The optimal pricing for a trade-in program in remanufacturing supply chain

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Abstract. We develop a model to investigate the optimal pricing for a trade-in program in remanufacturing supply chain. Customer choice behavior is introduced, and the generalized Nash bargaining framework is adopted to model the sale agent’s trade-in program in the business-to-business (B2B) market. Moreover, we analyze the impacts of bargaining power of customers on equilibrium decisions and firm profits.

1. Introduction
A trade-in program is an arrangement in which customers purchase a new product at a reduced price by returning an old product [1], and it is a popular approach to expanding product sales and stimulating market demand [2,3]. For example, Apple provides trade-in programs both in-store and online to encourage customers to exchange used products for credits to purchase new iPads, iPhones and Macs [4]. In China, Suning, JD.com and other online retailers offer digital products, computers, televisions, and other home appliances for trade-in programs. Other examples can be found on a wide variety of company websites, ranging from the highly desirable luxury durable goods manufacturers such as Audi, BMW, and Mercedes-Benz to the producers of the quasi-durable goods like HP, IBM, and Xerox [5].

Recently, with the increase in the acceptance of remanufactured products and supported by the push-up policy, the remanufacture of used products has become an important production activity for many companies. As the remanufacturing industry and trade-in strategy continue to grow, but the retailers/sale agents are strongly opposed to the presence of remanufacturing products, thus the optimal pricing policy for a trade-in program is an important question.

In this paper, we develop a model for this scenario: the OEM produces both the new and remanufactured products, and the sale agent is responsible for sales of the remanufactured products and launch a trade-in program.

2. Literature Review
Our model is most closely related to the literature on trade-in rebates in durable goods markets. The literature on trade-in rebates originates in the general theory of the durable goods. Prior studies pay...
close attention to the effects of the trade-in rebates in durable goods markets. Zhu et al. [6] argued that trade-in rebates can improve an original equipment manufacturer’s competitive position in a duopoly. Rao et al. [7] demonstrated that trade-in rebates can alleviate the inefficiencies arising from the lemon problem. Zhu et al. [8] and Kim et al. [9] investigated the effects of trade-in programs on customers’ willingness to pay (WTP). In addition to the above basic research, some researchers have examined pricing policy and the optimal decisions under different scenarios. Li et al. [10] studied trade-in programs in B2B markets where trade-in rebates are granted up front. Ray et al. [11] took age-dependent revenues into account, provided firms with insights to determine the optimal price and trade-in rebates. Yin and Tang [1] and Yin et al.[3] analyzed a two-period dynamic game to determine the optimal price and trade-in decisions by strategic consumers given the absence/presence of an upfront fee. Chen [12] considered three trade-in policies by optimizing pricing and/or trade-in rebates.

The aforementioned studies obtained some interesting findings for firms with trade-in programs. However, most of them do not consider the relationship between trade-in and remanufacturing. In recent years, trade-in programs have become firms’ main strategy to acquire used products for repair, remanufacture and recycling. Agrawal et al. [13] analyze when and how the OEM should provide trade-in program. Zhang et al. [4] investigated the effect of consumers’ purchase behavior on the economy and environment under a trade-in program with remanufacturing. Agrawal et al. [14] shows that trade-in program can help firms achieve successful price discrimination and weaken competition from third-party remanufacturers (3PRs). Ma et al. [15] studied firms’ optimal pricing decisions and provide offers a reference for providing “trade old for new” (TON) and “trade old for remanufactured” (TOR) simultaneously. Miao et al. [16] investigated the problem of remanufacturing with trade-ins and analyzed optimal pricing and remanufacturing decisions under the carbon tax policy and the cap and trade program. Xiao [17] studied optimal pricing and production decisions for manufacturers/retailers that adopt an exchange-old-for-new (EON) program.

The above papers regard trade-in programs as an effective recovery method for remanufacturing. Our paper, however, regards trade-in programs as a price discrimination method. This is a significant difference, because the trade-in program in our context is initiated by a sale agent and is operated independently of remanufacturing. In addition, most assumed that the used product is functional and can be resold, and thus has residual value for customers. In our paper, the used product could not be sold in the secondary market and have no residual value for the customers. This represents a significant difference when determining trade-in rebates. Moreover, to the best of our knowledge, only Agrawal et al. [14] and Li et al. [18] took the B2B market’s characteristic into consideration. We extend Agrawal et al. [14]’s model to investigate the optimal pricing for a remanufacturing supply chain that consists of one OEM and one sale agent.

3. Assumptions and Notations
A supply chain that consists of one OEM (the leader, player M), one sale agent (the follower, player S), and consumers (the corporate customers, player C). The OEM sells products through the sale agent. The sale agent can provide trade-in program for consumers.

3.1. Product Life Cycle
The product life duration is one period. After one period of use, the product ceases to provide functionality and use to the consumers. Used products can be either collected for materials recovery or remanufactured.

3.2. Customer Characteristics
Customers are heterogeneous, and each customer buys one unit at most in a period and the size of potential customers is normalized to 1. We set $v$ to represent the customer’s WTP for a new product and assume uniform distribution in $[0,1]$. We set the WTP for a remanufactured product as $\delta v$, where $\delta \in (0,1)$. The above assumptions have been used by many scholars, such as Ferrer et al. [20], Yenipazarli [21] and so on.
When the sale agent offers a trade-in rebate to the customer, we can get a customized final price $p_i(v)$ through a generalized Nash Bargaining Solution (GNBS). The GNBS is appropriate in a B2B context like our setting, which has been shown by Agrawal et al. [14].

We apply the GNBS model to our case as follows. Let $V_i$ represent the payoff from the negotiation over a certain trade-in price $p_i(v)$ for player $i \in (C, S)$. If the players agree on a negotiated price $p_i(v)$, the sale agent’s payoff is given by $V_S = p_i(v) - w_n$; the customer’s payoff is his surplus $V_C = v - p_i(v)$. Let $d_i$ denote the disagreement point for player $i$. When the negotiation breaks down, $d_i = 0$. Then, the outcome of the trade-in price is the solution to $\max_{p_i(v)}(V_C - d_C)^\beta(V_S - d_S)^{(1-\beta)}$, where $\beta \in [0,1]$ is the customer’s bargaining power and $1-\beta$ is the sale agent’s bargaining power.

### 3.3. Selling Price, Wholesale Price and Cost Structure

Let the selling price, wholesale price and unit production cost for a new product be denoted by $p_n$, $w_n$ and $c_n$, respectively. Let $p_r$, $w_r$ and $c_r$ denote the selling price, wholesale price and unit production cost for a remanufactured product, respectively. To guarantee that market demand is nonnegative, our model requires $c_n < 1$ and $c_r < \delta$. Like Agrawal et al. [14], we assume the recycling cost is 0 for every recycled item.

### 3.4. Specification of The Game

Our problem is a single-period game to determine firms’ optimal pricing decisions to maximize their profits. Specifically, the OEM sets the wholesale price and the sale agent optimally sets both the selling price and the customized trade-in price. We begin with customers’ purchasing decisions based on their WTP and then solve for the sale agent’s optimal price decisions. After characterizing the sale agent’s optimal responses to the wholesale prices, we solve the problem of the OEM that maximizes its profits by optimally choosing the wholesale prices. For ease of reference, we summarize the model’s parameters in Table 1.

| Parameters | Description |
|------------|-------------|
| $q_n$, $p_n$ | Production quantity and selling price of the new product, respectively |
| $q_r$, $p_r$ | Production quantity and selling price of the remanufactured product, respectively |
| $q_i$, $p_i(v)$ | Quantity of new products sold through the trade-in program and customized price in the trade-in program |
| $w_n$, $w_r$ | Unit production wholesale price for a new product and unit production wholesale price for a remanufactured product |
| $c_n$, $c_r$ | Unit production cost for a new product and unit production cost for a remanufactured product |
| $v$, $\delta$ | Customer WTP for new product and for a remanufactured product relative to a new product |
| $\beta$, $1-\beta$ | Bargaining power of customers and of the sale agent |
| $d_C$, $d_S$ | Disagreement point for the customer and for the sale agent |

### 4. Model and Solutions

When OEM provides both new and remanufactured products and the sale agent offers a trade-in program. Customers have four choices: buy a new product at the list price, buy a new product through the trade-in program, buy a remanufactured product, or remain inactive.
Lemma 1. Customers with WTP \( v \in \left[ \frac{p_n - p_r}{1 - \delta}, 1 \right] \) buy a new product at the list price. If \( p_r < p_n - w_n + w_r \), customers with WTP \( v \in \left[ \frac{w_n - w_r}{1 - \delta}, \frac{p_n - p_r}{1 - \delta} \right] \) buy a new product through the trade-in program at price \( p^*_r(v, p_r) = (1 - \beta)(1 - \delta)v + \beta(w_n - w_r) + p_r \); customers with WTP \( v \in \left[ \frac{p_r}{\delta}, \frac{w_n - w_r}{1 - \delta} \right] \) purchase a remanufactured product. The demand functions for the three types are given by:

\[
q_n = 1 - \frac{p_n - p_r}{1 - \delta}, q_r = \frac{p_n - p_r}{1 - \delta} - \frac{w_n - w_r}{1 - \delta}, q_r = \frac{w_n - w_r}{1 - \delta} - \frac{p_r}{\delta}.
\]

Lemma 1 characterizes the customer’s choice and product demand functions. From the demand functions, we find that the wholesale price of the new and remanufactured products will have a direct impact on the demand of the remanufactured product. In other words, the OEM can adjust the demand of the remanufactured product through the wholesale price.

As a result, the sale agent’s problem becomes:

\[
\max \Pi_S = (p_n - w_n)q_n + (p_r - w_r)q_r + \int_{\frac{p_r}{\delta}}^{\frac{w_n - w_r}{1 - \delta}} (p^*_r(v, p_r) - w_n)dv
\]

s.t. \( 0 \leq q_r \leq q_n \)

The OEM’s optimization problem can then be expressed as follows:

\[
\max \Pi_M = (w_n - c_r)(q_n^* + q_r^*) + (w_r - c_r)q_r^*
\]

After solving the model, we obtain the equilibrium optimal solutions in Proposition 2, where

\[
A = (1 + \beta)(\beta + \delta + \beta \delta)c_r + \beta(\beta + \delta + 3 \beta \delta)c_r,
\]

\[
B = (1 + \beta)(1 + \beta + \delta + 3 \beta \delta)c_n + \beta(1 + \beta + \delta + 3 \beta \delta)c_r,
\]

\[
F_1 = 4 \delta c_v(-1 + \delta - c_r) - 2(-1 + \delta)\delta c_v + (1 + \delta)c^2_r,
\]

\[
F_2 = -2 \delta c_v^2 - 2(-1 + \beta)(-1 + \delta)\delta c_v + (-1 + \beta(-1 + \delta) - \delta)c^2_r + 4 \delta c_v(1 - \delta + c_r).
\]

Proposition 1. There are two critical values, which define three scenarios that represent the optimal policies as shown in Table A1, where \( l^* = \frac{\delta ((1 + 3 \beta)(-1 + \delta) + (2 + 4 \beta)c_n)}{1 + \beta + \delta + 3 \beta \delta} \) and \( h^* = \frac{\delta(-1 + \delta + 2c_n)}{1 + \delta} \).

Proposition 1 indicates that the unit cost of remanufacturing is crucial to the optimal policy decisions of the supply chain: if \( c_r > h^* \), the OEM does not engage in remanufacturing, i.e., \( q^*_r = 0 \); if \( l^* \leq c_r \leq h^* \), the demand for remanufactured products is less than the new products sold at list price, i.e., \( q^*_n > q^*_r \); and if \( c_r < l^* \), the demand for remanufactured products is equal to the new products sold at list price, i.e., \( q^*_n = q^*_r \).

Corollary 1. Following from Table A1, this Corollary gives the effects of bargaining power of customers on optimal solutions.

| Table 2. The effects of bargaining power of customers on the optimal solutions | Optimal solutions (optimal profits) | \( c_r \geq h^* \) | \( l^* \leq c_r \leq h^* \) | \( c_r < l^* \) |
|---|---|---|---|---|
| \( p^*_1 \) | \( \_ \) | \( \_ \) | \( \_ \) | \( \_ \) |
| \( p^*_2 \) | \( 0 \) | \( 0 \) | \( \_ \) | \( \_ \) |
| \( p^*_r \) | \( \_ \) | \( \_ \) | \( \_ \) | \( + \) |
### Table 2

| Parameter | Value | Value | Value |
|-----------|-------|-------|-------|
| \(w_n\)  | 0     | 0     | –     |
| \(w_r\)  | 0     | 0     | –     |
| \(q_n\)  | +     | +     | +     |
| \(q_r\)  | 0     | 0     | +     |
| \(q_t\)  | +     | +     | –     |
| \(\Pi_n\) | –     | –     | +     |
| \(\Pi_r\) | 0     | 0     | +     |

We can obtain some interesting insights from Table 2:

1. When \(c_r \geq I^*\), the price of new products, the trade-in price and the profits of sale agent decrease with the bargaining power of customers; the quantity of new products and trade-in products increase with the bargaining power of customers; the bargaining power of customers has no impact on the price of remanufacturing products, wholesale prices and the profits of OEM.

2. When \(c_r < I^*\), the price of new products, the price of remanufacturing products, wholesale prices and the quantity of trade-in products decrease with the bargaining power of customers; the trade-in price, the quantity of new products and remanufacturing products, the profits of firms increase with the bargaining power of customers.

### 5. Conclusions

Motivated by the fact that trade-in programs and remanufacturing have been matters of widespread concern in practice, we analyze optimal price strategy of trade-in programs in a decentralized supply chain consisting of one OEM and one sale agent, and analyze the effects of bargaining power of customers on the optimal solutions. We first characterize customer choice behavior based on the consumer’s WTP and develop four supply chain models under four scenarios. Next, we derive the optimal price for each member and compare the firms’ optimal solutions. Our study fill in the gap on the research of trade-in program in B2B market and Supply Chain management. Some interesting findings are obtained: (1) the unit cost of remanufacturing is crucial to the optimal policy decisions of the supply chain. (2) When \(c_r \geq I^*\), the price of new products, the trade-in price and the profits of sale agent increase with the bargaining power of customers; the quantity of new products and trade-in products increase with the bargaining power of customers; the bargaining power of customers has no impact on the price of remanufacturing products, wholesale prices and the profits of OEM. (3) When \(c_r < I^*\), the price of new products, the price of remanufacturing products, wholesale prices and the quantity of trade-in products decrease with the bargaining power of customers; the trade-in price, the quantity of new products and remanufacturing products, the profits of firms increase with the bargaining power of customers.

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### Table A1. Equilibrium optimal solutions

|   | $c_i \geq \hat{c}_i$ | $\hat{c}_i \leq c_i < \hat{\ell}$ | $c_i < \ell$ |
|---|-------------------|--------------------------|------------------|
| $p_i$ | \( \frac{2 + \beta + \delta + 2b\delta + (\beta + \delta)c_i}{2(1 + \beta)(1 + \delta)} \) | \( \frac{4 + 2\beta - \delta + \beta\delta + 2\beta c_i + c_i - \beta c_i}{4 + 4\beta} \) | \( \frac{2 + 3\beta + \beta^2 + \delta + 10\beta\delta + 12\beta^2\delta - \beta\delta^2 - \beta^2}{2(1 + \delta + (2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $p'_i$ | \( \frac{\delta(1 + 2\delta + c_i)}{2(1 + \delta)} \) | \( \frac{1}{4}(3\delta + c_i) \) | \( \frac{\delta(1 + \beta + 2\delta + 11\beta\delta + 12\beta^2\delta + (1 + 3\beta + 2\beta^2)c_i +}{2(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $p''_i$ | \( (1 - \beta)(1 - \delta)v + \beta(w_i^0 - w_i^0) + p_i^* \) | \( (1 - \beta)(1 - \delta)v + \beta(w_i^0 - w_i^0) + p_i^* \) | \( (1 - \beta)(1 - \delta)v + \beta(w_i^0 - w_i^0) + p_i^* \) |
| $w_i$ | \( \frac{1}{2}(1 + c_i) \) | \( \frac{1}{2}(1 + c_i) \) | \( \frac{1 + 2\beta - 7\beta\delta + 10\beta^2\delta - \beta\delta^2 - 3\beta}{2(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $w'_i$ | \( \frac{\delta(\delta + c_i)}{1 + \delta} \) | \( \frac{1}{2}(\delta + c_i) \) | \( \frac{\delta(-\beta - 2\beta^2 + 5\beta\delta + 5\beta^2\delta + (1 + 3\beta + 2\beta^2)c_i +}{1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta)} \) |
| $q_i$ | \( \frac{\beta - \beta c_i}{2 + 2\beta + 2\delta + 2b\delta} \) | \( \frac{\beta(-1 + \delta + c_i - c_i)}{2(1 + \beta)(-1 + \delta)} \) | \( \frac{\beta(1 + \beta + \beta\delta - (1 + \beta)c_i - \beta c_i)}{2(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $q'_i$ | \( 0 \) | \( \frac{-(-1 + \delta)\delta - 2\delta c_i + (1 + \delta)c_i}{4(1 - \delta)\delta} \) | \( \frac{\beta(1 + \beta + \beta\delta - (1 + \beta)c_i - \beta c_i)}{2(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $q''_i$ | \( \frac{-1 + c_i}{2(1 + \beta)(1 + \delta)} \) | \( \frac{-1 + \delta + c_i - c_i}{2(1 + \beta)(-1 + \delta)} \) | \( \frac{1 + \beta - \beta\delta - (1 + \beta)c_i - \beta c_i}{2(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $\Pi_i$ | \( \frac{(1 + \delta + 2b\delta)(-1 + c_i)^2}{8(1 + \beta)(1 + \delta)^2} \) | \( \frac{(-1 + \delta)(2 + (1 + \beta)\delta) + F_i}{16(1 + \beta)(-1 + \delta)\delta} \) | \( \frac{1 + \beta + \beta\delta - (1 + \beta)c_i - \beta c_i}{8(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |
| $\Pi'_i$ | \( \frac{(-1 + c_i)^2}{4(1 + \delta)} \) | \( \frac{\beta(2 - 3\delta + \delta^2) + 2\delta c_i + F_i}{8(-1 + \delta)\delta} \) | \( \frac{1 + \beta + \beta\delta - (1 + \beta)c_i - \beta c_i}{4(1 + \delta + \beta(2 + 6\delta) + \beta^2(1 + 7\delta))} \) |