and charges the optimal coordinated retail price is given by:* $w^*(\tau) = c_m - (\Delta - b)\tau, 0 < \tau < 1$ *and* $F^* = \Pi^{*CDC} - \Pi_R^{-}$.

The proof of the proposition is in Appendix A.2. As stated in the above proposition, to ensure that the retailer's profit maximizing collection effort is indeed equal to the coordinated channel effort level, the manufacturer offers a wholesale pricing scheme contingent on the collection effort level characterized by the term $(\Delta - b)\,\tau$. Specifically, the manufacturer puts the retailer in a position where he directly internalizes the cost consequence of his collection effort. Besides ensuring the coordinated channel effort level, the contract also provides a means for making the retail price of the product equal to the coordinated channel price level, thereby making the process more efficient for the market (in terms of increased demand). Our findings are consistent with the extant literature in marketing and economics which shows that if the manufacturer transfers the

[24] A detailed explanation of these constraints can be found in Appendix A.2.

products at the realized unit cost of production, the coordinated channel retail price and profit levels can be attained in the decentralized setting.

In this paper, without loss of generality, we assume that all the efficiency gains are collected by the manufacturer, leaving the retailer with a profit level as high as he would have if the contract were not put into practice[25]. Hence, $F^* = \Pi^{*CDC} - \Pi_R^-$. *This fixed payment can be seen as a franchisee fee paid by the retailer to the manufacturer in order to have the rights not only to sell the product in the market but also to collect the disposed units.*

The operations and marketing literature have used quantity discounts and flexible ordering policies in conjunction with fixed payments (also referred to as franchisee fees) extensively as mechanisms for coordination in decentralized channels. *This paper also shows that wholesale pricing schemes can be used in conjunction with franchisee fees to coordinate reverse decentralized channels.*

When the manufacturer has only partial information about the collection cost structure of the retailer, then an effective retailer (low collection cost) has an incentive to signal a high collection cost structure to the manufacturer and increase his profits. When the complete information assumption about the cost of collection is not met, we find that the manufacturer can design a menu of contracts where each contract on the menu has a similar form as the contract defined for the full information environment. The menu is defined to induce the retailer to reveal his private information about the cost of collection to the manufacturer. Since the insights under incomplete information are similar to the full information case, we do not report the model analysis in detail (Savaskan et al. 2000).

The model presented to analyze the different product recovery systems shows that the coordinated system has the best performance for all parties, as the market demand and collection efforts are the highest, and the manufacturer and retailer pareto-optimize their profits in the coordinated system. In the decentralized reverse channels, we find that the most preferable agent to undertake the collection effort is the retailer, followed by the manufacturer. The model shows that unless the third party or the manufacturer has significantly better systems for collection (i.e., lower B

[25] Since the manufacturer is the principal in this model, the manufacturer can use her power to hold back all the gains of efficiency from channel coordination. However, in a real setting, the implementation of such a contract may be tenuous, and a more satisfactory arrangement will have both parties sharing the gains from coordination.

values than the other agents), the retailer should undertake the collection effort in a decentralized decision-making unit.

We also show that the results of a coordinated channel always pareto-dominate the results of a decentralized channel under complete information, and then discuss coordination mechanisms that the manufacturer can offer the retailer to exploit system efficiency gains. We now summarize the contributions and limitations of the paper and identify related topics of interest for future research.

6 Contributions, Limitations and Future Research

Designing effective product recovery systems has important ramifications for profitable organizations, regulatory bodies and the market. The first contribution of this paper has been to identify the appropriate reverse channel structure for OEMs to undertake their recollection effort. We show that firms can design recovery systems to enhance their profits and market demand, and in conjunction, can increase the degree of reusability of older products. Coordination mechanisms are suggested to better achieve the above aims by providing suitable incentives in the form of simple two-part tariffs (a per unit wholesale price coupled with a franchisee fee), to align the objectives of the members in the reverse channel. The results suggest that like other methods suggested in the literature (quantity discounts and flexible ordering policies), product recovery systems can also be used as effective tools for channel coordination. We can also show that if there is an asymmetry of information between the manufacturer and the retailer where the manufacturer does not know the retailer's cost of collection, she can create suitable contracts to minimize the impact of the asymmetry on her own and the system's profits.

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 "green" manufacturing practices in general, and product recovery systems in particular. We assume that for the agency who implements the recollection effort, an infrastructure for the logistics of getting products back from customers and delivering them to the OEM already exists independent of the recollection effort. Future research in this area should consider the impact of the fixed setup costs that are to be incurred in establishing a network for the reverse logistics function. Based on the model analysis and insights, we conjecture that a high cost of establishing such a network would make it even more appropriate for a forward distribution channel member (eg. retailers) to undertake the recollection effort, as such networks are already in place in typical systems for forward distribution activities. The paper considered only a single agent undertaking the recovery process. If there are multiple agents (eg. retailers) undertaking the recovery process in separate markets (such as geographically dispersed markets), the results of the model are not affected. Savaskan and Van Wassenhove (2000) study the impact of two retailers competing to recover and distribute to the same market. The location of the agents vis-a-vis the consumers and proximity to the market was not considered in this research. If the recovery is done through a fixed price delivery system (such as prepaid envelopes in the regular mail), then the results of the model are not affected. Studies that look at the impact of different agents undertaking recollection with different geographical distances from the consumer would be useful for enhancing the understanding of the logistics of product recovery systems.

We also assume that the firm has designed the product platform for reuse so that older products can be easily incorporated partially or wholly into the new product (Xerox 1997). An extension of this study should consider product platform design issues to make products easier to reuse. This research assumed that all the products that are recovered are usable for remanufacturing into new products. When products having different lifetimes are returned, it would be useful to incorporate yield factors into this study to determine the impact on product recovery. Future research should investigate the effect of the degree of product durability in the recovery process. While we modeled that reusing older products in new generations would incur lower unit variable costs due to savings in assembly equipment, material costs, etc. we did not explicitly study detailed practices for lowering unit variable costs. There is a need for empirical research in this area to quantify the sources of savings through product recovery, and to identify product categories where such savings are a substantial portion of the unit variable cost.

In this paper, the recollection effort is undertaken from products that have been sold in the past and are being returned in the period of consideration for the model. The results of the model are not affected in a more generic multi-period setting if products that recovered in the previous period are used for remanufacturing in the current period. A more in-depth study should be conducted on the effect of recovered products which have been recovered in multiple periods before for use in remanufacturing in the current period. We also did not consider the impact of competition between secondary markets for old products and the manufacturer's reuse of old products. Future research should look at the impact of this competition on the product recovery process. It is also plausible that the manufacturer could design a product line based on completely new products and refurbished or remanufactured products. A study on the design of such product lines and the related cannibalization issues would be useful for practice. We also did not model the customer's choice process in more detail. Future studies should consider consumer utility and choice issues in designing a product line with some remanufactured products.

At a more detailed level, the fixed costs of recollecting products were assumed to be a quadratic function of the fraction of current demand that is recovered from the market. Based on numerical studies, we conjecture that the results of the model will broadly hold for all convex recollection fixed cost structures. Also, the costs incurred by recollection agencies of holding inventory and transporting them in select lot sizes to the OEM over the product life-cycle have not been considered in the model. Future research should explicitly model costs associated with lot-sizing the old products and transporting them in these lot sizes to manufacturing facilities.

In summary, this paper makes a contribution to the literature on distribution channel design by drawing attention to reverse channels, and developing a model of the trade-offs underlying such systems. Our recommendation is that firms make a conscious choice of channel structure, as different channel structures are appropriate in different environments. The qualitative framework provided in Section 5 that summarizes the results of the model provides some guidance in this regard. A combined design of the forward and reverse channels can not only provide the firm with much needed flexibility to reduce logistics costs for forward and reverse activities, but also enable it to signal continued concern and action on environmental issues.

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APPENDIX

A.1 Proof of Propositions 1, 2, 3 and 4

Proof of Proposition 1: For the RC system, the proof of proposition 1 can be given as follows. First we show that the manufacturer's profit function is concave in w for a given b. This allows us to optimize the manufacturer's problem first over w for a given b and then examine the effect of b. Note that in the RC system, for a given w and b, the retailer solves the following problem: $\underset{p,\tau}{Max}\ (p-w)(\phi-\beta p)+b\tau(\phi-\beta p)-B\tau^2-A\tau(\phi-\beta p)$.

It can easily be shown that the optimal p and τ values as a function of b and w are given by:

$$p^* = \frac{\phi+\beta[w-(b-A)\tau^*]}{2\beta}$$

$$\tau^* = \frac{(b-A)}{2B}(\phi-\beta p^*)$$

The manufacturer takes into account the reaction function of the retailer (i.e., $p^*(w,b)$ and $\tau^*(w,b)$) and maximizes the following function for b and w.

$\underset{w,b}{Max}\ (w-c_m+(\Delta-b)\tau^*(w,b))D(p^*(w,b))$.

$\underset{w,b}{Max}\ \frac{2B}{4B-\beta(b-A)^2}(\phi-\beta w)(w-c_m)+\frac{2B(b-A)(\Delta-b)}{(4B-\beta(b-A)^2)^2}(\phi-\beta w)^2$.

To show that the manufacturer's profits are concave in w for a given b we examine the sign of $\frac{\partial^2\Pi_M}{\partial w^2}$. It follows that $\frac{\partial^2\Pi_M}{\partial w^2}=\frac{2B}{4B-\beta(b-A)^2}(-2\beta)+\frac{4B\beta^2(b-A)(\Delta-b)}{(4B-\beta(b-A)^2)^2}$. To show $\frac{\partial^2\Pi_M}{\partial w^2}\leq 0$ for a given b, one needs to show that $\frac{4B\beta^2(b-A)(\Delta-b)}{(4B-\beta(b-A)^2)^2}\leq\frac{4B\beta}{4B-\beta(b-A)^2}$ or equivalently $\beta(b-A)(\Delta-b)\leq 4B-\beta(b-A)^2$ which reduces to $\beta(b-A)(\Delta-A)<4B$. Since $4B>\beta(\Delta-A)^2$ holds from the non-negativity restriction on τ in the CDC system (Table 2) and $b<\Delta$ it follows that $\beta(b-A)(\Delta-A)<4B$ holds. Hence Π_M is concave in w for a given b.

In the the second part of the proof we examine the effect of b on the profits of the manufacturer. Hence, the proof of Proposition 1 for the RC system follows from the fact that $\frac{\partial\Pi_R^{RC}}{\partial b}$ and $\frac{\partial\Pi_M^{RC}}{\partial b}\geq 0$. To show these statements, note that $\frac{\partial\Pi_R^{RC}}{\partial b}=\frac{(\phi-\beta c_m)^2}{8\beta}\frac{-1}{(1-\frac{\beta(\Delta-A)(b-A)}{4B})^2}\frac{-\beta(\Delta-A)}{4B}$, which is always positive. $\frac{\partial\Pi_M^{RC}}{\partial b}=\frac{(\phi-\beta c_m)^2}{16\beta}\frac{N}{(1-\frac{\beta(\Delta-A)(b-A)}{4B})^4}$ where N is given by $(1-\frac{\beta(\Delta-A)(b-A)}{4B})^2(\frac{-2\beta(b-A)}{4B})-2(1-\frac{\beta(b-A)^2}{4B})(\frac{-\beta(\Delta-A)}{4B})$. $\frac{\partial\Pi_R^{RC}}{\partial b}$ is always positive if the factor N is positive. After some simplification, N turns out to be positive if $\frac{\beta(b-A)(\Delta-A)}{4B}\leq 1$, which follows from our assumption that τ^{*TPC} is non-negative (and hence, from Proposition 4, τ^{*RC}, τ^{*MC}, and τ^{*CDC} are non-negative). ■

We follow a similar procedure for the proof of the optimal b value in the TPC system. First we show that the manufacturer's profits are concave in w for a given b and then, we optimize over b. In the TPC system , the retailer and the third party solve the following problems respectively for $p^*(w)$ and $\tau^*(b)$: $\underset{p}{Max}\ (p-w)(\phi-\beta p)$ and $\underset{\tau}{Max}\ b\tau(\phi-\beta p)-B\tau^2-A\tau(\phi-\beta p)$.

The manufacturer takes into account the reaction functions of the retailer and the third party and solves the following optimization problem for w^*.

$$\underset{w}{Max}\ (\phi - \beta p^*(w))(w - c_m + (\Delta - b)\tau^*(b))$$

$$\underset{w}{Max}\ \frac{(\phi - \beta w)}{2}[w - c_m + \frac{(\Delta - b)(b - A)(\phi - \beta w)}{4B}]$$

To show that the manufacturer's profit is concave in w for a given b, we examine the sign of $\frac{\partial^2 \Pi_M}{\partial w^2}$.

Note that $\frac{\partial^2 \Pi_M}{\partial w^2} = -\beta[1 - \frac{\beta(b-A)(\Delta-b)}{4B}]$. By rearranging the terms, it follows that the concavity condition $\frac{\partial^2 \Pi_M}{\partial w^2} < 0$ reduces to $4B > \beta(b - A)(\Delta - b)$. From the non-negativity constraint on τ in the CDC system, it follows that $4B > \beta(\Delta - A)^2$. Since $\beta(b - A)(\Delta - b)$ is equivalent to $\beta(b - A)(\Delta - A) - \beta(b - A)^2$ which is less than $\beta(\Delta - A)^2$, the concavity condition $4B > \beta(b - A)(\Delta - b)$ also holds for a given b.

Next, we solve for the optimal b value which maximizes the manufacturer's profits. Note that the optimization of $\Pi_M(b) = \frac{\frac{(\phi - \beta c_m)^2}{8\beta}}{\left[1 - \frac{\beta(\Delta-b)(b-A)}{4B}\right]}$ w.r.t. b is equivalent to the minimization of the expression $\left[1 - \frac{\beta(\Delta-b)(b-A)}{4B}\right]$and, this expression is minimized when $\beta(\Delta - b)(b - A)$ is maximized. It can easily be shown that $b^* = \frac{\Delta + A}{2}$.

Proof of Proposition 2 : We divide the proof into three parts. (i) To prove $p^{*CDC} \leq p^{*RC}$,we have to show that

$\frac{\phi+\beta c_m}{2\beta} - \frac{1}{2}(\Delta - A)^2 \frac{\phi - \beta c_m}{4B - \beta\tau^2} \leq \frac{(3B - \beta(\Delta-A)(b-A))\phi + \beta B c_m}{\beta(4B - \beta(\Delta-A)(b-A))}$; or $\frac{\phi}{\beta}[\frac{2B - \beta(\Delta-A)^2}{4B - \beta(\Delta-A)^2} - \frac{3B - \beta(\Delta-A)(b-A)}{4B - \beta(\Delta-A)(b-A)}] \leq c_m[\frac{B}{4B - \beta(\Delta-A)(b-A)} - \frac{2B}{4B - \beta\Delta^2}]$. This reduces to showing that $\frac{\phi}{\beta}[\frac{-2B}{4B - \beta(\Delta-A)^2} + \frac{B}{4B - \beta(\Delta-A)(b-A)}] \leq c_m[\frac{B}{4B - \beta(\Delta-A)(b-A)} - \frac{2B}{4B - \beta(\Delta-A)^2}]$ or $\phi \geq \beta c_m$, since the quantity within the brackets is negative. This is true by assumption because of the requirement of positive profits for the manufacturer and retailer.

(ii) To prove $p^{*RC} \leq p^{*MC}$, we have to show that $\frac{(3B - \beta\Delta b)\phi + \beta B c_m}{\beta(4B - \beta\Delta b)} \leq \frac{3\phi + \beta c_m}{4\beta} - \frac{\phi - \beta c_m}{4}\frac{\Delta^2}{8B - \beta\Delta^2}$; or $\frac{\phi}{\beta}[\frac{3B - \beta\Delta b}{4B - \beta\Delta b} - \frac{6B - \beta\Delta^2}{8B - \beta\Delta^2}] \leq c_m[\frac{B}{4B - \beta\Delta b} - \frac{2B}{4B - \beta\Delta^2}]$ which reduces to showing that $\frac{\phi}{\beta}[\frac{B}{4B - \beta\Delta b} - \frac{2B}{4B - \beta\Delta^2}] \leq c_m[\frac{B}{4B - \beta\Delta b} - \frac{2B}{4B - \beta\Delta^2}]$. If $b > \frac{\Delta}{2}$ (Proposition 1),the quantity within the brackets is negative, so the inequality reverses and by assumption $(\phi \geq \beta c_m)$, the result is true.

(iii) To show that $p^{*MC} \leq p^{*TPC}$, we have to show $\frac{(\Delta-A)^2}{8B - \beta(\Delta-A)^2} \geq \frac{(b-A)(\Delta-b)}{4B - \beta(\Delta-b)(b-A)}$. This reduces to showing that $\frac{(\Delta-A)^2}{2} \geq (\Delta - b)(b - A)$, which follows from simple algebra.

To show $(\Delta - A)^2 \geq 2(\Delta - b)(b - A)$,or to show $\Delta^2 + A^2 - 2\Delta b + 2b^2 - 2Ab \geq 0$

This reduces to showing $(\Delta - b)^2 + (A - b)^2 \geq 0$ ■.

Proof of Proposition 4: The proof of Proposition 3 follows from simple algebra. From Table 2, $\Pi_M^{*RC} \geq \Pi_M^{*MC}$, as $b = \Delta$ in the RC system, and $\Pi_M^{*MC} \geq \Pi_M^{*TPC}$, as $\frac{(\Delta-A)^2}{2} \geq (\Delta-b)(b-A)$ from the previous proof. The proofs of $\Pi_R^{*RC} \geq \Pi_R^{*MC} \geq \Pi_R^{*TPC}$ and $\Pi^{*CDC} \geq \Pi_T^{*RC} \geq \Pi_T^{*MC} \geq \Pi_T^{*TPC}$ are analogous.

Proof of Proposition 3: The proof of Proposition 3 is analogous to the previous proof.

The effect of $\mathbf{c}_m$ on τ : We examine the effect of $\mathbf{c}_m$ on τ for the manufacturer collecting case. Note that $\tau = \frac{(\phi-\beta c_m)(\Delta-A)}{8B-\beta(\Delta-A)^2}$. Substituting $\Delta = kc_m$, we obtain $\tau = \frac{(\phi-\beta c_m)(kc_m-A)}{8B-\beta(kc_m-A)^2}$. The first order derivative of τ w.r.t. c_m is given by:

$$\frac{\partial\tau}{\partial c_m} = \frac{[-\beta(kc_m-A)+k(\phi-\beta c_m)][8B-\beta(kc_m-A)^2]+2\beta k(kc_m-A)[(\phi-\beta c_m)(kc_m-A)]}{[8B-\beta(kc_m-A)^2]^2} = \frac{([k(\phi-2\beta c_m)+\beta A)]+2\beta k(kc_m-A)\tau^*}{[8B-\beta(kc_m-A)^2]}.$$

It follows that $\frac{\partial\tau}{\partial c_m} > 0$ for $c_m < \overline{c_m}$ where $\overline{c_m}$ is a threshold on unit cost and $\overline{c_m} = \frac{\phi+\beta A/k-2\beta A\tau^*}{2\beta-2\tau^*\beta k}$.

A.2 Coordination of the RC System under Full Information

The first constraint is the incentive compatibility constraint for the collection effort level which models the retailer's selection of an effort level that maximizes his profits. Specifically, given the contract $W(\tau)$, the retailer independently determines the profit maximizing value for τ which in turn sets the average unit cost of production for the manufacturer. Hence, by incorporating incentive compatibility, the manufacturer in this way accounts for the independent decision making process of the retailer. In a similar vein, the second constraint denotes the incentive compatibility for the retail price of the product, and accounts for the retailer's choice of a retail price which maximizes his profits. The third constraint is the individual rationality constraint, which ensures that the retailer finds the contract as profitable as his other alternative which is his profit level realised in the decentralized channel structure, Π_R^- .

Proof of Proposition 5: If the manufacturer decides to give the contract $(w^*(\tau), F^*)$ the retailer optimizes the following objective function to determine p and τ:

$$\underset{p,\tau}{Max}\ (p - c_m + (\Delta - b)\tau)D(p) + b * \tau * D(p) - C(\tau) - F^*$$

which simplifies to $\underset{p,\tau}{Max}\ (p - c_m + \Delta\tau)D(p) - C(\tau) - F^*$

The first order conditions w.r.t. retail price p and collection effort τ are given by:

for p: $(p - c_m + \Delta\tau)D'(p) + D(p) = 0$

for τ: $\Delta D(p) = \frac{dC(\tau)}{d\tau}$

Note that these two conditions are equivalent to the first order condition of the centrally coordinated channel for p and τ. Thus, the optimal retail price and the collection effort level chosen by the retailer in the decentralized system are given by:

$$\begin{aligned} p^* &= p^{*CDC} \\ \tau^* &= \tau^{*CDC} \end{aligned}$$

Evaluating the retailer's objective function at the optimal values of p^* and τ^*, we obtain :

$$\Pi_R^{*RC}(w^*(\tau), F^*, b) = \Pi^{*CDC} - \Pi^{*CDC} + \Pi_R^{*RC} = \Pi_R^-$$

Hence, the retailer is not worse off with the contract and therefore accepts it. As a result, he chooses p^{*CDC} and τ^{*CDC} for the optimal values of the retail price and the collection effort level, respectively.

Going back to the manufacturer's problem, it remains to be shown that the profits of the manufacturer are indeed maximized under this contract form. The objective function of the manufacturer evaluated at$(w^*(\tau), F^*)$ is given by:

$\Pi_M^{RC}(w^*(\tau), F^*) =$

$((c_m - \tau^*(\Delta - b) - (c_m - \Delta * \tau^*))D(p^*) - b * \tau^* * D(p^*) + F^* = \Pi^{*CDC} - \Pi_R^{*RC}$.

Since the products are transfered at the marginal cost to the retailer, the manufacturer's profits amount to the franchisee fee F^*, which is the maximum profit she can achieve while not leaving the retailer worse off[26]. Note that while deriving the optimal contract, we have not assumed any specific functional form for the market demand.

A.3 Coordination of the TPC System under Full Information

The manufacturer can achieve the coordinated channel profits in the TPC system by transferring products to the retailer at marginal cost of production of the CDC system $\left(i.e.\ w = c_m - \Delta\delta^{*CDC}\right)$and

[26] Alternatively, the manufacturer can also propose a take-it-or-leave-it contract to the retailer where she fixes the collection effort level at δ^{*CDC}, the wholesale price of the product at $w(\delta^{*CDC}) = c_m - (\Delta - b)\delta^{*CDC}$ and the fixed payment at $F^* = \Pi^{*CDC} - \Pi_R^-$. This contract structure also maximizes the manufacturer's profits while inducing the retailer to show the coordinated system collection effort level (Laffont and Tirole, 1993).

by setting $b = \Delta$. In order to extract the efficiency gains in the distribution and collection channels, the manufacturer sets two separate franchisee fees F_1^* for the retailer and F_2^* for the third party.

Under this wholesale pricing scheme the retailer's objective function is given by:

$$\underset{p}{Max}\ (p - c_m + \Delta\delta^{*CDC})\,(\phi - \beta p) - F_1^*$$

The first order condition for p^* amounts to:

$(p^* - c_m + \Delta\delta^{*CDC})\,(-\beta) + (\phi - \beta p^*) = 0$. It is easy to see that solution of this condition results in $p^* = p^{*CDC}$ and $D(p^*) = D(p^{*CDC})$.

In a similar fashion, the objective function of the third party is given by :

$$\underset{\tau}{Max}\ \ \Delta\tau D(p^*) - B\tau^2 - F_2^*$$

The first order condition for τ^* is given by: $\Delta D(p^*) - 2B\tau^* = 0$. solving, for τ^*, we obtain $\tau^* = \tau^{*CDC}$.

It is interesting to note that in order to achieve coordination in the TPC system, the manufacturer faces negative marginal profits from the sales of the products. Her resultant profits are determined through fixed payments of F_1^* and F_2^*.

The franchisee fees F_1^* and F_2^* which maximize the manufacturer's profits while not leaving the retailer and the third party worse off, are given by :

$$F_1^* = \Pi^{*CDC} + C\left(\tau^{*CDC}\right) - \Pi_R^-$$

$$F_2^* = \Delta\tau^{*CDC} D(p^{*CDC}) - C\left(\tau^{*CDC}\right) - \Pi_{TP}^-$$

where Π_R^- and Π_{TP}^- are the profits of the retailer and the third party in the decentralized uncoordinated channel structure.

Hence, the manufacturer's profit is given by:

$$\begin{aligned}\Pi_M^* &= -\Delta\tau^{*CDC} D(p^{*CDC}) + \Delta\tau^{*CDC} D(p^{*CDC}) - C\left(\tau^{*CDC}\right) - \Pi_{TP}^- \\ &\quad +\Pi^{*CDC} + C\left(\tau^{*CDC}\right) - \Pi_R^-\end{aligned}$$

which amounts to:

$$\Pi_M^* = \Pi^{*CDC} - \Pi_R^- - \Pi_{TP}^-$$

Hence, the manufacturer extracts all the efficiency gains from the coordination of the system.