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Distribution Channel Choice and Divisional Conflict in Remanufacturing Operations

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We consider a firm consisting of two divisions, one responsible for designing and manufacturing new products and the other responsible for remanufacturing operations. The firm will sell these new and remanufactured products either directly to the consumer (direct selling) or through an independent retailer (indirect selling). Our paper demonstrates that a firm's organizational structure can affect its marketing decisions. Specifically, a decentralized firm with separate manufacturing and remanufacturing divisions can benefit from indirect selling with higher firm profit, supply chain profit, and total consumer demand than direct selling. Moreover, this structure also induces a remanufacturable product design. In contrast, a centralized firm in which the manufacturing and remanufacturing divisions are consolidated is intuitively better off by choosing direct selling than indirect selling. Furthermore, we show that, surprisingly, when the focal firm sells through an independent retailer, a decentralized internal structure can result in higher supply chain profit than a centralized internal structure. We further investigate the case of dual dedicated channels and conclude that, while direct selling of remanufactured products and indirect selling of new products can better induce a remanufacturable product design and higher supply chain profit, it is not in the best interest of the firm in terms of total sales and firm profit.

Key words: remanufacturing; product design and pricing; channel choice; divisional conflict
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1. Introduction

Remanufacturing has become a significant and fast-growing industry worldwide with the U.S. being the leader in the production, consumption, and export of remanufactured goods (Vlaanderen 2018). In the last review by the U.S. International Trade Commission, the economic value of US remanufactured production was reported to be more than US$43 billion in 2012 (U.S. International Trade Commission 2012). Consistent with the overall growth in the manufacturing, during 2012-2017, an annual growth rate of 1.5% is observed in aircraft maintenance, repair and overhaul, and 2% in auto parts remanufacturing (Vlaanderen 2018). The amount of waste in electrical and electronic equipment has reached 41.8 million tons in 2014 and is expected to grow at a rate of 3-5% every year (Baldé et al. 2017), signifying the huge potential for the growth of remanufacturing. Many manufacturing firms, such as Bosch, DaimlerChrysler, and Océ, have separate divisions to produce new and remanufactured products (Toktay and Wei 2011). This is because either remanufacturing operations require significantly different processes from manufacturing, or the remanufacturing division can be treated as a profit center due to large production quantities. Caterpillar, for instance, established a remanufacturing division that had more than $2 billion in sales in 2007, and its Mississippi remanufacturing team had a workforce of more than 1,200 in 2014 (Ferguson and Souza 2010, Caterpillar 2014).

This research is motivated by the inter-divisional coordination issues faced by a Fortune 500 manufacturing company that has both manufacturing and remanufacturing operations. The two operations are conducted in dedicated in-house facilities and managed by new and remanufacturing divisions, respectively. Both new and remanufactured products reach customers through authorized dealers. Customers can return worn or broken products to the dealers, who either 1) replace parts if products can be functional again with simple parts replacement and cleaning, 2) send products to the remanufacturing facility if sophisticated repair and replacement work is required, or 3) dispose of products if they are significantly worn or damaged. Products returned to the remanufacturing facility will be processed to regain an “as new” or even better condition so they can be sold as remanufactured products; some returns will be disposed of if remanufacturing is not cost-effective.

Although the firm has been engaged in remanufacturing for decades, the remanufacturing operation still receives little support, according to the manager we interviewed. The remanufacturing division has minimal control over the product design that is normally incorporated into the manufacturing process. However, a remanufacturable product design may not be in the best interest of the manufacturing division for two primary reasons. First, the additional cost required to make new products remanufacturable reduces the incentive of the manufacturing division to choose a remanufacturable product design. For example, in the printer cartridge industry, the technical barriers to remanufacturing are introduced at the process design phase, whereby design decisions, such as the implementation of irreversible joining manufacturing, are made without the consideration of facilitating or encouraging re-use of the product at end-of-life (Kling et al. 2018). Second, the manufacturing division is concerned with the remanufacturing operations because of the potential product cannibalization, meaning that the sales of lower-priced remanufactured products can steal from the sales of new products (Atasu et al. 2010). Although it is not surprising to observe firm inefficiency as a result of the above concerns, it is not clear as to what extent divisional conflict between the manufacturing and the remanufacturing divisions influences the optimal product design and efficiency losses in terms of firm profits and product sales.

Another observation from the interviewed firm is that it relies on indirect selling in which both new and remanufactured products are sold only through its dealers. In fact, some manufacturers sell remanufactured products through their owned channels (e.g., GE Healthcare (2020) has established its own distribution channel called GoldSeal Refurbished Systems), while others use certified retailers (e.g., Caterpillar (2020) offers more than 7600 remanufactured products available from its dealer). Although there are many studies on channel choice, few have investigated its impact on product design decisions, especially those related to remanufacturing. Thus, in this research, we ask the following questions: What are the implications of internal structure (centralization or decentralization of manufacturing and remanufacturing operations) on channel choice (direct or indirect selling), and vice versa? How does this choice affect strategic remanufacturing decisions and therefore the environment? What are the resulting product design, product sales, and profits of different entities?

To examine the above questions, we consider a firm with one manufacturing division and one remanufacturing division. In an (internally) decentralized firm with separate manufacturing and remanufacturing divisions, each division determines the optimal retail (wholesale) price of its products to maximize its divisional profit if the firm chooses direct (indirect) selling. The manufacturing division can design new products to be non-remanufacturable and produce them at a base cost. Alternatively, it can design new products to be remanufacturable and produce them at a higher production cost, while the remanufacturing division can produce remanufactured products at a lower cost than the base cost. In contrast, in an (internally) centralized firm with consolidated manufacturing and remanufacturing divisions, the pricing and design decisions are made to maximize the firm's total profit. The retailer decides the retail prices of both products (if applicable) after knowing the wholesale prices.

Our results reveal that a centralized firm, with consolidated manufacturing and remanufacturing divisions, is intuitively better off by choosing direct selling over indirect selling. However, surprisingly, a decentralized firm, with separate manufacturing and remanufacturing divisions, can benefit from indirect selling. Compared with direct selling, indirect selling can not only induce remanufacturing but also increase supply chain profit, total demand, and even the profit of the manufacturing division. The intuition is that in the case of indirect selling, the retailer sells the new and remanufactured products, therefore having the incentive to mark down the price of the manufacturer's new products to ensure the supply of remanufactured products (originally new products) through the retailer. Consequently, more new products will be sold and the manufacturer will have a higher incentive to make the new products more remanufacturable. In other words, the existence of the retailer helps to alleviate conflicts between the manufacturing and remanufacturing divisions and benefits the manufacturer. In contrast, direct selling in a decentralized firm renders the retailer's incentive absent, thus discouraging remanufacturable product design and consequently hurting the manufacturer's profit.

We also found that, given the direct selling channel, a centralized internal structure is intuitively better than a decentralized internal structure in which the manufacturing and remanufacturing divisions do not coordinate. Nevertheless, when the focal firm sells through an independent retailer, a decentralized internal structure can result in higher supply chain profit than a centralized internal structure when a remanufacturable product design is optimal for the firm.

We further study the case of dual dedicated channels in which new (remanufactured) products are sold directly and remanufactured (new) products are sold through the retailer. In this case of dual dedicated channel structure, a remanufacturable product design is more achievable if the firm directly sells remanufactured products than if it directly sells new products. Direct selling of remanufactured products can result in more supply chain profit and, in some cases, increase the total sales when a remanufacturable product design is optimal for the firm. However, it will reduce the sales of new products as well as firm profit, and hence only benefit the retailer.

The remainder of this paper is organized as follows. The literature review is presented in Section 2. In Section 3, we formulate our models and examine the impact of internal structure (centralization or decentralization) on the channel choice (direct or indirect selling), optimal product architecture, and resulting demand and profits; we also discuss how the channel choice can affect the internal structure. In Section 4, we consider the dual distribution channel through which the firm sells new and remanufactured products separately. Section 5 discusses three model extensions by evaluating positive collection cost, optimized remanufacturability level, and partial decentralization, respectively. We conclude with a summary of our findings in Section 6. Proofs of propositions and lemmas are provided in the appendix.

2. Related Literature

This study is closely related to the literature on closed-loop supply chain management, as comprehensively reviewed by Guide and Van Wassenhove (2009), Souza (2013) and Abbey and Guide Jr (2018). A strand of papers analyzes profit maximization models to study the optimal design, pricing, and production decisions associated with remanufacturing. In particular, Atasu et al. (2008) identify the major factors that affect the profitability of remanufacturing for a monopolist, which include cost savings from remanufacturing, percentage of green consumers, market growth rate, and consumer valuation discounts for remanufactured products. Debo et al. (2005) find that investment in remanufacturability is driven by high production costs of a single-use product, low remanufacturing costs, and low additional costs to make a single-use product remanufacturable. Thus, firms need to analyze these factors prudently before deciding upon whether to design new products to be remanufacturable. Pricing new and remanufactured products is another critical issue in managing manufacturing and remanufacturing operations because it has been proven to be an effective strategy to control demand (Ferrer and Swaminathan 2006, 2010), segment the consumer market (Debo et al. 2005, Atasu et al. 2008), and limit competition (Majumder and Groenevelt 2001, Ferguson and Toktay 2006). A number of studies have also focused on the production quantity decision that basically answers how much can be remanufactured–which considers the availability of returned products or the acquisition of used products (Östlin et al. 2009, Galbreth and Blackburn 2010, Clottey et al. 2012)–and how much should be remanufactured–which considers the optimal number of products to be remanufactured (Ferrer and Swaminathan 2006, Ferguson et al. 2011, Özdemir et al. 2014, Raz and Souza 2018). Closely related to our paper, a set of papers in the literature of remanufacturing study the impact of competition between the original equipment manufacturer (OEM) and independent remanufacturers (Majumder and Groenevelt 2001, Ferguson and Toktay 2006, Ferrer and Swaminathan 2006). We contribute to this literature by endogenizing a product design (i.e., whether or not to design a product to be remanufactured) and by exploring the impacts of divisional conflicts between a manufacturing division that designs and produces new products and a remanufacturing division that remanufactures used products in the context of a dual-division firm.

In the remanufacturing literature, studies on the conflict and coordination between manufacturing and remanufacturing operations are rare. The interplay between the manufacturing division and the remanufacturing division is complicated because there is a lack of a common objective between the two divisions. Toktay and Wei (2011) study the divisional conflicts between such two divisions and propose a coordination scheme using transfer price. Studies show that contracts can be designed to coordinate the supply chain, optimize profit performance, and align each entity's objective with that of the entire supply chain (Cachon 2003, Cachon and Lariviere 2005, Jacobs and Subramanian 2012) and that certain form of incentives can coordinate two departments within an organization (Eliashberg and Steinberg 1987, Balasubramanian and Bhardwaj 2004, Dai and Jerath 2013, Dockner and Fruchter 2014). While these papers can help firms coordinate their external supply chain structures or internal conflict, they do not provide answers to how firms manage the interplay between their internal divisional structure on manufacturing and remanufacturing and firms' external distribution channel structures. In a similar spirit as Desai et al. (2004), we contribute by not only studying the effects of division conflicts between manufacturing and remanufacturing on firms'profits, sales, and product design but also exploring how a firm's choice of external distribution channel can mitigate the impact of internal divisional conflicts between manufacturing and remanufacturing within a firm.

Another related stream of literature focuses on the channel choice of a firm. Chiang et al. (2003) show that, in a price setting game between a manufacturer and its independent retailer, direct marketing not only improves the manufacturer's overall profitability by reducing the effect of double marginalization but also can benefit the retailer with a reduced wholesale price. Yao and Liu (2005) consider a dual-channel supply chain with a manufacturer-owned online store and a traditional retailer and demonstrated that the introduction of e-tailing can induce competitive pricing and payoffs. Cattani et al. (2006) analyze the "equal-pricing strategy," in which the manufacturer commits to a direct channel (Internet) retail price that equals its retailer's price in the traditional channel. They find that such commitment is truthful only if the Internet channel is significantly less convenient than the traditional channel. Cai (2010) shows that a single direct channel can outperform a dual-retailer channel. A dual channel with direct and retail channels can benefit both the supplier and the retailer, but it is not as profitable as a dual-retailer channel for the supplier when the direct channel is sufficiently weaker than the retail channel. In terms of channel choice related to remanufacturing operations, many previous studies emphasize the choice of reverse channel structure for the collection of used products from end-users (e.g., Savaskan et al. 2004, Savaskan and Van Wassenhove 2006, Atasu and Souza 2013). However, there is little discussion of the choice of appropriate distribution channel structure for the selling of new and remanufactured products. Retailers play an important role in the remanufactured-goods market and are more efficient in undertaking product collection activity in terms of the return rate than the firm itself (Savaskan et al. 2004, Shulman et al. 2010). A high collection rate can also be achieved through, but not limited to, leasing (Desai and Purohit 1999, Agrawal et al. 2012), trade-in rebates (Ray et al. 2005, Oraiopoulos et al. 2012), and a return contract to the retailer (Gümüş et al. 2013). Yan et al. (2015) show that if a manufacturer sells new products through an independent retailer, then it is more profitable for the manufacturer, as well as for the retailer, to sell remanufactured products through a third party than through its own e-channel. In our analysis, we consider the scenarios when the manufacturer sells both new and remanufactured products directly, sells both products indirectly through a retailer, and sells new products directly (indirectly) and remanufactured products indirectly (directly). We compare various scenarios to investigate how internal structure (centralization or decentralization of manufacturing and remanufacturing operations) affects the channel choice and the remanufacturing product design.

3. The Model and Channel Choice

The research questions of interest to us are: (1) Given the firm's internal structure on manufacturing and remanufacturing, what is the optimal distribution channel choice for the focal firm? Is it always optimal to choose direct selling rather than indirect selling through an independent retailer? (2) When the external channel structure is hard to change, is it beneficial to strategically decentralize the internal decisions on manufacturing and remanufacturing operations? The answers to these questions depend on the firm's business goal: whether to maximize the firm's profit, supply chain profit, total sales, or to induce remanufacturable product design. Thus, we first formulate our models (Section 3.1), and discuss the results with various goals when the internal structure is decentralized (Section 3.2) and centralized (Section 3.3). In Section 3.4, we answer the second question when the external structure is given.

3.1. Modeling Assumptions

The Firm. Consider a profit-maximizing firm with a manufacturing division and a remanufacturing division. The *manufacturing division* (denoted as D1) designs and produces new products, and the *remanufacturing division* (denoted as D2) remanufactures the returned products. Each division sells its products either directly or through a common retailer. D1 makes a design decision $k \in \{0,1\}$ at the beginning of the time horizon. If $k=0$, then new products are non-remanufacturable and can be produced at cost $c_1 > 0$ per unit by D1. In such a case, only new products are available in the market. Therefore, the production quantity of the remanufactured products and the divisional profit of D2 are both 0.

If $k=1$, then new products are remanufacturable and are produced at cost $c_1+\eta$ per unit, where the additional cost η is non-negative, to reflect the increased complexity required to make new products remanufacturable (Subramanian 2012). We assume $c_1+\eta<1$, where 1 represents the upper bound of consumer willingness-to-pay (WTP) for a new product, which will be discussed later. D2 can remanufacture the used remanufacturable products at cost $c_2 \geq 0$ per unit. Note that remanufacturing operations can include cleaning, replacing broken parts, disposing certain broken parts, and reassembling the products. We combine all these costs into a single overall remanufacturing cost. To avoid the trivial case where the firm has no incentive to undertake remanufacturing, we assume $c_2+\eta<c_1$. We also assume that D1 has the production capacity to fulfill any demand for new products. However, D2 cannot remanufacture more than the past sales of new products. For simplicity, we assume that all used products can be returned and remanufactured if the products are designed to be remanufacturable. This assumption applies to products that require frequent replacement or updates and that are not subject to significant wear and tear.

The cost of collecting and handling returned products are normalized to 0. These assumptions help us focus our analysis on issues that are important to this study. Nevertheless, we relax the above assumptions by analyzing non-zero collection cost in Section 5.1 and remanufacturability level in Section 5.2.

D1 and D2 decide the wholesale price w_1 and w_2 of new and remanufactured products, respectively, where $w_1, w_2 \in [0,1]$. In a decentralized firm, each division maximizes its divisional profit because the divisional manager's performance is usually measured based on the divisional profit (Toktay and Wei 2011). A division produces only if its divisional profit, the net of revenue and the internal transfer (if it exists) minus the cost, is positive.

For modeling convenience, we consider a single-period model, in which both new and remanufactured products are being sold in the same period. This model can be applied to the cases where similar products are introduced to the market repeatedly (Savaskan et al. 2004) or where a product's life cycle has reached its maturity stage so that prices and recovery rates are stable (e.g., Savaskan et al. 2004; Zikopoulos and Tagaras 2007; Atasu and Souza 2013).

The Retailer. The retailer, denoted as R, sells both new and remanufactured products and decides upon the retail prices p_1 and p_2 of the new and remanufactured products, respectively, in order to maximize its profit.

Consumers. Customer WTP for a new product is heterogeneous and uniformly distributed in the interval $[0,1]$. We assume a consumer's WTP to be independent of whether the product is remanufacturable or not, due to the distinction between consumers' consideration of product sustainability and conventional product characteristics (Galbreth and Ghosh 2013). On the other hand, as demonstrated in Guide and Li (2010) and Subramanian and Subramanyam (2012), a consumer's WTP for a remanufactured product is generally less than her WTP for a new product. Thus, we assume that if a consumer is willing to pay θ for a new product, then her WTP for a remanufactured product is $\delta \cdot \theta$, where $\delta \in (c_2, 1)$ is the discount factor for a remanufactured product. Note that δ needs to be higher than c_2 for the remanufactured products to be profitable. A consumer can choose between a new product and a remanufactured product, if applicable, depending on which one provides more customer surplus (the difference between WTP and the price). Each customer purchases at most one unit, either new or remanufactured. Note that consumers who would otherwise have a negative surplus do not purchase. In addition, the market size is normalized to 1. Under the above assumptions, similar to Desai and Purohit (1998), Ferguson and Toktay (2006), Vorasayan and Ryan (2006), Oraiopoulos et al. (2012), the inverse demand functions for new and remanufactured products are $d_1(p_1,p_2)=1-\frac{p_1-p_2}{1-\delta}$ and $d_2(p_1,p_2)=\frac{\delta p_1-p_2}{(1-\delta)\delta}$ when $k=1$, where d_1 and d_2 are the demand for new and remanufactured products, respectively, and $d_2\leq d_1$. If the new products are designed to be non-remanufacturable, then $d_1(p_1,p_2)=1-p_1$ and $d_2(p_1,p_2)=0$.

The technical notation in this section is summarized below:

c_1 =manufacturing cost per unit;

c_2 =remanufacturing cost per unit;

w_1 (w_2)=wholesale price of a new (remanufactured) product;

η =additional cost per unit to make a new product remanufacturable;

δ =WTP discount factor for a remanufactured product;

p_1 (p_2)=retail price of a new (remanufactured) product;

d_1 (d_2)=demand of new (remanufactured) products.

In all, our problem is defined on the parameter space $\Omega=\{(c_1,c_2,\delta,\eta)\,|c_2+\eta<c_1<1-\eta,\ c_2<\delta<1,\ 0\leq c_1,c_2,\eta\leq 1\}$.

Define Ω_S^X as the set of (c_1,c_2,δ,η) such that strategy $S\in\{\text{R1, R2, NR}\}$ is the equilibrium strategy in Model $X\in\{\text{C}\bar{\text{T}}, \bar{\text{C}}\bar{\text{T}}, \text{CT}, \bar{\text{C}}\text{T}\}$, where R1 denotes the strategy that the firm chooses a remanufacturable product design ($k=1$) but does not remanufacture all used products, R2 denotes the strategy that $k=1$ and the firm remanufactures all used products, NR denotes the strategy that the firm chooses a non-remanufacturable product design ($k=0$), C and $\bar{\text{C}}$ represent a centralized and decentralized firm, respectively, and T and $\bar{\text{T}}$ represent traditional (retail) channel and non-traditional (direct) channel, respectively. Thus, $\text{C}\bar{\text{T}}/\bar{\text{C}}\bar{\text{T}}$ represents that a centralized/decentralized firm only has direct sales (non-traditional channel), and $\text{CT}/\bar{\text{C}}\text{T}$ represents that a centralized/decentralized firm only has indirect sales through the retailer (traditional channel). Figure 1 provides a visual illustration of the four models.

Define Ω_{Re}^X as the set of (c_1,c_2,δ,η) such that a remanufacturable product design is optimal for the design decision maker under equilibrium in Model $X\in\{\text{C}\bar{\text{T}}, \bar{\text{C}}\bar{\text{T}}, \text{CT}, \bar{\text{C}}\text{T}\}$. By definition, $\Omega_{Re}^X=\Omega_{R1}^X\cup\Omega_{R2}^X$.

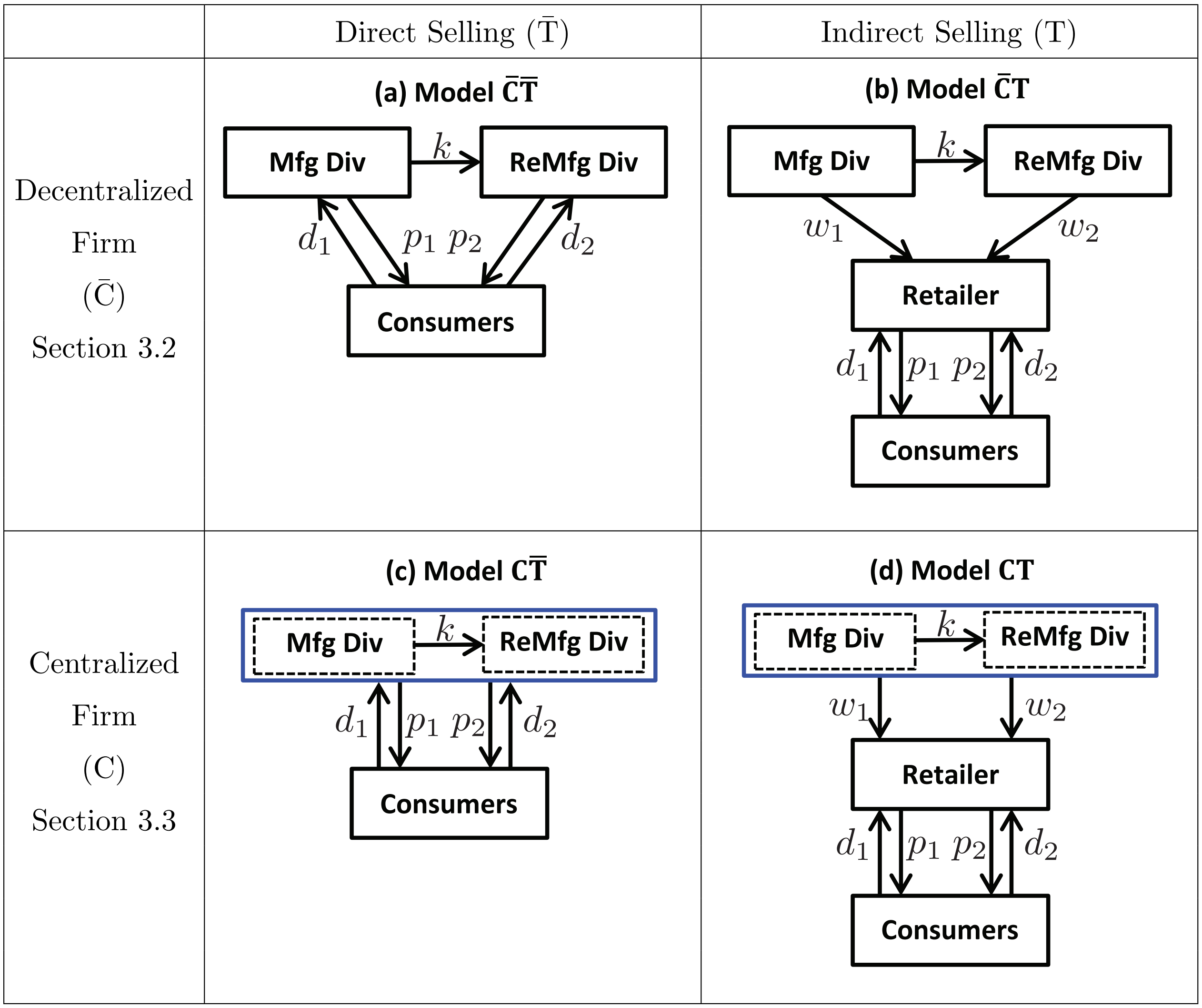


Figure 1 **Model Structures and Decisions**

3.2. Distribution Channel Choice by a Decentralized Firm

We first consider Model $\bar{\mathrm{C}}\bar{\mathrm{T}}$, in which a firm is decentralized and has two separate divisions: the manufacturing division (D1), which is responsible for designing and managing new products, and the remanufacturing division (D2), which is responsible for managing remanufactured products. Both divisions sell directly to the customers and make pricing decisions independently to maximize their own divisional profits. Let Π_1, Π_2, Π_F, and Π_{SC} denote D1's, D2's, the firm's, and the supply chain's optimal profit, respectively. We use superscript $\bar{C}\bar{T}$ to denote the results under equilibrium in Model $\bar{\mathrm{C}}\bar{\mathrm{T}}$. D1 first decides upon the product design k and the retail price p_1 of the new products. D1's objective is: $\Pi_1^{\bar{C}\bar{T}} = \max_{k,p_1} d_1\left(p_1,p_2\right)\left(p_1 - c_1 - k\cdot\eta\right)$, subject to $0 \le d_1\left(p_1,p_2\right) \le 1$. If $k=1$, then D2 decides upon the retail price p_2 of the remanufactured products and its objective is: $\Pi_2^{\bar{C}\bar{T}} =$

$\max_{p_2} d_2(p_1,p_2)\cdot(p_2-c_2)$, subject to $0\le d_2(p_1,p_2)\le d_1(p_1,p_2)$ and $d_1(p_1,p_2)+d_2(p_1,p_2)\le 1$. If $k=0$, then $\Pi_2^{\bar{C}\bar{T}}=d_2^{\bar{C}\bar{T}}=0$. The decision framework is illustrated in Figure 1(a). Note that when $k=0$, the remanufacturing division shown in Figure 1(a) will not exist. By definition, $\Pi_F^{\bar{C}\bar{T}}=\Pi_1^{\bar{C}\bar{T}}+\Pi_2^{\bar{C}\bar{T}}$, and it is easy to see that without a retailer, $\Pi_{SC}^{\bar{C}\bar{T}}=\Pi_F^{\bar{C}\bar{T}}$.

We solve the decision problems of Model $\bar{\text{C}}\bar{\text{T}}$ by backward induction and obtain the following lemma.

Lemma 1. *For a decentralized firm engaged in direct selling, strategy R1 or R2 is never optimal. In other words,* $\Omega_{R1}^{\bar{C}\bar{T}}=\Omega_{R2}^{\bar{C}\bar{T}}=\emptyset$, *or equivalently,* $k^{\bar{C}\bar{T}}=0$.

According to Lemma 1 and as illustrated in Figure 2(a), it is not optimal for the manufacturing division in the decentralized firm to design new products to be remanufacturable. Note that D1 is the decision maker who chooses $k^{\bar{C}\bar{T}}$ by comparing D1's profit with and without a remanufacturable product design. Intuitively, a remanufacturable product design increases D1's production cost (from c_1 to $c_1+\eta$) as well as introduces product cannibalization. Thus, NR is the strategy equilibrium if the firm is decentralized as in Model $\bar{\text{C}}\bar{\text{T}}$. In fact, even if there is no additional cost to make a new product remanufacturable (i.e., $\eta=0$), D1 would still choose strategy NR in order to avoid product cannibalization.

Next, we consider Model $\bar{\text{C}}$T, in which a decentralized firm has two divisions: the manufacturing division (D1) and the remanufacturing division (D2). Both divisions operate independently (as described in Model $\bar{\text{C}}\bar{\text{T}}$) and distribute their products through the same retailer, R. We use superscript $\bar{C}T$ to denote the results under equilibrium in Model $\bar{\text{C}}$T. In Model $\bar{\text{C}}$T, D1 first maximizes its divisional profit by optimizing the product design k and the wholesale price of new products w_1: $\Pi_1^{\bar{C}T}=\max_{k,w_1} d_1(p_1,p_2)(w_1-c_1-k\cdot\eta)$, subject to $0\le w_1\le 1$. If $k=1$, then D2 maximizes its divisional profit by optimizing the wholesale price of remanufactured products w_2: $\Pi_2^{\bar{C}T}=\max_{w_2} d_2(p_1,p_2)\cdot(w_2-c_2)$, subject to $0\le w_2\le 1$. If $k=0$, then D2 has no production and $\Pi_2^{\bar{C}T}=d_2^{\bar{C}T}=0$. Finally, after knowing the wholesale prices and product design, the retailer decides upon retail prices p_1 and p_2, as applicable, to maximize its profit: $\Pi_R^{\bar{C}T}=\max_{p_1,p_2} d_1(p_1,p_2)\cdot(p_1-w_1)+k\cdot d_2(p_1,p_2)\cdot(p_2-w_2)$, subject to $0\le k\cdot d_2(p_1,p_2)\le d_1(p_1,p_2)$ and $d_1(p_1,p_2)+d_2(p_1,p_2)\le 1$. The decision framework is illustrated in Figure 1(b). Note again that the remanufacturing division only exists in Figure 1(b) when $k=1$. We solve the decision problems by backward induction and obtain the following lemma.

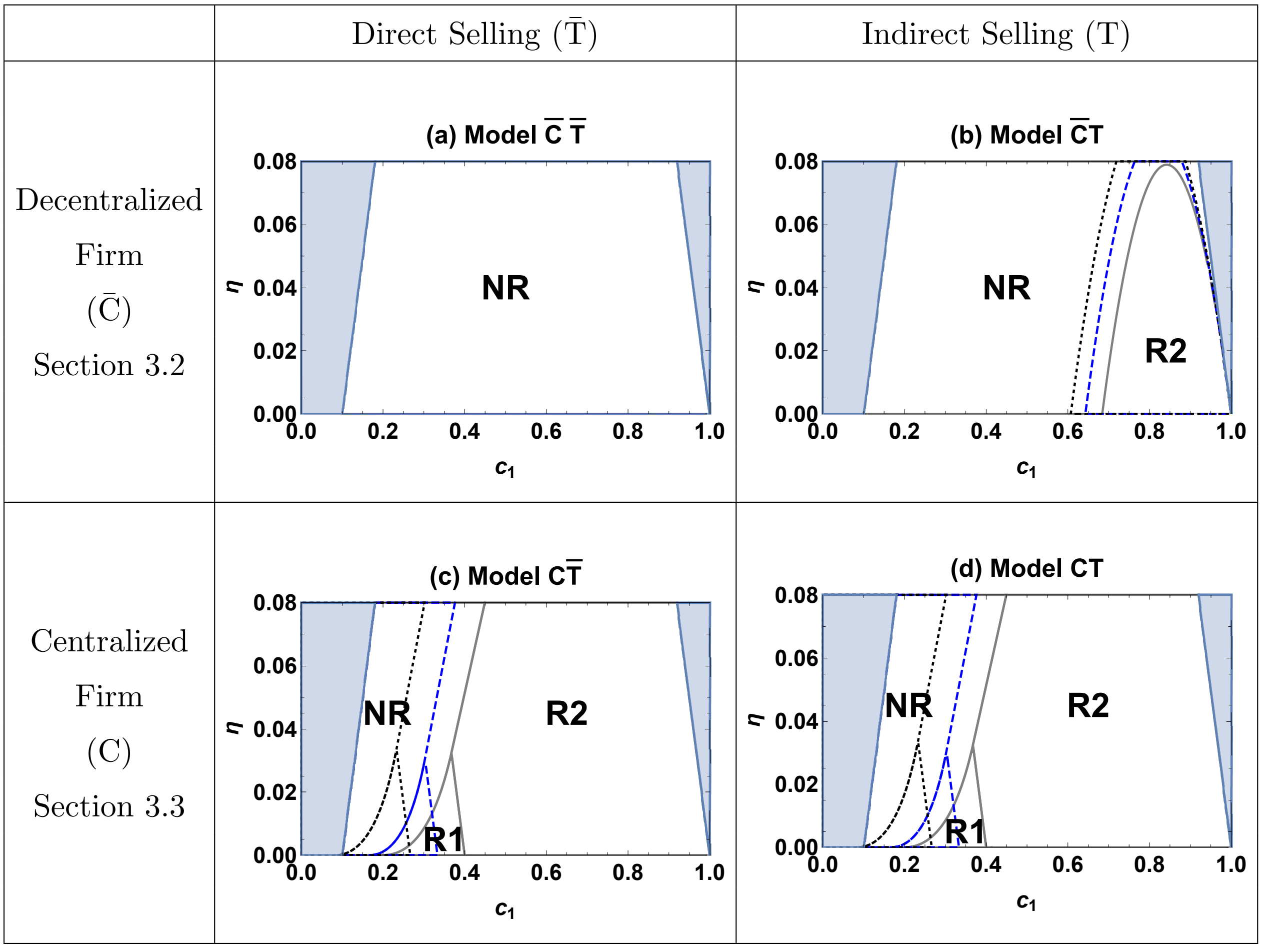


Figure 2 **Optimal Strategy**

Note. Solid line: $\delta = 0.5$, $c_2 = 0.1$; dashed line: $\delta = 0.6$, $c_2 = 0.1$; dotted line: $\delta = 0.6$, $c_2 = 0.05$. Shaded area is outside the bounds of parameter space Ω.

LEMMA 2. *For a decentralized firm engaged in indirect selling, strategy R1 is never optimal. However, for some values of the parameters, strategy R2 can be optimal. In other words,* $\Omega_{R2}^{\bar{C}T} \neq \emptyset$ *and* $\Omega_{R1}^{\bar{C}T} = \emptyset$.

Interestingly, different from Lemma 1, Lemma 2 signifies that it can be optimal for the manufacturing division to choose a remanufacturable product design in the presence of the retailer ($\Omega_{R2}^{\bar{C}T} \neq \emptyset$). This is true because the manufacturing division can extract surplus profit of remanufactured products from the retailer by charging a higher wholesale price of new products. If the remanufactured products are sufficiently profitable, the retailer is willing to accept the higher wholesale price without significantly increasing the retail price to ensure the supply of returned products. In essence, it is the retailer who gives up a fraction of its profit from remanufactured products to compensate the manufacturing division for choosing a remanufacturable product design. The indirect profit transfer from the retailer to D1 makes it possible for D1 to design the product to be remanufacturable and generate more divisional profit. The existence of the retailer can not only relieve the cannibalization of remanufactured products toward new product but also increase the profit of the manufacturing division.

Moreover, Lemma 2 and Figure 2(b) also reveal that when a remanufacturable product design is optimal, it is optimal to remanufacture all returned products. (i.e., $\Omega_{R1}^{\bar{C}T} = \emptyset$). If the retail prices of new and remanufactured products are set in such a way that $d_1 > d_2$, then the retailer's pricing scheme does not alleviate cannibalization. As a result, D1's profit with a remanufacturable product design will be less than D1's profit with a non-remanufacturable product design. In fact, in this case, D1 can always extract more surplus by increasing the wholesale price to the point that remanufacturing demand equalizes new product demand. As Figure 2(b) depicts, in general, a remanufacturable product design is optimal when manufacturing cost c_1 is relatively high, the remanufactured product is competitive with the new product (comparatively large δ), and the costs associated with remanufacturing (η and c_2) are relatively small. One interesting observation is that when η is comparatively small and c_1 is comparatively large, the optimal strategy can change from R2 to NR as c_1 increases. This is because, although a small η can encourage a remanufacturable product design, if $c_1 + \eta$ is too close to 1 (the highest WTP), then the demand of new products will be relatively small and the manufacturing division cannot extract enough surplus profit of remanufactured products from the retailer to cover the additional per-unit cost η.

In terms of the design decision, indirect selling through a retailer can help induce a remanufacturable product design in a decentralized firm (Lemma 2) while direct selling can never achieve this (Lemma 1). Thus, a decentralized firm can consider indirect selling if the firm wants to encourage a remanufacturable product design.

Next, we look into the impacts of distribution channel choice on the profits and demands in a decentralized firm.

Proposition 1. *For a decentralized firm,*

(a) there exists a set of parameters such that the manufacturing division makes a higher profit when selling to the consumer indirectly than directly. In other words, $\exists (c_1, c_2, \delta, \eta) \in \Omega_{Re}^{\bar{C}T}$ *such that* $\Pi_1^{\bar{C}T} > \Pi_1^{\bar{C}\bar{T}}$*;*

(b) there exists a set of parameters such that the firm's profit, the supply chain profit, and the total demand are higher when selling to the consumer indirectly than directly. In other words, $\exists(c_1, c_2, \delta, \eta) \in \Omega_{Re}^{\bar{C}T}$ *such that* $\Pi_F^{\bar{C}T} > \Pi_F^{\bar{C}\bar{T}}$, $\Pi_{SC}^{\bar{C}T} > \Pi_{SC}^{\bar{C}\bar{T}}$, *and* $d_1^{\bar{C}T} + d_2^{\bar{C}T} > d_1^{\bar{C}\bar{T}} + d_2^{\bar{C}\bar{T}}$*;*

(c) for all parameter sets where remanufacturing is not optimal, the manufacturing division's profit, firm's profit, supply chain profit, and total demand are higher when selling to the consumer directly than indirectly. In other words, $\Pi_1^{\bar{C}T} \leq \Pi_1^{\bar{C}\bar{T}}$, $\Pi_F^{\bar{C}T} \leq \Pi_F^{\bar{C}\bar{T}}$, $\Pi_{SC}^{\bar{C}T} \leq \Pi_{SC}^{\bar{C}\bar{T}}$, *and* $d_1^{\bar{C}T} + d_2^{\bar{C}T} \leq d_1^{\bar{C}\bar{T}} + d_2^{\bar{C}\bar{T}}$ *for* $\forall(c_1, c_2, \delta, \eta) \in \Omega_{NR}^{\bar{C}T}$*.*

Proposition 1(a) reveals that the manufacturing division D1 can benefit from a remanufacturable product design when the firm switches from direct selling to indirect selling, as explained in Lemmas 1 and 2. Moreover, according to Proposition 1(b) and as illustrated in Figure 3, for a decentralized firm, indirect selling can not only induce remanufacturing but also increase the firm's profit, supply chain profit, and total demand. Intuitively, profit or demand increase occurs only when a remanufacturable product design is chosen, as implied by Proposition 1(c). The availability of remanufactured products can attract demand from consumers who otherwise would not purchase new products at higher prices, and potentially benefits the focal firm and the supply chain. In fact, in Figure 3, when c_1 is sufficiently large (e.g.,$c_1 = 0.88$) and the ratio η/c_1 is sufficiently small (e.g. $\eta/c_1 = 2.3\%$), a decentralized firm can double it's own profit, supply chain profit, and total demand by switching from direct selling to indirect selling (from Model $\bar{\text{C}}$T to Model $\bar{\text{C}}\bar{\text{T}}$). However, as stated in Proposition 1(c), in the case when indirect selling cannot induce a remanufacturable product design, the focal firm should choose direct selling over indirect selling.

3.3. Distribution Channel Choice by a Centralized Firm

We now consider Model C$\bar{\text{T}}$, in which the firm is centralized and is the only decision maker for both the manufacturing and remanufacturing operations. The firm maximizes the firm's total profit by optimizing the product design k and retail prices p_1 and p_2 according to the framework presented in Figure 1(c). We use superscript $C\bar{T}$ to denote the results under equilibrium in Model C$\bar{\text{T}}$. Thus, the firm's objective is: $\Pi_F^{C\bar{T}} = \max_{k,p_1,p_1} d_1(p_1, p_2)(p_1 - c_1 - k \cdot \eta) + k \cdot d_2(p_1, p_2) \cdot (p_2 - c_2)$, where the first part of the profit function is the profit from selling the new product and the second part is the profit selling the remanufactured product, subject to $0 \leq d_2(p_1, p_2) \leq d_1(p_1, p_2)$ and $d_1(p_1, p_2) + d_2(p_1, p_2) \leq 1$. We solve the decision problems of Model C$\bar{\text{T}}$ by backward induction. It is easy to see that $\Pi_{SC}^{C\bar{T}} = \Pi_F^{C\bar{T}}$.

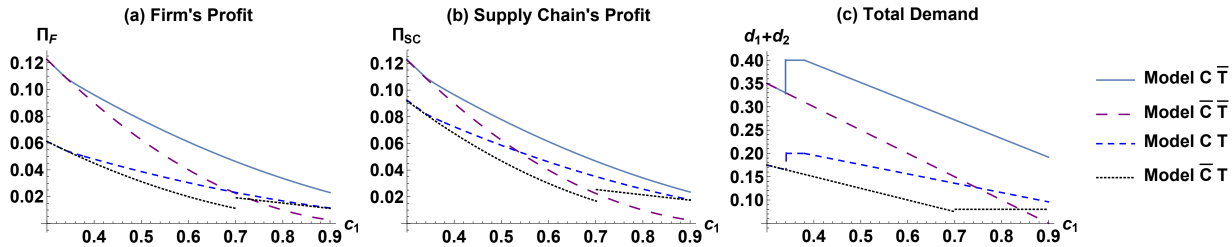


Figure 3 **Model Comparison: Firm's Profit, Supply Chain Profit, and Total Demand (**$\delta = 0.5$, $c_2 = 0.1$, $\eta = 0.02$**)**

As illustrated in Figure 2(c), it can be optimal for the firm to remanufacture only part of the used products when the cost of a remanufacturable product design (η) is nominal. In fact, if $\eta = 0$, then it is always optimal for the centralized firm to design the new products to be remanufacturable to reap the benefit of remanufacturing. On the other hand, the firm should either design the new products to be non-remanufacturable (strategy NR) or design them to be remanufacturable and remanufacture all return products (strategy R2) when η is sufficiently large. The intuition behind this is that an integrated firm with a high design cost for remanufacturing is reluctant to produce remanufacturable products if it is unable to take full advantage of remanufacturing.

Similar to the decentralized firm's Model $\bar{\text{C}}$T, Model CT represents the case that the centralized firm distributes its products through the retailer. The firm first maximizes its total profit by optimizing the product design k and wholesale prices w_1 and w_2 according to the framework presented in Figure 1(d). After knowing the wholesale prices and product design, the retailer decides upon retail prices p_1 and p_2, as applicable, to maximize its profit. Let superscript CT denote the results under equilibrium in Model CT. Thus, the firm's objective is: $\Pi_F^{CT} = \max_{k,w_1,w_2} d_1(p_1,p_2)(w_1 - c_1 - k \cdot \eta) + k \cdot d_2(p_1,p_2) \cdot (w_2 - c_2)$, subject to $0 \le w_1, w_2 \le 1$, and the retailer's objective is the same as in Model $\bar{\text{C}}$T. We solve the decision problems by backward induction. By comparing Model C$\bar{\text{T}}$ with Model CT, we obtain the following proposition.

Proposition 2. *For a centralized firm,*

(a) the set of parameters for which the firm finds a particular strategy optimal is the same regardless whether the firm is selling directly or indirectly. In other words, $\Omega_S^{CT} = \Omega_S^{C\bar{T}}$ *for* $\forall S \in \{R1, R2, NR\}$*;*

(b) the firm's profit, supply chain profit, demand of new products, and demand of remanufactured products are higher when selling direct than selling through a retailer. In fact, $\Pi_F^{C\bar{T}} = 2\Pi_F^{CT}$, $\Pi_{SC}^{C\bar{T}} = \frac{4}{3}\Pi_{SC}^{CT}$, $d_1^{C\bar{T}} = 2d_1^{CT}$, *and* $d_2^{C\bar{T}} = 2d_2^{CT}$.

Proposition 2(a) indicates that the strategy space in Model CT is identical to the strategy space in Model C$\bar{\text{T}}$ (Figures 2(c) and 2(d) are identical for any given parameter set), which means that adding the retailer will not restrict the possible remanufacturing design decision of a centralized firm. However, as shown in Proposition 2(b) and illustrated in Figure 3, the firm's total profit, the demand for new products, and the demand for remanufactured products will reduce by half if a centralized firm switches from direct selling to indirect selling. This is similar to the case of typical centralized versus decentralized selling with no remanufacturing; adding one additional layer (the retailer) to the distribution channel is detrimental to the interests of both the firm and the supply chain as a result of double marginalization. Hence, it is not surprising that a centralized firm is better off choosing direct selling over indirect selling.

3.4. Optimal Internal Structure: Integrated or Decentralized Remanufacturing?

In this subsection, we explore how the external structure (e.g., direct selling or indirect selling) of the firm affects its optimal internal structure (e.g., integration or decentralization of remanufacturing operations).

First, we consider how the external structure affects the focal firm's internal design decision. On the one hand, Lemma 1 and Proposition 2(a) highlight that it is not optimal for the manufacturing division to choose a remanufacturable product design if the firm with direct selling is decentralized ($\Omega_{Re}^{\bar{C}\bar{T}} = \emptyset$); a firm with direct selling can only find it profitable to design a product to be remanufacturable if it is centralized ($\Omega_{Re}^{C\bar{T}} \neq \emptyset$). In addition, Lemma 2 indicates that when a firm chooses indirect selling, internal centralization can encourage a remanufacturable product design. In fact, one can show that $\Omega_{Re}^{\bar{C}T} \subset \Omega_{Re}^{CT}$. That is, in a supply chain with an independent retailer, a remanufacturable product design is less likely to be chosen if the firm is decentralized (Model $\bar{\text{C}}$T) than if the firm is centralized (Model CT). This is true because a remanufacturable product design not only results in product cannibalization but also incurs an additional unit cost η to D1, both adversely affecting D1's profit. In all, we conclude that internal centralization is more likely to induce a remanufacturable product design than internal decentralization when the external structure is given.

Proposition 3 further summarizes the impacts of the optimal internal structure, for a given external structure, on profits and demands.

PROPOSITION 3. *(a) For a firm engaged in direct selling, the profit and sales are higher when the firm is centralized than decentralized. However, it is possible in some cases that the demand for new products is higher when the firm is decentralized than centralized. In other words,* $\Pi_F^{C\bar{T}} \geq \Pi_F^{\bar{C}\bar{T}}$ *and* $d_1^{C\bar{T}} + d_2^{C\bar{T}} \geq d_1^{\bar{C}\bar{T}} + d_2^{\bar{C}\bar{T}}$ *for* $\forall (c_1, c_2, \delta, \eta) \in \Omega$*;* $\exists (c_1, c_2, \delta, \eta) \in \Omega_{Re}^{C\bar{T}}$ *such as* $d_1^{C\bar{T}} < d_1^{\bar{C}\bar{T}}$*.*

(b) For a firm engaged in indirect selling, the firm's profit and total demand are higher when the firm is centralized than decentralized. However, it is possible that the supply chain profit is lower when the firm is centralized than decentralized. In other words, $\Pi_F^{CT} \geq \Pi_F^{\bar{C}T}$ *and* $d_1^{CT} + d_2^{CT} \geq d_1^{\bar{C}T} + d_2^{\bar{C}T}$ *for* $\forall (c_1, c_2, \delta, \eta) \in \Omega$*;* $\exists (c_1, c_2, \delta, \eta) \in \Omega_{Re}^{CT}$ *such as* $\Pi_{SC}^{CT} < \Pi_{SC}^{\bar{C}T}$*.*

Proposition 3(a) states that when the focal firm sells its product directly to the customer, it is more beneficial for the firm to integrate its manufacturing and remanufacturing operations in order to maximize firm profit and total sales. In addition, selling both new and remanufactured products results in higher total sales than only selling non-remanufacturable products, despite the fact that the sales of new products may shrink in the former case as a result of product cannibalization. This result is consistent with prior literature on remanufactured products' cannibalization effects (Ferguson and Toktay 2006; Atasu et al. 2008; Guide and Li 2010). Overall, as depicted in Figures 3(a) and (c), given a direct selling channel, a centralized internal structure is better than a decentralized internal structure in terms of firm profit and total sales.

Similar to the direct selling case discussed above, Proposition 3(b) concludes that, when the focal firm sells through an independent retailer, it is more beneficial for the firm to integrate its manufacturing and remanufacturing operations in order to generate more firm profit and sales. As illustrated in Figures 3(a) and (c), curve Π_F^{CT} is always above curve $\Pi_F^{\bar{C}T}$, and curve $d_1^{CT} + d_2^{CT}$ is always above curve $d_1^{\bar{C}T} + d_2^{\bar{C}T}$. However, in terms of supply chain profit, a decentralized internal structure can be more profitable when a remanufacturable product design is optimal for the firm and the remanufacturing constraint ($d_1^{\bar{C}T} \geq d_2^{\bar{C}T}$) is binding. Prior literature has shown that supply chain profits improve with competing manufacturers using retailers (e.g., McGuire and Staelin 1983). Here, we demonstrated that the supply chain profits can also benefit from internal conflict when selling through a retailer. Nevertheless, higher supply chain profit does not mean a higher focal firm's profit. This happens because the retailer's profit goes up by a much higher amount than the decrease in the firm's profit.

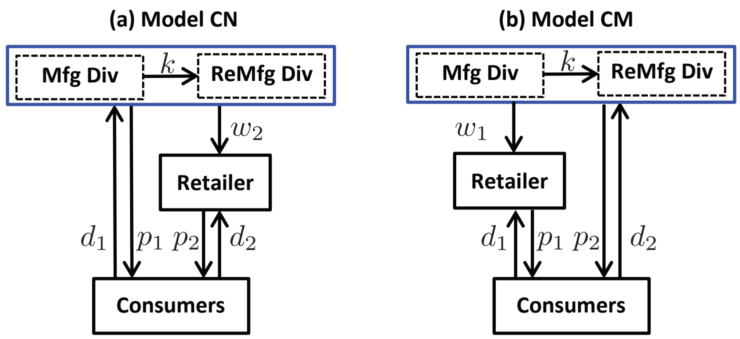


Figure 4 Model Decisions of Dual Dedicated Channels

In this section, we assume that the focal firm can choose only a single channel, either a direct or an indirect channel, to sell both new and remanufactured products. In practice, new and remanufactured products targeting different market segments may be sold in separate channels. Thus, next, we will study a dual dedicated distribution structure.

4. Dual Dedicated Channels

In this section, we consider a dual dedicated distribution structure in which the focal firm sells new/remanufactured products directly and sells remanufactured/new products through an independent retailer. We formulate the two versions of dual dedicated channel models and provide structural results in Section 4.1. We then compare a dual dedicated channel structure with a single channel structure in Section 4.2. Note that the manufacturing division in a decentralized firm will always design the new products to be non-remanufacturable if the firm uses dual dedicated channels. This is because, different from Model $\bar{\mathrm{C}}$T, the manufacturing division cannot reap any profit of remanufacturing from the remanufacturing division or from the dedicated retailer who sells only the remanufactured products. Thus, in this section, we restrict our study on the dual dedicated distribution channels chosen by a centralized firm.

4.1. Two Models of Dual Dedicated Channels

One common practice for many manufacturers is to sell new products to the customers directly and use third-party retailers to sell remanufactured products. For example, Dell, famous for its successful direct sales business model, outsources its consumer product remanufacturing operations and sales (Abbey et al. 2015). Concerns about brand equity and market cannibalization are the main reasons for choosing such dual-distribution channels (Tibben-Lembke and Rogers 2002, Agrawal et al. 2015). To investigate the performance of such a structure (hereafter referred to as Model CN), we consider a centralized firm that is engaged in both manufacturing and remanufacturing operations. The firm first decides the retailer price of new products and the wholesale price of remanufactured products charged to the retailer R. The retailer then decides the retail price of remanufactured products. The decision framework is illustrated in Figure 4(a). We use superscript CN to denote the results under equilibrium in Model CN, and solve the decision problems by backward induction. The firm should design new products to be remanufacturable and remanufacture all returned products when c_1 is large enough. However, it is not optimal for the firm to remanufacture used products when the cost of producing new product c_1 is sufficiently small, as illustrated in Figure 5(a).

Another approach of managing new and remanufactured products by some manufacturers is to sell the new products through the retailer and keep full control of the sales of the remanufactured products (i.e., directly selling of remanufactured products). Yan et al. (2015) pointed out that reduced prices and regulatory policies can discourage retailers from selling remanufactured products.

To investigate the performance of the dual distribution channel in which new products are sold indirectly through the retailer while remanufactured products are sold directly from the manufacturer (hereafter referred to as Model CM), we consider a centralized firm that is engaged in both manufacturing and remanufacturing operations. The firm first decides the wholesale price of the new products charged to the retailer, R, and the retail price of remanufactured products. The retailer then decides the retail price of new products. We use superscript CM to denote the results under equilibrium in Model CM, and again solve the decision problems (see Figure 4(b) for decision framework) by backward induction. As depicted in Figure 5, it is more profitable for the manufacturer to choose a remanufacturable product design than a non-remanufacturable design only if c_1 is sufficiently large, in which case the manufacturer will remanufacture and sell as many returned products as possible. A similar result is found in previous studies (see, for example, Atasu et al. 2008). If c_1 is small enough, the manufacturer will design the product to be non-remanufacturable (strategy NR) and the result will be the same as strategy NR under Model CT. Intuitively, a remanufacturable product design is optimal when remanufactured products are competitive with new products (large δ) and the remanufacturing cost is low (small c_2). Note that strategy R1 is not an optimal strategy. When only a fraction of the returned products are remanufactured, the focal firm can always raise the wholesale price

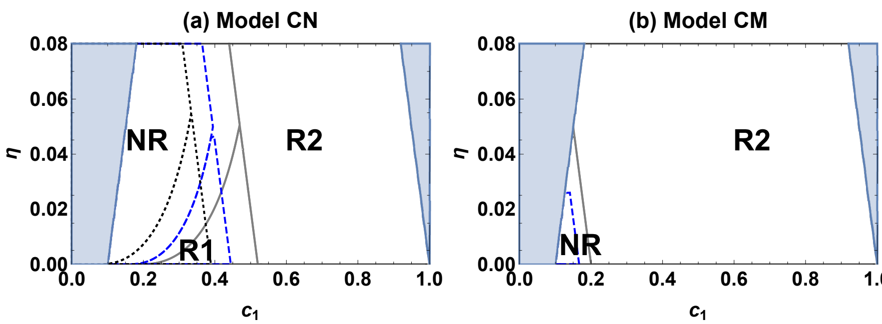


Figure 5 **Optimal Strategy in Models CN and CM**

Note. Solid line: $\delta = 0.5$, $c_2 = 0.1$; dashed line: $\delta = 0.6$, $c_2 = 0.1$; dotted line: $\delta = 0.6$, $c_2 = 0.05$. Shaded area is outside the bounds of parameter space Ω.

of new products to some extent such that the wholesale profit of new products will increase and the supply of return products will not be affected. Thus, the optimal strategy will eventually convert to strategy R2.

4.2. Model Comparison

By comparing Model CM (where the focal firm sells the remanufactured products and the retailer sells the new products) with Model CN (where the retailer sells the remanufactured products and the focal firm sells the new products), we have the following results:

PROPOSITION 4. *(a) The set of parameters for which Model CN has remanufacturable product design as optimal will also be optimal for Model CM (but not vice-versa). Moreover, strategy R1 is never optimal in Model CM. In other words,* $\Omega_{R2}^{CM} = \Omega_{Re}^{CM} \supset \Omega_{Re}^{CN}$*;*

(b) There exist a set of parameters such that R2 is optimal under Model CM and that the supply chain profit and total demand for Model CM is higher than the supply chain profit and total demand, respectively, for Model CN. In other words, $\exists\,(c_1, c_2, \delta, \eta) \in \Omega_{R2}^{CM}$ *such that* $\Pi_{SC}^{CM} > \Pi_{SC}^{CN}$ *and* $d_1^{CM} + d_2^{CM} > d_1^{CN} + d_2^{CN}$*;*

(c) The firm's profit under Model CN is no less than the firm's profit under Model CM but the manufacturing division's profit under Model CN is no higher than the manufacturing division's profit under Model CM. In other words, $\Pi_F^{CM} \le \Pi_F^{CN}$ *and* $d_1^{CM} \ge d_1^{CN}$ *for* $\forall\,(c_1, c_2, \delta, \eta) \in \Omega$.

Proposition 4(a) states that there is a larger region where remanufacturable product design is achievable when the firm directly sells remanufactured products than when it directly sells new products. The intuition behind this is that the manufacturer can exclusively obtain all the profits from remanufacturing in the former case. In addition, direct selling of remanufactured products (Model CM) can result in more supply chain profit and increase the total sales for some cases when a remanufacturable product design is optimal for the firm. However, such a dual dedicated channel will reduce the sales of new products, as stated in Proposition 4(b). Moreover, it will also reduce firm profit even though the firm can charge a wholesale price to extract new product profits from the retailer, which explains why Model CM is not frequently observed in reality. This result, combined with Proposition 4(c), implies that the retailer receives more benefits from the dual-channel Model CM than the focal firm does.

Proposition 4 emphasizes that maximizing firm profit and choosing a greener design is not consistent. A similar result is also found by Yan et al. (2015), who demonstrate that when the focal firm sells new products through an independent retailer, it is more environmentally friendly to sell remanufactured products through the firm's own e-channel than through a third party. But the firm needs an incentive to sell remanufactured products directly as the profit is less than in the other case. Proposition 4(a) complements their findings by implying that, to encourage a remanufacturable product design or maximize supply chain profit, the regulator may consider providing an incentive to the manufacturer to choose a direct channel to sell remanufactured products.

Next, we compare Models CN and CM with the models discussed in Section 3. We obtain the following observations.

First, for a centralized firm, dual dedicated channel Model CM is most likely to induce a remanufacturable product design, as compared with all other models, while the other dual dedicated channel, Model CN, is less likely to achieve it. The intuition behind this is that the focal firm will prioritize remanufactured products over new products if it exclusively enjoys the benefits of remanufacturing and gains only a fraction of new product profits (Model CM), and vice versa (Model CN). Another finding is that a remanufacturable product design is more attractive to a centralized firm (Models $\mathrm{C\bar{T}}$, CT, CM, and CN) than a decentralized one (Models $\mathrm{\bar{C}\bar{T}}$ and $\mathrm{\bar{C}T}$). Thus, requiring all firms to choose the same level of greenness in product design is unfair; rather, the regulator should encourage the consolidation of manufacturing and remanufacturing divisions within a firm.

Second, a centralized firm, having full control over the retail distribution channel is more profitable than controlling only one channel, which in turn is more profitable than having no control over the distribution channel. A centralized firm generally gains more profit than

Table 1 **Parameter ranges for numerical studies**

Parameter	Increment	Min	Max
c_1	0.1	0.1	0.9
δ	0.2	0.1	0.9
c_2	0.1	0.1	$\min(\delta, c_1 - 0.1)$
η	0.01	0.01	$\min(c_1 - c_2, 1 - c_1)$
c_r	0.01	0.01	0.1

a decentralized firm. Similarly, the supply chain benefits if a centralized firm integrates its distribution channels, and the more the channels are centralized, the more the benefits increase ($\Pi_{SC}^{C\bar{T}} \geq \Pi_{SC}^{CN} \geq \Pi_{SC}^{CT}$).

Third, in terms of total demand, a centralized firm generally sells more products than a decentralized firm. To maximize total sales, a firm would rather strategically decentralize the distribution channel than decentralize the internal manufacturing-remanufacturing operations.

5. Discussion

5.1. Collection Cost

The previous models assume that there is no additional cost to collect used products. In this subsection, we relax the assumption by allowing a positive collection cost for a centralized firm or the remanufacturing firm in a decentralized firm to collect used products. If the collection cost is proportional to the collection rate, then the problem can be analyzed using the model in Section 3 but with a higher c_2, which is straightforward. In this section, we focus on the case when the collection cost is a quadratic function of the collection rate and is independent of the sales of remanufactured products, as commonly seen in the previous literature (see, for example, Savaskan et al. (2004)). Let $\gamma \in [0, 1]$ be the targeted collection rate optimized by the centralized firm or the remanufacturing division in a decentralized firm. Then, the centralized firm or the remanufacturing division in a decentralized firm incurs a collection cost $c_r \times \gamma^2$, where $c_r > 0$ is the collection cost coefficient. Note that $c_r = 0$ represents the base models discussed in the previous sections where there is no collection cost. Also note that the firm cannot remanufacture more than the collected used products. Thus, $d_2 \leq \gamma \times d_1$.

Due to the complexity of this model extension, we study each of the four models (Model $\mathrm{C\bar{T}}$, $\mathrm{\bar{C}\bar{T}}$, CT, $\mathrm{\bar{C}T}$) with a collection cost using a numerical study by varying the feasible

Table 2 Number of parameter combinations yielding different equilibrium strategies

Model\Equilibrium	NR ($d_2 = 0$)	R1 ($0 < d_2 < d_1$)	R2 ($0 < d_2 = d_1$)	Total
$\bar{\mathrm{C}}\bar{\mathrm{T}}$	48,000	0	0	48,000
$\bar{\mathrm{C}}\mathrm{T}$	47,628	0	372	48,000
$\mathrm{C}\bar{\mathrm{T}}$	43,848	0	4,152	48,000
CT	45,430	0	2,570	48,000

system parameters. The range of each parameter for this study is provided in Table 1. A total of 48,000 parameter combinations were studied and the resulting equilibria, classified into three categories, are summarized in Table 2.

One observation from Table 2 is that strategy R1 ($0 < d_2 < d_1$) is never optimal. This is because, as a profit maximizer, the firm (or the remanufacturing division) is not willing to collect more than what is needed if the collection cost is associated with the collection rate. Thus, the production constraint $d_2 \leq \gamma \times d_1$ is always binding (i.e., $d_2 = \gamma \times d_1$). According to Table 2 and Lemma 1, there is no change to the equilibrium of Model $\bar{\mathrm{C}}\bar{\mathrm{T}}$ (always NR), which is intuitive because the additional collection cost simply makes remanufacturing less attractive. Also, a non-remanufacturable product design (strategy NR) is more likely to be optimal when the collection cost is positive than when it is zero. Nevertheless, the collection cost affects the equilibrium under Model $\mathrm{C}\bar{\mathrm{T}}$ and Model CT differently. Recall that in the base models, $\mathrm{C}\bar{\mathrm{T}}$ and CT have the same design decision (Proposition 2(a)). However, the numerical study reveals that collection cost discourages remanufacturing to a greater extent under Model CT than under Model $\mathrm{C}\bar{\mathrm{T}}$, indicating that a centralized firm without a retailer is more likely to choose a remanufacturable product design than a centralized firm with a retailer with a non-zero collection cost. This observation is also illustrated in Figure 6(c)-(d) in which region R2 is larger in Model $\mathrm{C}\bar{\mathrm{T}}$ than in Model CT.

5.2. Remanufacturability Level

In Section 3, the design decision is assumed to be binary. That is, the product is designed to be either non-remanufacturable ($k = 0$) or 100% remanufacturable ($k = 1$). To check the robustness of our model, we consider a case in which a centralized firm or the manufacturing division in a decentralized firm can optimize the remanufacturability level $k \in [0, 1]$, a continuous decision variable defined as the fraction of products that can be remanufactured, i.e., $d_2 \leq k \cdot d_1$. Thus, consistent with our previous definition, the product is

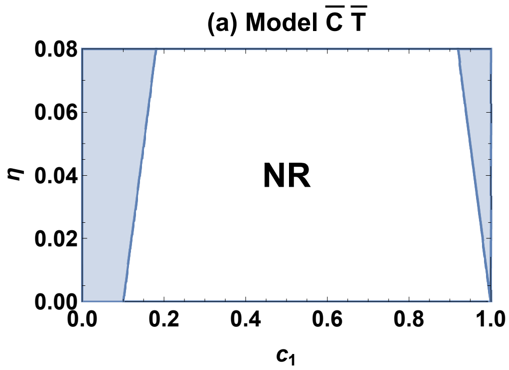
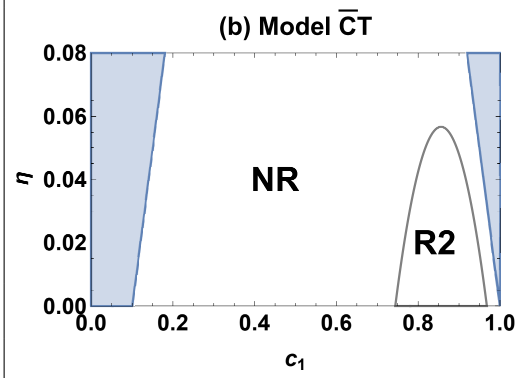
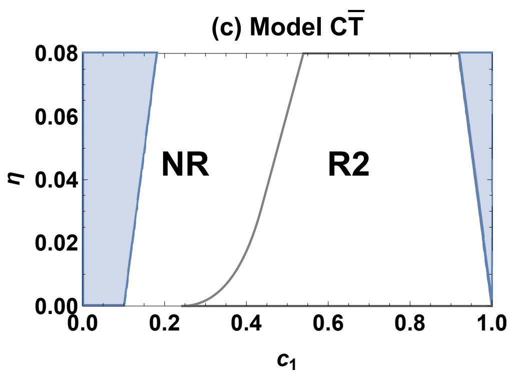
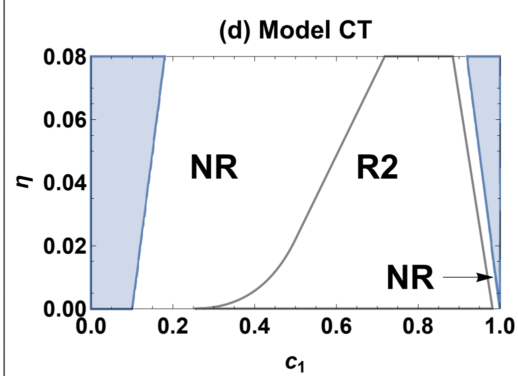
	Direct Selling ($\bar{\mathrm{T}}$)	Indirect Selling (T)
Decentralized Firm ($\bar{\mathrm{C}}$)		
Centralized Firm (C)		

Figure 6 **Optimal strategy with a nonzero collection cost ($\delta = 0.5$, $c_2 = 0.1$, $c_r = 0.01$)**

Note. Shaded area is outside the bounds of parameter space Ω.

non-remanufacturable if $k = 0$, and the product is 100% remanufacturable if $k = 1$. $k \in (0, 1)$ implies a need for the disposal activities by either the retailer or the remanufacturing division in the motivating case. Furthermore, following the literature (Debo et al. 2005, 2006, Robotis et al. 2012), we assume that the firm (in Models C$\bar{\mathrm{T}}$ and CT) or the manufacturing division (in Models $\bar{\mathrm{C}}\bar{\mathrm{T}}$ and $\bar{\mathrm{C}}$T) incurs a cost of $\eta \cdot k^2$ to achieve a remanufacturability level k, reflecting the diminishing impact of design and production efforts.

Again, we solve each of the four models using a numerical study by varying the feasible system parameters (c_1,δ,c_2,η), as provided in Table 1. Figure 7 depicts the optimal remanufacturability level k^*, which maximizes the profit of the firm (in Models C$\bar{\mathrm{T}}$ and CT) or the profit of the manufacturing division (in Models $\bar{\mathrm{C}}\bar{\mathrm{T}}$ and $\bar{\mathrm{C}}$T) when $\delta = 0.6$, $c_2 = 0.1$, $c_1 = 0.8$. Intuitively, the optimal remanufacturability level decreases as the additional cost to make a product remanufacturable becomes more expensive (higher η). When η is sufficiently small, the design decision-maker is willing to make the product 100% remanufacturable ($k = 1$).

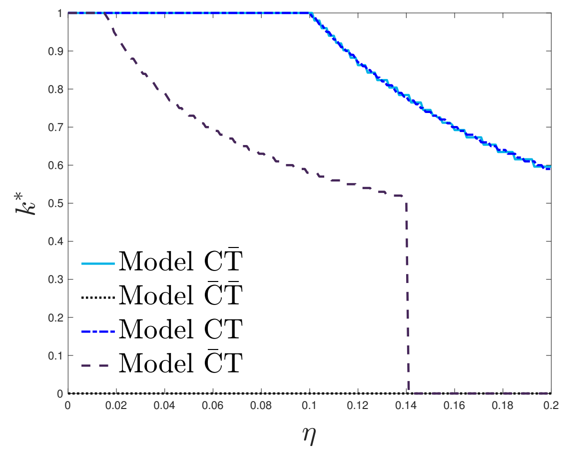


Figure 7 Optimal remanufacturability level k^* ($\delta = 0.5$, $c_2 = 0.1$, $c_1 = 0.8$)

This can be true even if the firm is decentralized (Model $\mathrm{C\bar{T}}$) as the manufacturing division can extract profit from remanufacturing by setting a higher wholesale price. In addition, the firm will generally choose a higher remanufacturability level when it is centralized than decentralized (i.e., in general, $k^{CT} \geq k^{\bar{C}T}$ and $k^{C\bar{T}} \geq k^{\bar{C}\bar{T}}$). Nevertheless, similar to the base model, when a decentralized firm sells directly to the customer, the manufacturing division will always design the product to be non-remanufacturable, regardless of the value of η (i.e., $k^{\bar{C}\bar{T}} \equiv 0$).

Based on our numerical study on the continuous remanufacturability level k, Lemmas 1 and 2, and Propositions 1(a)-(c), 2(a)-(b), and 3(a) still hold. However, we also obtain some findings different from those in the base model when k is either 0 or 1. First, strategy R1 ($0 < d_2 < k \cdot d_1$) can never be optimal because the design decision-maker, who incurs the additional cost to make the product remanufacturable, is not willing to choose a remanufacturability level more than what is needed. Thus, the production constraint $d_2 \leq k \cdot d_1$ is always binding (i.e., $d_2 = k \cdot d_1$) when $k > 0$. Second, different from Proposition 3(b), $\Pi_{SC}^{CT} \geq \Pi_{SC}^{\bar{C}T}$ for all $(c_1, c_2, \delta, \eta) \in \Omega$ when k is continuous. This is because, in Model $\mathrm{\bar{C}T}$, the manufacturing division can increase its profit by optimizing the continuous remanufacturability level k, resulting in a decline in profit for the remanufacturing division, the retailer, and hence the total supply chain. Overall, our main results derived from the models in Section 3 is robust with respect to the remanufacturability level.

5.3. Partial Decentralization

The motivating case discussed in the introduction can be best represented by the decentralized models in which the remanufacturing design decision (whether to design the new products to be remanufacturable) is made by or highly influenced by the manufacturing division. This is especially true when the firm has a strong manufacturing division. However, in some industries or companies, the remanufacturing design decision is indeed made at the firm level. In such a case, the design decision is optimized for the purpose of maximizing the profit at the firm level. This approach can be represented by the centralized models where the profits of both the manufacturing and remanufacturing divisions will be considered. By comparing the decentralized model with the centralized model, we can answer the following questions: if the firm has the capability to decide on the remanufacturing, should the firm decide that at the firm level or should the firm delegate that decision to the manufacturing division? Is it always better for the firm to make the decision at the firm level? Our analysis indicates that when the decentralized firm makes the remanufacturing decision at the firm level, the manufacturing division may not cooperate with the firm's decision. In fact, the manufacturing division can increase the wholesale price when selling through a retailer or increase the retail price when selling directly. Consequently, the firm's control of the remanufacturing design may backfire and hurt the firm.

In order to evaluate the above scenario, we consider a partially decentralized model in which the firm first decides the remanufacturing design decision by maximizing the firm's total profit, and then the manufacturing division and the remanufacturing division decide the retail (wholesale) prices of new and remanufactured products, respectively, if the firm sells directly (indirectly), hereafter called Model $\hat{\mathrm{C}}\bar{\mathrm{T}}$ ($\hat{\mathrm{C}}\mathrm{T}$). We solve both models using a numerical study by varying feasible system parameters in a similar fashion as described in Section 5.1. Although, intuitively, the firm profit under Model $\hat{\mathrm{C}}\bar{\mathrm{T}}$ ($\hat{\mathrm{C}}\mathrm{T}$) is higher than that under Model $\bar{\mathrm{C}}\bar{\mathrm{T}}$ ($\bar{\mathrm{C}}\mathrm{T}$), it is worth noting that total demand under Model $\hat{\mathrm{C}}\bar{\mathrm{T}}$ ($\hat{\mathrm{C}}\mathrm{T}$) can be lower than that under Model $\bar{\mathrm{C}}\bar{\mathrm{T}}$ ($\bar{\mathrm{C}}\mathrm{T}$). In fact, for most feasible system parameter sets, the total demand of a decentralized firm with direct selling decreases as the decision-maker of the remanufacturing design switches from the manufacturing division to the firm. This analysis indeed is consistent with our motivating industry example that the remanufacturing division often complains of not receiving enough support while this support can be the product design or the wholesale/retail price of the new product. If the wholesale/retail price is too high, then it limits the sales of new products and thus the availability of products to be remanufactured. This analysis also echoes the long-standing discussions on design-manufacturing conflicts in industry practice and literature where the design department and manufacturing departments conflict on how products should be designed such that design departments often do not appreciate the impact of product design on manufacturing costs while manufacturing departments do not appreciate the benefits of product design on serving new markets (Adler 1995, Mukhopadhyay and Gupta 1998, Folkestad and Johnson 2001, Vandevelde and Van Dierdonck 2003, Balasubramanian and Bhardwaj 2004, Rosen and Kishawy 2012).

6. Conclusions

In this paper, we seek insights for firms that consider tapping into remanufactured-goods markets and firms that seek to increase profit by optimizing the internal manufacturing-remanufacturing structure and the choice of distribution channel. Motivated by some examples found in practice, we model a firm comprising both a manufacturing and a remanufacturing division and a retailer through which the firm sells its products. Given this construct, we derive the optimal strategy in terms of internal and external design architecture, design, and pricing decisions.

We evaluate the interplay between internal structure and distribution channel choice in a remanufacturing context. We show that a firm's organizational structure can affect its marketing decisions: a centralized firm should choose direct selling rather than indirect selling to avoid double marginalization. However, a decentralized firm can find indirect selling more appealing than direct selling because such a channel choice can increase firm profit, supply chain profit, total demand, and even the profit of the manufacturing division. This is because the existence of the retailer moderates the focal firm's divisional conflict and enables the manufacturing division to benefit from a remanufacturable product design. In addition, given a direct distribution channel, a centralized internal structure is intuitively better than a decentralized internal structure. Counterintuitively, however, given an indirect distribution channel, a decentralized internal structure can result in higher supply chain profit than a centralized internal structure.

In addition, we study the impacts of internal structure and distribution channel choice on product design in remanufacturing. If a firm is centralized, then the channel choice will not influence the optimal design decision (remanufacturable or not). Yet, if a divisional conflict exists in the focal firm, then direct selling prevents the manufacturing division from designing the new products to be remanufacturable. Interestingly, in order to induce a remanufacturable product design, a decentralized firm can strategically decentralize the distribution channel.

A centralized firm with dual dedicated channels is more likely to design the new products to be remanufacturable than a decentralized firm or a centralized firm with indirect selling of both new and remanufactured products. Between the two dual dedicated channel structures that we discussed, indirect selling of new products (Model CM) can result in more supply chain profit and, in some cases, increase the total sales when a remanufacturable product design is optimal for the firm. But the indirect selling of remanufactured products (Model CN) generally benefits the firm more than the retailer. By jointly comparing different channel structures, we conclude that in order to promote a remanufacturable product design, the regulator should encourage the consolidation of manufacturing and remanufacturing divisions within a firm.

We note that our results are based in part on the assumption that η is non-negative to reflect the increased complexity required to make new products remanufacturable. Nevertheless, we also consider the possibility the product, by its nature, is remanufacturable and it requires additional cost to make the product non-remanufacturable (negative η). We made three observations based on our analytical and numerical study. First, intuitively, the negative additional cost of producing remanufacturable products can encourage remanufacturing because the production saving can sometimes outweigh the product cannibalization effect under certain circumstance. However, the manufacturing division may be still reluctant to design the products to be remanufacturable when the production saving is not significantly large, which is consistent with our main findings. Second, a centralized firm may find it optimal to design the product to be remanufacturable; however, it may sometimes remanufacture no products at all. This scenario exists only when the manufacturing division or the firm does not face competition. If a firm is decentralized, then the manufacturing division will only design the product to be remanufacturable when remanufactured products co-exist. In reality, manufacturers may intentionally design the products to be non-remanufacturable in order to deter competition from third-party remanufacturers. Third, when the manufacturing department and the remanufacturing department sell through a retailer instead of selling directly, the manufacturing can have a stronger incentive to make the new product remanufacturable with a negative η, which is indicated in our base model.

In closing, our findings are based on the assumption of only one common retailer. Therefore, expanding the options for a large number of competitive retailers can be an immediate extension. Also, we assume that the cost to manufacture a new product and the cost to make a new product remanufacturable are independent. Our main insights will not change qualitatively if these two costs are positively correlated (by replacing η with $f(c_1)$, where $f(\cdot)$ can be any function that reflects the positive relationship between c_1 and η). Moreover, cradle-to-grave responsibility enforced by regulators can force the manufacturing division to choose a remanufacturable design, which helps coordinate divisional conflicts. Thus, a viable direction for future research is to examine how a "cradle-to-grave" policy delineates the minimum percentage of returned products that should be remanufactured and resold to the market. Nevertheless, we hope our paper will inspire more research on the interplays of a firm's internal structure and external distribution channel structure.

Acknowledgments

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Table 3 **D2's Optimal Strategy in Model $\bar{C}\bar{T}$ for given k and p_1**

Case	Condition	d_1^*	d_2^*	p_2^*
1	$k=1$ & $\frac{c_2}{\delta} \le p_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$	$\frac{2(1-\delta)-(2-\delta)p_1+c_2}{2(1-\delta)}$	$\frac{p_1\delta-c_2}{2(1-\delta)\delta}$	$\frac{\delta p_1+c_2}{2}$
2	$k=1$ & $\frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta} \le p_1 \le 1$	$\frac{1-p_1}{1+\delta}$	$\frac{1-p_1}{1+\delta}$	$\frac{(2p_1-1+\delta)\delta}{1+\delta}$
3	$k=1$ & $p_1 \le \frac{c_2}{\delta}$ or $k=0$	$\frac{1-c_1}{2}$	$-$	$-$

Appendix

Proofs are restricted to the parameter space Ω and $p_1, p_2, w_1, w_2 \in [0,1]$ (referred to as "the assumption"), as described in detail in Section 3.1. Profit maximizing problems are solved using the method of Lagrange multipliers unless stated otherwise. Sequential decision problems are solved by backward induction.

Proof of Lemma 1

In Model $\bar{C}\bar{T}$, D1 first decides k and $p_1 \in [0,1]$. If $k=1$, then D2 decides $p_2 \in [0,1]$.

We first solve D2's problem when $k=1$. Given that $d_1 = \frac{1-\delta-p_1+p_2}{1-\delta}$ and $d_2 = \frac{\delta p_1 - p_2}{(1-\delta)\delta}$, $d_1 \ge d_2$ implies that $p_2 \ge \frac{(2p_1-1+\delta)\delta}{1+\delta}$. Also note that if $p_2 < \frac{(2p_1-1+\delta)\delta}{1+\delta}$, then D2 can always increase p_2 to $\frac{(2p_1-1+\delta)\delta}{1+\delta}$ so that D2's profit and sales of remanufactured products both increase. Hence, it is not optimal for D2 to price remanufactured products at $p_2 < \frac{(2p_1-1+\delta)\delta}{1+\delta}$. Meanwhile, $d_2 \ge 0 \Rightarrow p_2 \le \delta p_1$. Thus, given $k=1$ and any p_1, D2's problem is $\Pi_2 = \max\limits_{p_2} \frac{\delta p_1 - p_2}{(1-\delta)\delta}(p_2 - c_2)$ *s.t.* $\max\{c_2, \frac{(2p_1-1+\delta)\delta}{1+\delta}\} \le p_2 \le \delta p_1$. D2's optimal strategy is illustrated in Table 3.

Next, we solve D1's problem. If $k=0$, then $d_1 = 1-p_1$ and D1's problem is $\Pi_1^{NR} = \max\limits_{p_1}(1-p_1)\cdot(p_1-c_1)$ *s.t.* $c_1 \le p_1 \le 1$. Thus, we have $d_1^{NR} = \frac{1-c_1}{2}$, $p_1^{NR} = \frac{1+c_1}{2}$ and $\Pi_1^{NR} = \frac{(1-c_1)^2}{4}$. If $k=1$, then D1's problem is $\Pi_1 = \max\limits_{p_1} \frac{1-\delta-p_1+p_2}{1-\delta}(p_1 - c_1 - \eta)$ *s.t.* $c_1 + \eta \le p_1 \le 1$, where d_1 and the constraints are given in Table 3. One can show that it is not optimal for D1 to set $p_1 \le \frac{c_2}{\delta}$ when $k=1$. Hence, we only need to consider cases 1 and 2 in Table 3.

Case 1 ($\frac{c_2}{\delta} \le p_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$). D1's problem is $\Pi_1 = \max\limits_{w_1} \frac{2(1-\delta)-(2-\delta)p_1+c_2}{2(1-\delta)}(p_1 - c_1 - \eta)$ *s.t.* $\max\left\{\frac{c_2}{\delta}, c_1+\eta\right\} \le p_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$.

(1-1) If $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1 + \eta \le \frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$, then $p_1^* = \frac{(c_1+\eta)(2-\delta)+2(1-\delta)+c_2}{2(2-\delta)}$, $\Pi_1^{1-1} = \frac{[2(1-\delta)-(c_1+\eta)(2-\delta)+c_2]^2}{8(2-\delta)(1-\delta)}$, $d_1 = \frac{2(1-\delta)-(c_1+\eta)(2-\delta)+c_2}{4(1-\delta)}$, $d_2 = \frac{\delta[2(1-\delta)+(c_1+\eta)(2-\delta)]-c_2(4-3\delta)}{4(2-\delta)(1-\delta)\delta}$. However, $\Pi_1^{1-1} \le \Pi_1^{NR} = \frac{(1-c_1)^2}{4}$ when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1 + \eta$. To see this, note that $\Pi_1^{1-1} \ge \Pi_1^{NR}$ is equivalent to $c_1 \le \frac{\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2]+c_2(2-\delta)-(2-\delta)^2\eta}{(2-\delta)\delta}$. Also, Π_1^{1-1} is valid when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1 + \eta$ or equivalently, $c_1 \ge \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta$. However, $\frac{\partial}{\partial\eta}\left(\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta - \frac{\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2]+c_2(2-\delta)-(2-\delta)^2\eta}{(2-\delta)\delta}\right) = \frac{\sqrt{2(1-\delta)(2-\delta)}+2(1-\delta)}{\delta} > 0$ while $\left(\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} - \eta - \frac{\sqrt{2(1-\delta)(2-\delta)}[\delta(1-\eta)+2\eta-c_2]+c_2(2-\delta)-(2-\delta)^2\eta}{(2-\delta)\delta}\right)|_{\eta=0} = \frac{[\sqrt{2(1-\delta)(2-\delta)}-2(1-\delta)](\delta-c_2)}{(2-\delta)\delta} \ge 0$. Therefore, $\Pi_1^{1-1} \le \Pi_1^{NR}$ is true when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1 + \eta$, which means this subcase is dominated by strategy NR.

(1-2) If $\frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le c_1 + \eta \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, then $p_1^* = \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, $\Pi_1^{1-2} = \frac{(\delta-c_2)[2-2\delta-(c_1+\eta)(3-\delta)]}{(3-\delta)^2\delta} + \frac{(\delta-c_2)c_2(1+\delta)}{(3-\delta)^2\delta^2}$ and $d_1 = d_2 = \frac{\delta-c_2}{(3-\delta)\delta}$. Note that (i) $\Pi_1^{1-2} \le \Pi_1^{1-1}$ when $\frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le c_1 + \eta \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$; (ii) $\Pi_1^{1-1} \le \Pi_1^{NR}$ when $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le c_1 + \eta$ and (iii)

Table 4 The Retailer's Optimal Strategy in Model $\bar{\text{C}}$T for given k, w_1, and w_2

Case	Condition	d_1^*	d_2^*
1	$k=1$ & $\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta},0\right\}\leq w_2\leq \delta w_1$	$\frac{1-\delta-w_1+w_2}{2(1-\delta)}$	$\frac{\delta w_1-w_2}{2(1-\delta)\delta}$
2	$k=0$ or $k=1$ & $w_2>\delta w_1$	$\frac{1-w_1}{2}$	0
3	$k=1$ & $0\leq w_2\leq \frac{(2w_1-1+\delta)\delta}{1+\delta}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$	$\frac{1+\delta-w_1-w_2}{2(1+3\delta)}$

Table 5 D2's Optimal Strategy in Model $\bar{\text{C}}$T for given w_1 and $k=1$

Case	Condition	d_1^*	d_2^*	w_2^*
A	$\frac{c_2}{\delta}\leq w_1\leq \frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta}$	$\frac{1}{2}-\frac{(2-\delta)w_1-c_2}{4(1-\delta)}$	$\frac{w_1\delta-c_2}{4(1-\delta)\delta}$	$\frac{w_1\delta+c_2}{2}$
B	$\frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}\leq w_1\leq 1$	$\frac{1+\delta-w_1-c_2}{4(1+3\delta)}$	d_1^*	$\frac{1+\delta-w_1}{2}$
C	$\frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta}\leq w_1\leq \frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}$	$\frac{1-w_1}{2(1+\delta)}$	d_1^*	$\frac{(2w_1-1+\delta)\delta}{1+\delta}$

$\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta}\leq \frac{c_2\left(4-\delta-\delta^2\right)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$ is always true since $c_2\leq\delta$. Therefore, this subcase is dominated by strategy NR.

(1-3) If $c_1+\eta\leq \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta}$, then $p_1^*=\frac{c_2}{\delta}$, $\Pi_1^{1-3}=\frac{(\delta-c_2)[c_2-(c_1+\eta)\delta]}{\delta^2}$, $d_1=\frac{\delta-c_2}{\delta}$ and $d_2=0$. This case is dominated by strategy NR since $d_2=0$.

Case 2 ($\frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta}\leq p_1\leq 1$). D1's problem is $\Pi_1=\max_{p_1}\frac{1-p_1}{1+\delta}(p_1-C_1)$ $s.t.$ $\max\{C_1,\frac{2(1-\delta)}{3-\delta}+\frac{(1+\delta)c_2}{(3-\delta)\delta}\}\leq p_1\leq 1$, where $C_1=c_1+\eta$.

(2-1) If $C_1\geq\frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta}$, then $p_1^*=\frac{1+C_1}{2}$, $\Pi_1^{2-1}=\frac{(1-C_1)^2}{4(1+\delta)}$, and $d_1=d_2=\frac{1-C_1}{2(1+\delta)}$. However, this subcase is dominated by strategy NR because $\Pi_1^{2-1}=\frac{(1-C_1)^2}{4(1+\delta)}\leq\frac{(1-c_1)^2}{4}=\Pi_1^{NR}$.

(2-2) If $C_1\leq\frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta}$, then $p_1^*=\frac{2(1-\delta)\delta+(1+\delta)c_2}{(3-\delta)\delta}$, $\Pi_1^{2-2}=\frac{(\delta-c_2)(\delta[2-2\delta-C_1(3-\delta)]+c_2(1+\delta))}{(3-\delta)^2\delta^2}$, and $d_1=d_2=\frac{\delta-c_2}{(3-\delta)\delta}$. However, this subcase is dominated by strategy NR because $\frac{(1-c_1)^2}{4(1+\delta)}\geq\frac{(1-C_1)^2}{4(1+\delta)}\geq\frac{(\delta-c_2)(\delta[2(1-\delta)-C_1(3-\delta)]+c_2(1+\delta))}{(3-\delta)^2\delta^2}$.

In all, it is not optimal for D1 to choose a remanufacturable design. Thus, Lemma 1 follows. □

Proof of Lemma 2

Firstly, we solve the retailer's problem. Given w_1, w_2 and k, the retailer maximizes $\Pi_R=\max_{p_1,p_2}d_1(p_1,p_2)\cdot(p_1-w_1)+k\cdot d_2(p_1,p_2)\cdot(p_2-w_2)$ subject to $0\leq k\cdot d_2(p_1,p_2)\leq d_1(p_1,p_2)$ and $d_1(p_1,p_2)+k\cdot d_2(p_1,p_2)\leq 1$. Table 4 summarizes the retailer's optimal strategy.

Secondly, we solve D2's problem. If $k=0$, then D2 makes no production and $\Pi_2^{NR}=0$. If $k=1$, then for any w_1, then D2's problem is $\Pi_2=\max_{w_2}d_2(w_2-c_2)$. Note that D2 will remanufacture only if $\Pi_2\geq 0$, which implies that $w_2\geq c_2$ must hold. One can show that it is not optimal for D1 to choose $k=1$ if $w_2\geq\delta w_1$. Thus, we only need to consider two cases given in Table 4: Case 1 ($\Pi_2=\max_{w_2\geq c_2}\frac{\delta w_1-w_2}{2(1-\delta)\delta}(w_2-c_2)$ $s.t.$ $\max\left\{\frac{(2w_1-1+\delta)\delta}{1+\delta},0\right\}\leq w_2\leq\delta w_1$) and Case 3 ($\Pi_2=\max_{w_2\geq c_2}\frac{1+\delta-w_1-w_2}{2(1+3\delta)}(w_2-c_2)$ $s.t.$ $0\leq w_2\leq\frac{(2w_1-1+\delta)\delta}{1+\delta}$). In a similar fashion to the proof of Lemma 1, we obtain D2's strategy, which is summarized in Table 5.

Thirdly, we solve D1's problem. If $k=0$, then D1 sets $w_1^{NR}=\frac{1+c_1}{2}$. Consequently, $d_1^{NR}=\frac{1-c_1}{4}$, $\Pi_1^{NR}=\frac{(1-c_1)^2}{8}$. Note that D1 can always choose $k=0$ and earn at least Π_1^{NR}. If $k=1$, then $\Pi_1^R=\max_{w_1\geq C_1}d_1(w_1-C_1)$,

Table 6 Optimal Strategy and Solutions in Model $\bar{C}T$

Strategy	$k^{\bar{C}T}$	Cond.	$w_1^{\bar{C}T}$	$w_2^{\bar{C}T}$	$d_1^{\bar{C}T}$	$d_2^{\bar{C}T}$	$\Pi_1^{\bar{C}T}$	$\Pi_2^{\bar{C}T}$	$\Pi_R^{\bar{C}T}$
R2-1	1	$\Omega_{2-1}^{\bar{C}T}$	$\frac{1+c_1+\eta+\delta-c_2}{2}$	$\frac{1-c_1-\eta+\delta+c_2}{4}$	$\frac{1-c_1-\eta+\delta-c_2}{8(1+3\delta)}$	$d_1^{\bar{C}T}$	$\frac{(1-c_1-\eta+\delta-c_2)^2}{16(1+3\delta)}$	$\frac{\Pi_1^{\bar{C}T}}{2}$	$\frac{\Pi_1^{\bar{C}T}}{4}$
R2-2	1	$\Omega_{2-2}^{\bar{C}T}$	1	$\frac{\delta}{2}$	$\frac{\delta-c_2}{4(1+3\delta)}$	$d_1^{\bar{C}T}$	$\frac{(\delta-c_2)(1-c_1-\eta)}{4(1+3\delta)}$	$\frac{(\delta-c_2)^2}{8(1+3\delta)}$	$\frac{\delta^2}{16(1+3\delta)}$
NR	0	$\Omega_{NR}^{\bar{C}T}$	$\frac{1+c_1}{2}$	–	$\frac{1-c_1}{4}$	–	$\frac{(1-c_1)^2}{8}$	–	$\frac{\Pi_1^{\bar{C}T}}{2}$

$\Omega_{2-1}^{\bar{C}T} = \left\{(c_1, c_2, \delta, \eta) \middle| \frac{1+5\delta+\eta+c_2-(\delta-\eta-c_2)\sqrt{2(1+3\delta)}}{1+6\delta} \le c_1 \le 1-\delta-\eta+c_2 \right\}$

$\Omega_{2-2}^{\bar{C}T} = \{(c_1, c_2, \delta, \eta) \,\Big|\max\left\{1-\delta-\eta+c_2, \frac{1+2\delta+c_2-\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta}\right\} \le c_1 \le \frac{1+2\delta+c_2+\sqrt{(\delta-c_2)(\delta-2\eta-6\delta\eta-c_2)}}{1+3\delta} \;\&\; \eta \le \frac{\delta-c_2}{2(1+3\delta)}\}$

$\Omega_{NR}^{\bar{C}T} = \left\{(c_1, c_2, \delta, \eta) \,\middle|\, (c_1, c_2, \delta, \eta) \in \Omega - \Omega_{2-1}^{\bar{C}T} - \Omega_{2-1}^{\bar{C}T} \right\}$

where d_1 is given in Table 5 and $C_1 = c_1 + \eta$. Note that D1 will not choose a remanufacturable product design if $\Pi_1 < 0$, which implies that $w_1 \ge C_1$ must hold. Thus, we consider the following three cases:

Case A ($\frac{c_2}{\delta} \le w_1 \le \frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta}$): $\Pi_1 = \max_{w_1 \ge C_1} \frac{2(1-\delta)-(2-\delta)w_1+c_2}{4(1-\delta)}(w_1 - C_1)$

(A1) If $\frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta} \le C_1 \le \frac{c_2(4-\delta-\delta^2)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta}$, then $w_1^* = \frac{C_1(2-\delta)+2(1-\delta)+c_2}{2(2-\delta)}$, $\Pi_1^{A1} = \frac{[2(1-\delta)-C_1(2-\delta)+c_2]^2}{16(2-\delta)(1-\delta)}$.

(A2) If $\frac{c_2(4-\delta-\delta^2)+2\delta(1-\delta)^2}{(3-\delta)(2-\delta)\delta} \le C_1 \le \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, then $w_1^* = \frac{2(1-\delta)\delta+c_2(1+\delta)}{(3-\delta)\delta}$, $\Pi_1^{A2} = \frac{(\delta-c_2)[2-2\delta-C_1(3-\delta)]}{2(3-\delta)^2\delta} + \frac{(\delta-c_2)c_2(1+\delta)}{2(3-\delta)^2\delta^2}$.

(A3) If $C_1 \le \frac{c_2(4-3\delta)-2(1-\delta)\delta}{(2-\delta)\delta}$, then $w_1^* = \frac{c_2}{\delta}$, $\Pi_1^{A3} = \frac{(\delta-c_2)(c_2-C_1\delta)}{2\delta^2}$, $d_1 = \frac{\delta-c_2}{2\delta}$ and $d_2 = 0$. This case is dominated by strategy NR because $\Pi_1^{A3} < \Pi_1^{NR}$.

Case B ($\frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta} \le w_1 \le 1$): $\Pi_1 = \max_{w_1 \ge C_1} \frac{1+\delta-w_1-c_2}{4(1+3\delta)}(w_1 - C_1)$

(B1) If $\frac{1+2\delta-7\delta^2+(3+7\delta)c_2}{1+5\delta} \le C_1 \le 1-\delta+c_2$, then $w_1^* = \frac{1+C_1+\delta-c_2}{2}$, $\Pi_1^{B1} = \frac{(1-C_1+\delta-c_2)^2}{16(1+3\delta)}$.

(B2) If $C_1 \le \frac{1+2\delta-7\delta^2+(3+7\delta)c_2}{1+5\delta}$, then $w_1^* = \frac{1+4\delta-\delta^2+c_2(1+\delta)}{1+5\delta}$, $\Pi_1^{B2} = \frac{(\delta-c_2)[1+4\delta-\delta^2-C_1(1+5\delta)+c_2(1+\delta)]}{2(1+5\delta)^2}$.

(B3) If $C_1 \ge 1-\delta+c_2$, then $w_1^* = 1$, $\Pi_1^{B3} = \frac{(\delta-c_2)(1-C_1)}{4(1+3\delta)}$.

Case C ($\frac{2(1-\delta)}{3-\delta} + \frac{(1+\delta)c_2}{(3-\delta)\delta} \le w_1 \le \frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}$): $\Pi_1 = \max_{w_1 \ge C_1} \frac{1-w_1}{2(1+\delta)}(w_1 - C_1)$

(C1) If $\frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta} \le C_1 \le \frac{1+3\delta-2\delta^2+2c_2(1+\delta)}{1+5\delta}$, then $w_1^* = \frac{1+C_1}{2}$, $\Pi_1^{C1} = \frac{(1-C_1)^2}{8(1+\delta)}$.

(C2) If $C_1 \ge \frac{1+3\delta-2\delta^2+2c_2(1+\delta)}{1+5\delta}$, then $w_1^* = \frac{1+4\delta-\delta^2+(1+\delta)c_2}{1+5\delta}$, $\Pi_1^{C2} = \Pi_1^{B2}$.

(C3) If $C_1 \le \frac{(1-3\delta)\delta+2c_2(1+\delta)}{(3-\delta)\delta}$, then $w_1^* = \frac{2(1-\delta)\delta+(1+\delta)c_2}{(3-\delta)\delta}$, $\Pi_1^{C3} = \Pi_1^{A2}$.

Lastly, we obtain D1's strategy by comparing profits across all cases, which is illustrated in Table 6. The two sets of solution associated with strategy R2 in Table 6 correspond to (B1) and (B3), respectively. Lemma 2 follows because $\Omega_{R2}^{\bar{C}T} = \Omega_{2-1}^{\bar{C}T} \cup \Omega_{2-2}^{\bar{C}T}$. □

Proof of Proposition 1

To prove part (a), note that $\Pi_1^{\bar{C}T} > \Pi_1^{\bar{C}\bar{T}}$ only when $k^{\bar{C}T} = 1$. According to the proof of Lemma 1, $\Pi_1^{\bar{C}\bar{T}} = \frac{(1-c_1)^2}{4}$. Let us consider Strategy R2-2 in Table 6: for $\forall (c_1, c_2, \delta, \eta) \in \Omega_{2-2}^{\bar{C}T}$, $\Pi_1^{\bar{C}T} = \frac{(\delta-c_2)(1-c_1-\eta)}{4(1+3\delta)} > \Pi_1^{\bar{C}\bar{T}}$ if and only if $\frac{2+5\delta+c_2-\sqrt{(\delta-c_2)(\delta-4\eta-12\delta\eta-c_2)}}{2(1+3\delta)} \le c_1 \le \frac{2+5\delta+c_2+\sqrt{(\delta-c_2)(\delta-4\eta-12\delta\eta-c_2)}}{2(1+3\delta)}$. For example, let $c_1 = \frac{2+5\delta+c_2}{2(1+3\delta)}$, $\eta = \frac{\delta}{16}$, and $c_2 = \frac{\delta}{4}$. The above condition can be satisfied. Nevertheless, one can show that $\Pi_1^{\bar{C}T} \le \Pi_1^{\bar{C}\bar{T}}$ for $\forall (c_1, c_2, \delta, \eta) \in \Omega_{2-1}^{\bar{C}T}$.

Similar to part (a), part (b) only holds when $k^{\bar{C}T} = 1$. It is easy to verify that $\Pi_F^{\bar{C}T} > \Pi_F^{\bar{C}\bar{T}}$, $\Pi_{SC}^{\bar{C}T} > \Pi_{SC}^{\bar{C}\bar{T}}$, and $d_1^{\bar{C}T} + d_2^{\bar{C}T} > d_1^{\bar{C}\bar{T}} + d_2^{\bar{C}\bar{T}}$ when $\delta = \frac{9}{10}$, $c_1 = \frac{2+5\delta+c_2}{2(1+3\delta)}$, $\eta = \frac{\delta}{16}$, and $c_2 = \frac{\delta}{4}$.

Table 7 Optimal Strategy and Solutions in Model C$\bar{T}$

Strategy	$k^{C\bar{T}}$	$p_1^{C\bar{T}}$	$p_2^{C\bar{T}}$	$d_1^{C\bar{T}}$	$d_2^{C\bar{T}}$	$\Pi_F^{C\bar{T}}$
R1	1	$\frac{1+c_1+\eta}{2}$	$\frac{c_2+\delta}{2}$	$\frac{1-c_1-\eta-\delta+c_2}{2(1-\delta)}$	$\frac{\delta(c_1+\eta)-c_2}{2(1-\delta)\delta}$	$\frac{(1-c_1-\eta-\delta+c_2)^2}{4(1-\delta)}+\frac{(\delta-c_2)^2}{4\delta}$
R2	1	$\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)}$	$\frac{\delta(c_1+c_2+2\delta+\eta}{1+3\delta}$	$\frac{1-c_1-\eta+\delta-c_2}{2(1+3\delta)}$	$d_1^{C\bar{T}}$	$\frac{(1-c_1-\eta+\delta-c_2)^2}{4(1+3\delta)}$
NR	0	$\frac{1+c_1}{2}$	–	$\frac{1-c_1}{2}$	–	$\frac{(1-c_1)^2}{4}$

$\Omega_{R1}^{C\bar{T}}=\left\{(c_1,c_2,\delta,\eta)\middle|\frac{\sqrt{(1-\delta)\eta(2\delta-2c_2+\eta)}+c_2-\eta}{\delta}<c_1<\frac{c_2(1+\delta)}{2\delta}+\frac{1-\delta-2\eta}{2}\right\}$
$\Omega_{R2}^{C\bar{T}}=\{(c_1,c_2,\delta,\eta)\,\big|c_1\geq\max\left\{\frac{c_2(1+\delta)}{2\delta}+\frac{1-\delta-2\eta}{2},\frac{2\delta+\eta+c_2-(\delta-c_2-\eta)\sqrt{1+3\delta}}{3\delta}\right\}$
$\Omega_{NR}^{C\bar{T}}=\{(c_1,c_2,\delta,\eta)\,\big|(c_1,c_2,\delta,\eta)\in\Omega-\Omega_{R1}^{C\bar{T}}-\Omega_{R2}^{C\bar{T}}\}$

Table 8 Optimal Strategy and Solutions in Model CT

Strategy	k^{CT}	w_1^{CT}	w_2^{CT}	d_1^{CT}	d_2^{CT}	Π_F^{CT}	Π_R^{CT}
R1	1	$\frac{1+c_1+\eta}{2}$	$\frac{c_2+\delta}{2}$	$\frac{1-c_1-\eta-\delta+c_2}{4(1-\delta)}$	$\frac{\delta(c_1+\eta)-c_2}{4(1-\delta)\delta}$	$\frac{(1-c_1-\eta-\delta+c_2)^2}{8(1-\delta)}+\frac{(\delta-c_2)^2}{8\delta}$	$\frac{\Pi_F^{CT}}{2}$
R2	1	w_1*	$\frac{1+c_1+\eta+\delta+c_2}{2}-w_1$	$\frac{1-c_1-\eta+\delta-c_2}{4(1+3\delta)}$	d_1^{CT}	$\frac{(1-c_1-\eta+\delta-c_2)^2}{8(1+3\delta)}$	$\frac{\Pi_F^{CT}}{2}$
NR	0	$\frac{1+c_1}{2}$	–	$\frac{1-c_1}{4}$	–	$\frac{(1-c_1)^2}{8}$	$\frac{\Pi_F^{CT}}{2}$

*: w_1 must satisfy $w_1\in\left[\frac{1+4\delta-\delta^2+(c_1+\eta+c_2)(1+\delta)}{2(1+3\delta)},\min\left\{\frac{1+\delta+c_1+\eta+c_2}{2},1\right\}\right]$

$\Omega_S^{CT}=\Omega_S^{C\bar{T}}$ for $\forall S\in\{R1,R2,NR\}$

Last, we prove part (c). According to Lemma 1, $\Omega_{NR}^{\bar{C}\bar{T}}=\Omega$, $d_1^{\bar{C}\bar{T}}=\frac{1-c_1}{2}$, $d_2^{\bar{C}\bar{T}}=0$, and $\Pi_1^{\bar{C}\bar{T}}=\Pi_F^{\bar{C}\bar{T}}=\Pi_{SC}^{\bar{C}\bar{T}}=\frac{(1-c_1)^2}{4}$ for $\forall(c_1,c_2,\delta,\eta)\in\Omega$. According to Lemma 2, $d_1^{\bar{C}T}=\frac{1-c_1}{4}$, $d_2^{\bar{C}T}=0$, $\Pi_1^{\bar{C}T}=\Pi_F^{\bar{C}T}=\frac{(1-c_1)^2}{8}$, $\Pi_R^{\bar{C}T}=\frac{\Pi_1^{\bar{C}T}}{2}$, and $\Pi_{SC}^{\bar{C}T}=\Pi_1^{\bar{C}T}+\Pi_R^{\bar{C}T}=\frac{3(1-c_1)^2}{16}$ for $\forall(c_1,c_2,\delta,\eta)\in\Omega_{NR}^{\bar{C}T}\subset\Omega$. Thus, Proposition 1(c) follows. □

Proof of Proposition 2

Similar to Lemma 1, we obtain the firm's optimal strategies in Model C$\bar{T}$ (as summarized in Table 7) and in Model CT (as summarized in Table 8). Note that, by definition, $\Pi_R^{C\bar{T}}=0$ for $\forall(c_1,c_2,\delta,\eta)\in\Omega$. By comparing Table 7 with Table 8, Propositions 2(a) and 2(b) follow. □

Proof of Proposition 3

To show Proposition 3(a), we only need to compare the results derived from Lemma 1 with those in Table 7. According to Lemma 1, $\Pi_1^{\bar{C}\bar{T}}=\Pi_F^{\bar{C}\bar{T}}=\frac{(1-c_1)^2}{4}$, $d_1^{\bar{C}\bar{T}}=\frac{(1-c_1)^2}{2}$, and $d_2^{\bar{C}\bar{T}}=0$ for any $\forall(c_1,c_2,\delta,\eta)\in\Omega$. Thus, it is easy to prove that $\Pi_F^{C\bar{T}}\geq\Pi_F^{\bar{C}\bar{T}}$ and $d_1^{C\bar{T}}+d_2^{C\bar{T}}\geq d_1^{\bar{C}\bar{T}}+d_2^{\bar{C}\bar{T}}$ for $\forall(c_1,c_2,\delta,\eta)\in\Omega$.

Moreover, $d_1^{C\bar{T}}<d_1^{\bar{C}\bar{T}}$ only occurs when $k^{C\bar{T}}=1$. One can show that $d_1^{C\bar{T}}<d_1^{\bar{C}\bar{T}}$ when $(c_1,c_2,\delta,\eta)\in\Omega_{R1}^{C\bar{T}}$ and $c_1\leq\frac{c_2-\eta}{\delta}$ or $(c_1,c_2,\delta,\eta)\in\Omega_{R2}^{C\bar{T}}$ and $c_1\geq\frac{2\delta+\eta+c_2}{3\delta}$. For example, letting both c_2 and η be sufficiently small (close to 0) and c_1 be sufficiently large (close to 1), we have $d_1^{C\bar{T}}<d_1^{\bar{C}\bar{T}}$ for any δ.

To show Proposition 3(b), we only need to compare the results in Table 6 with those in Table 8. Next, we show that there exists $(c_1,c_2,\delta,\eta)\in\Omega_{Re}^{CT}$ such as $\Pi_{SC}^{CT}<\Pi_{SC}^{\bar{C}T}$. We consider when c_1 is sufficiently large such that $(c_1,c_2,\delta,\eta)\in\Omega_{R2}^{CT}\cap\Omega_{2-2}^{\bar{C}T}$. In such a case, $\Pi_{SC}^{CT}=\Pi_F^{CT}+\Pi_R^{CT}=\frac{3(1-c_1-\eta+\delta-c_2)^2}{16(1+3\delta)}$ and $\Pi_{SC}^{\bar{C}T}=\Pi_1^{\bar{C}T}+\Pi_2^{\bar{C}T}+$

Table 9 Optimal Strategy and Solutions in Model CM

Strategy	k^{CM}	Condition	d_1^{CM}	d_2^{CM}	Π_F^{CM}	Π_R^{CM}
R2	1	$c_1+\eta \geq \max\left[\frac{c_2}{\delta}, \frac{c_2+\delta\eta+\eta-(\delta-c_2-\eta)\sqrt{1+\delta}}{\delta}\right]$	$\frac{1+\delta-c_1-c_2-\eta}{4(1+\delta)}$	d_1^{CM}	$\frac{(1+\delta-c_1-c_2-\eta)^2}{8(1+\delta)}$	$\frac{\Pi_F^{CM}(1-\delta)}{2(1+\delta)}$
NR	0	$c_1+\eta < \max\left[\frac{c_2}{\delta}, \frac{c_2+\delta\eta+\eta-(\delta-c_2-\eta)\sqrt{1+\delta}}{\delta}\right]$	$\frac{1-c_1}{2}$	$-$	$\frac{(1-c_1)^2}{4}$	$-$

Table 10 Optimal Strategy and Solutions in Model CN

Strategy	k^{CN}	d_1^{CN}	d_2^{CN}	Π_F^{CN}	Π_R^{CN}
R1	1	$\frac{2-2\delta-(2-\delta)(c_1+\eta)-c_2}{4(1-\delta)}$	$\frac{c_2-\delta(c_1+\eta)}{4(1-\delta)\delta}$	$\frac{[\delta(c_1+\eta)-c_2]^2+2(1-\delta)\delta(1-c_1-\eta)^2}{8(1-\delta)\delta}$	$\frac{(c_2-\delta(c_1+\eta))^2}{16(1-\delta)\delta}$
R2	1	$\frac{1-c_1-c_2+\delta-\eta}{2(1+4\delta-\delta^2)}$	d_1^{CN}	$\frac{(1-c_1-c_2+\delta-\eta)^2}{4(1+4\delta-\delta^2)}$	$\frac{\Pi_F^{CN}(1-\delta)\delta}{1+4\delta-\delta^2}$
NR	0	$\frac{1-c_1}{2}$	$-$	$\frac{(1-c_1)^2}{4}$	$-$

$\Omega_{R1}^{CN} = \left\{(c_1,c_2,\delta,\eta) \,\middle|\, \max\left\{\frac{c_2}{\delta}-\eta, \frac{\sqrt{2(1-\delta)\eta(\delta(2-\eta)-2(c_2-\eta))}+c_2-(2-\delta)\eta}{\delta}\right\} \leq c_1 \leq 1-\frac{(1+\delta)(\delta-c_2)}{(3-\delta)\delta}-\eta\right\}$

$\Omega_{R2}^{CN} = \left\{(c_1,c_2,\delta,\eta) \,\middle|\, c_1 \geq \max\left\{1-\frac{\left(\sqrt{1+4\delta-\delta^2}+1\right)(\delta-c_2-\eta)}{(4-\delta)\delta}, 1-\frac{(1+\delta)(\delta-c_2)}{(3-\delta)\delta}-\eta\right\}\right\}$

$\Omega_{NR}^{CN} = \{(c_1,c_2,\delta,\eta)\,|(c_1,c_2,\delta,\eta)\in\Omega-\Omega_{R1}^{CN}-\Omega_{R2}^{CN}\}$

$\Pi_R^{\bar{C}T} = \frac{(\delta-c_2)(1-c_1-\eta)}{4(1+3\delta)}+\frac{(\delta-c_2)^2}{8(1+3\delta)}+\frac{\delta^2}{16(1+3\delta)}$. One can show that $\Pi_{SC}^{CT} < \Pi_{SC}^{\bar{C}T}$ when $c_1 > \frac{\delta-c_2+3(1-\eta)+\sqrt{\delta^2+4c_2\delta-2c_2^2}}{3}$ or $c_1 < \frac{\delta-c_2+3(1-\eta)-\sqrt{\delta^2+4c_2\delta-2c_2^2}}{3}$. For example, letting η and c_2 be sufficiently small (close to 0) while δ and c_1 be sufficiently large (close to 1), the above conditions and results hold. □

Proof of Proposition 4

First, we derive the equilibrium in Model CM. If $k=0$, then the problem is reduced to Model C$\bar{\text{T}}$ with $k=0$. Thus, $\Pi_F^{CM}=\Pi_{SC}^{CM}=\frac{(1-c_1)^2}{4}$, $d_1=\frac{1-c_1}{2}$, and $d_2=0$. If $k=1$, then the retailer's problem is $\Pi_R^{CM}=\max\limits_{p_1}(1-\frac{p_1-p_2}{1-\delta})\cdot(p_1-w_1)$, such that *s.t.* $\frac{\delta p_1-p_2}{(1-\delta)\delta}\leq 1-\frac{p_1-p_2}{1-\delta}$ and $p_1\geq w_1$. Similar to Lemma 1, we obtain the retailer's optimal strategies in Model CM:

If $w_1\leq\min\left(\frac{p_2}{\delta},-\delta+p_2+1\right)$, then $d_1=\frac{-\delta+p_2-w_1+1}{2(1-\delta)}$, $d_2=\frac{\delta(-\delta+p_2+w_1+1)-2p_2}{2(1-\delta)\delta}$, and $\Pi_R=\frac{(-\delta+p_2-w_1+1)^2}{4(1-\delta)}$.
If $\frac{p_2}{\delta}\leq w_1\leq\frac{(1-\delta)\delta+(\delta+1)p_2}{2\delta}$, then $d_1=d_2=\frac{\delta-p_2}{2\delta}$ and $\Pi_R=\frac{(\delta-p_2)((\delta+1)p_2+\delta(-\delta-2w_1+1))}{4\delta^2}$.
If $-\delta+p_2+1\leq w_1\leq\frac{(1-\delta)\delta+(\delta+1)p_2}{2\delta}$, then $d_1=\frac{-\delta+p_2-w_1+1}{1-\delta}$, $d_2=\frac{\delta w_1-p_2}{(1-\delta)\delta}$, and $\Pi_R=0$.

The firm's problem is $\Pi_F^{CM}=\max\limits_{w_1,p_2}d_1(w_1-c_1-\eta)+d_2(p_2-c_2)$ subject to $d_2\leq d_1$ and $d_1+d_2\leq 1$, where d_1 and d_2 are defined in the retailer's optimal strategies. Similar to Lemma 1, we obtain the firm's optimal strategies in Model CM (as summarized in Table 9).

Second, we derive the equilibrium in Model CN. If $k=0$, then the problem is reduced to Model C$\bar{\text{T}}$ with $k=0$. If $k=1$, then the retailer's problem is $\Pi_R^{CN}=\max\limits_{p_2}\frac{\delta p_1-p_2}{(1-\delta)\delta}\cdot(p_2-w_2)$, such that *s.t.* $\frac{\delta p_1-p_2}{(1-\delta)\delta}\leq 1-\frac{p_1-p_2}{1-\delta}$ and $p_2\geq w_2$. And the firm's problem is $\Pi_F^{CN}=\max\limits_{p_1,w_2}d_1(p_1-c_1-\eta)+d_2(w_2-c_2)$ subject to $d_2\leq d_1$ and $d_1+d_2\leq 1$. Similar to Model CM, we obtain the firm's optimal strategies in Model CN (as summarized in Table 10).

Propositions 4(a) and 4(c) can be shown by comparing Table 9 with Table 10. To show Proposition 4(b), we consider $(c_1,c_2,\delta,\eta)\in\Omega_{Re}^{CM}\cap\Omega_{NR}^{CN}$. In such a case, $d_1^{CM}+d_1^{CM}>d_1^{CN}+d_1^{CN}$ if and only if $\eta<c_1\delta-c_2$,

and $\Pi_{SC}^{CM} > \Pi_{SC}^{CN}$ if and only if $\eta < c_1\delta - c_2$. Thus, let $\eta = c_2 = 0$, $c_1 = \frac{1}{3}$, and $\delta = \frac{1}{2}$. It is easy to verify that $(c_1, c_2, \delta, \eta) \in \Omega_{Re}^{CM} \cap \Omega_{NR}^{CN}$ and $\eta < c_1\delta - c_2$. $\square$

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